A SYNOPTIC CLIMATOLOGY OF SOUTH AFRICAN RAINFALL VARIATIONS

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A Thesis Submitted to the Faculty of Science,
University of the Witwatersrand, Johannesburg,
for the Degree of Doctor of Philosophy

Johannesburg, 1986

ABSTRACT

General circulation controls on the annual rainfall cycle and on the inter-annual rainfall variations over the central interior of South Africa are examined. The major type of synoptic system delivering rainfall to the region is one in which circulations at tropical and temperate latitudes are linked through interaction of a westerly trough with a low over tropical Africa. These systems supply 36 per cent of the rainfall and changes in frequency of the systems are major determinants of monthly rainfall departures. Meridional flow is poleward at all levels for these systems such that energy and momentum are transported from tropical to temperate latitudes by the mean circulation. Generation of momentum and energy in the tropics, which force a Hadley Circulation across southern Africa, is a necessary condition for the formation of these systems. The annual rainfall cycle is controlled by the annual cycle of energy release over southern tropical Africa which is dependent upon latitudinal displacements of the Inter-Tropical Convergence Zone. Rainfall anomalies are determined in part by inter-annual variations in tropical energy release. The net toroidal circulation over southern Africa is a Hadley Cell only in the high seasons. In the transitional seasons a Ferrel Circulation is dominant. Two factors account for the changes in the toroidal circulation - stronger forcing of the Hadley Circulation by tropical energy release in the January to March summer and eastward displacements of a standing wave over the subtropical Atlantic Ocean in the transitional seasons. Control of rainfall anomalies by changes in tropical heat release is thus stronger in summer than in the transitional seasons. The Southern Oscillation represents a major control on tropical heat release over Africa. The Southern Oscillation signal is transmitted to southern Africa via the Walker Circulation across the tropical Indian Ocean. The sense of the Walker Circulation changes between summer and the transitional seasons such that control on heat release is stronger in summer. Rainfall anomalies are thus determined to a greater extent by changes to the Walker Circulation in summer than in the transitional seasons.

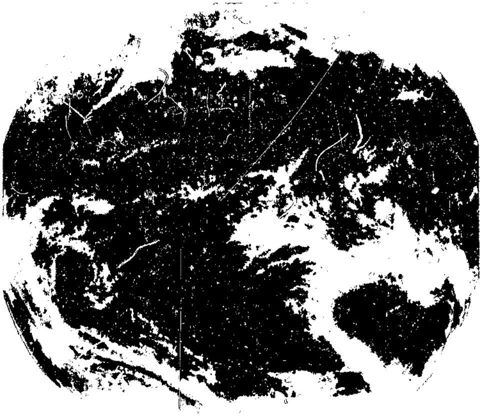
I declare that this thesis is my own, unaided work. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

24 March 1986

To Olwen and Kilda

Isobaric maps of mean pressure do not provide a satisfactory basis for explaining the differences between the summer and winter climates of southern Africa. The normal circulations are similar in the two seasons and there is no marked seasonal change in the direction of the prevailing winds. In order to understand the summer rains and winter droughts it is necessary, as in temperate latitudes, to examine individual synoptic situations. Those with which the summer rains are associated are neither frequent enough nor sufficiently strongly developed to impose a characteristic pattern upon the isobars of mean pressure.

S.P. Jackson, 1952



Frontispiece. METEOSAT image on 22 February 1979 of a tropical-temperate trough with associated cloud band across southern Africa.

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PREFACE

Over few inhabited regions of the globe is rainfall as variable as in the subtropics. Situated below the regions of atmospheric descent in the Hadley and Ferrel Cells the subtropics are semi-arid and desert regions as a whole with sufficient rainfall to support only suitably-adapted life forms. Certain subtropical regions, typically on the eastern sides of the continents and close to warm ocean currents, are favoured with sufficient rainfall to support extensive agriculture and industry. Yet even in these regions rainfall remains distinctly variable from year to year, with periods of abundant rainfall alternating with periods of drought. As population pressure on the available land mounts so there is progressive migration into the more arid regions and attendant increased dependence of the population on changes in the climatic, and in particular in the rainfall, environment.

Widespread attention was first drawn to the impacts of rainfall variations in the African subtropics during the Sahelian drought of the early 1970's, which had severe consequences for a population that had migrated into the region during a decade of abundant rainfall in the 1950's. Insufficient rainfall to adequately support the Sahelian population has continued into the 1980's during which decade severe drought has afflicted the southern African subtropics also The determination of the dynamics of droughts in regions such as the African subtropics represents a major challenge to atmospheric scientists as no exhaustive account of the causes of the droughts over either region of Africa has yet been given. Dynamics of rainfall variations over subtropical southern Africa, and in particular over a region in the central interior of South Africa, form the focus of the study presented in this thesis. Annual average rainfall over the region is of the order of 500 mm - sufficient for dryland farming of crops such as corn in years of normal or above-normal rainfall. Rainfall distributions are, however, such that below-normal rainfall occurs more frequently than above-normal rainfall. Crop failures have occurred regularly in the region during the early years of the 1980's.

The fundamental unit in which the dynamics of rainfall variations may be studied is the synoptic system. In a recent statement the Director of the South African Weather Bureau has expressed the opinion that "it is undoubtedly true that South African weather systems and the associated weather and weather phenomena have as yet not been adequately described". The accuracy of this statement beyond doubt. Dynamic mechanisms forcing the development of convective or stratiform clouds over the subcontinent also remain obscure. Important limitations are therefore present in the level of understanding of the dynamics of rainfall systems over southern Africa and in the manner in which the development of these systems is controlled by the general circulation of the atmosphere so as to produce periods of above- and below-normal rainfall.

Two premises are accepted as a basis for the work covered in this thesis. The first is that study of the origins of the annual rainfall cycle over the subcontinent is a prerequisite to the investigation of the causes of the rainfall variations. The second that the origins of the rainfall variations are inadequately understood and may only be interpreted in terms of circulation variations on the global scale. Investigation of the causes of the rainfall variations is thus made only after examination of the origins of the annual rainfall cycle. In 1952 S.P. Jackson noted that "those (synoptic systems) with which the summer rains are associated are neither frequent enough nor sufficiently strongly developed to impose a characteristic pattern upon the isobars of mean pressure". It is insufficient to study either the annual cycle or the variations in terms simply of the overall circulation. Rather they should be studied in terms of rain-bearing synoptic systems. A classification of synoptic types producing rainfall is therefore developed to act as a pivot around which the annual cycle and the variations are studied and interpreted. Intra-annual and inter-annual variations in the circulation and in the meridional momentum fluxes across the central interior of South Africa are interpreted in terms of changes in frequencies of the major types of synoptic systems to develop models of the general circulation controls on the rainfall cycle and on the variations. Associations between the rainfall and the Southern Oscillation, the major known mode of global circulation variations, are incorporated into the latter model.

Specific objectives pursued are:

a) to define a classification of the various circulation types over the central interior of South Africa;

b) to determine the contributions of rainfall under each circulation type towards the mean annual rainfall and towards the variations;

c) to detail the thermodynamic and kinematic structures and the *meridional momentum* fluxes for the overall atmosphere and for each of the types of systems;

d) to develop a model of the general circulation controls on the annual rainfall cycle over the western Orange Free State;

e) to investigate the changes to the circulation parameters and to the meridional momentum flux accompanying the rainfall variations and hence;

f) to develop models of the general circulation controls on the rainfall variations over the western Orange Free State and,

g) to detail the extent to which the circulation variations are related to the Southern Oscillation.

The thesis is divided into three sections. In Part I the background literature is reviewed and the classification of circulation types developed. The annual cycle of rainfall and the circulation is studied in Part II and a model of the origins of the annual rainfall cycle developed. Rainfall and circulation variations are studied in Part III and dominant circulation controls on the rainfall variations are summarised in appropriate models. The extent to which phase changes of the Southern Oscillation may represent mechanisms forcing the circulation variations is also explored.

During the course of the research sections of the work have been published. Substantial portions of Chapter 2 have appeared in the *Journal of Climatology* and of Chapter 3 in the *South African Geographical Journal*. Part of Chapter 10 has been presented at the *1st International Conference on Southern Hemisphere Meteorology*. Other papers covering relevant work have been published in the *Journal of Climatology* and the *South African Journal of Science* and in the proceedings volumes of the *Seminar on Principal Component Analysis in the Earth Sciences* and the *2nd South African National Hydrology Symposium*. Unpublished presentations of the work were made at six South African conferences.

Many people have assisted me during the various stages of the work and I gratefully acknowledge their contributions. All rainfall and upper-air data were provided by the South African Weather Bureau. Messrs. J.S. van Rhyn, J.A. Koch, E.E. Katsiambirtas and I. Ktorides were responsible either for the quality checks or for the subsequent provision of the data. Several librarians at the Weather Bureau and at the University libraries have provided prompt responses to my many and often unusual requests. Initial programming assistance for the manipulation of the rainfall data bases was provided by Mr. D. Lubinsky and Miss H. Struthers. Miss H. Barron made an invaluable contribution towards the initial interpretation of the satellite images. Throughout, the cartography section of the Geography Department - Mr. P.J. Stickler, Mrs W.A. Job and Mrs. W. van Balderen - produced graphic work of high quality. Discussions with other scientists on various aspects of the work are greatly appreciated. Thanks go to Drs. T.G.J. Dyer, J.J. Taljaard, S.E. Nicholson and M.J. Salinger and to Professors S.P. Jackson, D. Sharon, H. van Loon, M.W. Browne and F.E. Steffens. Other members of the Climatology Research Group and climatology students of the Geography Department provided humour and encouragement and on occasion, albeit sometimes unwittingly, important stimulation. In particular thanks go to Mrs. J.A. Lindesay and Mr. S.A. Harangozo for many discussions and for undertaking parallel research arising out of the results presented in this thesis. Finally to my supervisor, Professor P.D. Tyson, goes my gratitude for his encouragement, for his assistance and for his creation of the opportunity for me to undertake the work. The study has been funded as part of a five-year programme entitled 'The Climatic Change Project' by the National Committee for Weather, Climate and Atmospheric Research of the Council for Scientific and Industrial Research, Pretoria.

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LIST OF SYMBOLS

c_p specific heat at constant pressure
g acceleration due to gravity
L Latent heat
r mixing ratio
T temperature
u zonal component
v meridional component - *northerly, i.e. poleward, components are positive*
w vertical component
x distance in the east-west direction
y distance in the north-south direction
z distance in the vertical direction
ε_d dry static energy ($= c_pT + gz$)
ε_T total static energy ($= c_pT + gz + Lr$)
δ_{ij} Kronecker delta ($= 1$ if $i = j$ or 0 otherwise)
$\overline{}$ temporal average
$'$ deviation from temporal average
[ ] zonal average
$*$ deviation from zonal average

LIST OF ACRONYMS

BEWMEX	Bethlehem Weather Modification Experiment
CSIR	Council for Scientific and Industrial Research, Pretoria
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DST	Data Systems Test
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GHOST	Global Horizontal Sounding Technique
GLAS	Goddard Institute for Space Studies Laboratory for Atmospheric Sciences
GMS	Geosynchronous Meteorological Satellite
IGY	International Geophysical Year
ITD	Intertropical Discontinuity
MIT	Massachusetts Institute of Technology

MONEX	Monsoon Experiment
NATO	North Atlantic Treaty Organisation
NCAR	National Center for Atmospheric Research, Boulder, Colorado
NOAA	National Oceanic and Atmospheric Adminstration
PSCM	Progressive Southerly Cyclonicity Meridional
SHAP	Southern Hemisphere Atmospheric Project
TIROS	Television and Infra-Red Operational Satellite
TWERLE	Television Wind, Energy Conversion and Reference Level Experiment
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WMO	World Meteorological Organisation
WMONEX	Winter Monsoon Experiment

PART I

BACKGROUND AND THE CLASSIFICATION

CHAPTER 1

BACKGROUND

RAINFALL VARIATIONS OVER SOUTH AFRICA

Rainfall over South Africa is a function both of time and space. Well-defined seasonal rainfall regimes are spatially distributed across the subcontinent such that the phase of the annual rainfall cycle over the interior of the country, with its summer maximum, is closely inverse to that over the west coast (Keen and Tyson, 1973; McGee, 1977) (Fig. 2-1). Two approaches have been adopted in the development of statistical descriptions of the variations. In the first the emphasis has been on the temporal rather than on the spatial aspects. Despite numerous investigations into the possibility of trends in the rainfall over the country (e.g. Vorster, 1957; Hofmeyr and Schulze, 1963; Louw, 1965; Brook and Mametse, 1970; Tyson *et al.*, 1975; Onesta and Verhoef, 1976) no evidence has been obtained for the existence of either positive or negative tendencies except, perhaps. over limited regions (Dyer, 1976a). Similarly there are few regions in the entire continent over which defined trends are present (Ogallo, 1979). An alternative hypothesis that the rainfall undergoes quasi-periodic fluctuations as opposed to linear trends has been extensively studied both over South Africa (Schumann and Thompson, 1934; Tyson, 1971, 1980; Tyson *et al.*, 1975; Tyson and Dyer, 1975; Tilbury, 1975; Vines, 1980; Louw, 1982; Kelbe *et al.*, 1983) and over other regions of the continent (Dehsara and Cehak, 1970; Rodhe and Virji, 1976; Dyer and Marker, 1978; Ogallo, 1979; Eckert, 1980; Masson, 1980; Nicholson and Entekhabi, 1985a, 1985b). Quasi-periodicities are certainly present in various areas but generally account for only a small proportion of the variance at each location. In the second approach spatial in addition to temporal characteristics of the variations have been described through the use of either simple statistics (e.g. Schulze, 1965; Louw, 1979a, 1979b; Gillooly and Dyer, 1979; van

Rooy, 1980) or principal component analyses (Dyer, 1975, 1976a, 1979a, 1980a, 1980b, 1981, 1982). Results of the principal component analyses in particular testify to the spatial in addition to the temporal complexities of the fields of the variations and to the dependencies of the fields on rainfall from different types of synoptic systems even across regions with similar mean rainfall cycles.

A unifying objective of many of the statistical investigations has been to provide a foundation for the long-range prediction of rainfall over the subcontinent. About 30 per cent of the variance of the annual rainfall totals over South Africa may be explained by quasi-periodicities of the order of 18 years, a proportion that has proved sufficient to act as a basis for providing estimates of future rainfall tendencies over the interior of the country on time scales of the order of 10 years (Tyson and Dyer, 1975, 1978; Dyer, 1976b, 1977; Dyer and Tyson, 1977). To date these estimates have satisfactorily reflected observations (Lindesay, 1984) but the physical basis for deducing future rainfall tendencies from historical fluctuations has not been defined. Work to formulate an appropriate foundation has begun (Tyson, 1981; Miron and Tyson, 1984). Other statistically-based forecasting techniques promising improved spatial and/or temporal resolution of the prognoses over that provided by Tyson and Dyer (1978) have been partially developed. Techniques include those based on associations of rainfall with surface pressure (Dyer, 1976c, 1979a), sunspot cycles (Dyer and Gosnell, 1978) and temperature (Dyer, 1980c) in addition to further methods based on quasi-periodicities (Katsiambirtas and Louw, 1980; Louw, 1982). No confirmatory studies of the predictions made by any of these techniques have been made.

Various statistical techniques for long-range rainfall prediction have been developed for many areas of the World, the most promising of which are based on teleconnections with atmospheric and oceanographic anomalies in other parts of the globe (Nicholls, 1980). To date only Dyer (1976c, 1979a) has attempted to use teleconnections (with the latitude of the high pressure system off the east coast of Australia) for long-range prediction over South Africa. More detailed models of the general circulation controls on rainfall over southern Africa than presently available are required prior to the development of forecast models based on teleconnections. Ideally such models would incorporate spatial variations on intra- and inter-seasonal scales that are associated with the different types of synoptic systems so that any teleconnections associated with each type of system may be individually identified. Spatial scales of investigations of the circulation changes accompanying the rainfall variations over South Africa have, to date, been restricted to that of the subcontinent in two types of studies. Both the overall circulation changes between wet and dry periods (Rubin, 1956; Triegaardt and Kits, 1963; Hofmeyr and Gouws, 1964; Tyson, 1981; Miron and Tyson, 1984) and the circulations associated with specific rainfall events have been examined. The latter group of analyses include case studies of synoptic situations producing excessive rainfall over short periods (Triegaardt and Kraus, 1957; Triegaardt, 1961a; Estie, 1978, 1981) or extended periods (King and van Loon, 1958; Taljaard, 1981a) or damaging hail (Held, 1977; Held and van den Berg, 1977; Held and Carte, 1979; Kelbe and Garstang, 1986). There are also a few equivalent investigations of the circulation during dry periods (King and van Loon, 1958; Schulze, 1984). No systematic studies of the daily circulation types associated with either dry weather or rainfall over any region of the country have, however, been conducted. It is presently difficult to determine the representativeness of the circulations revealed by the case studies or the manners in which the observed circulation changes reflect the various types of systems associated with rainfall or dry weather. Nor is it possible to ascertain the contributions of the types of systems investigated in the case studies to the mean circulation, to the rainfall or to the circulation and rainfall variations over any given region. Should the use of teleconnections be efficacious for long-range rainfall prediction over southern Africa, as is implied by Dyer's (1976c) results, then the recognition of the major circulation types over the subcontinent and the establishment of their links with the general circulation may provide the basis of an efficient method for the identification of the required predictors. It is towards the development of a suitable synoptic climatology of circulation types, of simple models of the atmospheric dynamics in which the major types are synthesised into the general circulation and of the identification of a teleconnection possibly suitable for prediction of southern African rainfall that the work presented in this thesis is directed.

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HYPOTHESIS AND DATA

The hypothesis on which the thesis is developed is that monthly rainfall totals over the central interior of South Africa increase with enhanced poleward momentum fluxes across the subcontinent. A rationale for this hypothesis is presented in Chapter 5 while its validity is tested in Chapter 10. Formulating the hypothesis in terms of adjustments in one of the fundamental parameters of the general circulation, rather than directly in terms of circulation differences between wet and dry periods, facilitates interpretation of the links between both the cycle of annual rainfall over the central interior of South Africa and the rainfall variations with the global-scale circulation.

Rainfall variations over two regions in the central interior of South Africa are studied. Both regions lie in the Orange Free State, one in the west and the other in the east. The term *rainfall season* is used to refer to the months October to April following Harrison (1983b). For reasons outlined in Chapter 7 the high seasons are defined as *summer*, which refers to the period January to March, and *winter*, which refers to the period July to September. The *autumnal transitional season* includes the months April to June and the *vernal transitional season* the months October to December. Two sets of rainfall data have been used, both supplied after quality checks by the South African Weather Bureau. These include monthly rainfall district data across the country and daily mean rainfall depths estimated from data from 79 stations in both study regions. District data are available from 1921 and data for individual stations from 1946. Both data sets terminate at the end of 1977. Satellite images obtained from polar-orbiting satellites have been published by the United States Department of Commerce (1967-1977). Annual rainfall over the Orange Free State during the 1967 to 1977 period ranged from extremely dry to unusually wet. Upper-air data for all South African stations for the period 1968 to 1977 have been subjected to quality controls by the South African Weather Bureau. Upper-air data are available on a regular daily basis only for the study region in the western Orange Free State, from the station at Bloemfontein (29°6'S, 26°18'E) situated *centrally within the area. All other climatological data have been obtained* from the World Weather Records and the Monthly Climatic Data for the

World (Smithsonian Institute, 1934, 1944, 1947; United States Weather Bureau, 1959, 1966-1968; United States Department of Commerce, 1957-1977).

ANALYSIS TECHNIQUES

Two exploratory techniques for subdividing data sets into orthogonal subsets are employed, namely principal component and harmonic analysis. Principal component analysis is applied to district rainfall data in Chapter 2 in the development of the classification of system types, to the monthly rainfall totals from each type in Chapter 9 to determine the type(s) of system principally responsible for the rainfall variations, and to some indicators of circulation adjustments in the southern African region derived from satellite imagery in Chapter 9 to determine the fundamental modes of the circulation changes that account for the rainfall variations. Seasonal cycles of various parameters are studied through appropriate harmonic analyses of monthly data. These parameters include the rainfall from each type of system in Chapter 3, the basic upper-air circulation variables and the various components of the poleward momentum flux at Bloemfontein in Chapters 4 and 5 respectively, and the circulation and flux variations with rainfall in Chapters 8 and 10.

Principal component analysis is a multivariate technique in which the number of dimensions of a data set is reduced without major loss of information. Frequently there is a major degree of collinearity between the various variables of a data set and principal component analysis is often used as a preliminary filter to reduce associated effects in subsequent analyses. No model is assumed in principal component analysis and thus, in the strictest terms, the extracted components are purely mathematical functions with no guaranteed real physical properties. Experience indicates, however, that the components normally reflect physical properties inherent in the data set. Only a brief outline of the essentials of principal component analysis will be given here. Comprehensiv[illegible]ents may be found in many textbooks including Kendall (1975) a[illegible]dia *et al.* (1979).

The components are linear combinations of the original observations in the data matrix defined such that: a) the first component extracts the maximum variance possible from that of the set; b) the second component extracts the maximum possible of the remaining variance subject to the restriction of orthogonality with the first component; c) all further components extract the maximum possible of the remaining variance subject to the restriction of orthogonality with all higher components. Given n variables within the data set then n components will be created which together retain the complete variance of the set. Often, however, the major proportion of the variance is captured by a relatively small number of the higher components and the remaining components, for most practical purposes, may be discarded. Thus there is a net decrease in the number of dimensions to be considered in addition to the reduction achieved in the problems associated with collinearity amongst the variables. Components may be extracted from the covariance or correlation matrices of the data set. In this study components have been extracted from the correlation matrices.

In n-dimensional space a data set may be viewed as n vectors of varying magnitudes measured as projections on n oblique (i.e. correlated) axes. A new set of n orthogonal *principal axes* is defined from the same origin such that the variance of the data along the first axis representing the first principal component is a maximum. Similarly the second principal axis is selected so that the variance along the axis is a maximum subject to the axis being orthogonal to the first, and so on. The directions of the principal axes are defined by the *eigenvectors* of the covariance or correlation matrix. A simple geometric interpretation of the eigenvectors has been given for the case of a 2 by 2 data matrix in which they are the primary and secondary axes of the ellipse centred at the origin passing through the data points in two-dimensional space (Gould, 1967). In this case the length of either eigenvector is given by the appropriate *eigenvalue*. In the more general case the eigenvalues measure the variance of the data along the eigenvectors and are the roots of the characteristic equation of the appropriate matrix. Calculation of the cosines of the angles between the principal and the original axes produces the *loadings* matrix. When components have been extracted from the correlation matrix the loadings represent the correlations between the principal and the original axes and may be obtained simply by scalar multiplication of the eigenvectors by the square roots of the corresponding eigenvalues. Magnitudes of the loadings for each variable on each component normally facilitate clustering of variables into groups for which there is or is not a high degree of collinearity. Two simple techniques are employed to achieve the clustering of the variables. In the case of the rainfall analyses of Chapter 2 spatial mapping of the loadings is used to permit subjective clustering of the rainfall districts into groups whereas in all other cases clusters are formed from those variables with loadings exceeding an *a priori*-selected value. Projections of the original vectors on the eigenvectors are contained in scores matrix which represents correlations between the components and the observations. Scores are calculated in Chapter 2 where they represent time series of rainfall associated with each component. These time series are employed in Chapters 9 and 10 to obtain correlations of rainfall with other geophysical time series. Computational details of principal component analysis are provided in Appendix A.

Mathematically optimal vectors in n-dimensional space need not necessarily be the outcome of a principal component analysis. Consider the simple case in which the original data set forms two similar clusters in n-dimensional space. Extraction of the maximum possible variance in this event will result in the eigenvector of the first component being directed towards the centre of gravity of the two clusters rather than towards either of the clusters themselves. Rotation of the eigenvectors may be applied to handle this situation and to simplify the interpretation of the components. A discussion of the principals of rotation as developed for factor analysis is provided by Comrey (1973). Rotation of principal components is a valid technique when components have been extracted from the correlation matrix (Browne, 1983). An example of components of South African rainfall prior to and after rotation is given by Dyer (1975). Varimax rotation, introduced by Kaiser (1958), tends to increase high loadings and decrease low loadings. Resultant distribution changes after Varimax rotation have been used to assist the interpretation of the components derived in Chapter 9. Component interpretation in Chapter 2 relies on the spatial distribution rather than on the magnitudes of the loadings and consequently no rotation has been applied.

Harmonic analysis is a technique by which cyclic data may be resolved into *sums* of sine and cosine series. Complete mathematical details of the technique are discussed by Rayner (1971) and Bloomfield (1976) and are summarised in Appendix A. Two applications of harmonic analysis are commonly adopted in meteorology. In the first zonal harmonics are extracted from uniformly-spaced data around a line of latitude. If, for example, the data were 500 mb heights then the zeroth harmonic is the mean height around the zone and the first harmonic represents a single sine curve describing deviations of the heights from the mean, i.e. the displacement of the centre of the polar vortex from the pole itself, and is often referred to as wave 1. Other harmonics similarly represent higher numbers of waves fitted to the data and are referred to as waves 2, 3 and so on. The second application, used in Chapters 3, 4, 5, 8 and 10, fits harmonics to time series at a point. Because monthly data are used in all cases only six harmonics in addition to the zeroth harmonic (i.e. the mean) may be derived. The first harmonic then represents the annual cycle of the parameter, the second harmonic the semi-annual cycle, and so on. Application of either technique runs into interpretation problems when the data may not simply be resolved into harmonics. For example, a harmonic analysis of surface elevations around the Equator would not produce a single harmonic in which the continents may be immediately recognised because these are not uniformly distributed around the globe. Several of the higher harmonics would together describe the disposition of the continents. Despite this problem harmonic analysis, like principal component analysis, remains a valid and valuable technique with which to make instructive exploratory investigations of da a sets.

CHAPTER 2

A GENERALISED CLASSIFICATION OF SOUTH AFRICAN RAIN-BEARING SYNOPTIC SYSTEMS

INTRODUCTION

Classification of circulation types has frequently been adopted in meteorological research as a technique to assist interpretation of the complex flow changes associated with both the mean circulation and its variations over a given region. It is normally assumed in classification approaches that climatic means are reflections of the integrated effects of each circulation type across a number of years while climatic variations are the consequences of associated inter-seasonal frequency adjustments. A further implicit assumption is that the variance of the circulation within each type may to a first approximation be neglected such that climatic averages and variations may be viewed as simple aggregates of the weighted means of each circulation type. Although this latter assumption may not necessarily be valid there is consensus that classifications provide valuable tools for preliminary climatic investigations. An extensive review of the objectives, techniques, applications and problems of the classification approach has been given by Barry and Perry (1973).

Most classifications have been developed in terms of either pressure or flow fields through techniques which emphasise the typical spatial distribution of pressure over a region (e.g. Lund, 1963; Kutzbach, 1967; Brinkmann, 1981), the distribution of pressure systems such as anticyclones and depressions (e.g. Elliott, 1951; Vowinckel and Oosthuizen, 1953; Vowinckel, 1954; van Loon, 1958; Yoshino, 1968; Barry *et al.*, 1981), the direction of the flow over a region in combination with the disposition of synoptic systems (e.g. Barry, 1960; Murray and Lewis, 1966; Lamb, 1972) or the movement of specific types of systems such as cyclones (e.g. Thomas, 1960a, 1960b). Rainfall statistics are subsequently developed and interpreted in terms of the flow represented by each category within the classification. Four pressure field classifications have been developed in southern Africa using surface data alone. Vowinckel (1955a, 1956) subjectively developed models of typical flow fields associated with fine or various types of wet weather across both South Africa (specifically for the Pretoria region) and southern Mozambique (specifically for the Maputo region). Alternatively, using Lund's (1963) objective technique, Longley (1976) identified several dominant circulation types in terms of characteristic 'pattern days' over four sections of South Africa in both the winter and summer seasons. Both the seasonal variation and an indication of the contribution to regional rainfall for each synoptic type are provided by the two classifications for South Africa but in neither case is an indication given of the importance of individual synoptic types in the determination of rainfall anomalies. A fourth scheme, derived originally to facilitate the study of wind power potential along the South African coastline (Diab and Garstang, 1984), has been applied to the study of rainfall over the eastern Transvaal (Diab, 1984). In all schemes the dynamics of each system have not been examined such that the mechanisms producing the associated rainfall remain to be investigated.

An alternative approach to the development of a classification over southern Africa is followed in this Chapter. The upper-air circulation is undoubtedly of critical importance in the control of cloud development over the region but upper-air data are too scarce to be used to formulate a classification. In order to partially bypass this problem the traditional *approach described above is reversed and the rainfall itself is used to* define the classification. Associated circulation fields are subsequently estimated for each category. One disadvantage of this technique is that it is limited to rainfall events - no sub-classification of circulations producing dry weather may be formulated. A classification for the eastern Orange Free State has already been subjectively developed along these lines using a combination of satellite and surface pressure data for one rainfall season in which the prime parameter for inclusion of an event in a particular category was the distribution of cloud over the subcontinent as revealed by METEOSAT imagery (Erasmus, 1980). Surface data were used to ensure similarity of the surface dynamics for each type of system. Monthly statistics of the rainfall and of the tropospheric circulation for each type of system were subsequently deduced.

A technique is employed here in the development of a classification which has major advantages over Erasmus' (1980) method. Satellite imagery is used in combination with a principal component analysis of monthly rainfall fields to develop the classification by identifying those synoptic systems whose spatial cloud and hence rainfall distributions, as revealed by the satellite imagery, matches the spatial loadings fields of the higher components. The inclusion of the principal component analysis in the technique has the potential advantages that the spatial fields are objectively defined and that an estimate of the rainfall variance accounted for at any point by each system may be obtained. Time series of rainfall from each of the classified systems also result from the principal component analysis and the future use of these in the study of the interactions between the systems and the general circulation will be discussed.

ANALYSIS TECHNIQUE

Since the first application of principal component analysis to statistical forecasting (Lorenz, 1956) many meteorological fields have been studied by this technique including Northern Hemisphere 500 mb heights (Craddock and Flood, 1969; Horel, 1981), European and North American surface temperatures (Gray, 1981; Rasmusson *et al.*, 1981) and annual cyclone frequencies over eastern North America (Hayden, 1981). Principal component analysis has frequently been used as a technique for developing objectively-defined classifications of meteorological parameters (e.g. Christensen and Bryson, 1966; Brinkmann, 1981) although, when used in the analysis, rainfall has never solely formed the basis of the classification. Nevertheless increasing attention has been paid in recent years to the study of rainfall through the determination of principal components, usually to form the basis of a subsequent statistical analysis of the spatial and temporal properties of rainfall over a region, to facilitate the study of associations between rainfall fields and the atmospheric circulation or to identify regions with common precipitation characteristics. Principal component analysis, or related techniques, has been applied to the study of rainfall over North America (Stidd, 1967; Kutzbach, 1967; Sellers, 1968; Skaggs, 1975; Willmott, 1977, 1978; Klugman, 1978; Johnson, 1980; Walsh and Mostek, 1980; Diaz and Fulbright, 1981; Diaz, 1981; Walsh *et al.*, 1982; Karl and Koscielny, 1982; Legates and Willmott, 1983; Kim *et al.*, 1984; Granger, 1984), North America and Eurasia (Barnett and Preisendorfer, 1978), the British Isles (Perry, 1970a; Gregory, 1975; Johnston, 1981; Wigley *et al.*, 1984; Logue, 1984; Woodworth, 1985), various parts of Europe (Tabony, 1981; Molteni *et al.*, 1983; Goossens, 1985), Israel (Gabriel, 1972), India and south-east Asia (Gadgil and Iyengar, 1980; Bedi and Bindra, 1980; Rakhecha and Mandal, 1981; Reiter, 1983; Campbell *et al.*, 1983; Cadet and Diehl, 1984; Suppiah and Yoshino, 1984), Hawaii (Lyons, 1982), the global tropics (Kidson, 1975), various sections of north Africa (Aoyade, 1977; Klaus, 1978; Gregory, 1982; Melice and Wendler, 1984), East Africa (Ogallo, 1980), Mauritius (Dennett, 1978), the southern continents (Pittock, 198 , parts of South America (Pittock, 1980; Teixera and Reiter, 1985), Australia (Wright, 1974; Pittock, 1975; Austin and Yapp, 1978; Wigley and Qipu, 1983) and New Zealand (Salinger, 1980). In South Africa principal components have been employed to delimit regions of like precipitation characteristics (Dyer, 1975), to investigate links between rainfall and the general circulation (Dyer, 1979a) and to provide descriptions of rainfall fields and of their properties (Dyer, 1979b, 1980a, 1980b, 1981, 1982; Mather, 1983; Kelbe, 1983; Kelbe *et al.*, 1983).

Two major problems present themselves in any principal component analysis. The first is the selection of the cut-off level below which all subsequent components will be rejected. The second, of particular importance here, is the physical interpretation of the retained components. Frequently some *a priori*-defined numeric value is employed to determine the cut-off level, such as an eigenvalue of unity, as suggested by Kaiser (1960), an explained variance of (say) 90 per cent (used in the present study for the initial retention of components), a specified number of components or a limiting eigenvalue as determined by the scree test (Cattell, 1966). All such techniques, although retaining mathematical consistency, suffer from the imposition of physical arbitrariness. There can be little doubt that the most satisfactory method, but normally the most difficult to apply in practice, is to limit the number of components to those to which a physical interpretation may be attached. This latter approach requires the *a priori* acceptance of the postulate that acceptable physical interpretations of the results of the purely mathematical manipulations, at least for the higher components, may be found. There are no theoretical grounds for, nor indeed any general agreement on, the acceptance of this postulate but experience suggests that it may be true (e.g. Christensen and Bryson, 1966; Kutzbach, 1967; Salinger, 1980). The postulate is accepted here.

In the present case principal component analysis is applied to extract eigenvectors describing spatial patterns of rainfall anomaly distributions. To a certain extent the geographical shape of the area over which data are analysed predetermines the spatial distribution of the loadings on the higher components (Buell, 1975). The loadings fields of the eigenvectors, when mapped, nevertheless delineate clusters of rainfall districts over which rainfall anomalies are coherent. Inspection of the loadings fields and the correlation matrices confirms that the regions of highest loadings on the major components define areas over which rainfall anomalies are well correlated (Sharon, 1983a). Such anomalies represented on a given component are surmised to result from variations in rainfall from a single type of synoptic system whose spatial rainfall distribution matches that of the loadings field of the component. Identification of the system will be simplified if the spatial rainfall distribution remains quasi-constant for all systems of that type and that no other type produces a similar distribution. As will be seen the two conditions are satisfied by the major disturbances over South Africa.

Ideally the analysis should be run on daily rainfall series. Problems of missing and occasionally inaccurate data, not to mention the marked spatial inhomogeneities associated with short-period convective rainfall, however mitigate against this approach. Instead monthly (September to April) district rainfall data for 64 districts across South Africa (Fig. 2-1) for the period 1921 to 1977 have been utilised. These have the advantages of being means taken across a minimum of five representative stations within limited, climatologically-uniform areas defined by the South African Weather Bureau and of being reasonably uniformly distributed across the country. Thus the influences of inaccurate data and of local-scale spatial inhomogeneities, in addition to those resulting from

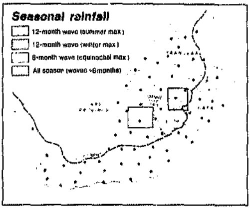


Figure 2-1. Seasonal rainfall distribution across South Africa (after Keen and Tyson, 1973). The dots locate the centres of the 64 South African Weather Bureau rainfall districts for which data were used in the analysis. The Escarpment separates the high interior plateau from the lower-lying coastal regions. Rectangles define the areas of the eastern and western Orange Free State.

non-uniformly distributed data (Karl *et al.*, 1982), are reduced. The price paid for the use of the district data is the loss of information over the far north-east and much of the dry north-west of the country. As the objective is to identify daily circulation features the data have been standardised by district (to a mean of zero and a standard deviation of unity) to eliminate the effects of spatial and locational (e.g. altitude) variations. This approach varies from earlier work on the same data set (using July to June totals for the period 1921 to 1975) in which percentage variations from the means were treated either as raw (Dyer, 1982) or standardised (Dyer, 1981) input to the analyses.

In a study of rainfall over a 2° by 2° block of the eastern Orange Free State it has been demonstrated that monthly rainfall totals could be adequately described by the frequency of rain days alone (Harrison, 1983b). These results have been verified for the western Orange Free State. Thus monthly rainfall totals at any point will be determined simply by the frequency of passage of each type of system. If, during certain months, a given type of system crosses a region rather more or rather less frequently than normal then the change will be reflected in both the resulting rainfall totals and in the correspondingly higher or lower scores of the eigenvector describing the relevant pattern. The identification of the synoptic systems surmised to be represented on each component were consequently deduced by inspecting polar-orbiting satellite imagery during months of unusually high or low scores (defined as deviations in excess of one standard deviation from normal) for an increased or reduced frequency of systems whose rainfall pattern matches the loadings field of the eigenvector.

One further aid was used to assist the identification process. Most eigenvectors include both positive and negative loadings. On a daily basis this indicates that relevant systems producing rainfall over the (say) positive region will most likely be associated with dry weather over the negative region, and *vice versa*. The zero loading isopleth provides a rough indication of the limit of influence of either system notwithstanding any overlap that may occur. A *principle of mutual exclusiveness* of circulation patterns may, in consequence, be proposed. That is, in order for rain from one system to be disassociated with contemporaneous rain from the alternate system, the atmospheric circulation giving rise to the one system should preclude that of the alternate system.

THE CLASSIFICATION

Tropical-temperate troughs

The major component of the September to April period, Component A, accounts for in excess of 35 per cent of the variance in all months (Fig. 2-2). Spatial loadings fields in all months are similar to that of January (Fig. 2- [illegible]). A [illegible]th-west to south-east ridge of high loadings crosses the central interior of the country, with weak and sometimes negative loadings on the south-west coast and relatively weak positive loadings

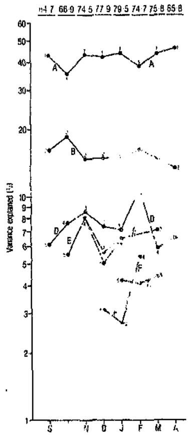


Figure 2-2. Variance (per cent) explained by each component discussed in the text numbered by month. Components given similar physical interpretations are linked and given an identifying letter. The identification of Component E was ambiguous in December. The underlined figures give the variance explained by Components A to F.

over the northern Transvaal and southern and eastern coasts. A weak surface trough of like orientation to that of the major axis of Component A but displaced westward has been detected in summer mean pressure fields. Deepening of the trough appears to coincide with periods of heavier rainfall (Rubin, 1956; Taljaard, 1958; Hofmeyr and Gouws, 1964). The trough is frequently found in daily summer 850 mb height analyses and is normally associated with a well-defined boundary separating moist

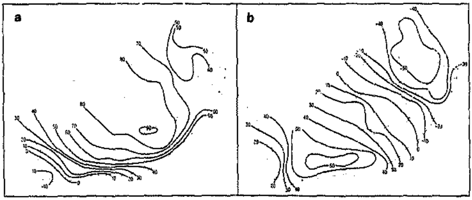


Figure 2-3. a) Loadings ($x10^{-2}$) on the ,irst January component as an example of Component A. b) Loadings ($x10^{-2}$) on the second January component as an example of Component B.

air to the east from dry air to the west. Thunderstorms, which develop preferentially within a 300 km zone extending eastward from the boundary, denoting the zone to be a region of surface convergence (Taljaard, 1958).

No indication of the dynamic nature of the surface trough was available until satellite observations revealed its axis to frequently delineate the western boundary of a band of clouds connecting the tropical cloud masses over central Africa to a temperate cyclone to the south of the continent (Figs. 2-4 and 2-5 and Frontispiece). On such occasions the trough is a surface manifestation of circulations associated with one of several cloud bands distributed around the Southern Hemisphere (Streten, 1973) and marks, according to Johnson (1969), "the strong confluence of the low-level flow into an asymptote of convergence along or on the eastern edge of the band". Mesoscale observations in the eastern Orange Free State have confirmed that the bands develop in regions of marked forced low-level convergence between air flows around two eastward-moving anticyclones in conjunction with a baroclinically-unstable atmosphere. They are often associated with surface cold frontal passage. South African meteorologists have expressed the opinion that fronts rarely invade the interior of the country during the rainfall season months (Triegaardt and Kraus, 1957; Taljaard, 1972).

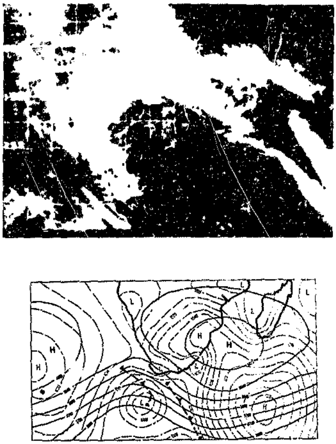


Figure 2-4. Top - TIROS-N image of a truncated trough with associated cloud band terminating at a coastal depression on 21 February 1979. Lower - Surface (over oceans - mb - dashed), 850 mb (over land - gpm - dashed) and 500 mb (gpm - full) corresponding 1200Z analyses adapted from South African Weather Bureau analyses.

Case studies of known fronts, all associated with severe weather conditions, have been provided by Triegaardt and Kraus (1957), Tucker (1971), Held and van den Berg (1977), Estie (1978) and Held and Carte (1979). The eastern Orange Free State observations indicated, however, that the fronts were associated with marked mesoscale wind direction shears but only with relatively small temperature and pressure deviations. Neither of the latter may be readily resolved by conventional synoptic

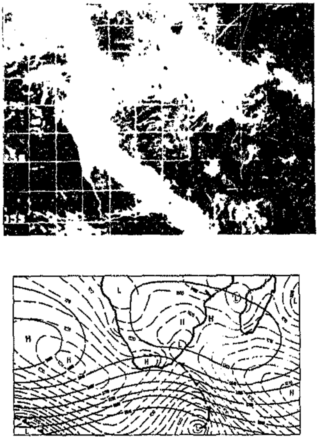


Figure 2-5. As Figure 2-4 but for a tropical-temperate trough with associated cloud band terminating at a temperate cyclone (not seen on satellite image - see Frontispiece) on 22 February 1979.

analyses. Subsequent analyses have suggested that the mean frequency of transit of the bands across the interior of South Africa during the warmer months, and hence of frontal passage, is of the order of once in seven days. This figure is in agreement with results obtained from International Geophysical Year data (van Loon, 1965) and from spectral analyses of daily pressure at South African coastal stations (Preston-Whyte and Tyson, 1973). Surface troughs initially associated with bands may, however, subsequently be replaced by cold-low level highs. Surface circulation features are unreliable guides to the presence of a cloud band. The bands appear to form uniquely, however, on the leading edges of cyclone wave troughs, as indicated by Johnson (1969) and Streten (1973), at times when a tropical low extending throughout much of the troposphere is present over central Africa at about 20°S (Harangozo and Harrison, 1983). In view of the continuity in time and space of the upper-air (rather than the surface) trough systems associated with cloud bands will be titled tropical-temperate troughs. These systems are equivalent to the 'polar trough in the easterlies' discussed by Riehl (1945).

Studies of satellite imagery point to two basic forms taken by tropical-temperate troughs, each producing similar spatial rainfall distributions. In the first (Fig. 2-4) the associated cloud band terminates at a coastal disturbance on the south coast - these systems will be titled truncated troughs; in the second (Fig. 2-5) the connection to the temperate cyclone is complete. The first form frequently precedes the second, as in Figures 2-4 and 2-5. Daily cloud band locations in the vicinity of Africa for the two months of January during the period of the satellite record with the highest and lowest scores on Component A are shown in Figure 2-6. With no allowance made for missing or problematic data bands were present during both months on 23 days with similar frequencies for the months of January in other years. The frequency of band formation is thus independent of rainfall over southern Africa. Marked variations in the locations of the bands and hence of the troughs occur, however, between wet and dry months. During the wet month of January 1974 (Fig. 2-6a) the bands were concentrated over the interior of South Africa, with few in the region of Madagascar. A marked shift in band locations towards the Madagascar region occurred during the dry month of January 1969 (Fig. 2-6b).

Components A and B together explain close to 60 per cent of the total variance in all months (Fig. 2-2). The loadings field of Component B bisects that of Component A into two regions of opposite sign, the zero loading isopleth on Component B (Fig. 2-3b) running approximately along the major axis on Component A (Fig. 2-3a). Equivalent orientations of the two oppositely-loaded regions on Component B to that of the major axis on Component A suggest that Component B might also represent rainfall from tropical-temperate troughs. Bands were frequent over the

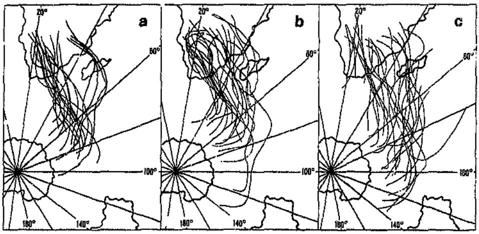


Figure 2-6. Daily central axes of cloud bands estimated from satel' 'magery for a) January 1974; b) January 1969; c) January

western interior during January 1974, a month with a high positive score on Component B and heavy rains over the normally dry Karoo (Taljaard, 1981a) (Fig. 2-6a). In January 1975, with a high negative score on Component B and drought over sections of the Karoo, a much reduced frequency of bands over the western parts occurred (Fig. 2-6c). Conversely the frequency of bands over the eastern interior increased from 1974 to 1975. Component A describes, therefore, the general rainfall associated with the north-west to south-east orientated troughs, whereas Component B differentiates between periods of preferential relocation of the troughs over the subcontinent to the east or to the west of the axis on Component A.

Component C explains a little over four per cent of the variance of the rainfall of the months January to March (Fig. 2-2). The loadings field of this Component (not illustrated) includes four cells of similar orientation to the major axis on Component A. The Component appears to provide further spatial differentiation between trough locations.

Cloud bands, similar to those over South Af are one of the major characteristic features of the Southern H ere circulation visible on most satellite images. Seasonal and annual climatological mean locations

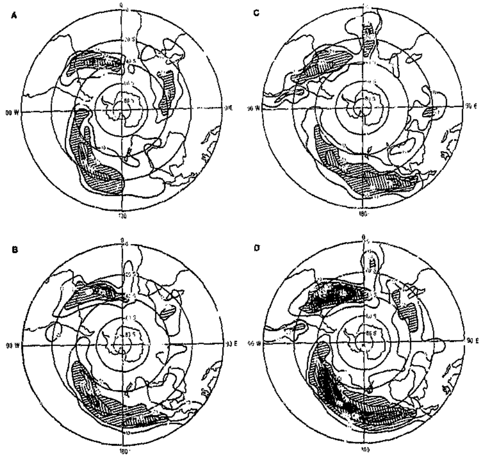


Figure 2-7. Locations of cloud bands over the Southern Hemisphere during the period November 1968 to October 1971 in a) December to March, b) April, May, October and November, c) June to September and d) the year adapted from Streten (1973). Plots were developed from five-day average brightness satellite mosaics and isopleths give percentage frequencies that axes of bands were located within 5° latitude by 10° longitude squares.

of the bands (Fig. 2-7) have been deduced from 5-day average satellite brightness fields by Streten (1973). Band numbers during any given period range between zero and seven but during the austral summer season the most common number is three. Of these three two are normally the quasi-permanent bands, present throughout the year, of the central

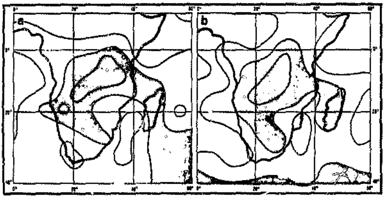


Figure 2-8. Brightness patterns in the southern African region for a) February 1971 and b) February 1969 adapted from Krueger and Winston (1974). Heavy stippling denotes the brightest areas (high cloudiness) and light stippling the darkest areas (low cloudiness).

Pacific and Atlantic Oceans. The band across the Indian Ocean is the only one to undergo a seasonal locational migration, anti-phase to that of the Indian Ocean Anticyclone, between the western ocean in summer and the eastern ocean in winter. Two oceanic regions of band locations appear in Figure 2-7 on either side of South Africa but that in the Atlantic Ocean in winter reflects the sea fog and the stratus decks of the region. Streten (1973) suggests that the Madagascar region is the climatologically-preferred location of the African bands. It should be noted, however, that the period of analysis on which these results are based was a predominantly dry one over southern Africa and as such, as in Figure 2-6, was one in which the bands tended to develop preferentially across Madagascar rather than across the subcontinent. Also indicated in Figures 2-6 and 2-7 is a tendency for the bands and hence the troughs to be bimodally distributed in space off the east coast of southern Africa. The bimodal distribution is well displayed in satellite brightness fields (Fig. 2-8 - cf. also Fig. 3a of Heddinghaus and Krueger, 1981) and has been suggested as a possible cause of the relatively low rainfall over the Limpopo Valley along the northern border of South Africa (Harrison, 1984c).

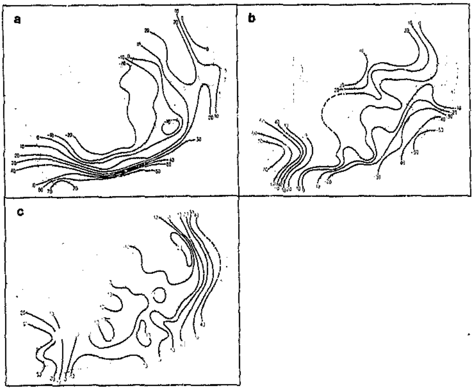


Figure 2-9. a) Loadings ($x10^{-2}$) on the third January component as an example of Component D. b) Loadings ($x10^{-2}$) on the fourth January component as an example of Component E. c) Loadings ($x10^{-2}$) on the sixth January component as an example of Component F.

Coastal depressions

Component D, which may be identified from September to April, reaches peaks of explained variance in November and February (Fig. 2-2). A negatively-loaded area is present in the loadings field of Component D across the central and western interior of the country (Fig. 2-9a). High positive loadings are found along the southern coast, extending to a weak positive area across Natal and the Transvaal. Orography appears to play a role in the definition of the field immediately to the north of the south coast (cf. Fig. 2-1). Rain along the south coast occurs with the passage

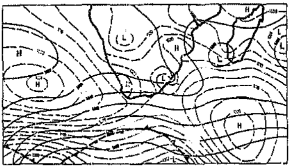


Figure 2-10. As Figure 2-4 but for the coastal depression of 9 February 1979 - a case with more extensive inland cloud than often found.

of coastal depressions ahead of cold fronts and, infrequently, of the front itself. The majority of the cyclonic disturbances are shallow coastal lows but study of the satellite imagery indicates that some of the depressions develop through a significant depth of the troposphere and bring extensive cloudiness and rain onto the interior plateau (Fig. 2-10). Rainfall from bands of cumulonimbus clouds, which on occasion connect the tropical cloud masses with the coastal depressions across the eastern parts of the country, possibly provides a basis for the interpretation of the positive loadings in this area. Coastal lows form in several areas of the world but those along the South African coast are probably the best developed and have been the subject of several theoretical studies (Gill, 1977; Bannon, 1981; Anh and Gill, 1981). Spectral analysis of surface pressures at stations around the South African coast has indicated that the typical frequency of passage of coastal lows along the coast, about once in seven days, remains quasi-constant throughout the year (Preston-Whyte and Tyson, 1973). There are, however, several different types of coastal lows, the typical modes of behaviour of which have been descri' 'd by Estie (1984). The major distinguishing feature between the archetypal coastal lows and the coastal depressions of the present classification appears to be the relative location west of the vortex of the upper-level westerly wave associated with the cold front. Coastal lows are limited in the vertical direction to about the 850 mb level by the subtropical inversion, a consequence of the lack of coupling between the lower vortex and the upper-level wave. Should the phase difference between the lower and upper-level systems be reduced such that the wave overlies the surface low then development may proceed into the upper-troposphere (Estie, 1984; Anonymous, 1984) with the consequent formation of a coastal depression.

Subtropical cyclones

Few discussions of the synoptic situation described by the negative loadings on Component D have appeared in the literature. The region in question is covered by clusters of cumulonimbus clouds extending southward from the tropics. In general the cloud clusters terminate inland from the south coast and develop under conditions in which the surface flow is dominated by an intense cell of high pressure resident on the east coast (Fig. 2-11). A strong low-level flux of moist air is, consequently, present but the South African Weather Bureau 850 mb analyses frequently fail to indicate the presence of any surface disturbance which might explain the rainfall. Upper-level westerly waves are in all instances remote from the continent. On some occasions a cyclonic vortex, normally limited to the upper troposphere, is clearly apparent in the satellite imagery and inspection of radiosonde data has indicated

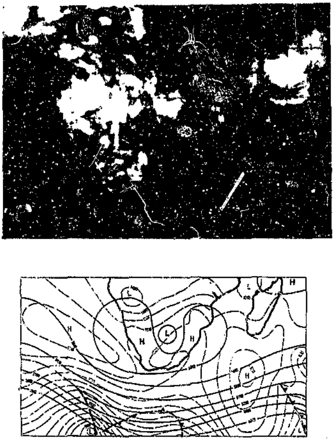


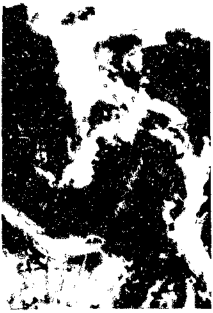
Figure 2-11. As Figure 2-4 but for the subtropical cyclone of 18 January 1976 (NOAA-4 image - note the 24-hour data break at approximately 30°E).

this to be cold cored. This latter property together with the disturbances' tropical origins suggests that the systems may be similar to the summer-time tropical oceanic upper-level cold-cored lows observed over the Atlantic and Pacific Oceans. Sometimes referred to as subtropical cyclones these lows have most recently been discussed by Kousky and Gan (1981), Shimamura (1981, 1982), Kelley and Mock (1982) and Johnson and Snook (1983). If this is the case then their structure may be different from the lows of the tropical circulations at 15 to 20°S which, according to Taljaard (1972), extend throughout much of the troposphere and are cold cored only in the lower layers and warm cored above. The two different types of lows may normally be readily differentiated in the satellite imagery. Subtropical cyclones are associated with heavy rainfall over parts of South Africa - a case study for a system identified in the satellite images as a subtropical cyclone has been given by de Villiers (1977). Heavy falls from 'east wind troughs', which are probably equivalent to subtropical cyclones, tend to be concentrated into the period December to March according to Taljaard (1982a). In February 1972 there may have been an unusual contribution to rainfall on this component when Cyclone Eugenie, one of the rare Indian Ocean tropical cyclones to mount the interior plateau of Africa, provided rainfall with a distribution spatially consistent with the negative region of the loadings field of Component D.

The atmospheric circulation patterns required for the development of the synoptic systems described by Component D conform with the principle of mutual exclusiveness. Coastal depressions and subtropical cyclones are primarily disturbances within the westerly and tropical easterly flows respectively. In synoptic terms development of a coastal depression requires the presence of upper-level divergence as supplied by a westerly wave. The fact that the interior regions are normally devoid of cloud at such times indicates that upper-level convergence must dominate this area. Alternatively subtropical cyclones develop under conditions of upper-level divergence in the tropical easterly flow together with, normally, attendant upper-level convergence over the coastal regions. Displacements of the zone of convergence are reflected in latitudinal adjustments in the location of the upper-level subtropical high.

West coast cyclones

Component E, which may be traced from October to March but for reasons presently not understood does not appear in February, accounts for in excess of 7 per cent of the variance in the outer-season months of November and March (Fig. 2-2). Two major regions of high loadings appear on the component, a primary positive area over the central western Cape coast and a negative area along the Natal coast (Fig. 2-9b). Cyclones



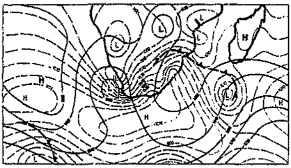


Figure 2-12. As Figure 2-4 but for the west coast cyclone of 30 January 1975 (NOAA-4 Image - note the 24-hour data break at approximately 30°E).

affecting the west coast appear to give rise to the positively-loaded region. These develop either close to the land mass or in the subtropical eastern Atlantic Ocean and, when in the vicinity of the coast, are generally connected by cloud bands to the tropical cloud masses over northern Namibia (Fig. 2-12). Frequently the tropical masses and rainfall extend into the north-eastern portions of the country and possibly account for the positive loadings there. During such sequences the eastern coastal and inland regions tend to remain dry under the influence of a strong cell of high pressure. Studies of the subsequent behaviour of the cyclones indicate that they usually follow courses towards the south-east and head into the southern Indian Ocean with minimal influence on rainfall over other areas of the country. Hence these systems are not to be confused with the coastal depressions described by Component D. There do not appear to be any studies of these or of similar systems either over South Africa or elsewhere in the world.

East coast troughs

Rain over Natal, described by the negative loadings on Component E, falls with the passage of a deep overland surface low pressure system located towards the northern end of a cold front. The clouds associated with such a trough extend into the interior but are separated from the tropical masses to the north (Fig. 2-13). Several case studies of east coast troughs which produced heavy rainfall, including that of van Heerden (1971), have been made.

Whereas mutual exclusiveness on Component D is maintained by a latitudinal differentiation between tropical and temperate disturbances exclusiveness on Component E results from an equivalent primarily longitudinal differentiation. West coast cyclones appear to develop only at times of active tropical convection, an observation suggestive of a dynamic link with the easterlies in their formation. Tropical upper-level divergence is thus present over the western portions of the country at such times, with westerly upper-level convergence associated with the dry weather over the eastern regions. Alternatively, upper-level convergence usually dominates the west coast and divergence associated with a cyclone wave the east coast with the passage of a trough. Longitudinal displacements of the upper-level subtropical high reflect the shift in the zone of convergence.

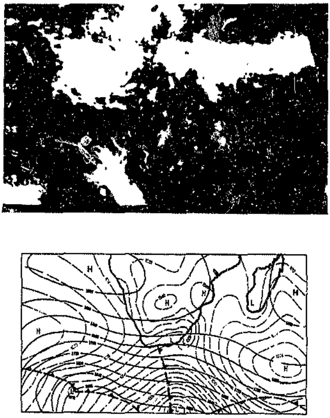


Figure 2-13. As Figure 2-4 but for the east coast trough of 17 March 1979.

Tropical depressions and cyclones

Component F appears only in the months of December to February and is most prominent in the latter month (Fig. 2-2). Except for a belt along the east coast loadings on this component are weak (Fig. 2-9c) and no physical interpretation of the fields over the western areas has been found. Only to the east of roughly the 30°E meridian are relatively high positive loadings found. Inspection of the satellite imagery suggests that rain in this region results from the southbound passage of tropical depressions and cyclones (cf. the rainfall distributions for several tropical

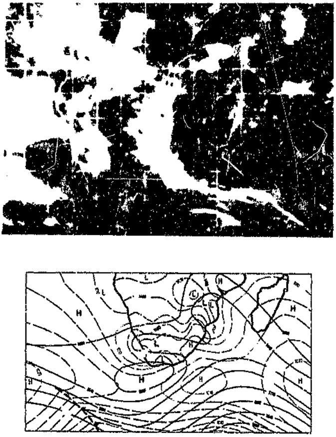


Figure 2-14. As Figure 2-4 but for the tropical cyclone of 30 January 1976 (NOAA-4 image).

cyclones presented by Dunn, 1985) (Fig. 2-14). Suppressed conditions normally dominate the adjacent interior when a tropical cyclone is located over the eastern coastal belt. Tropical cyclones regularly form in the western Indian Ocean during the later austral summer months (Pellatt, 1972; Gray, 1978) but rarely supply rainfall to South Africa itself. Those systems that do affect the continent seldom mount the interior plateau (Sellick, 1958) but re-curve back into the Indian Ocean after brushing the eastern littorial. Although not included in the period studied here the summer of 1983/84 was exceptional in this respect as two cyclones supplied heavy rainfall over southern Mozambique and northern Natal within a short period of January and February 1984 (Poolman and

Terblanche, *1984*; Kovacs *et al.*, 1985). A list of the major cyclones since 1958 that have directly affected South Africa has been provided by Poolman and Terblanche (1984) while case studies of some of these storms have been made by Gouws (1966a) and Quinn (1977). In late February and early March 1978 a remarkable tropical vortex, which initially resembled an overland tropical cyclone in the satellite imagery, travelled south over southern Africa between the 20th and 26th parallels (Kumar, 1977). During the later part of the period the vortex became embedded within a tropical-temperate trough across South Africa.

Cut-off lows

Although not directly incorporated into the classification cut-off lows are also important rain-bearing systems over South Africa. Cut-off lows may be responsible on occasion for heavy rainfall over limited parts of the country, particularly during the transitional seasons (Taljaard, 1982a). Case studies of systems producing exceptional rainfall have been given by le Roux and Taljaard (1952), Triegaardt and Kraus (1957), Stranz and Taljaard (1965), Estie (1981) and Taljaard (1985).

DISCUSSION

A generalised classification of the major synoptic systems responsible for rainfall over South Africa has been developed and is summarised in Figure 2-15. Tropical-temperate troughs with associated cloud bands connecting the tropical cloud masses to temperate cyclones are the most important contributors to rainfall over the interior of the country, as also over Zimbabwe (Smith, 1985). Subtropical cyclones also contribute to the rainfall over the interior of the subcontinent. Rainfall along the coasts and the adjacent interior regions is supplied by coastal depressions, cyclones on the west coast and east coast troughs. Tropical depressions

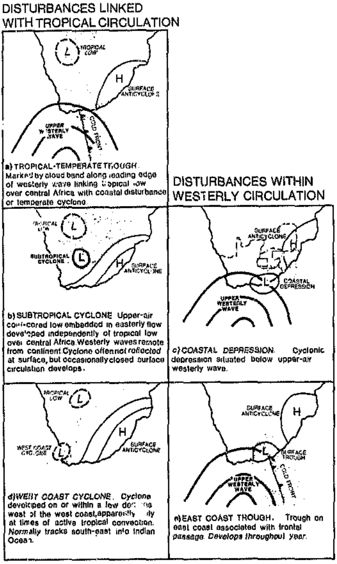


Figure 2-15. Generalised classification of rain-bearing synoptic systems over South Africa. Stippled areas suggest typical cloud distributions. Lower troposphere circulation features are suggested by thin, full lines, upper troposphere features by thick, full lines and features p· throughout most of the troposphere by dashed '' lcal cyclones are not illustrated.

and cyclones affect the easternmost regions of the country, and on rare occasions the interior, during the high rainfall season months. Cut-off lows have not been uniquely identified in the analysis. Known cases have appeared in the satellite imagery as being either embedded in tropical-temperate troughs, as producing cloud distributions similar to those of the subtropical cyclones or as disturbances with rainfall distributions incompatible with any of the loadings fields. Mean circulation fields for each type of system as deduced by Harangozo (1986) are consistent with those given in Figures 2-4, 2-5, 2-10, 2-11, 2-12 and 2-13. It is important to note that most rainfall over the interior of the country results from systems that develop contemporaneously with convective outbreaks over central Africa. Consequently periods of limited tropical convective activity over the continental latitudinal 10 to 20°S belt may be expected to be predominantly dry over South Africa. Any future comprehensive theory of the causes of the rainfall variability over the country must therefore incorporate aspects of the variability over central Africa also.

Consistent results have been obtained between months for the higher components whose loadings fields remain notably uniform in terms of both the locations and the magnitudes of the major regions of high positive and negative loadings. Such an outcome may only be expected provided a quasi-constant spatial distribution of rainfall from each similar system is maintained between months. Studies of the satellite imagery indicate that this condition was met. Several reasons for this may be suggested in which the local physiography and the location of the country in relation to the major circulation features of the hemisphere play major roles. The almost complete absence of temperate cyclones with their variable tracks over the country during the rainfall season months must be an important contributing factor. For instance, the tropical-temperate troughs produce quasi-uniform rainfall distributions regardless of the location of the terminating temperate cyclone while rainfall distributions from coastal disturbances are constrained by the topography of the subcontinent. One possible reason that identification of the rainfall distributions associated with the cut-off lows was not possible from the analyses is that these tend to be inconsistent from storm to storm by contrast with the distributions from the other types of system. The results presented here are, therefore, the consequence of a unique set of physiographic and climatological controls on rainfall distributions over South Africa and there is no reason to expect similar outcomes of comparable analyses for regions elsewhere in the world.

The new classification may be compared with the earlier schemes of Longley (1976) and Erasmus (1980). Unfortunately Vowinckel's (1955a) scheme, developed prior to the satellite era, cannot readily be contrasted with the results given here. The satellite images for the summer pattern days categorised by Longley (1976) have been inspected for the presence of the systems classified here. The coastal disturbances of the present classification appear on one or more of Longley's pattern days for the coastal regions. Rainfall on the pattern days for the interior of the country resulted in all cases from purely tropical disturbances, i.e. *on no pattern day for the interior were tropical-temperate troughs present across the subcontinent*. This observation may be taken as an indication of the difficulties involved in identifying upper-tropospheric circulation conditions suitable for rainfall from surface data alone. Circulations associated with tropical-temperate troughs, whether terminating at a coastal disturbance or at a temperate cyclone, are the major suppliers of rainfall over the eastern Orange Free State according to Erasmus (1980). Coastal depressions and east coast troughs are also important contributors to rainfall over the region. Subtropical and west coast cyclones as well as tropical cyclones were not included in Erasmus' (1980) classification.

Study of the monthly loadings fields has facilitated the identification of the most important rain-bearing synoptic systems over South Africa, has provided an indication of the spatial coverage of rainfall from each system and, through the loadings, has given an estimate of the rainfall variance of each district accounted for by the systems. None of the disturbances has, to date, been subjected to any systematic synoptic analyses and, at present, the basic large-scale atmospheric circulation patterns required for their development have not been defined. Although the study of these circulation patterns forms the main thrust of the work reported in this thesis an alternate approach to the problem is provided by the present analysis.

Through the principal component analyses approximate *individual* 57-year time series for the identified synoptic systems have been derived which, at least for the tropical-temperate troughs, are realistic representations of the true series of rainfall from the systems (Harrison, 1984d). While the time series will not be discussed in detail they provide a potentially important link in the search for the atmospheric circulation controls on South African rainfall and may permit the identification of the separate controls on each system. One frequent application of principal component analysis of rainfall time series has been to assist in the identification of atmospheric circulation controls on rainfall over a particular region, either by inspecting periods of unusually high or low scores on a given component for consistent circulation anomaly patterns (Salinger, 1980; Dyer, 1982) or by correlating the component scores with other geophysical time series (Kidson, 1975; Pittock, 1975, 1980; Dyer, 1979a; Walsh *et al.*, 1982). Care is necessary, however, in the interpretation of the results. Correlation of component with other geophysical time series requires, as a consequence of the principle of mutual exclusiveness, the implicit assumption that all synoptic systems represented on an eigenvector are similarly, but inversely, controlled by the same geophysical phenomenon. This important assumption remains to be tested and for the monthly series developed here may only be automatically valid for components describing rainfall from tropical-temperate troughs. The imposition of the same climatic control on the frequency of development of, say, subtropical cyclones and coastal depressions (on Component D) is not so immediately acceptable but is equally not implausible. Nevertheless the principal component scores may form an important link in future studies of the interactions between the general circulation and South African rainfall on the global scale and are used for this purpose in Chapters 9 and 10.

CONCLUSIONS

Through a combination of principal component analysis of standardised monthly rainfall fields and inspection of satellite imagery a generalised classification of rain-bearing disturbances over South Africa has been developed. Tropical-temperate troughs with associated cloud bands connecting the tropical circulations with mid-latitude cyclones are the major contributors to rainfall over the interior of the country. Lesser contributors to interior rainfall include tropical and subtropical cyclones. Coastal rainfall results from cyclonic or frontal disturbances. This classification forms the basis of the structure of the stratifications of the rainfall and atmospheric circulation data used in the remainder of this thesis. As such the classification facilitates interpretation of the rainfall variations over the central interior of South Africa in terms of the accompanying atmospheric circulation vacillations in a manner not previously attained.

PART II

ANNUAL CYCLES OF RAINFALL AND THE CIRCULATION OVER THE CENTRAL INTERIOR OF SOUTH AFRICA

CHAPTER 3

THE ANNUAL RAINFALL CYCLE

INTRODUCTION

Several different types of synoptic systems occur over the central interior of South Africa and changes in the frequency and amount of rainfall from each of these systems determines the courses of the annual cycles of both the circulation and the rainfall. Temporal distributions of the various circulation types may be readily ascertained through examination of the associated rainfall totals and rain day frequencies. Harmonic analysis has often been used to determine the phases and amplitudes of the annual and shorter-period cycles present in average monthly data. One of the earliest applications of a technique which resembles harmonic analysis to monthly rainfall data was that of Schumann and Hofmeyr (1938) in South Africa. Single sine waves were fitted to data from individual stations to delineate regions with coherent annual cycles. Since the first full application of harmonic analysis to rainfall over the United States of America (Horn and Bryson, 1960) the technique has been applied in many areas including other parts of North America (Sabbagh and Bryson, 1962; Walker, 1964; Shulman and Leblang, 1974; Scott and Shulman, 1979), central America (Hastenrath, 1968), tropical South America (Caviedes, 1981), central Africa and some South Atlantic islands (van Loon, 1972a), South Africa (McGee and Hastenrath, 1966), India (Lettau and White, 1964), the south-west Pacific islands (Fitzpatrick *et al.*, 1966), Australia (Fitzpatrick, 1964) and New Zealand (Rayner, 1971). In addition annual and semi-annual cycles have been surveyed through harmonic analyses on the global scale (Hsu and Wallace, 1976a). In all cases only the integral cycle, rather than the cycles of rainfall from the various types of systems, was studied.

Catalogues of circulation types may be used to study the seasonal frequency distributions of each type together with the distributions of rainfall (Barry and Perry, 1973; Barry *et al.*, 1981) but there do not appear to be any applications of harmonic analysis to data stored in the catalogues. Yet the technique is potentially a powerful one that permits identification of the major contributors to the integral cycles, of any cycles present for individual systems but hidden in the integral data and of phase changes between the overall and the systems' cycles. Harmonic analysis is applied in this Chapter to monthly totals over the Orange Free State of rainfall and of rainfall from each circulation type to identify the systems principally accounting for the amplitudes and phases of the main cycles in the integral data.

THE CATALOGUE OF CIRCULATION TYPES

Satellite images have been utilised to develop a catalogue of circulation types for the 11-year period 1967 to 1977 through subjective classification of daily synoptic situations into the categories illustrated in Figure 2-15. Note that truncated troughs are not illustrated in Figure 2-15. Cloud bands link tropical lows with west coast cyclones (Fig. 2-12) and it is rainfall from the bands rather than from the cyclones that affects the Orange Free State. The term west coast troughs will be used in reference to these systems. Rainfall season classes were used throughout the year. Surface synoptic charts supplied by the South African Weather Bureau were used to assist the classification procedure. All rainfall systems which could not be included in one of the major categories were grouped under the heading 'unclassified'. Cut-off lows account for many of the unclassified events in the winter months, but during the rainfall season the majority were weak systems producing localised convective showers. Tropical-temperate troughs, truncated troughs, west coast troughs and subtropical cyclones, for which the cloud link to the tropical circulations is continuous, will be referred to collectively as *tropical systems*. East coast troughs, coastal depressions and unclassified systems, the majority of which were not linked to the tropical cloud masses, will similarly be referred to as *temperate systems*.

THE CONTRIBUTIONS OF INDIVIDUAL SYSTEMS TO THE ANNUAL RAINFALL CYCLE

Tropical systems supplied about 60 per cent of the total rainfall over both areas of the Orange Free State during the period 1967 to 1977 of which the major contribution came from the tropical-temperate troughs (Fig. 3-1a). West coast troughs provided more rainfall to the western than to the eastern Orange Free State. Of the other systems none delivered more than 17 per cent of the total rainfall. Unclassified systems, by contrast, accounted for more rain days over the eastern Orange Free State than any other system including the tropical-temperate troughs (Fig. 3-1b). Rainfall over both areas fell from tropical systems on only 40 per cent of the rain days and consequently mean daily rainfall was higher for the tropical than for the temperate systems (Fig. 3-1c). Similarly, both the mean areal coverage of the rainfall (Fig. 3-1d) and the mean highest point rainfall (Fig. 3-1e) were higher for the tropical than for the temperate systems. The absolute highest point rainfalls were recorded from tropical-temperate troughs but t[illegible] is no clear differentiation between statistics for tropical and te[illegible] systems in this case (Fig. 3-1f).

A significant reduction in the amount of data that need be handled in the study of the rainfall variations problem may be effected, without major loss of information, by considering *significant* rainfall only (Harrison, 1983b). Days of significant rain are defined, following Riehl *et al.* (1973), as days on which the rainfall exceeded the mean daily rainfall across all days in the study period, including the no rain days. The *minimum rainfall for inclusion as a significant rain* day, for the period 1946 to 1977, is thus 2.8 mm in the eastern and 2.1 mm in the western Orange Free State. Significant rain days account for 84 per cent of the summer rainfall but for only 39 per cent of the rain days in the eastern Orange Free State. Equivalent figures for the western Orange Free State are 87 and 39 per cent respectively. *Exclusion of non-significant days from the* 1967 to 1977 data results in a substantial reduction in the number of rain days (Fig. 3-2b) but in only a small decrease in the included total rainfall (Fig. 3-2a). The largest decreases in both parameters occur for the unclassified group. Tropical systems accounted for a higher pro-

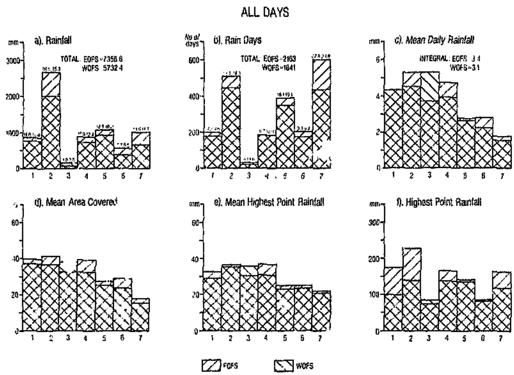


Figure 3-1. Integral rainfall system statistics for the period 1967 to 1977. In a) and b) ordinates are totals for the 11 years. Classes are marked by: 1 - Truncated troughs; 2 - Tropical-temperate troughs; 3 - West coast troughs; 4 - Subtropical cyclones; 5 - East coast troughs; 6 - Coastal depressions; 7 - Unclassified systems. Figures above blocks in a) and b) indicate percentage contributions of each system to eastern and western Orange Free State totals respectively.

portion of the significant rain days (about 62 per cent) than temperate systems. The distinction between statistics of mean daily rainfall, mean areal coverage and mean highest point rainfalls for tropical and temperate systems is largely eliminated by considering the significant rain days only (Figs. 3-2d and 3-2e). In the remainder of this Chapter significant rainfall only will be considered, except where otherwise stated. The major effect is to reveal trends in the data more clearly than would oth-

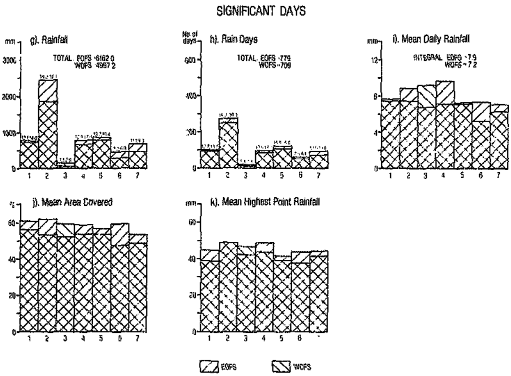


Figure 3-2. As Figure 3-1 but for significant rain days. Note the change of ordinate scale for c) from that of Figure 3-1c.

erwise be the case through the reduction of the 'noise' generated by the large number of light rain days.

Distributions of ranked daily significant rainfall from each system may be described through the expression

$$y = \alpha x \exp(\beta x) + \varepsilon$$

where x is the cumulative percentage of the number of rain days, y is the cumulative percentage of the rainfall, α and β are constants and ε is an error term (Harrison, 1983b). Increasing values of β indicate increasing skewness of the distribution. The expression describes the distribution of daily rainfall amounts independently of the number of rain days. Distributions of daily rainfall amounts for all tropical systems other than the truncated troughs over the eastern Orange Free State are more highly skewed than the integral distribution (Table 3-1), indicating that the tropical systems tend to account for the heavier rainfall. The range of values of β for the western Orange Free State varies from that for the east because of the lower bound on the limit of significant rain days (2.1 as against 2.8 mm). Highest skewness over the west is associated with the east coast troughs and the unclassified systems. The east coast troughs, rather than the tropical systems, therefore provide the heavier rainfall in the west.

Rainfall over the Orange Free State is limited mainly to the summer months (Fig. 3-3). Mean monthly rainfall is highest in January over the east and in February over the west. The seasonal cycles of the number of rain days are similar to those of the rainfall. Rainfall from tropical-temperate troughs, which dominates the rainfall cycle over the Orange Free State during the period 1967 to 1977, accounts for 60 per cent of the rainfall in January (Fig. 3-4). Like those for most of the other systems, the monthly distributions of both rainfall and rain days for these troughs are bimodal with the major peak in January. In the case of truncated troughs the major peak occurs in November. Subtropical cyclones, which develop over the Orange Free State most frequently in February, alone are unimodally distributed throughout the

Table 3-1. Values of β ($x10^{-2}$) for significant rainfall and for significant rainfall from each system. Values are given for both the eastern and the western Orange Free State. In excess of 99.5 per cent of the variance was explained by the model in all cases. The systems are arranged in order of decreasing values of β over the east.

System	East	West
Tropical-temperate troughs	1.32	1.27
West coast troughs	1.22	1.25
Subtropical cyclones	1.21	1.29
Integral	1.18	1.33
Truncated troughs	1.14	1.32
Coastal depressions	1.14	0.99
Unclassified	1.13	1.43
East coast troughs	1.06	1.45

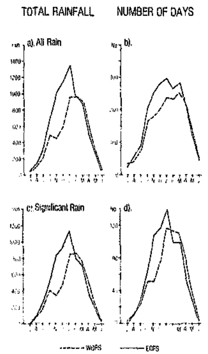


Figure 3-3. Annual cycles of rainfall and of frequency of rain days both for all rainfall, a) and b), and for significant rainfall, c) and d). Full lines - eastern Orange Free State; broken lines - western Orange Free State. Ordinates represent totals for the period 1967 to 1977. Note the change of ordinate scale between b) and d).

year. Rainfall from subtropical cyclones is greatest, however, over the eastern Orange Free State in December with only a secondary maximum in February.

East coast troughs supply rainfall throughout the year apart from the mid-winter months (Fig. 3-4). Distributions for these troughs are trimodal. Coastal depressions are most important during the early summer months through until December and then again in March. Rainfall from unclassified systems is mainly limited to the early and late winter months but peaks in the contributions of the unclassified systems to both rainfall and rain days occur in December. Between them east coast troughs and

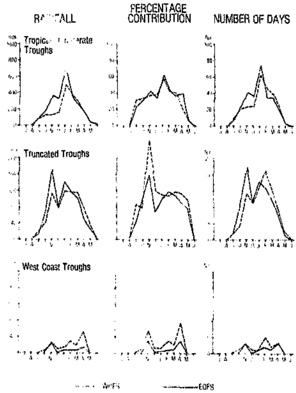


Figure 3-4. Annual cycles of significant rainfall, of percentage contribution to integral significant rainfall and of frequency of significant rain days for each type of system. Full lines - eastern Orange Free State; broken lines - western Orange Free State. Months along the abscissae. Ordinates represent totals for the period 1967 to 1977. Note that the ordinate scales for the tropical-temperate troughs and for the percentage contributions of the east coast troughs and the unclassified systems differ from those of the remaining systems.

unclassified systems account for the greater proportion of the winter season rainfall whereas tropical systems dominate the rain patterns in the summer months.

Results of the harmonic analyses of total rainfall and of significant rainfall are similar in terms of explained variances and phase angles indicating that the elimination of the non-significant rainfall has little effect on the

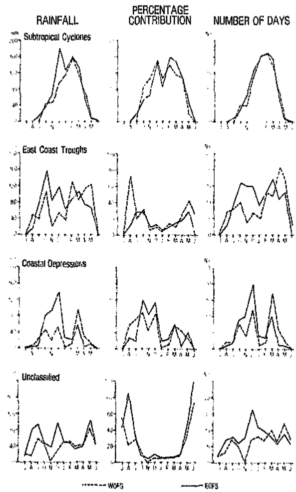


Figure 3-4 continued.

seasonal cycles. More than 90 per cent of the variance is captured by the first harmonic (annual cycle) of the rainfall for both areas (Table 3-2), in agreement with the results of McGee and Hastenrath (1966). Only over the western Orange Free State does the second harmonic (six-month cycle) contribute an appreciable proportion of the variance. Similarly the annual cycle is dominant in the seasonal rainfall distributions for all tropical systems apart from the west coast troughs. The second harmonics account for more than 10 per cent of the variance for rainfall from the west coast troughs and the temperate systems apart from the unclassified systems. A semi-annual cycle (45 per cent of the variance) with maxima in late Ap[illegible] October is also present in monthly frequencies of cut-off lows which produce heavy rainfall over South Africa (Taljaard, 1982a).

Phase angles of the annual cycles of rainfall from many of the systems correspond closely with that of the total rainfall (Figs. 3-5a and 3-5c) with early and late January maxima over the eastern and western Orange Free State respectively. Approximately half of the amplitude of the annual wave is accounted for by rainfall from the tropical-temperate troughs in both areas. Phase angles for rainfall from few of the systems differ

Table 3-2. Variances explained by the six harmonics of significant integral rainfall and of the significant rainfall for each system. Explained variances in excess of 10 per cent are emphasised. Upper rows refer to the eastern Orange Free State; lower rows to the western Orange Free State.

Harmonic	1	2	3	4	5	6
Synoptic system						
Integral	97.6	0.5	0.0	0.2	0.8	0.9
	90.4	6.4	1.4	1.4	0.3	0.0
Tropical-temperate troughs	82.0	3.8	0.8	4.4	6.0	2.9
	79.6	10.2	3.2	3.5	2.5	1.1
Truncated troughs	80.6	1.0	5.0	4.5	4.6	4.3
	90.7	1.4	1.9	1.4	2.1	2.5
West coast troughs	17.8	13.4	17.5	12.1	33.6	5.6
	41.0	13.2	9.4	7.3	24.4	4.7
Subtropical cyclones	87.8	3.2	2.1	3.1	2.5	1.3
	90.0	6.3	1.4	0.2	0.4	1.7
Coastal depressions	58.6	15.2	9.0	4.9	11.1	1.3
	19.3	25.7	15.6	22.1	17.2	0.0
East coast troughs	49.8	34.0	1.3	1.4	12.5	1.0
	26.9	32.2	6.6	10.0	14.4	9.9
Unclassified	3.4	0.9	60.5	24.4	10.2	0.5
	20.8	4.5	65.0	0.8	7.8	1.0

by more than 15° (15 days) from those of the integral distributions. The amplitude of the six-month wave is about three times as large over the western, with mid-March/September peaks, than over the eastern Orange Free State, with mid-June/December peaks (Figs. 3-5b and 3-5d). Over the eastern Orange Free State the amplitude of the wave is exceeded by that of rainfall from the tropical-temperate troughs. Phase angles for rainfall from all systems differ by more than 30° (15 days) from those of the respective integral distributions.

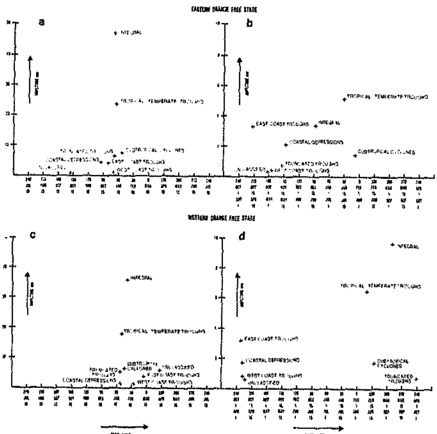


Figure 3-5. Amplitudes (ordinates) and phase angles (abscissae) of the first, a) and c), and second, b) and d), harmonics of the significant rainfall distributions of Figures 3-2 and 3-3. Amplitudes have been adjusted to an annual basis. Phase angles are marked with the date(s) of the maxima.

DISCUSSION

The annual rainfall cycle over the Orange Free State (Fig. 3-3) results from contributions of varying amplitudes, phases and periods from a number of types of systems (Figs. 3-4 and 3-5). Tropical systems and associated rainfall dominate the annual cycles accounting for more than 50 per cent of both the significant rainfall and the significant rain days for the months October to April (Fig. 3-6). Temperate systems account for more than 50 per cent of the rainfall and of the rain days only in the relatively dry winter months of May to September, and for all rainfall from June to August. Further, rainfall from tropical-temperate troughs outweighs rainfall from any other type of system, in confirmation of the earlier results of Erasmus (1980). The circulation of the tropical-temperate troughs is thus a major component of the integral circulation while rainfall from the troughs largely determines the amplitude and the phase of the annual cycle over the Orange Free State.

A hiatus in the monotonic rise of monthly mean rainfall in December, as occurs for rainfall from the tropical systems other than the subtropical cyclones (Fig. 3-4), is a common feature of statistics for many stations in the Transvaal and the Orange Free State (Schulze, 1965; Louw, 1979a). For the period 1967 to 1977 this hiatus is perhaps only weakly apparent in the eastern Orange Free State data and appears in November in the western Orange Free State data (this latter minimum does not appear in data for the 31-year period 1946 to 1977). The hiatus arises from a sharp decrease in rainfall from the tropical-temperate troughs. Rainfall from the temperate systems and from the subtropical cyclones increase in December in comparison to the adjoining months but insufficiently to offset the decrease from the troughs. The December hiatus is apparent in the frequency of thunderstorm days (le Roux, 1953) and in the distributions of monthly mean precipitable water and of daily probabilities of rain in the Orange Free State (Louw, 1979b). A similar break in the rains occurs in Zimbabwe in late January (Lineham, 1972). Schulze (1965) has suggested that the November rainfall peak might be associated with a 'temperate' or 'cyclonic' rainfall regime and the January peak with a 'tropical' regime. No support for this suggestion is obtained from the

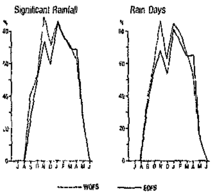


Figure 3-6. Percentage monthly contributions to integral significant rainfall and number of significant rain days by the tropical systems. Full lines - eastern Orange Free State; broken lin. - western Orange Free State.

present results as tropical systems account for about 80 per cent of the rainfall and the rain days in both November and January (Fig. 3-6).

Study of the satellite images indicates that there was a general decrease in December in the frequency of all tropical-temperate troughs in the African region, a decrease which was often, but not always, apparent in data for individual years. The effect evolves, therefore, on a scale comparable with that of the general circulation and is not merely a local phenomenon. East coast and tropical-temperate troughs develop under broadly similar conditions of the westerly circulation in that both systems are associated in their temperate sections with westerly cyclone waves. The only immediately apparent difference between the two is that the east coast troughs troughs have no cloud link to the tropics. Equivalently coastal depressions may be similar to truncated troughs apart from the lack of the tropical connection. Both of these temperate systems provide more rainfall in December than in the surrounding months. The inference is that for presently unknown reasons the circulation in December inhibits the formation of links between the tropical circulations and the temperate systems. The decrease in frequency of all tropical-temperate troughs in the African sector in December indicates that the major circulation changes occur in the tropical rather than in the temperate regions. By comparison the January circulation is more conducive to tropical-temperate interaction than that for any other month while the circulation for November is particularly suitable for the formation of truncated troughs (Fig. 3-4).

The peak of the annual cycle changes from early January over the eastern Orange Free State to early February over the west, a change matched by corresponding adjustments in the annual cycles of rainfall from the tropical systems (Fig. 3-5). Thus the rainfall maximum occurs later in the season over the more western parts, as demonstrated by the harmonic analysis of McGee and Hastenrath (1966) and the observations of Schulze (1965) and Louw (1979b). Spectral analysis of rainfall across the country has suggested, on the other hand, that the annual wave progresses *eastward* during the rainfall season (Keen and Tyson, 1973). No physical interpretation of this discrepancy can be given. The westward propagation of the annual wave in time results from an imbalance in the seasonal distribution of rainfall across the Province, rainfall being deficient over the west in comparison to over the east until February (Fig. 3-3). Parity in the frequency of rain days is reached only in April but in the frequency of significant rain days in February. In the later rainfall season months western rainfall and rain day frequency exceed those of the east. No single system or group of systems is responsible for the low early season rainfall over the western parts - only the west coast troughs deliver equal rainfall to both areas (Fig. 3-4). Percentage contributions to monthly rainfall for both areas from most systems are similar throughout the year. From February tropical-temperate troughs and subtropical cyclones supply roughly equal amounts of rainfall to both areas. Truncated, west coast and east coast troughs and coastal depressions, on the other hand, all deliver more rain to the west than to the east during the later part of the season. Rainfall from all systems, therefore, contributes towards the equalisation over the two areas, but that from only certain of the systems, the east coast troughs in particular, accounts for the excess rainfall over the west (Fig. 3-4). The east coast troughs also tend to contribute the heavier rainfall over the west (Table 3-1). Hence the late season western rainfall peak results from an increased temperate in addition to tropical circulation influence.

The six-month rainfall wave also progresses westward during the season (Figs. 3-5b and 3-5d). The summer maximum of the six-month wave occurs in mid-December over the east and in early March over the west. Thus the wave is almost 180° out of phase over the two regions of the Orange Free State. Both harmonic (McGee and Hastenrath, 1966) and spectral (Keen and Tyson, 1973) analyses have indicated that the six-month wave is of greatest amplitude over the western sections of the country where it reaches maxima during the equinoctial months (Fig. 2-1). Present results confirm these facts but also indicate that *rainfall from no individual system has a six-month wave corresponding in phase to that of the integral wave.* Over both areas only rainfall from the tropical-temperate troughs and the subtropical cyclones have midsummer maxima on the six-month wave. Maxima for the remaining systems occur in early April/October in the west and a month later in the east. Second harmonics may arise from purely mathematical origins and do not necessarily reflect identifiable physical mechanisms. It is often difficult to determine the appropriate source of the second harmonic when its amplitude is small in comparison with that of the first harmonic. The second harmonic may, for instance, describe the deviations of an annual cycle away from a pure sine wave. Alternatively, for stations with a pronounced dry season, both the amplitude and the phase of the second harmonic may be constrained mathematically to counterbalance the 'negative' rainfall amounts appearing on the first harmonic during the dry season, an effect referred to as 'phase locking' by Hsu and Wallace (1976a). It is, perhaps, reasonable to propose that a second (or lower) harmonic has a physical origin only when a plausible mechanism has been identified or when the cycle is evident on inspection of the raw data. No *a priori* reason may be forwarded to expect a six-month cycle in the rainfall and inspection of Figures 3-2 and 3-3 suggests that only for the west coast and east coast troughs and coastal depressions do rainfall and frequency maxima with spacings of approximately six months exist. There appears, therefore, to be no physical basis for the apparent equinoctial rainfall maximum over the western Orange Free State, a feature which may be present in the integral statistics as a result of the asymmetric temporal rainfall distributions. Second harmonics for rainfall from the individual systems may arise in a similar manner although those for the tropical-temperate troughs and the subtropical cyclones may result from phase locking while those for the west coast and east coast troughs and coastal depressions may reflect real phenomena.

CONCLUSIONS

Harmonic analyses of rainfall from the major types of rain-bearing systems over the Orange Free State reveal that the annual cycles of rainfall and of the circulations associated with rainfall are dominated by those of tropical systems, i.e. systems for which there is a continuous cloud link to the tropical circulation. Rainfall from tropical systems accounts for more than 60 per cent of the total over both areas and for more than 80 per cent in January. Tropical-temperate troughs constitute the major class of tropical system in terms of frequency and of contribution to Orange Free State rainfall. Rainfall from tropical systems is largely responsible for the phase and amplitude of the rainfall wave over the interior of the country and for the December rainfall hiatus. Whereas rainfall from and frequencies of the tropical systems are dominated by the annual cycle those of the temperate systems are also modulated on higher frequencies and in particular on a semi-annual cycle. Phases of the semi-annual cycles are not coherent with those for the integral cycle and thus there is no physical basis for the apparent equinoctial maximum of the six-month wave observed over the western Orange Free State.

Only 250 km separates the centres of the two regions of the Orange Free State yet marked differences in the details of the system contributions towards annual rainfall cycles over the regions occur. These differences have been illustrated in terms of the changes in the phases of the rainfall and of the contributions to total rainfall from each of the types of systems. A detailed interpretation of these spatial adjustments requires the development of circulation statistics for both regions but these are presently available only for the western Orange Free State. Rainfall and rainfall variations over the western Orange Free State therefore form the major foci in the remainder of this thesis.

CHAPTER 4

THE ANNUAL CYCLE OF THE ATMOSPHERIC CIRCULATION

INTRODUCTION

The history of the development of circulation climatologies for the Southern Hemisphere extends back into the nineteenth century. Data from the extensive shipping fleets of the late nineteenth and first half of the twentieth centuries facilitated the development of climatologies of surface temperatures, pressures and winds over the predominantly oceanic Southern Hemisphere (van Loon, 1972b, 1972c, 1972d; Hastenrath and Lamb, 1977, 1979a). Upper-air circulation climatologies have primarily been established in the past 30 years although preliminary analyses for the lower troposphere were attempted through extrapolation of surface data (Teisserenc de Bort, 1893). Regular upper-air soundings from a limited network of stations first became available after the Second World War but the major stimulus to the expansion of the data network came with the International Geophysical Year of 1957 to 1958. Based on data from the International Geophysical Year and from careful analysis of daily surface and upper-air fields in the South African Weather Bureau's Southern Hemisphere Atmospheric Project a series of atlases were developed (Taljaard *et al.*, 1969; van Loon *et al.*, 1971; Jenne *et al.*, 1971; Crutcher *et al.*, 1971) which have formed the foundation for an extensive series of discussions of the hemisphere's large-scale circulation (van Loon, 1965, 1967a, 1972a, 1972b, 1972c, 1972d; Taljaard, 1967, 1972; van Loon *et al.*, 1968; Starr *et al.*, 1969; Viswanadham *et al.*, 1980). Further expansions of the reporting network since 1960 have facilitated the development of additional climatologies based on radiosonde data (Newell *et al.*, 1972; Oort and Peixoto, 1983; Peixoto and Oort, 1983) but there remain large areas over which extrapolation of data is necessary. New platforms for data collection over the oceanic regions, including floating buoys (Guymer and Le Marshall, 1981) and, in particular, satellites have rendered possible the development of high-quality daily hemispheric data sets from which improved details of the circulation are being obtained (Le Marshall and Kelly, 1981; Bengtsson *et al.*, 1982; Le Marshall *et al.*, 1983). Data collected during FGGE have also permitted development of detailed climatologies of the flow over the Indian and western Pacific Oceans (Sumi and Murakami, 1981; Murakami and Sumi, 1982; Cadet, 1983).

Climates of the continental areas have naturally been easier to study than those of the hemisphere and available climatologies include those for South America (Kreuels *et al.*, 1975; Chu and Hastenrath, 1982). Atlases of the surface circulation have been prepared for Africa (Jackson, 1961; Thompson, 1965) both of which also incorporate basic details of that of the upper air. Data from the network of pilot and sounding stations were used for the earliest studies of the mean circulation over South Africa (Cox, 1935; Jackson, 1952; Hofmeyr, 1952, 1953, 1954; Taljaard, 1953). The radiosonde network was expanded for the International Geophysical Year and collected data formed the basis of the first systematic studies of the upper-air circulation over the continent (Hofmeyr, 1961, 1962, 1970). Subsequent climatologies for South Africa itself have all been developed based on conventional data (Schulze, 1965; Katsiambirtas, 1979; Taljaard, 1981b).

As a preliminary to the study of the controls on the frequency of development through the year of the various types of synoptic systems exerted by circulation in the southern African region a climatology of the circulation over Bloemfontein is developed in this Chapter. Only the integral circulation is considered as the average circulation for each type of system is discussed elsewhere (Harangozo, 1986). Objectives include the development of an overview of the atmospheric structure over the central interior of South Africa within the context of that of the Southern Hemisphere and the investigation of the properties of the meridional flow, a parameter of major importance in terms of the hypothesis that rainfall variations are related to the meridional momentum flux. Harmonic analysis of monthly mean values is employed to investigate the structures of and hence the controls on the seasonal cycles of each parameter.

DATA

Basic upper-air statistics have been tabulated for all radiosonde stations in South Africa and Namibia (Fig. 4-1 and Table 4-1) by Katsiambirtas (1979) and the mean monthly circulation over southern Africa as revealed by these data described by Taljaard (1981b). Monthly mean values of temperature, geopotential height, mixing ratio, dry and total static energy and zonal and meridional wind components in addition to the monthly standard deviations of temperature, geopotential height and zonal and meridional wind speeds have been calculated from Bloemfontein data at the surface (around 870 mb) and at 850, 800, 700, 600, 500, 400, 300, 200, 150 and 100 mb. Above 100 mb the number of observations declines rapidly with height. Data for the 1200 GMT ascent were used (0000 GMT ascent data are available only from 1974). Analyses of the various standard deviations are presented in Appendix B. For the meridional component a reversal of the normal convention has been used in that *a northerly, i.e. poleward, wind is taken as being positive.*

The problems involved in handling upper-air data are well known. Notwithstanding sampling errors biases may develop in the data set towards light wind (Priestly and Troup, 1964) and, possibly with certain of the older balloon tracking facilities, towards cloud-free conditions. Further bias may be introduced by the continued collection of thermodynamic data while the balloon is no longer being tracked. This latter bias is present in the Bloemfontein data in that the number of temperature observations at 100 mb is typically 80 per cent of the number at the surface in any month while the corresponding proportion of wind observations at the same level is typically 55 per cent. Such biases may affect in an unknown manner any of the upper-air statistics discussed in this thesis. Nevertheless, following Newell *et al.* (1972), it will be assumed that all errors introduced are random and sum to zero. Consequently statistics have been calculated from all available data. Of all the parameters recorded by radiosondes the atmospheric moisture content is the most difficult to measure accurately. Rasmusson (1972) has discussed the problems involved. Over the period studied three different types of radiosonde have been released at Bloemfontein and there is some concern over the consistency and accuracy of the humidity values meas-

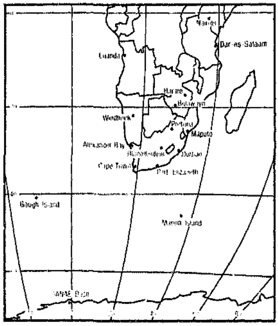


Figure 4-1. Locations of southern Africa radiosonde stations.

ured by each of these types of equipment (McGee, 1976; Taljaard, 1983). With reference to the present results it is felt that any errors should

Table 4-1. Locations of selected stations in the Southern Hemisphere.

Alexander Bay	28°34'S	16°32'E	Harare	17°50'S	31°01'E
Bloemfontein	29°06'S	26°18'E	Luanda	8°51'S	13°14'E
Bulawayo	20°09'S	28°37'E	Maputo	25°55'S	32°34'E
Cape Town	33°58'S	18°36'E	Marion Island	46°53'S	37°52'E
Cocos Island	12°11'S	96°49'E	Nairobi	1°18'S	36°45'E
Dar es Salaam	6°53'S	39°12'E	Port Elizabeth	33°59'S	25°36'E
Darwin	12°26'S	130°52'E	Pretoria	25°55'S	28°13'E
Djakarta	6°11'S	106°50'E	SANAE Base	70°18'S	2°21'W
Durban	29°58'S	30°57'E	Tahiti	17°33'S	149°37'W
Easter Island	27°10'S	109°26'W	Windhoek	22°29'S	17°28'E
Gough Island	40°21'S	9°53'W			

be reflected quasi-uniformly in the mean statistics for all months and so mixing ratios have been calculated directly from the data with no corrections applied. Thus the annual moisture cycle as discussed below should be representative of actual conditions even if the absolute magnitudes of the calculated mixing ratios are in error.

THE ANNUAL CYCLE

Thermodynamic parameters

The oceans play a major role in the control of the temperature cycle over the Southern Hemisphere. Maximum temperatures of the surface air over the oceans at around 30°S are reached in mid-February rather than in late December (van Loon, 1972b; White and Wallace, 1978), a phase which remains constant in the cycle of the zonally-averaged temperature as high as 300 mb (van Loon *et al.*, 1968; Newell *et al.*, 1974). Above 300 mb the time of the maximum shifts from February to mid-August at 100 mb. Over Bloemfontein the surface air temperature reaches a maximum in early January, indicating a continental control on the annual wave directly related to the cycle of insolation (Fig. 4-2a). Continental controls are also reflected in the amplitude of the surface wave which is double that of the zonal average, as is also the case over Australia (van Loon, 1972b). Between the surface and the 300 mb level the date on which the temperature maximum is reached changes progressively from early to mid-January, indicating that the continental control is dominant at least to this level. Only near the amplitude minimum at 200 mb does the phase match that of the oceanic atmosphere below 300 mb. The amplitude of the annual wave, like the magnitude of the temperature itself, remains greater than that of the zonal average up to the 300 mb level. In the stratosphere the amplitude increases again to 4.5°C, a value comparable with that below 200 mb and larger than those given by either van Loon *et al.* (1968) and Newell *et al.* (1974) for the zonal mean or van Loon

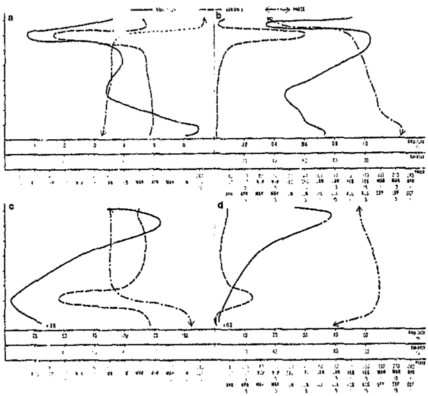


Figure 4-2. Results of harmonic analyses of monthly mean temperature and geopotential height fields at Bloemfontein: a) 1st. harmonic of temperature; b) 2nd. harmonic of temperature; c) 1st. harmonic of geopotential height; d) 2nd. harmonic of geopotential height. In c) and d) surface values refer to harmonics of the pressure itself using the amplitude abscissa scale in units of mb x 10^{-1}.

and Jenne (1970a) for the African region. The date of the maximum at Bloemfontein (mid-July) is about one month prior to that given by the earlier analyses. Temperature variations in the lower equatorial stratosphere have been modelled in terms of the differences in the tropical meridional circulations between the northern and southern summers (Reed and Vlcek, 1969), the lower temperatures accompanying the more vigorous ascent in tropical latitudes of the austral summer. Following Oort and Rasmusson (1970) these circulations are strongest in February and August, during which months the annual lower stratospheric temperature wave at 30°S reaches its lowest and highest values respectively. Over Bloemfontein the maximum temperature at 100 mb is reached in mid-July contemporaneously with the minimum in the layer between 500 and 300 mb at the same location and during a period of persistent subsidence over the subcontinent. Thus there appears to be a local extension of the continental control on the temperature cycle into the lower stratosphere in terms of both the phase and the amplitude of the annual wave. Variances explained by the annual temperature wave (above 90 per cent everywhere except near the 200 mb amplitude minimum) remain similar both in the zonal average (van Loon *et al.*, 1968) and at Bloemfontein at all levels.

A mid-winter peak in the surface pressure is a standard continental feature in the Southern Hemisphere subtropics (Hsu and Wallace, 1976b; van Loon and Rogers, 1984) and is present at Bloemfontein (Fig. 4-2c). The amplitude of the Bloemfontein surface pressure wave, 3.6 mb, is somewhat lower than the estimates of van Loon (1972c) and Hsu and Wallace (1976b) (6 and 5 mb respectively) based on data in the atlas of Taljaard *et al.* (1969). The reversal of phase between the lower and the upper troposphere is consistent with the annual temperature wave and occurs in means across the oceanic sector 60 to 120°E (van Loon, 1972c). Amplitudes at Bloemfontein tended to be uniformly lower than those obtained for that sector although at 200 mb the amplitude is comparable with that of the zonal average. In accordance with the continental influence on the annual temperature wave the peak of the height wave develops contemporaneously with that of the temperature wave (Fig. 4-2a) and earlier than that in the 60 to 120°E sector. The phase of the geopotential height wave remains steady into the stratosphere and so does not reflect the reversal of the temperature wave. A primary barotropic structure of the annual thermodynamic wave is signified by the synchronism of the temperature and height cycles in the layers between 600 and 300 mb. The amplitude of the height wave is rather smaller, however, than required to compensate for that of the temperature wave, a result that suggests that a baroclinic component to the wave is also present. In the lower troposphere and in the stratosphere the structure of the wave is principally baroclinic. At no level does the variance explained by any lower harmonic exceed that accounted for by the first, although at the level of the phase change at 700 mb the first four harmonics all account for more than 15 per cent of the variance.

Below 500 mb the annual specific humidity cycle, which never accounts for less than 93 per cent of the variance, reaches its maximum up to a month later than the appropriate maxima or minima in the temperature and geopotential waves (Fig. 4-3a). Accordingly the moisture cycle is not directly associated with the annual thermodynamic cycle. Phase angles increase slowly with altitude such that at the surface the maximum occurs on 5 February as against 20 January at 400 mb. The cycle of the mean monthly precipitable water is dominated by the first harmonic. This cycle peaks on 1 February, a result in good agreement with earlier calculations for the years 1967 and 1968 (McGee, 1978).

The seasonal distribution of the dry static energy is that of a stable atmosphere. In the distribution of total static energy most of the influence of the addition of the latent energy appears in the lower layers of the atmosphere during the relatively moist summer months (Fig. 4-4). During the rainfall season the energy minimum typical of the conditionally-unstable tropical and subtropical atmospheres becomes elevated to the 600 mb level as compared to its location at around 800 mb during the more stable winter months. Variances explained by the six harmonics of the distributions of both dry and total static energy remained similar at all levels. The major effects of the addition of the latent energy are to approximately double the amplitudes of the waves in the lower troposphere and to adjust somewhat the phase angles of these waves. Below 600 mb the maximum of the first harmonic occurs around 5 to 10 January for the dry static energy on account of the continental controls but around 20 January for the total static energy (Fig. 4-3c). This latter peak date remains quasi-constant up to 200 mb above which level the phase reverses to a mid-winter peak. The annual cycle of the total static energy thus reflects that of the temperature rather than that of the geopotential heights in confirmation of the observation that temperature changes are not fully compensated by appropriate thickness changes. One consequence of the constancy of the phase of the annual cycle of the total static energy in the troposphere is that the maximum thermodynamic instability over Bloemfontein develops around 20 January.

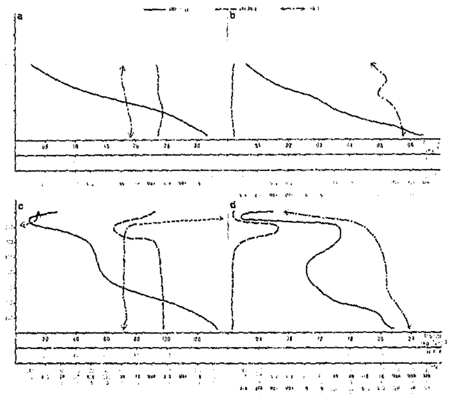


Figure 4-3. As Figure 4-2 but for: a) 1st. harmonic of specific humidity; b) 2nd. harmonic of specific humidity; c) 1st. harmonic of total static energy; d) 2nd. harmonic of total static energy.

Kinematic parameters

At all levels the first harmonic of the monthly distribution of the zonal wind is dominant (Fig. 4-5a). The phase of the annual wave indicates that the August zonal wind maximum cannot be directly related to the thermodynamic cycle over Bloemfontein with its January peak. Bloemfontein lies at a latitude at which the first harmonic of the zonally-averaged geostrophic wind dominates the annual cycle (van Loon *et al.*, 1968). The amplitude of the wave at Bloemfontein is less than that of the zonal mean which is dominated by the stronger winds over the eastern hemisphere (van Loon, 1972d).

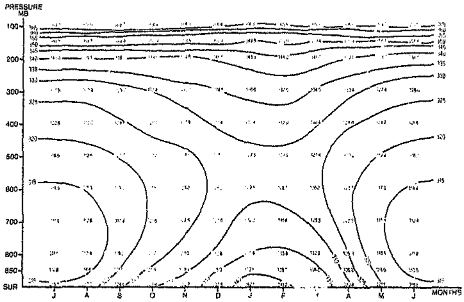


Figure 4-4. Seasonal distribution of total static energy at Bloemfontein (J kg^{-1}x10^{3}).

Throughout all months the mean meridional flow at levels up to 600 mb is poleward but above that level the direction of the flow reverses four times during the year (Fig. 4-6), reversals reflected in the results of the harmonic analyses. The variance explained by the first harmonic exceeds that accounted for by the second only up to 700 mb above which level the second harmonic is dominant (Figs. 4-5c and d). Equivalently the phase of the second harmonic is such that summer maxima are limited to the period 25 January (200 mb) to 5 March (700 mb) whereas the phase for the annual wave varies continuously with height except below 700 mb where the maximum occurs around 5 November, roughly at the time of the surface zonal component annual maximum.

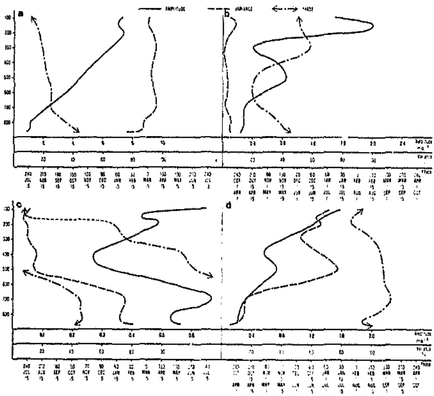


Figure 4-5. As Figure 4-2 but for: a) 1st. harmonic of zonal component; b) 2nd. harmonic of zonal component; c) 1st. harmonic of meridional component; d) 2nd. harmonic of meridional component.

THE SEMI-ANNUAL CYCLE

Kinematic parameters

Above 500 mb the second harmonic explains over 50 per cent of the variance of the distribution of the meridional component at all levels (Fig. 4-5d). Low-level maxima of the meridional flow occur around 850 to 800 mb but the height of the upper-level maximum (200 mb) is clearly defined

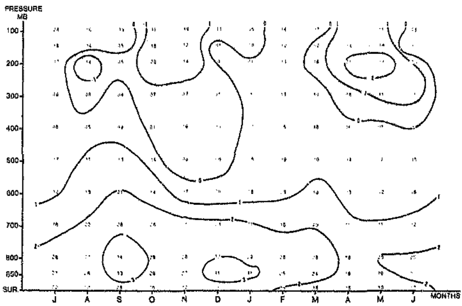


Figure 4-6. Seasonal distribution of the meridional component at Bloemfontein (ms⁻¹). Northerly, i.e. poleward, winds are positive. Stippled areas denote equatorward winds.

only at times of peak equatorward flow. Above 700 mb the maximum poleward flow on the second harmonic corresponds to within a few days with the maximum/minimum of the zonal flows on the annual cycle. Only at 150 mb does the second harmonic explain as much as eight per cent of the variance of the zonal components (Fig. 4-5b).

Thermodynamic parameters

The major contribution of the second harmonic to the thermodynamic cycle is to the temperature distribution at 200 mb where it accounts for 60 per cent of the variance (Fig. 4-2b). The amplitude of the harmonic at 200 mb, 1°C, is greater than that for the zonal mean at 30°S (van Loon *et al.*, 1968) and is comparable with that for the oceanic sector 60 to 120°E (van Loon and Jenne, 1970b). The second harmonic is of importance to the cycle of geopotential heights only in the vicinity of the phase change around 700 mb (Fig. 4-2d). The relationship between the temperature and geopotential six-month waves is similar to that between the corresponding annual waves. Between 600 and 200 mb the maxima occur almost simultaneously in late February/August but near the surface and above 200 mb the waves tend towards an anti-phase relationship with one another. As in the case of the annual waves the temperature changes on the semi-annual cycle are not fully compensated by appropriate thickness changes. Thus changes on both the annual and the six-month thermodynamic waves through much of the troposphere are quasi-barotropic in nature but in the highest and lowest levels both waves have a baroclinic structure. At 200 mb the second harmonic of the distribution of the total static energy accounts for 32 per cent of the variance (Fig. 4-3d), the level at which the second harmonic of the temperature explains 60 per cent of the variance. No reflection of the 700 mb maximum in the geopotential heights is present in the semi-annual energy wave.

DISCUSSION

Differences in the heat budgets of the southern African land mass and of the surrounding oceans, such that the highest surface temperatures are achieved in early January at Bloemfontein and in mid-February over the oceans, are important determinants of the seasonal cycles of the atmospheric circulation above the western Orange Free State. Controls on the temperature cycles exerted by the properties of the underlying surfaces extend upward to at least the stratospheric jet-stream zone[1] such that continental influences are dominant in the determination of both the

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[1] The zones are: boundary zone - surface to 700 mb; barotropic zone - 700 to 300 mb; jet-stream zone in two parts - the tropospheric jet-stream zone from 300 to 200 mb and the stratospheric jet-stream zone from 200 to 100 mb.

phases and the amplitudes of the cycles of the temperature and pressure above Bloemfontein (the various atmospheric zones and their properties are described in Appendix C). Maximum atmospheric moisture concentrations do not, however, occur in early January but rather in early February at about the same time as highest sea surface temperatures off the east coast of the subcontinent. One consequence of the differences in the phases of the annual cycles of the temperature and of the specific humidity is that the monthly-mean energy stratification, and hence of the thermodynamic stability, of the atmosphere is determined by the continental controls in conjunction with the controls on the moisture concentrations. Mixed maritime and continental controls on the phases of the temperature cycles at other southern African stations result in cycles of the pressure gradients across the central interior of South Africa with different phases to that of the temperature at Bloemfontein (see Appendix D) with resultant effects on the seasonal cycles of the wind components. Presumably the differences in the phases of the cycles of the moisture and of the temperature result in part from the mixed maritime and continental controls on the pressure gradients. Examples of the associations between the cycles of the pressure gradients of the winds at Bloemfontein may be given for both the zonal and meridional components.

Above 700 mb the phase of the annual wave of the zonal component at Bloemfontein corresponds closely with that of the zonal mean which in turn is consistent with the annual cycle of the zonal mean temperature gradient across 30°S (van Loon *et al.*, 1968; Newell *et al.*, 1974). The maximum zonal wind on the first harmonic corresponds to within a few days with the maximum pressure gradients across 30°S as estimated through harmonic analysis of differences between 200 mb monthly mean heights at Pretoria and Port Elizabeth, the first harmonic of which explains 94 per cent of the variance. In geostrophic terms the pressure gradient wave imposes a variation of 7.3 ms^{-1} on the zonal wind, a figure which compares well with the observed 7.2 ms^{-1}. Mean zonal winds in the upper-troposphere are thus in quasi-geostrophic balance with the pressure gradients. Below 700 mb in the boundary zone the maximum of the zonal wind is delayed by up to two months from that in the upper-troposphere (Fig. 4-5a) but at 800 mb the pressure gradient between Pretoria and Port Elizabeth reaches a maximum on the same date as at 200 mb. The amplitude of the wave at 800 mb, 1.1 ms^{-1}, is somewhat less than that required for geostrophic balance (1.8 ms^{-1}). No equivalent change in phase in the lower troposphere occurs in the zonally-averaged data (van Loon *et al.*, 1968) and there is, therefore, a marked ageostrophic component in the boundary zone mean wind, as noted by Taljaard (1981b). The ageostrophic component is probably related to the influence of the topography on the flow.

Seasonal changes in the pressure gradient in the zonal direction across Bloemfontein introduce a semi-annual cycle into the distribution of the meridional component, a significant result in terms of the hypothesis that rainfall varies with the poleward momentum flux. Harmonic analysis of pressure gradients between the coastal stations of Durban and Alexander Bay has been used to estimate the degree of geostrophic balance of the meridional winds in both the lower layers, i.e. at 800 mb where the annual wave of the distribution is dominant, and near the tropopause, i.e. at 200 mb where the six-month cycle is dominant. The stations are not, however, ideally suited to the purpose because the mean 200 mb height at Alexander Bay is higher than that at Durban in all months apart from January. The height difference results from the former station's location to the west of the axis of the upper-level trough commonly located across the interior of the subcontinent during rain spells. At 800 mb on the first harmonic (33 per cent of the variance) the gradient reaches a maximum in early March whereas the poleward wind maximum is in November. Boundary zone meridional winds, as low-level zonal winds, thus contain a marked ageostrophic component. At 200 mb the second harmonic explains 47 per cent of the variance of the cycle of Durban-Alexander Bay pressure gradients with the phase corresponding closely with that of the Bloemfontein meridional winds although height cycles at both coastal stations are dominated by the annual cycle (see Appendix D). The semi-annual cycle in the upper-tropospheric gradient is a consequence of the non-coherence of the phases of the annual cycles at the coastal stations which results from varying continental and maritime influences. Reasonable agreement is obtained at both levels between the estimated magnitudes of the appropriate waves of the geostrophic wind (0.4 ms^{-1} at 800 mb and 0.7 ms^{-1} at 200 mb) and the observed values (0.5 ms^{-1} at both levels). In terms of the close phase relationship between the gradient and the component it may be inferred that the flow at Bloemfontein is in quasi-geostrophic balance.

One important aspect of the results is the lack of a corresponding inverse six-month cycle in the boundary zone meridional winds to that in those of the upper troposphere. The persistent mean northerly flow in the lower atmosphere is consistent with the presence of a Ferrel Cell over the central interior of South Africa during the transitional months. During the high seasons only the upper-level flow reflects that of a Hadley Cell with the result that a transport of mass from tropical to temperate latitudes occurs. Poleward mean flow at most levels over southern Africa is also noted in the meridional cross-sections of Newell and Kidson (1979) and of Lindesay (1986). Assuming that the ageostrophic low-level circulation is a result of orographic effects induced by the elevated subcontinental plateau then the meridional toroidal circulation switches between the Hadley and Ferrel Cells according to the phase of the semi-annual cycle. Further the changes in the 200 mb meridional circulation on the semi-annual cycle together with the in-phase semi-annual cycle of the temperature at that level are indicative of the presence of the subtropical jet-stream to the south and to the north of Bloemfontein in the high and transitional seasons respectively (a summary of the properties of the meridional circulation in the Southern Hemisphere and of the jet is given in Appendix D).

The introduction of a semi-annual cycle in the sense of the toroidal circulation through the year implies that there are important related changes in the dynamics of the atmosphere over the central interior of South Africa. No comprehensive model of the circulation controls of the rainfall cycle may therefore be developed without incorporating relevant aspects of circulation changes on the semi-annual cycle in addition to those on the annual cycle. Components of the circulation of the Southern Hemisphere modulated on a semi-annual cycle are reviewed and the origins of the cycle discussed in Appendices D and E. Several important properties of the circulation changes associated with the semi-annual cycle are summarised in Figure 4-7. First, meridional components modulated on semi-annual cycles are limited to the central parts of the subcontinent. Secondly, the circulation over the eastern parts of the subcontinent is anomalously anticyclonic and anomalously cyclonic in the high and the transitional seasons respectively. Thirdly, the 200 mb component at Gough Island is in the opposite direction to that at Bloemfontein on the semi-annual cycle, suggesting that a standing wave lies over the Atlantic

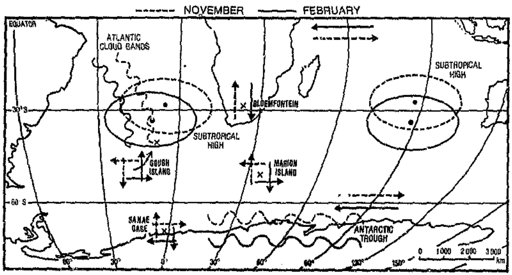


Figure 4-7. Schematic illustration of some major surface and 200 mb features of the semi-annual cycle in the African sector of the Southern Hemisphere (repeated from Figure E-1). Median locations are given for November (dashed) and February (full) of the: subtropical anticyclones from McGee and Hastenrath (1966); Atlantic cloud band between 30 and 40°S from Streten (1973); zonally-averaged sub-Antarctic trough from van Loon (1971a). 200 mb winds at Bloemfontein, Gough and Marion Islands and SANAE Base (marked with crosses) were taken from the present results while the tropical and polar zonal winds are based on van Loon et al. (1968). At polar latitudes the appropriate turning points fall in April and October rather than in February and August.

Ocean and that its longitudinal location is modulated on the cycle. The wave lies further west in the high seasons. Fourthly, the longitudinal loc'tion of the Atlantic cloud band, like that of the wave, is modulated on the semi-annual cycle and it is suggested that the locations of the bands and hence of the tropical-temperate troughs over South Africa may be similarly modulated. Phases of the semi-annual cycles in the circulation differ between low and high latitudes. Phases of the semi-annual waves at Bloemfontein are in closer correspondence with those in the tropical, rather than in the polar, atmosphere

Thus the seasonal cycle of the atmospheric environment over the central interior of South Africa is complex with waves of varying phases and periods dominant in the different cycles of the prime circulation parameters as a result of the interactions between the continental and maritime controls on atmospheric temperature. Because of the non-uniformity of the cycles the mean circulation in each month is unique. Inspection of the October to March circulation fields for each type of system and for dry days over the western Orange Free State presented by Harangozo (1986) indicates that the structures of the systems also vary on a monthly basis on cycles which are not always identical to those for the integral circulation. Inter-month changes in the dynamics of the systems must accompany the changes in the mean circulation.

CONCLUSIONS

South Africa's subtropical location and its surrounding oceans are two of the major determinants of the circulation over the interior of the country. Only the zonal flow above the boundary zone is largely unmodified from that of the atmosphere over the oceans at 30°S; all other circulation parameters including the thermodynamic parameters and the meridional flow are influenced by the presence of the land mass. Continental influences control the cycles of the temperature and pressure through the troposphere and into the lower stratosphere but that of the moisture is also related to maritime factors. As a result the energy structure of the atmosphere is determined by both continental and maritime influences.

One of the major effects of the mixed continental and maritime controls on the circulation is the development of a semi-annual cycle in the longitudinal pressure gradient with the consequent derivation of an equivalent cycle in the meridional circulation across Bloemfontein. This cycle is in phase with the semi-annual cycles in the tropical and subtropical atmosphere of the Southern Hemisphere. As a result of the reversals of the barotropic and jet-stream zones' meridional flow the toroidal circulation is modulated on the semi-annual cycle with the Hadley Cell dominant in the high seasons and the Ferrel Cell in the transitional seasons. Circulation changes on the semi-annual cycle represent important components of the seasonal changes of the atmospheric structure over the central interior of South Africa. Continental and maritime controls thus combine to produce annual and semi-annual cycles of varying phases and periods in the circulation over the western Orange Free State and to define the environment within which the various types of rain-bearing systems are embedded.

CHAPTER 5

MERIDIONAL MOMENTUM FLUXES

THE HYPOTHESIS

The tropical-temperate troughs that maintain major cloud bands in the Southern Hemisphere are distributed within a number of zones located over the oceans and across the land masses of southern Africa (during the rainfall season months) and Australia (throughout the year). Locations of the bands and hence of the troughs vary longitudinally within the zones on both short and long time scales and it has been suggested that these displacements may, in part, account for rainfall variations across Australia in the winter months and over the subtropical Pacific Ocean islands (Streten, 1973). Troughs in the vicinity of the African continent tend to lie either over the African subcontinent itself or across Madagascar; during wet spells in southern Africa troughs tend to overlie the subcontinent rather than Madagascar whereas in dry spells the pattern reverses. The leading edges of upper westerly waves form the subtropical and temperate portions of the troughs (Streten, 1973; Harangozo and Harrison, 1983; Tapp and Barrell, 1984) and accompanying rainfall over South Africa is thus associated with a poleward flow at those levels (Harangozo, 1986). One of the apparently consistent characteristics of the atmospheric circulation during wet periods is the enhancement of the poleward component of the flow across the country. Synoptic studies of heavy rainfall events (Triegaardt and Kraus, 1957; Triegaardt, 1961a, 1961b; Gouws, 1966b; Taljaard, 1981a) and comparisons of wet and dry period mean circulations at the surface and in the upper-air (Triegaardt and Kits, 1963; Hofmeyr and Gouws, 1964) in addition to direct analyses of wind directions (Miron and Lindesay, 1983; Miron and Tyson, 1984) have all indicated that the poleward flow strengthens during wet spells. Longitudinal movements of the troughs, adjustments to the meridional flow and variations in rainfall across South Africa may thus be interrelated.

Inspection of satellite images reveals that cloud bands in the Southern Hemisphere are normally rooted in regions of active tropical convection and, in particular, convection over the tropical land masses. Recognition of this fact has led to the suggestion that the bands may be visual markers of channels of energy efflux from the tropics to temperate latitudes (Johnson, 1969; Streten, 1973). This postulate appeared to have been verified in a quantitative study of the energy structure of the atmosphere over the North Pacific Ocean at times when bands equivalent to those of the Southern Hemisphere were rooted in Pacific typhoons (Erickson and Winston, 1972). Analyses of the structure of the Southern Hemisphere atmosphere at 200 mb using data from the EOLE constant level balloon experiment do not, however, substantiate the concept of channels of energy efflux associated with the bands but instead suggest that the bands form in regions of poleward eddy fluxes of momentum. According to the theory of Eliassen and Palm (1961) the eddy energy flux is in the opposite direction to the momentum flux and the bands may accordingly form in regions of energy flux *into* the tropics (Webster and Curtin, 1975). Evidence to support the postulated opposition of momentum and energy eddy fluxes at subtropical and temperate latitudes in the Southern Hemisphere has been obtained for two summer months of the FGGE year by Paegle and Baker (1982) but the theory has not been confirmed for the circulations of the bands themselves. Recalling that longitudinal movements of the tropical-temperate troughs in the vicinity of the subcontinent are related to rainfall variations over the continental interior it may be hypothesised that rainfall over the summer rainfall region of South Africa varies directly with the poleward momentum flux across the region.

As a direct consequence of the dearth or data over the oceans most studies of the momentum balance and of the associated fluxes over the Southern Hemisphere have been based either on zonally-averaged Eulerian wind data (Obasi, 1963a; Kidson *et al.* 1969; Newell *et al.*, 1969; Newell *et al.*, 1972; Newton, 1972; Johnson, 1983; Oort and Peixoto, 1983; James, 1983) or on Lagrangian data obtained from constant-level balloons (Solot and Angell, 1969, 1973; Angell, 1972; Webster and Curtin, 1974).

he basic structure of the zonally-averaged circulation of the hemisphere has been revealed through these studies which have thus contributed towards the understanding of the climate of the hemisphere as a whole. Yet marked regional deviations of the circulation from the zonal means occur across the hemisphere (Krishnamurti, 1971a; Newell *et al.*, 1972; Newton, 1972; Webster and Curtin, 1975; Physick, 1981; Trenberth, 1981, 1982; Webster, 1983) which to date have received limited attention and which are of immediate importance to local climates. Momentum fluxes and the momentum budget over several areas of the Northern Hemisphere, including North America (Holopainen *et al.*, 1980) and western Europe (Holopainen, 1982), have been examined but equivalent Southern Hemisphere studies have been [illegible] mainly to the relatively data-rich Australasian region (Priestley, [illegible]; Yoshida, 1967; Tucker, 1973; Newell et *al.*, 1974; Brock, 1982). No previous studies have been undertaken for southern African. Values of all components of the meridional momentum flux are calculated by month in this Chapter both for the integral circulation and for each of the types of systems in the classification. Harmonic analysis is used to investigate the seasonal cycles of each component.

BACKGROUND

Detailed discussions of the basic theory of the global momentum balance and of the meridional fluxes required to achieve the balance may be found elsewhere (Lorenz, 1967; Palmen and Newton, 1969; Reiter, 1969). Only the essential details will be provided here in an approach following that of Newton (1972). The vertically-integrated absolute angular momentum, M, of the atmosphere at a point at latitude ϕ is given by

$$M = \int_{p_t}^{p_0} (a^2 \cos^2\phi \; \Omega + a\cos\phi \; u) dp/g \qquad 5\text{-}1$$

where a represents the radius of the Earth and the variation of height between the surface (at pressure p_0) and the top of the atmosphere (at pressure p_t, taken as 100 mb) has been ignored; Ω is the angular velocity of the Earth and u is the zonal wind speed relative to the surface. The first right-hand term, referred to as the earth or Ω angular momentum, is the angular momentum of the atmosphere were it in solid rotation with the planet. The second right-hand term, the relative angular momentum, is the angular momentum of the atmosphere relative to the Earth. Absolute angular momentum increases with a stronger westerly component of the zonal wind.

The flux of momentum (M_ϕ) associated with the meridional wind component, v, is given by

$$M_\phi = \int_{p_1}^{p_0} v(a\cos\phi\ \Omega + u)a\cos\phi\ dp/g \qquad 5\text{-}2$$

where poleward meridional flows are positive. Values of all variables may be decomposed in the usual manner into a monthly mean value (denoted by an overbar) and a deviation from the mean (denoted by a prime), e.g. $u = \bar{u} + u'$ such that Equation 5-2 becomes

$$\overline{M}_\phi = \int_{p_1}^{p_0} (a\cos\phi\ \Omega\bar{v} + \bar{v}\bar{u} + \overline{v'u'})a\cos\phi\ dp/g. \qquad 5\text{-}3$$

The three right-hand terms represent the flux of earth angular momentum and the fluxes of relative angular momentum by the mean (the circulation flux) and the transient fluxes respectively. The first two terms define the flux by the toroidal circulation.

In order to compare the Bloemfontein results with those obtained for the zonal means it is necessary to integrate equation 5-3 around a line of latitude, so that

$$[\overline{M}_\phi] = 2\pi a^2\cos^2\phi\int_{p_1}^{p_0}(a\cos\phi\ \Omega[\bar{v}] + [\bar{v}][\bar{u}] + [\bar{v}^*\bar{u}^*] + [\overline{v'u'}])dp/g \qquad 5\text{-}4$$

where square brackets indicate zonal means and asterisks deviations from the zonal means. The last three right-hand terms now represent the relative angular momentum fluxes by the mean flow, by the standing eddies and by the transient eddies. Employing single station data it is not possible to estimate the standing eddy flux in the African region, but this flux is negligibly small at 30°S both over the hemisphere (Newell *et al.*, 1972; Webster and Curtin, 1974; Oort and Peixoto, 1983) and in the Australian region (Yoshida, 1967). It will be assumed that the standing eddies may be neglected in the present calculations, an assumption consistent with the results of Webster and Curtin (1975) for southern Africa. Comparisons between the zonally-averaged and the Bloemfontein results may be made by contrasting the latter as zonal means against the former.

Momentum fluxes have also been calculated for each type of system. A 'no rain' category has also been included in the analysis. Days were included in this latter category whenever there was no recorded rainfall over the western Orange Free State irrespective of any rain that may have fallen over other parts of the subcontinent. Data for days on which satellite images were missing have been excluded from the analyses. Data have been grouped into 'rain' and 'no rain' categories and these distributions harmonically analysed.

Given I subsets each containing n_i events within the data set of N events then the terms of Equation 5-4 may be decomposed as:

$$\bar{v} = (1/N)\sum_i n_i \bar{v}_i \qquad 5\text{-}5$$

$$\bar{v}\bar{u} = (1/N^2)\left(\sum_i n_i^2 \bar{v}_i \bar{u}_i + \sum_{ij}(1-\delta_{ij}) n_i n_j \bar{v}_i \bar{u}_j\right) \qquad 5\text{-}6$$

$$\overline{v'u'} = (1/N)\sum_i n_i \overline{{}_i{}'u_i{}'}. \qquad 5\text{-}7$$

Note that in Equation 5-7 deviations are calculated from the *Integral* means rather than from the means for each system. In the identity for the circulation flux, $\bar{v}\bar{u}$, two terms are required for the decomposition. The first term represents the circulation flux associated with each system calculated independently of the integral mean while the second is the sum of the cross products of the means for each system. In most months the magnitude of the second term is larger than that of the first but within the framework of the decomposition the cross-product term has no direct physical interpretation.

ANNUAL CYCLE OF THE MOMENTUM FLUXES

The seasonal cycle of the zonal wind at Bloemfontein is dominated throughout the surface to 100 mb layer by the first harmonic (Fig. 4-5a). Hence the relative angular momentum (Fig. 5-1a) also follows a simple seasonal cycle with a minimum in February and maximum in July, an equivalent result to that obtained for the zonal mean at 30°S from International Geophysical Year data (van Loon, 1965). Reductions in relative angular momentum are referred to as spindown, defined by

$$(\partial \bar{M}/\partial t) = a\cos\phi\ (\partial/\partial t)\int_{p_1}^{p_0} \bar{u}\, dp/g. \qquad 8$$

Spindown is two to three times as rapid between October and February as between July and October (Fig. 5-1a). Spinup is achieved over five months only, the major changes occurring between March and April and between June and July. The seasonal cycle of the relative angular momentum over Bloemfontein is dominated by the first harmonic with its maximum (minimum) in mid-August (mid-February) (Table 5-1).

The distribution of the earth angular momentum flux, as of the meridional components in the barotropic and jet-stream zones (Fig. 4-6), is modulated on a six-month cycle (Fig. 5-1b) with maximum values of the poleward flux in the high seasons. The second harmonic accounts for 78 per cent of the variance of the flux distribution with peak poleward transports in mid-February and mid-August (Table 5-1). Maxima in the six-month cycle of the poleward fluxes occur contemporaneously with the turning points of the annual relative angular momentum cycle.

Signs of the circulation flux are determined by $\bar{v}$ but magnitudes are controlled by both $\bar{u}$ and $\bar{v}$. Accordingly maxima of $\bar{v}\bar{u}$ are located in the jet-stream zone (Fig. 5-2) at levels in which the six-month cycle of $\bar{v}$ is most clearly defined. Maximum fluxes occur above 200 mb when the flow is directed equatorward, but the level of the maximum poleward flux varies between the winter (150 to 100 mb) and summer (200 mb) seasons. These level changes are associated with the equivalent variations in the level of the zonal component maximum following the latitudinal displace-

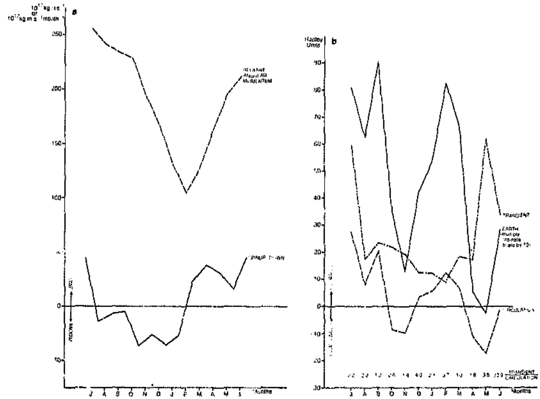


Figure 5-1. Mean monthly values of a) the vertically-integrated relative angular momentum and spindown and of b) the earth angular momentum and the circulation and transient relative angular momentum fluxes. Abscissa in b) in Hadley Units (10^{18} kg m^2s^{-2}). Multiply abscissa in b) by 10 for earth angular momentum flux. Figures in the lower part of b) give the absolute ratio of the transient to the circulation relative angular momentum flux. Poleward fluxes are positive.

ments of the subtropical jet stream (see Appendix D). Peak values of the poleward flux are only one third of those of the equatorward flux except at and above 150 mb in July. Below 400 mb the circulation flux is generally of comparatively small magnitude and is always (except at 500 mb in the early rainfall season months) directed poleward. A peak develops in the flux in the boundary and barotropic zones in the second half of the year with maxima in August and September in association with the stronger zonal winds of these months (cf. Fig. 4-5a). Seasonal flux variations are dominated by the annual cycle in the boundary and lower barotropic zones with *maximum* poleward fluxes in September or October (Figs. 5-3a and b). Above 600 mb the second harmonic explains in excess of 50 per cent of the variance at most levels with maxima in the late

Table 5-1. Details of first and second harmonics of the momentum fluxes. Amplitudes (Amp) are Hadley Units (10^{18} kg m^2s^{-2}). Column headed 'Var' gives variance explained by harmonic while that headed 'Max' lists approximate date of maximum poleward flux. For second harmonics dates are for the rainfall season poleward maxima. In second column an 'I' indicates results for integral data, an 'R' results for rain days and 'NR' results for no rain days.

	Annual Wave			Semi-annual Wave		
	Amp	Var	Max	Amp	Var	Max
Relative angular momentum - $\int \overline{u}\, dp/g$.						
I	65.6	95.7	15 Aug	9.0	1.8	20 Nov
R	69.7	89.5	10 Aug	18.[illegible]	6.4	12 Nov
NR	62.4	95.6	23 Aug	4.3	0.5	7 Jan
Earth angular momentum flux - $\int \overline{v}\, dp/g$.						
I	100.8	5.7	15 Oct	373.5	77.8	13 Feb
R	183.1	54.3	20 Jan	46.8	3.5	12 Oct
NR	209.7	24.8	15 Aug	324.3	59.3	10 Feb
Circulation relative angular momentum flux - $\int \overline{v}\,\overline{u}\, dp/g$.						
I	4.5	6.2	5 Sep	14.9	69.0	7 Feb
R	1.5	23.1	10 Mar	1.2	14.4	1 Jan
NR	1.8	2.0	15 Sep	10.2	60.6	10 Feb
Transient relative angular momentum flux - $\int \overline{v'u'}\, dp/g$.						
I	17.0	52.4	25 Jun	8.4	12.8	5 Dec
R	5.8	37.6	5 May	5.2	29.7	5 Nov
NR	14.0	53.6	15 Jul	7.3	14.6	23 Dec
Total relative angular momentum flux - $\int \overline{vu}\, dp/g$.						
I	19.1	41.7	5 Jul	12.1	16.6	20 Jan
R	6.7	41.5	25 Apr	4.8	21.3	10 Nov
NR	15.0	36.5	20 Jul	12.3	24.7	25 Jan

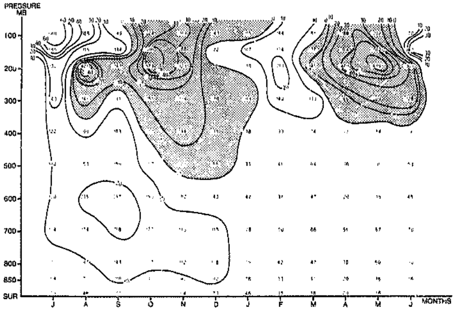


Figure 5-2. Seasonal and vertical distribution of the circulation flux of relative angular momentum at Bloemfontein. Surface (SUR) is at approximately 870 mb. Stippled areas denote equatorward (negative) fluxes. Units are m^2s^{-2}.

summer and winter months. Sixty-nine per cent of the variance of the vertical integral of the circulation flux (Fig. 5-1b) is accounted for by the second harmonic with peak positive (i.e. poleward) fluxes on 7 February and 7 August, a few days prior to those of the earth ar···lar momentum flux (Table 5-1).

Maxima of the transient relative angular momentum flux are also located in the jet-stream zone but at somewhat lower levels in winter (around 250 mb in July) than in summer (around 150 mb in December) (Fig. 5-4). The flux is nearly always directed poleward (i.e. positive correlation between the eddies of the zonal and meridional winds). Only in the lowest layers between October and February is the flux systematically directed equatorward; an equivalent feature is depicted on the surface December to February maps of Newell *et al.* (1972). More than the first two harmonics are required to explain the major part of the variance of the flux at most levels (Figs. 5-3c and d) Only near the surface and at 150

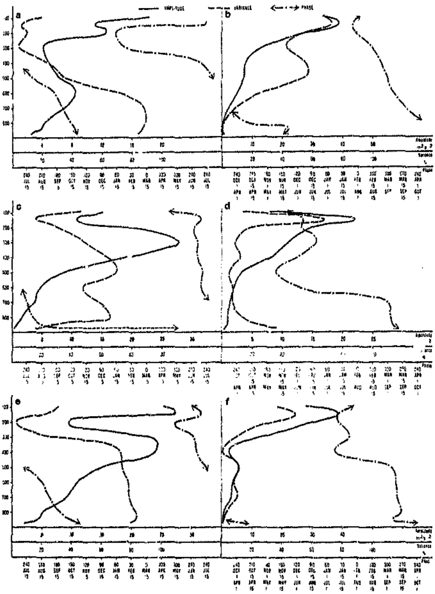


Figure 5-3. Results of harmonic analyses of relative angular momentum fluxes at Bloemfontein: a) 1st. harmonic of the circulation flux; b) 2nd. harmonic of the circulation flux; c) 1st. harmonic of the transient flux; d) 2nd. harmonic of the transient flux; e) 1st. harmonic of the total flux; f) 2nd. harmonic of the total flux. Amplitudes in m^2s^{-2}.

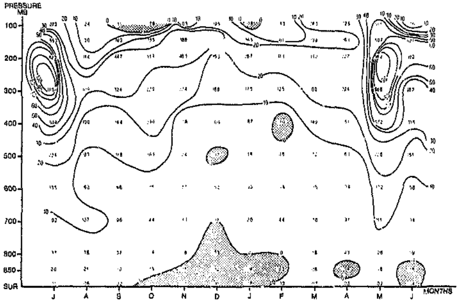


Figure 5-4. As Figure 5-2 but for the transient relative angular momentum flux.

mb does the six-month cycle account for more than 20 per cent of the variance but the waves at these two levels are almost exactly mutually anti-phase. In the jet-stream zone the maximum poleward fluxes occur in early June and December. Elsewhere the annual wave dominates the seasonal cycle with the maximum poleward flux in June, as is also the case for the vertically-integrated flux (Fig. 5-1c and Table 5-1). Peaks of the six-month wave occur with those in the jet-stream zone in early June and December. Amplitudes of the first two harmonics are, at most levels, at least double the amplitudes for the zonal averages at 30°S (Newell *et al.*, 1974) and the levels of the amplitude maxima at Bloemfontein and over the hemisphere corresponded closely. The range of values of the flux at 200 mb at Bloemfontein is markedly greater than that at 30°S deduced by Webster and Curtin (197)). Phase angles of the annual and of the boundary zone semi-annual waves at Bloemfontein agree to within about one month with those for the zonal mean but in the barotropic and jet-stream zones the semi-annual wave at Bloemfontein is anti-phase to that of the zonal mean.

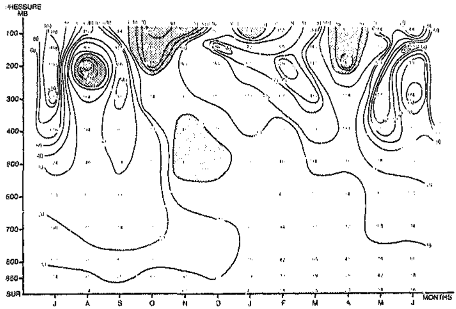


Figure 5-5. As Figure 5-2 but for the total relative angular momentum flux.

In most months at most levels the magnitude of the transient is greater than that of the circulation flux but the absolute value of the ratio of the former to the latter rarely exceeds two (Figs. 5-1b, 5-2 and 5-4). Neither component is dominant, therefore, in the determination of the total relative angular momentum flux (Fig. 5-5). Like the transient flux the total flux is, in general, directed poleward. Regions of equatorward fluxes occur primarily in the jet-stream zone in April, August and October. The phases of the first and second harmonics of the flux (Figs. 5-3e and f) are compromises between those of the equivalent harmonics for the transient and circulation fluxes (Figs. 5-3a to d). The first harmonic explains in excess of 70 per cent of the variance of the flux at most levels in the boundary and barotropic zones with maxima in winter. A peak in the amplitude of the six-month wave is located at 150 mb with maxima in early January and July. In the harmonics of the vertically-integrated flux poleward maxima on the annual and six-month waves occur in early July and in late January and late July respectively (Table 5-1).

MOMENTUM TRANSPORT BY SYNOPTIC SYSTEMS

Distributions of the vertically-integrated relative angular momentum associated with each type of synoptic system follow that of the integral relative angular momentum (Fig. 5-6). Minimum values generally occur in February but in January for the truncated and the east coast troughs and in March for the no rain days. Monthly maximum values are normally associated with the systems which develop in conjunction with westerly waves, the truncated and tropical-temperate troughs and the east coast troughs. Inversely minimum values and therefore strongest easterly components are associated with the primarily tropical systems, the west coast troughs and the subtropical cyclones. On no rain days the relative angular momentum is greater than the integral value in August to October and in December to February. In most months the mean relative angular momentum varies by less than a factor of two across the systems.

Earth angular momentum is transported poleward on rain days and equatorward on no rain days in all months except that in July, August and September the no rain flux is poleward (Fig. 5-7b). During the transitional seasons magnitudes of the rain and no rain fluxes are similar such that the net flux is close to zero (Fig. 5-1b). In the July to September period both fluxes are poleward while in summer the rain day flux is dominant and thus in these two periods the net flux is poleward. The second harmonic accounts for 59 per cent of the variance of the no rain flux with a phase angle and an amplitude close to that of the integral flux (Table 5-1). No equivalent wave is present in the rain day flux, the variance of which is dominated by the first harmonic with the maximum in mid-January. Six-month cycles appear to be present in the seasonal cycles (Fig. 5-7a) for the coastal depressions and the unclassified systems in addition to of the no rain days. For the remaining systems inspection of Figure 5-7a suggests that the fluxes follow primarily annual cycles. Minima occur in December for the truncated troughs, in January for the tropical-temperate troughs and the subtropical cyclones, in February for the west coast troughs and in March for the east coast troughs. Strongest poleward fluxes are supplied by the three types of systems associated with cloud bands in most months. The other classified rainfall

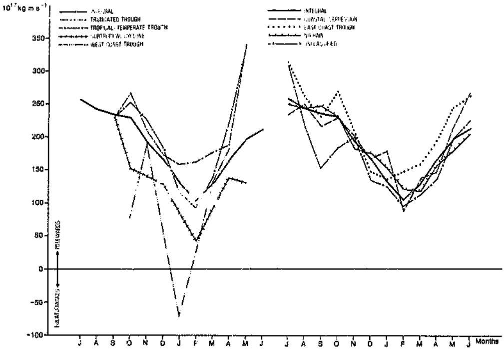
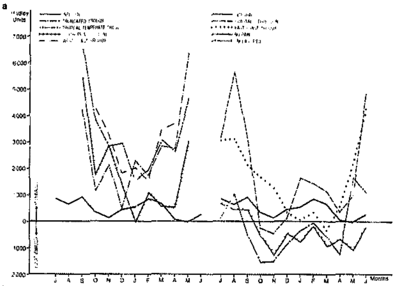


Figure 5-6. Monthly mean values of the vertically-integrated relative angular momentum of the synoptic systems.

systems also transport earth angular momentum poleward in all months except October and November for the coastal depressions, March for the east coast troughs and, possibly, January for the subtropical cyclones. Earth angular momentum fluxes associated with the unclassified systems are equatorward except in the months May to August.

Weightir the fluxes of Figure 5-7a by the frequency of each type of system (Equation 5-5) produces estimates of the contribution of each system towards the integral flux (Fig. 5-7b). During the rainfall season the major parts of the poleward and equatorward fluxes are carried on the tropical-temperate troughs and the no rain days respectively. Tropical-temperate troughs are the only system for which the meridional wind remains poleward at all levels in the months October to March (Harangozo, 1986). The net flux contributed by the tropical-temperate troughs remains quasi-constant despite the inter-month changes in the



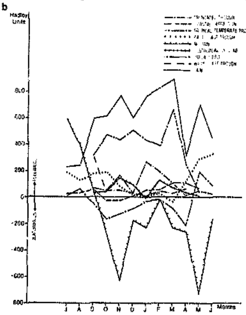
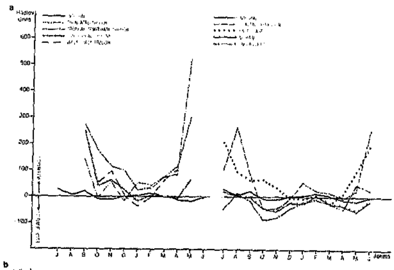


Figure 5-7. Monthly mean values of the vertically-integrated flux of earth angular momentum by each type of system: a) mean flux for each system; b) contribution of system fluxes to total flux. Units along abscissa are Hadley Units (10^{18} kg m^2s^{-2}).

frequency of the troughs (Fig. 3-4). Fluxes contributed by the remaining rainfall systems are, in general, small by comparison. During the winter months the east coast troughs and the unclassified systems, in addition to the no rain days, provide a sizeable proportion of the flux.



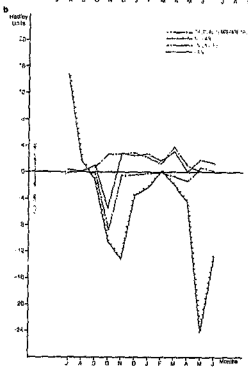


Figure 5-8. As Figure 5-7 but for circulation fluxes. In b) fluxes for only certain systems are shown - those for the remaining systems are negligible.

The semi-annual cycle is dominant in the distribution of the no rain circulation flux with poleward maxima in mid-February and August (Fig. 5-8b and Table 5-1). Momentum is transported poleward on rain days in all months except October. The latter flux is of insufficient magnitude to offset the equatorward flux on the no rain days such that the net flux is equatorward in the transitional seasons (Fig. 5-1b). No particular harmonic of the rain day circulation flux distribution is dominant (Table 5-1). Seasonal cycles of the fluxes for the individual systems (Fig. 5-8a) are similar to the corresponding earth angular momentum fluxes and the tropical-temperate troughs and the no rain days are the major individual contributors to the flux (Fig. 5-8b). The larger portion of the total flux comes, however, from the cross-product terms of Equation 5-6 in most months but it may be demonstrated that the major contributions to these terms comes from the more frequent systems. Tropical-temperate troughs and no rain days, as for the earth angular momentum flux, therefore provide the bulk of the circulation flux during the rainfall season months

From May to September the transient relative angular momentum flux on no rain days, which is directed poleward throughout the year, is markedly greater than that on rain days (Fig. 5-9b). During the rainfall season the magnitudes of the two fluxes are comparable (except in December) and that on the rain days exceeds that on the no rain days from February to April. Rain day fluxes are also always poleward except in August and December and are higher in the first than in the second half of the year. Fifty-four per cent of the variance is explained by the annual wave of the no rain transient flux with a maximum in July but for the rain flux the annual and semi-annual waves are of similar amplitudes (Table 5-1). This latter semi-annual cycle, with May and November maxima at the time of the peak Ferrel Circulation, is almost exactly *anti-phase* to the corresponding wave of the circulation flux on the no rain days. Further the amplitudes of the harmonics are similar such that the circulation flux on no rain days tends to counterbalance the transient flux on rain days. In the transitional months these two fluxes are closely opposed (Figs. 5-8b and 5-9b). Both semi-annual waves are of sufficient amplitude to appear in the cycles of the total relative angular momentum fluxes on both rain and no rain days (Table 5-1). Average monthly transient fluxes supplied by each system (calculated from Equation 5-7) are poleward in most months (Fig. 5-9a). No particular rain system makes a dominant contribution to the net flux although the tropical-temperate troughs account for the greater part of the poleward flux in the transitional seasons (Fig. 5-9b). Only the tropical-temperate troughs amongst the rainfall systems transport the transient flux poleward in all months. Inspection of Figure 5-9a suggests that the semi-annual cycle of the rain flux is present in the distributions for at

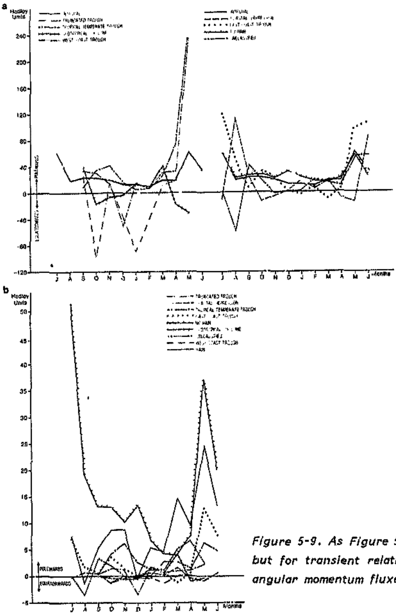


Figure 5-9. As Figure 5-7 but for transient relative angular momentum fluxes.

least the tropical-temperate troughs and the coastal depressions and that that of the coastal depressions is anti-phase to that of the integral rain flux.

DISCUSSION

Theories of the global atmospheric momentum budget state that westerly angular momentum is transferred from the earth to the atmosphere in the region of the tropical easterlies and is lifted into the upper atmosphere through the toroidal circulation and through vertical mixing of momentum in regions of active convection. Except in a limited latitudinal zone on either side of the equator the toroidal terms of Equation 5-4 play no significant role in the latitudinal transport of momentum on the hemispheric scale; the flux of earth angular momentum is identically zero through conservation of mass within a zone on suitable time scales, i.e.

$$\int_0^{p_{surf,e}} [\bar{v}]dp = 0 \qquad 5\text{-}9$$

while most available observational evidence suggests that the relative angular momentum flux by the mean flow is small compared to that by the transients (Newell, *et al.*, 1972; Webster and Curtin, 1974; Oort and Peixoto, 1983). Transients are consequently primarily responsible for transporting the required flux across the subtropics whence vertical eddies and the toroidal circulations of the Hadley and Ferrel Cells transfer the momentum back to the lower atmosphere from where it is returned to the earth through surface stresses in the westerly wind belt. A problem with the observational confirmation of the negligibility of the circulation flux lies in the accurate estimation of $[\bar{v}]$ in the Southern Hemisphere, the value of which has normally been deduced indirectly from global mass and momentum budget requirements (Gilman, 1965; Newell et *al.*, 1972; Oort and Peixoto, 1983). Direct calculations from Eulerian observations have indicated that at 30°S the magnitude of the circulation flux may be non-negligible (Oort, 1978; Houghton and Chervin, 1982) but the result is thought to originate in the poor spatial distribution of data for the hemisphere.

Bloemfontein lies close to 30°S, the latitude at which the zonal mean boundary between the Hadley and Ferrel Cells roughly lies (Newell *et al.*, 1972). At this latitude the transient flux dominates the total hemispheric flux but the circulation over Bloemfontein differs markedly from that of the longitudinal mean as a result of the diverse continental and maritime controls on the meridional flow. Conservation of mass within a zone, as expressed by Equation 5-9, does not hold at this single station partly because of the persistent poleward drift in the boundary zone. Only in April, May and November does the vertical integral of the meridional velocity approximate to zero (Fig. 5-1b). In most months the integral is positive such that there is a systematic poleward mass flux throughout the year except in May. Accordingly the toroidal terms make considerably more important contributions to the meridional flux of momentum across the central interior of South Africa than to the net flux across the hemisphere. In eleven months the absolute flux is dominated by the poleward flux of earth angular momentum; only in May do eddies make the major contribution offsetting the equatorward earth angular momentum flux. The absolute flux is, therefore, modulated primarily on the six-month rather than on the annual wave of the circulation.

The poleward earth angular momentum flux across Bloemfontein must be counterbalanced by an equivalent equatorward flux elsewhere in the same latitudinal zone. The major non-cancelling fluxes required to balance the budget on the hemispheric scale come from the transports of relative angular momentum which are modulated primarily on the annual cycle (Fig. 5-3 and Table 5-1). By simple averaging of the monthly values the annual mean relative angular momentum flux may be estimated at 28.6 HU (HU ≡ Hadley Units ≡ 10^{18} kg m^2s^{-2}) resulting from contributions of 25.6 HU from the transient flux and only 3.0 HU from the circulation flux. On an annual basis, therefore, the transients dominate the flux, a result consistent with that obtained for the zonal average. The relatively small contribution of the circulation flux, however, results from the nullifying effect of circulation changes modulated on the six-month cycle and not from any presumed small magnitude of the circulation as compared to the transient flux (the mean circulation flux calculated without regard to sign is 10.9 HU). In a study of the flux at two stations in the vicinity of 30°S in the New Zealand region Priestley (1951) estimated the circulation flux to be roughly one half of the transient flux across the year. The upper-tropospheric circulation flux over South America at 30°S is greater than the transient flux (Virji, 198[illegible] Alternatively the circulation flux is negligible over Australia (V[illegible] 57). Although small on the hemispheric scale circulatio[illegible] therefore important on the regional scale both around New Zealand on annual time scales and at Bloemfontein and over South America on time scales of one month.

Two reasons based on the influence of circulation changes on the six-month cycle may be offered to explain why the local importance of the toroidal fluxes has not been recognised to date. In the southern African sector of the Southern Hemisphere the semi-annual wave in the meridional wind is most pronounced over the central interior of the sub-c ıtinent, is almost non-existent in northern Namibia and is of reverse phase at Gough Island. Consequently a six-month cycle of the circulation flux over other regions may either not be present or may be of inverse phase to that over South Africa. Thus flux variations on the cycle are partially spatially self-cancelling. A second reason is that the periods of averaging selected in the past have tended to conceal the six-month wave. In general monthly flux estimates have used data for the months of January and July only (e.g. James, 1983) while three-month seasonal estimates have always been calculated across groupings of December, January and February, etc. (e.g. Newell *et al.*, 1972). Inspection of Figure 5-1b indicates that appropriate three-month seasons, less likely to suppress the six-month wave, would include the group January, February and March.

The annual relative angular momentum flux of 28.6 HU compares well with other estimates for the Southern Hemisphere (Table 5-2). It should be noted that direct absolute comparisons are not necessarily valid as the results presented in T ɔie 5-2 are based on transients calculated from mean flows estimated acr ɩ a variety of averaging periods. Many of the earlier estimates indicaʋɛd that the inter-seasonal variation in the flux is small, the largest rangɔ being that of 18 HU obtained by Kidson *et al.* (1969). Over the cent ·al interior of South Africa, by comparison, the poleward flux varies between 6.5 HU in April when the transient and circulation fluxes counteract one another and 86.3 HU in July when they support each other. This enhanced inter-season variation may result from the fact that the earlier estimates were made from averages across data for several rather than for single months. More importantly it is a consequence of the mixed continental and maritime controls on the flow over Bloemfontein which give rise to a greater amplitude of the annual cycle of the flux compared to that for the zonal mean. Over Australia

Table 5-2. Estimates (in some cases corrected to hemispheric scale) of the poleward flux of relative angular momentum across 30°S (36°S for Priestley's data) from the present and earlier studies. Units are Hadley Units (10^{18} kg m^2s^{-2}).

	DJF	MAM	JJA	SON	YEAR
Priestley 1951					33
Obasi 1963a					26
Yoshida 1967	28	39	40	32	38
Kidson *et al*. 1969	25		43		34
Newell *et al*. 1972	26	31	38	33	32
Newton 1972	30	34	39	35	34
Oort and Peixoto 1983	24		33		29
Present results	18	25	48	22	29

the seasonal fluxes at 30°S correspond closely with those of the zonal mean (Yoshida, 1967; Newton, 1972).

Partitioning of the fluxes r rain and no rain components reveals that significant differences i roperties of the meridional circulation on the two types of day In the October to March period the flow is generally poleward on rain days and generally equatorward above 700 mb on no rain days such that the Hadley Circulation is dominant on the former and the Ferrel Circulation on the latter types of days (Harangozo, 1986). Consequently the associated toroidal fluxes are in opposite directions except in winter when the no rain flux is also poleward. Phases and a tudes of the various cycles of the fluxes on the rain and no rain o . are such that the fluxes often counterbalance one another. Amplitudes of the annual cycles of the toroidal fluxes on both types of day, for example, are similar but phases are closely opposed such that the fluxes are nearly mutually cancelling. Zero net fluxes would result were there not a persistent polew d drift across Bloemfontein manifest on the rain days. Similarly the . partial compensation between the no rain circulation flux and the transient flux on both the annual and semi-annual cycles. Cycles arying amplitudes and phases which are not apparent from inspection integral fluxes alone thus combine to determine the forms of the temp distributions of the integral fluxes.

Important differences in the do periods of the modulations of the rain and no rain fluxes occur. Rain earth angular momentum fluxes are primarily modulated on an annual cycle; the semi-annual cycle of the integral flux arises from appropriate changes to the equatorward no rain flux. Alternatively the transient flux on rain rather than on no rain days is modulated on a semi-annual cycle. Diverse sources and controls on the fluxes on the two types of days are signified by these phase and period dissimilarities. Annual and semi-annual cycles in the rain fluxes are also partitioned between the fluxes for the various types of systems. Semi-annual cycles in the toroidal fluxes are apparently present for the coastal depressions and the unclassified systems although the annual cycle is dominant in the net rain fluxes. The semi-annual cycle in the rain transient flux appears to be the result of fluxes associated with the tropical-temperate troughs. For coastal depressions the semi-annual wave in the transient flux is anti-phase to that in the flux on the tropical-temperate troughs suggesting that the corresponding cycles of the structural modes (i.e. the wavelength, amplitude and efficiency of momentum transport) of the waves accompanying these two types of systems are inverse to one another. Flux changes on either cycle for all systems may not be explained simply in terms of frequency changes (cf. Fig. 3-4) and must therefore result from inter monthly adjustments to the dynamic structures of the systems. More than 50 per cent of the rain earth angular momentum flux is carried on the tropical-temperate troughs during the rainfall season and the transient flux on these systems is similarly dominant in the transitional seasons. Contributions towards the latter flux are similar for all systems in the summer months. Overall therefore the bulk of the poleward absolute flux is associated with the tropical-temperate troughs. Cycles of the rain toroidal and transient fluxes are thus most closely represented by those of the fluxes for the tropical-temperate troughs. In all months the tropical-temperate trough transient flux is poleward in partial confirmation of the inference of Webster and Curtin (1975) that the cloud bands are located in regions of above-average fluxes.

Strongest poleward transient fluxes are supplied in most months on the no rain days but the corresponding mean flow in the jet-stream zone, at levels at which the bulk of the transient flux is carried, is anomalously equatorward. In order for the $\overline{v'u'}$ correlation to be positive the westerly zonal component must also be weaker than normal on dry days, a fact confirmed for most months by Harangozo (1986). Thus *the poleward transient flux on dry days results from an equatorward transport of a* *weaker zonal component in comparison to that of the integral circulation.* Inversely poleward fluxes on rain days arise from the anomalous poleward transport of an enhanced westerly zonal component. These conditions are typical of tilted troughs (Machta, 1949) in which more momentum is carried poleward on the leading edges in association with rainy conditions than equatorward on the trailing edges above dry weather to produce a net poleward transport. According to Webster and Curtin (1975) southern Africa is, for unresolved reasons, a preferred region of development of enhanced tilt of westerly waves and thus of increased efficiency of momentum transport.

The semi-annual cycle in the transient flux on rain days may arise from one or more of three possible causes: either from a corresponding variation in the frequency of the rainfall systems, all other factors remaining constant, or from corresponding changes in either or both of the correlation between the zonal and meridional winds on rain days or the magnitude of the zonal and/or meridional wind variances. No accordant alterations in the frequencies of the rainfall systems exist (Fig. 3-2) but in the jet-stream zone there are seasonal changes in both the correlations between the wind components (46 per cent of the variance with one maximum in mid-December) and variations in the wind variances (Fig. B-2) of appropriate phases. Inter-monthly changes in the structure of the waves are indicated by these results such that maxima in the amplitudes of the upper-tropospheric waves and highest efficiency in the transport of momentum on rain days are attained in May and November. These are the months of anomalous cyclonic flow over the western Indian Ocean and in which the South Atlantic Anticyclone, according to McGee and Hastenrath (1966), is displaced eastward towards Africa on the six-month cycle (Fig. 4-7). With the shifts of the anticyclone there may be related changes in the wavelengths of the troughs associated with rainfall over the western Orange Free State such that the typical wavelength is a minimum at periods of maximum amplitudes of the waves in May and November. The semi-annual cycle in the flux is indicative of a stronger baroclinic structure of the atmosphere in the transitional than in the high seasons, i.e. when the Ferrel rather than the Hadley Circulation is dominant. Possible affiliated changes in rainfall patterns include an increased spatial organisation of the storms in the transitional seasons than in the summer season (Sharon, 1983b) and intra-annual adjustments in the diurnal rainfall cycle (Mather and Harrison, 1986).

CONCLUSIONS

Magnitudes of the meridional relative angular momentum fluxes across the central interior of South Africa are similar but the properties of the temporal distributions of the fluxes are unlike those of the zonal means. The two major disparities both relate to the toroidal fluxes which make important contributions to the absolute flux across Bloemfontein but not to that across the hemisphere and which are modulated on a semi-annual cycle not previously detected in fluxes at 30°S. The presence of a semi-annual cycle in the mean meridional flow is the source of the cycle in the toroidal fluxes. As a result of the permanent mean poleward flow in the boundary zone there is a poleward mass flux across Bloemfontein in eleven months of the year with strongest fluxes in conjunction with the Hadley Circulations of the high seasons. Circulation fluxes are equatorward in the transitional seasons. Transient fluxes remain poleward throughout the year and are modulated primarily on an annual cycle with strongest fluxes in July.

Distributions of the fluxes on rain and no rain days and for the individual types of systems differ markedly from those of the integral circulation. Toroidal fluxes for the rain days remain poleward throughout the year (except for the circulation flux in October) and are modulated on an annual cycle with strongest fluxes in January. During the rainfall season over 50 per cent of the earth angular momentum flux is carried along the tropical-temperate troughs. Fluxes on the no rain days are equatorward except in winter and are modulated according to the semi-annual cycle of the meridional circulation. Transient fluxes on both rain and no rain days are poleward throughout the year because of the tilted structure of the westerly troughs over the subcontinent. No rain fluxes are modulated on an annual cycle with a winter peak but rain fluxes are modulated according to both an annual and a semi-annual cycle. Peaks occur in May and in May and November respectively for the two cycles.

Phases of the semi-annual cycles of the rain circulation and the no rain transient fluxes are closely opposed. Transient fluxes for the tropical-temperate troughs appear to be modulated on the semi-annual cycle of the rain fluxes and make the major contribution of any type of system to the flux in the transitional seasons.

Adjustments to all components of the flux through the year indicate that changes to the dynamic structures of the various types of systems occur between months. In particular adjustments following phase changes of the semi-annual cycle indicate that there is a stronger baroclinic structure of the atmosphere in the transitional than in the high seasons. Lengths of the westerly waves are reduced in the transitional seasons when the standing wave across the Atlantic Ocean is displaced eastward and the Ferrel Circulation is dominant in the flow across the central interior of South Africa. In summer, when the Hadley Circulation is dominant and the Atlantic wave is displaced westward, the structure of the atmosphere is less baroclinic and the maximum poleward toroidal fluxes on rain days occur. The atmospheric environment within which the various types of rain-bearing systems are embedded is more complex than revealed by earlier studies with circulation changes modulated on both an annual and a semi-annual cycle contributing towards the circulations which govern the course of the annual rainfall cycle.

CHAPTER 6

RAINFALL AND THE MOMENTUM BUDGET

INTRODUCTION

The diverse properties of the meridional fluxes on the rain and the no rain days need to be accounted for in any comprehensive model of the circulation controls on the annual rainfall cycle over the central interior of South Africa. These properties include the opposing directions of the toroidal fluxes and the differences in the periods and the phases of the dominant modulating waves of the flux components. In this Chapter a basic outline for such a model is developed by considering the properties of the various dynamic mechanisms contributing towards the maintenance of the zonal component on both rain and no rain days. Tropical-temperate *troughs supply about 35 per cent of the rainfall over the western Orange* Free State, a contribution that reaches 60 per cent in January and determines the course of the annual rainfall cycle. Tropical-temperate troughs are also the most common type of rainfall system and thus the circulation on rain days is regulated primarily by that for the troughs. These troughs also account for the major portions of the poleward momentum transport during the rainfall season whereas the equatorward transports by the mean circulation are effected primarily on the no rain days. Thus the details of the desired model may be simplified by incorporation of only the circulations associated with the tropical-temperate troughs and the dry days.

The zonal flow at a point at any level of the atmosphere is maintained according to

$$(\partial\bar{u}/\partial t) = -(\partial/\partial y)\overline{v'u'} + v((\bar{u}/a)\tan\phi - (\partial\bar{u}/\partial y)) + \bar{v}f$$
$$- (\partial/\partial x)\overline{u'^2} - u(\partial\bar{u}/\partial x) - (\partial/\partial z)\overline{w'u'} - \bar{w}(\partial\bar{u}/\partial z) \qquad 6\text{-}1$$

where the first right-hand term represents the latitudinal convergence of the transient momentum flux, the second the changes in the relative angular momentum resulting from meridional displacements of the circulation associated with the mean flow and with the convergence of the medians and the third, the Coriolis torque, the transformation of earth angular momentum to relative angular momentum. Changes to the zonal flow forced by the longitudinal transient flux convergence and by advection of the zonal flow in a longitudinally-sheared circulation are described by the fourth and fifth [illegible]-hand terms. Similarly adjustments to the zonal flow throug[illegible]tical convergence of westerly momentum and through the vertic[illegible]n of momentum in a sheared flow are expressed by the sixth an[illegible]venth terms. In the tropics the sixth term describes vertical mixing of momentum in cumulus towers and is referred to as the 'cumulus friction' term. Vertical integration of *Equation* 6-1 yields an expression for the maintenance of the relative angular momentum at any location. Equation 6-1 is frequently used in time-mean form in which case the left-hand side reduces to zero and only the mean ageostrophic meridional component appears in the Coriolis torque term. *In the following the full form of* the equation will be retained to facilitate interpretation of both the seasonal cycle of the integral zonal components at all levels and of the cycles for the tropical-temperate troughs and the no rain days. Estimates of the magnitudes of several of the terms may not be *made from the present data but the results of* the harmonic analyses provide a route towards the interpretation of Equation 6-1 at Bloemfontein.

The toroidal terms

Of the toroidal terms the Coriolis torque is generally of greater magnitude than the other terms in Equation 6-1 except at latitudes close to the Equator. Westerly momentum is generated when v is poleward, as in the upper branch of the Hadley Cell. Inversely westerly momentum is destroyed by the Coriolis torque in the upper branch of the Ferrel Cell. In the boundary zone at Bloemfontein the mean meridional flow is always poleward (Fig. 4-6) and thus westerly momentum is generated through the year. The Coriolis torque may be the prime forcing function maintaining the zonal flow as the phases of the annual cycles of the meridional and zonal boundary zone components are in close correspondence (Fig. 4-5). Above the boundary zone the meridional wind undergoes a semi-annual cycle but no equivalent wave occurs in the zonal component (Fig. 4-5b). Nor is one present in the zonal mean winds at 30°S (van Loon *et al.*, 1968). Generation or extinction of westerly momentum through some of the remaining terms of Equation 6-1 must therefore counterbalance the semi-annual cycle in the Coriolis torque. Westerly momentum is generated on rain days as a result of the poleward upper-tropospheric flows while it is similarly destroyed in most months on no rain days. Maximum destruction on no rain days occurs in May and November and in these months the relative angular momentum on no rain days is weaker than on rain days (Fig. 5-6). In February and August when the no rain torque is either weak or, in the latter month, generates westerly momentum, the relative angular momentum on no rain days is higher than on rain days.

Latitudinal transient flux convergence

In general the latitudinal transient momentum convergence is of similar magnitude to but opposes the action of the Coriolis torque (Newell *et al.*, 1972). It is plausible therefore that the convergence might undergo a six-month oscillation of appropriate magnitude and phase to offset the generation or annihilation through the Coriolis torque. It is not possible to directly test this supposition at Bloemfontein with the present data but evidence exists to suggest that it may be valid. Poleward transient fluxes at 500 mb south of 30°S followed a quasi-six-month oscillation during the International Geophysical Year with maxima in March and August but at 30°S, as at Bloemfontein itself, the annual cycle was dominant (Newton, 1972). Equivalent results at temperate latitudes were obtained from the GHOST data as well as indications that the latitudinal convergence of the transient flux and the Coriolis torque tended to oppose one another on six-month cycles on the hemispheric scale (Solot and Angell, 1969, 1973; Angell, 1972). There are no comparable results for the subtropics but the semi-annual cycle in the transient flux on rain days may indicate that an equivalent cycle is present in the flux convergence. No semi-annual cycle occurs in the relative angular momentum on no rain days (Table 5-1) and thus a six-month cycle of generation of westerly momentum by transient flux convergence may counterbalance the destruction by the Coriolis torque. A weak six-month wave is, however, present in the relative angular momentum on rain days with westerly maxima closely contemporaneous with the equivalent poleward maxima of the transient flux. Generation through the convergence term may therefore undergo a semi-annual cycle on rain days in phase with the cycle in the poleward transient flux.

Longitudinal transport and transient flux convergence

According to James (1983) the longitudinal terms may be of sufficient magnitude to make an important contribution to the maintenance of the zonal flow. Only at around 150 mb does the second harmonic explain more than 10 per cent of the variance of $\overline{u'^2}$ (Fig. B-2b), the cycle of which is dominated by the annual wave. In view of this fact and of the absence of a large-amplitude second harmonic in the local or global zonal winds it seems reasonable to conclude that generation through the transient convergence and the longitudinal transport of momentum follows a predominant annual cycle.

The mountain torque

The zonal mean meridional flux at a given latitude is balanced by the stresses (i.e. the surface and mountain torques) to either side of that latitude (Newell *et al.*, 1972). No similar balance between the stresses and the flux may necessarily be expected on scales below the hemispheric but it will be assumed in the following that the meridional fluxes observed at Bloemfontein may be interpreted in terms of stresses in the southern African sector of the hemisphere alone. Thus adjustments to the atmospheric westerly momentum from convergence of momentum into the region will be neglected below. The mountain torque exerted by the raised African plateau on the atmosphere is of comparable magnitude to that associated with the South America uplands and is thus a major component of the hemispheric net torque (Newton, 1972). The surface pressure gradient across the plateau, as represented by Durban and Alexander Bay monthly mean 1000 mb pressure heights, is positive in seven months of the year (Fig. 6-1a). The gradient as estimated from differences in 850 mb heights or from the vertical integral of the torque to the 850 mb level is also positive in most months. The mountain torque of the plateau thus generates (when the gradient is positive) or destroys atmospheric westerly momentum according to the period of the year. There are marked semi-annual cycles in the mountain torque (Table 6-1) despite the

Table 6-1. Details of first and second harmonics of the mountain torque between Durban and Alexander Bay. Amplitudes (Amp) are in metres (see text for details). Column headed 'Var' gives variance explained by harmonic while that headed 'Max' lists approximate dates of maximum transfer of westerly momentum into atmosphere. For second harmonics dates are for rainfall season maxima.

	Annual Wave			Semi-annual Wave		
	Amp	Var	Max	Amp	Var	Max
1000 mb	0.81	53.5	30 Mar	0.39	12.4	22 Mar
850 mb	0.54	42.9	5 May	0.38	20.3	1 Mar
1000-850 mb	0.43	30.9	7 Sep	0.34	19.9	14 Jan

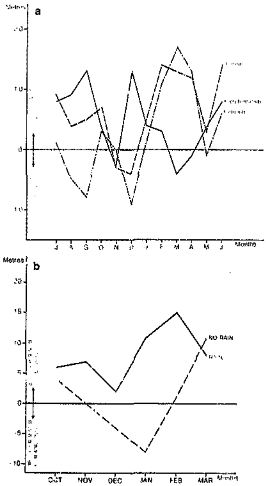


Figure 6-1. a) Mountain torque across South Africa as represented by standard level height differences (metres) at 1000 and 850 mb between Durban and Alexander Bay; b) Monthly mean 850 mb height gradients between Durban and Alexander Bay for rain (solid line) and no rain (dotted line) days in the western Orange Free State adapted from Harangozo (1986).

fact that the second harmonic makes an insignificant contribution towards the 1000 and 850 mb height distributions at both stations. Phase angles of the semi-annual cycles in the gradients are such that the peak transfer of westerly momentum into the atmosphere occurs at around the same times as the maxima of the poleward flows (cf. Table 5-1) and of anomalous anticyclonic flow across the western Indian Ocean (Fig. 4-7). No previous indicators of a semi-annual wave in, or even of a possible change in the direction of, the mountain torque of the African plateau at 30°S have been obtained (e.g. Newton, 1971) although the results of Wei and Schaack (1984) indicate that the African torque at 15°S reverses seasonally. The sign of the total mountain torque of the Southern Hemisphere does, however, vary during the year (Newton, 1971; Newell *et al.*, 1972; Wei and Schaak, 1984; Wahr and Oort, 1984). Throughout the months October to March the height gradient between Durban and Alexander Bay at 850 mb is positive on rain days but it is negative on no rain days in December and January (Fig. 6-1b). Westerly momentum is therefore transferred to the atmosphere except in December and January on no rain days. In all six months except March the gradient, and hence the transfer to the atmosphere, is stronger on the rain days.

Surface stresses

Relative angular momentum is generated and destroyed through stresses between the surface and the easterly winds in the tropics (and polar regions) and the westerly winds in the temperate latitudes respectively. The fact that the flux by the mean flow in addition to the mountain torque at 30°S follow six-month waves suggests that the surface stresses in the regions where the momentum is transferred from and to the planet should also undergo six-month cycles. To be in phase with the cycle of the toroidal fluxes maximum generation and strongest easterly winds should occur in February and August together with strongest westerly winds in temperate latitudes. In the oceanic sector 60 to 120°E the cycle of the surface tropical zonal winds is dominated by the annual wave but at 15 to 25°S the second harmonic explains about 10 per cent of the variance with maximum easterlies in February and August (van Loon and Jenne, 1970b). Over southern Africa both the phase of and the variance explained by the harmonics of the zonal components are variable. At Maputo the second harmonic of the 850 mb zonal wind distribution is dominant with maximum easterlies in February and August but at Harare and anticyclonic flow across the western Indian Ocean (Fig. 4-7). No previous indicators of a semi-annual wave in, or even of a possible change in the direction of, the mountain torque of the African plateau at 30°S have been obtained (e.g. Newton, 1971) although the results of Wei and Schaack (1984) indicate that the African torque at 15°S reverses seasonally. The sign of the total mountain torque of the Southern Hemisphere does, however, vary during the year (Newton, 1971; Newell *et al.*, 1972; Wei and Schaak, 1984; Wahr and Oort, 1984). Throughout the months October to March the height gradient between Durban and Alexander Bay at 850 mb is positive on rain days but it is negative on no rain days in December and January (Fig. 6-1b). Westerly momentum is therefore transferred to the atmosphere except in December and January on no rain days. In all six months except March the gradient, and hence the transfer to the atmosphere, is stronger on the rain days.

Surface stresses

Relative angular momentum is generated and destroyed through stresses between the surface and the easterly winds in the tropics (and polar regions) and the westerly winds in the temperate latitudes respectively. The fact that the flux by the mean flow in addition to the mountain torque at 30°S follow six-month waves suggests that the surface stresses in the regions where the momentum is transferred from and to the planet should also undergo six-month cycles. To be in phase with the cycle of the toroidal fluxes maximum generation and strongest easterly winds should occur in February and August together with strongest westerly winds in temperate latitudes. In the oceanic sector 60 to 120°E the cycle of the surface tropical zonal winds is dominated by the annual wave but at 15 to 25°S the second harmonic explains about 10 per cent of the variance with maximum easterlies in February and August (van Loon and Jenne, 1970b). Over southern Africa both the phase of and the variance explained by the harmonics of the zonal components are variable. At Maputo the second harmonic of the 850 mb zonal wind distribution is dominant with maximum easterlies in February and August but at Harare and

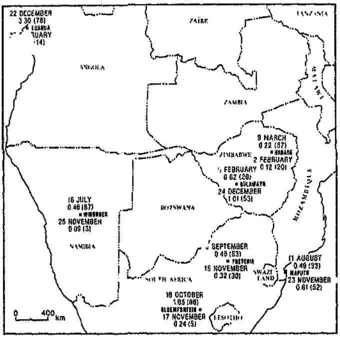


Figure 6-2. Dates of (summer) maxima of the annual (upper values) and semi-annual (lower values) 850 mb .nal component waves at sele..ed southern African stations. Figures give amplitudes of waves in ms-¹ and, in brackets, explained variances.

Luanda the phase is reversed (Fig. 6-2). At Bulawayo, Pretoria and at Bloemfontein itself the phase is consistent with that over the Indian Ocean. To the south of Africa 50 per cent of the variance of the surface zonal component distribution at 50°S is explained by the second harmonic with maximum westerlies in February and August (an Loon and Jenne, 1970b). It may be inferred that relative angular momentum as transported across the central interior of South Africa is generated at about 20°S over the eastern parts of the subcontinent represented by Maputo, Bulawayo and Pretoria and is returned to the planet at about 50°S. Maxima in the zonal mean surface stresses occur at these latitudes (Newell *et al.*, 1972; Wahr and Oort, 1984) which are located within the Southern Hemisphere source and sink regions of relative angular momentum in the December to February period (Fig. 6-3). The dominant cyclone track over the Indian Ocean lies at the latitudes in which momentum is returned to the planet (Trenberth, 1982).

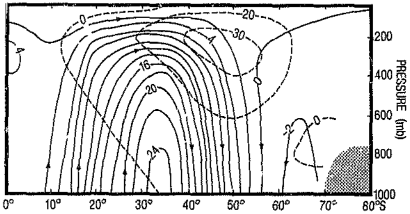


Figure 6-3. Streamlines of the non-divergent component of zonal mean transport of relative angular momentum in December to February (adapted from Oort and Peixoto, 1983). Stippling marks the Antarctic continent. Units are Hadley Units (10^{18} kg m^2s^{-2}.).

Rainfall systems associated with net poleward momentum fluxes in tilted troughs may only exist provided there is generation or convergence of westerly momentum equatorward of the trough. Should generation through stresses at 20°S be of importance to the budget, as assumed in the preceding, then rainfall systems such as the tropical-temperate troughs *must* be accompanied by strengthened surface easterly flow northward of the western Orange Free State. Evidence that the annual mean easterly surface component over Zimbabwe and northern Namibia is stronger in wet than in dry years over South Africa (Tyson, 1984) supports the contention that westerly momentum generated through surface stresses at 20°S is an important component of the poleward flux across the South African plateau on rain days.

Vertical fluxes

Vertical fluxes, which transfer momentum between the surface sources and sinks and the upper-tropospheric region of maxima in the meridional transport, are difficult to estimate. According to Newell *et al.* (1974) the mean vertical motion over South Africa at 500 mb is downwards through the year but estimates of the topographically-forced low-level motion indicate that it is upwards in the high seasons (Vianello, 1985). Thus the direction of the mean flux is presently not known. Mean surface winds at Bloemfontein in all months both for the integral circulation and for each system (Harangozo, 1986) are westerly, indicating that the South African plateau is a sink region of atmospheric westerly momentum. Overall momentum is transported downwards, therefore, by all systems. The flux may not necessarily, however, be downwards on all days. Surface easterlies occur throughout the year but are more common in summer than in winter and during the night than during the day, being dispersed in the latter period by downward mixing of westerly momentum. The layer of easterlies may extend, particularly during the summer months, to the 500 mb level or beyond. Deep easterly flows are normally associated with rainfall and with generation of atmospheric westerly momentum through surface stresses and the mountain torque. These flows may therefore be associated with upward momentum transport.

The partitioning of the vertical flux at Bloemfontein into the mean and transient components has not been determined but may be temporally dependent. It is suggested in Appendix I that both the mean vertical motion and the transient flux convergence may be modulated on semi-annual cycles of opposing phase with the mean motion anomalously upwards in the high seasons. Should this postulate be valid then there is anomalous upwards transport through the mean flow in the high seasons in periods of the dominant Hadley Circulation and through the flux convergence in the transitional seasons when the baroclinicity of the atmosphere reaches a maximum.

TROPICAL-TEMPERATE TROUGHS AND POLEWARD MOMENTUM FLUXES

Based on the preceding discussion it may be inferred that the major mode of the circulation associated with poleward momentum transport across South Africa is one in which westerly momentum is generated through surface stresses in an easterly flow and vertical lifting of the momentum is achieved through either the mean vertical motion or cumulus friction at 20°S prior to poleward export and final destruction at about 50°S. The mountain torque also contributes towards the total generation but the latitude of lifting of this momentum has not been determined. No detailed studies of the circulation at 20°S have been undertaken but it is possible using available data to deduce some of the details of the mechanisms controlling the momentum budget of the region.

Tropical-temperate troughs are the major type of system achieving the transport of momentum poleward across southern Africa. Tropical-temperate troughs appear to be invariably linked through a tropical low at about 20°S with the tropical cloud masses over central southern Africa (Harangozo and Harrison, 1983), a fact confirmed by inspection of both satellite images and surface synoptic charts during the development of the catalogue of circulation types. Cumulus friction within the cloud masses may supply a proportion of the required vertical flux at 20°S. Circulation controls on the formation of the lows are therefore equivalent to those regulating the momentum budget at 20°S.

No studies of the dynamics of the lows have been pursued but some insight into the conditions required for their formation may be obtained through analogy with results for equivalent systems elsewhere in the world. During the northern summer there is a quasi-continuous train of westward-propagating easterly waves across the Sahel at around 15°N. The waves provide a high proportion of the rainfall over the Sahelian zone (Newell and Kidson, 1984). Certain consistent dynamic characteristics of the waves have been recognised on the basis of results from a number of pertinent studies (Burpee, 1972, 1974; Pedgley and Krishnamurti, 1976; Rennick, 1976; Reed *et al.*, 1977; Norquist et *al.*, 1977). These characteristics include a low-level cold core, a mid-tropospheric warm core and upper-tropospheric cold core and development of the waves in the vicinity of the easterly jet at 650 mb. Instability of the internal jet (change in the sign of the meridional gradient of the potential vorticity - Charney and Stern, 1962) and barotropic instability (change in the sign of the meridional gradient of the absolute vorticity) are both present and the wave energy is derived from both the horizontal and vertical shears of the basic current. It has been suggested that adjustments in the easterly vertical shear and hence in attendant variations in the conditions suitable for the production of easterly waves may account for the rainfall fluctuations over the Sahelian zone as based on observations of a stronger 200 mb flow in the wet summer of 1969 as compared to in the drought summer of 1972 (Kanamitsu and Krishnamurti, 1978). Not only are the rainfall and the strength of the easterly flow at 200 mb in the region of 15°N directly related however (Kidson, 1977) but the rainfall is indirectly related to the strength of the low-level jet. Thus in *dry* periods there is a net *increase* in the vertical shear (Newell and Kidson, 1984) such that increased wave energy is available despite the weakened upper-tropospheric easterly flow.

Of the characteristics of the wet-period flow over the Sahel two appear to have fairly general applicability in the tropics of the Eastern Hemisphere, namely the upper-level easterly flow and the presence of barotropic instability. Higher rainfall totals are accompanied by strengthening of the 200 mb easterly flow for both the Indian (Kobayashi, 1974; Kanamitsu and Krishnamurti, 1978; Tanaka, 1982) and the winter monsoon (Tanaka, 1981; McBride, 1983) and over Venezuela (Riehl, 1977a). The direct association between tropical convection and easterly flow at 200 mb over the Eastern Hemisphere has been demonstrated by Webster (1983). The direction of the flow reverses in the Western Hemisphere where westerlies cover the convection over the Amazon Basin. It will be assumed that tropical lows over southern Africa form only with an upper-level easterly zonal current (the mean summer zonal flow at 200 mb and 20°S is westerly - Figure 6-4), an assumption consistent with the analyses of Lindesay (1986). By the very nature of the circulation around the low an easterly surface flow and hence generation of momentum must also be present. Barotropic instability of the flow is the fundamental mechanism responsible for the formation of the Sahelian waves (Mak, 1983) and is of major importance to the development of Indian monsoon depressions (Satyan *et al.*, 1981; Goswami *et al.*, 1981; Lindzen

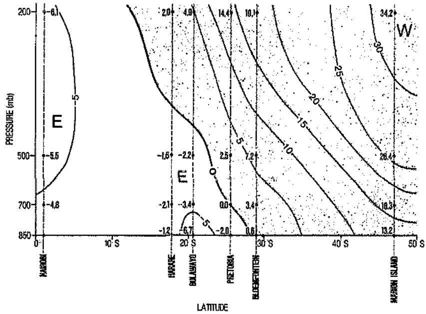


Figure 6-4. Mean January to March zonal wind components (ms^{-1}) along the 30°E meridian from the equator to 50°S for the period 1958 to 1983 after Lindesay (1986). Westerly flows are positive.

et al., 1983) and of tropical disturbances over the central Pacific Ocean (Nitta and Yanai, 1969) and over northeastern Brazil (Rao, Marques and Bonatti, 1984). Few data are available to test the degree of instability of the summer mean flow over Africa at 20°S but inspection of mean January to March zonal wind data for the period 1958 to 1983 along the 30°E meridian (Fig. 6-4) indicates that the flow may be barotropically unstable. The speed of the easterly flow in the lower layers at Bulawayo is markedly higher than at either Harare or Pretoria with the result that the sign of the meridional gradient of the relative vorticity reverses in the vicinity of the former station. Order of magnitude calculations indicate that the meridional relative vorticity gradient is larger than that of the Coriolis parameter such that the sign of the absolute vorticity gradient reverses at about 20°S. Hence the flow is barotropically unstable. Magnitudes of the zonal component at Bulawayo may also be indicative of the presence of a low-level jet at 20°S.

There is one major aspect in which the northern and southern African waves differ - at no time do the Sahelian waves come under the direct influence of a westerly trough from the north whereas the equivalent situation is a common occurrence in the south. A type of rainfall system develops over the Sahel which involves the linking of westerly waves and disturbances in the low-level easterly flow but these systems are restricted primarily to the transitional seasons (Nicholson, 1981). About 70 per cent of summer rainfall systems over northern Venezuela, on the other hand, develop in conjunction with westerly waves intruding equatorward from the North Atlantic Ocean (Riehl, 1977a). According to Riehl (1977b) such troughs offer a mechanism for extraction of the heat from the tropical zone necessary to maintain the meridional temperature gradient required to drive the Hadley Cell. The troughs also supply suitable dynamic conditions for enhanced development of tropical disturbances over Venezuela. Over Brazil, as over southern Africa, troughs penetrate well into the interior of the continent (Kousky, 1979) and these incursions are frequently associated with ensuing reductions in pressure and intensified convection over the Amazon Basin (Kousky and Ferreira, 1981; Virji and Kousky, 1983). Cloud bands over the South Atlantic Ocean mark at least some of these tropical/temperate links (see Figure 9 of Kousky and Ferreira, 1981, and Figure 2 of Virji and Kousky, 1983). Intensification of tropical systems over southern Africa also occurs in association with equatorward-intruding westerly waves (Bhalotra, 1973; Kumar, 1978; Acharya and Bhaskara Rao, 1981). Enhanced energy generation and also presumably lifting of momentum through mixing in the convection accompany the intensification of the tropical systems. As in the Venezuela region heat extraction from the African tropical systems along the tropical-temperate troughs may drive the Hadley Circulation present in conjunction with the troughs. Tropical heat release and cumulus friction are two of the major driving functions of the Hadley Circulation, the Circulation accelerating in periods of active convection at low latitudes with attendant above-normal heat release and cumulus friction (Rind and Rossow, 1984; Zillman and Johnson, 1985). The anomalous poleward flow on days with tropical-temperate troughs is therefore indicative of a poleward acceleration of the meridional circulation forced by heat and momentum generation at 20°S.

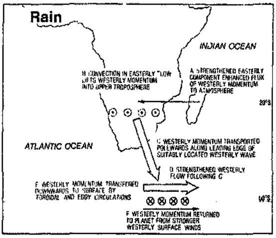


Figure 6-5. Schematic model of mean summer circulation associated with rainfall from tropical-temperate troughs. Single arrows represent low-level flows and double arrows upper-tropospheric flows; arrow heads represent regions of ascent and arrow tails regions of descent.

A model of the circulation on days with tropical-temperate troughs across South Africa may now be proposed (Fig. 6-5). Convection develops over central Africa at about 20°S with an easterly flow at the surface and at 200 mb in association with barotropic instability and with instabilities associated with the upper-level circulation and, possibly, with the internal jet. A wave forms in the easterly flow within which develops a closed tropical low. Westward propagation of the wave into the Atlantic Ocean, as happens for the waves over North Africa, is blocked by the column of cool air extending above the cold ocean surface off the coasts of Namibia and Angola, temperature conditions which are not replicated off the west coast of North Africa (Newell *et al.*, 1972). The wave may consequently lie quasi-stationary over tropical Africa and in such a case is referred to as a 'standing wave in the easterlies' by Taljaard (1972). Westerly momentum is transferred to the atmosphere in the surface easterly flow and is raised to the upper troposphere through mixing in the convective motions. Westerly momentum is also transferred to the atmosphere through the mountain torque with the high pressure system along the east coast of the subcontinent but it is not certain that this momentum is lifted at 20°S. Generation of momentum and heat release in the convection provide suitable conditions for the forcing of a Hadley *Cell across southern Africa.*

Convection, and consequently the generation of heat and momentum, is intensified with interaction between the circulation around the tropical low and a westerly trough associated with a temperate cyclone passing to the south of the continent. Further the trough provides a suitable channel for the poleward transport of both energy and momentum by the mean flow and marks the Hadley Circulation forced by the heat and momentum generation. Particularly during the transitional seasons the troughs develop pronounced tilts such that efficient poleward momentum transport occurs. Circulation changes on the semi-annual cycle result in a decreased efficiency of the transport in the summer season. The cold front associated with the trough penetrates the interior of the *country and forced convergence along the front together with a* baroclinically-unstable atmosphere and an influx of moisture in the easterly flow provide conditions suitable for the development of convection along the trough. Viewed from a satellite this latter region of convection appears as part of a continuous cloud link between the tropical low and the temperate cyclone. Momentum is subsequently returned to the planet in the region of the Indian Ocean storm track at 50°S.

THE EQUATORWARD MOMENTUM FLUX ON NO RAIN DAYS

The model devised above for the circulation associated with the tropical-temperate troughs is not applicable for that on no rain days in which the momentum flux is equatorward and the magnitude of the flux is modulated on a semi-annual cycle with peak fluxes in May and November. Following the arguments given above for the poleward flux the no rain equatorward flux may be traced back to regions of atmospheric ascent above surface easterlies. No common synoptic system giving dry weather at Bloemfontein together with easterly surface winds to the south of the city exists and thus distant sources of the flux must be sought. There appear to be two possible such sources. One is the region to the south of the Antarctic trough where the strongest easterlies are in June and December at about the time that the trough is furthest north (Fig. 4-7). Antarctica is a source of temperate latitude angular momentum throughout the year (Oort and Peixoto, 1983). The phase of the semi-annual cycle at Bloemfontein is however consistent with that of the circulation over the tropics rather than that over Antarctica indicating that a tropical rather than a polar source of the momentum exists.

Tropical South America and/or the adjacent oceans are possible sources of the momentum whence it is transported poleward in the vicinity of the trough over the Atlantic Ocean associated with the semi-permanent cloud band (Webster and Curtin, 1975) after lifting over the Amazon Basin. Poleward momentum fluxes over the South Atlantic Ocean are amongst the strongest of the hemisphere (Angell, 1972; Webster and Curtin, 1975; Trenberth, 1982). The longitudinal location of the cloud band and hence of the trough undergoes a six-month oscillation which brings it closest to Africa in November and May (Fig. 4-7), the months of the strongest equatorward fluxes over Bloemfontein on no rain days. Re-curvature of the flow under constraints of maintenance of absolute vorticity (or absolute momentum) would, given a suitable wavelength of the resulting standing wave, result in an equatorward flow across southern Africa. Presumably the wavelength is such that it accounts for the strongest equatorward flow which occurs when the standing wave is displaced towards the east in the transitional seasons (Fig. 5-8a). If any of the westerly momentum transported equatorward over South Africa is returned after subsidence to the planet in the vicinity of the subcontinent it would appear as westerly maxima in the surface winds in May and November. May and November maxima are observed at Bloemfontein, Pretoria, Bulawayo, Maputo and over the Indian Ocean (Fig. 6-2). The six-month cycle in the low-level zonal flow over the Indian Ocean may therefore, in part, be forced from the Atlantic Ocean. Strengthened westerly components over Africa at 20°S result in an increase in the dynamic stability and hence in a reduction in the convection. Heat release, the generation of momentum and the forcing of the Hadley Circulation across South Africa decline and the region becomes a momentum sink.

Some of the momentum carried equatorward across southern Africa may subsequently be re-exported poleward to the east of the subcontinent.

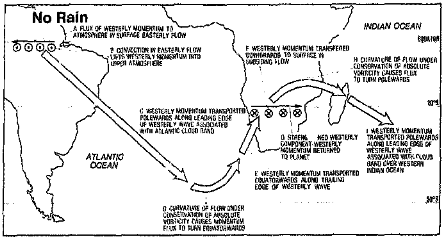


Figure 6-6. As Figure 6-5 but for no rainfall over the western Orange Free State.

Although not always present troughs marked by cloud bands are frequently located off the east of the continent on *no rain* days at Bloemfontein (Fig. 2-6) and may denote suitable channels of momentum efflux. The relative angular momentum circuit is envisaged as: a) generation of westerly momentum over the Amazon Basin and the tropical Atlantic Ocean; b) lifting in the Amazon Basin convection; c) poleward transport over the South Atlantic Ocean in the vicinity of the cloud band; d) curvature of the flow in the temperate South Atlantic Ocean such that some of the flux returns equatorward across South Africa; e) any momentum not returned to the planet through subsidence over the subcontinent and the Indian Ocean is re-exported poleward in the vicinity of the band situated to the east of the continent after re-curvature of the flow at about 20°S (Fig. 6-6). The low phase of the Southern Oscillation (defined in Chapter 9) is usually associated with below-normal rainfall over South Africa (Harrison, 1983a; Lindesay *et al.*, 1986; Lindesay, 1986) and thus marks periods in which the above mode of circulation may be most clearly defined. Mean December to February 200 mb wind anomalies in the low phase have been derived by Arkin (1982). A clear correspondence between the circuit deduced above and Arkin's results, which explicitly illustrate the standing wave across the Atlantic Ocean, is apparent (Fig. 6-7). Arkin's data indicate further that momentum is exported from South America at 20°S in addition to at the Equator, that

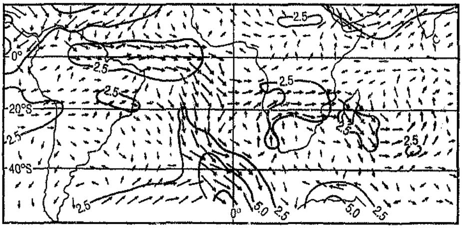


Figure 6-7. December to February mean 200 mb wind anomalies over the southern Atlantic and Indian Oceans during the low phase of the Southern Oscillation (after Arkin, 1982). Isotachs labelled in ms^{-1}. Stippling outlines the flow discussed in the text.

much of the momentum does not re-curve over the South Atlantic Ocean but is returned to the planet in the vicinity of Antarctica and that there is also a direct flux of momentum eastward across the tropical Atlantic to southern central Africa.

CONCLUSIONS

Models of the mean circulations accompanying both rainfall and dry weather over the central interior of South Africa have been developed through consideration of the properties of the various components of the momentum budget over southern Africa. Different sources of the momentum transported meridionally across southern Africa on rain and no rain days exist. South America marks a source for the no rain days. Momentum generated over the Amazon Basin is carried along a standing wave over the South Atlantic Ocean, the trailing edge of which is marked by a cloud band, and ultimately equatorward in the upper branch of a

Ferrel Cell across southern Africa. Momentum may subsequently be exported poleward in the vicinity of the cloud band in the Madagascar region. Tropical-temperate troughs across southern Africa form when a westerly trough interacts with a region of tropical convection over Africa at 20°S. The trough provides conditions suitable for intensification of the convection which in turn forces a Hadley Circulation across southern Africa. Heat released and momentum lifted in the convection is transported poleward along the leading edge of the trough. Cloud develops in association with dynamic forcing along the cold front of the trough resulting in both rainfall over the subcontinent and the appearance on satellite images of a cloud band.

Several of the components of the momentum budget, including the Coriolis, surface and mountain torques and possibly the latitudinal and vertical flux convergences and the mean vertical flux, are modulated on a semi-annual cycle such that details of the models are time dependent. For example, the intensity of the no rain circulation flux varies on the cycle following longitudinal displacements of the Atlantic Ocean standing wave. The efficiency of the poleward transport along the troughs similarly varies with the wave displacements such that highest efficiency occurs in the transitional seasons. Details of the influence of the semi-annual cycle and of the circulations associated with rainfall systems other than the tropical-temperate troughs must, of course, be incorporated into future, more comprehensive, models. The models as developed above are, nevertheless, adequate to provide the basis for an examination of the controls on both the annual rainfall cycle and the rainfall variations over the central interior of South Africa.

CHAPTER 7

GENERAL CIRCULATION CONTROLS ON THE ANNUAL RAINFALL CYCLE

INTRODUCTION

Several studies of the circulation through the year over South Africa provide the necessary background for examination of the causes of the seasonal rainfall cycles over the various parts of the subcontinent. Earlier investigations are summarised by MacGregor (1955) while more recent synopses have been provided by Taljaard (1958, 1972, 1981b) and Trewartha (1981). Several surface circulation features appear in summer but not in winter mean patterns, the most prominent of which is the north-west to south-east oriented trough over the western parts of the interior (Jackson, 1952; Taljaard, 1953). Cloud bands frequently develop to the east of the troughs. In contrast to the marked seasonal variations in the surface flow there are no equally-defined changes in the upper-air circulation which account for the summer rainfall peak and the winter dry season over the central interior, the flow remaining anticyclonic throughout the year (Jackson, 1952). Consequently the annual rainfall cycle has been attributed to changes in atmospheric stability and moisture content following latitudinal and longitudinal movements of the oceanic subtropical high pressure systems on either side of the subcontinent (Trewartha, 1981; McGee and Hastenrath, 1966). Between the peak season months the South Atlantic Anticyclone undergoes a latitudinal shift of 6° to a maximum southerly location in January (McGee and Hastenrath, 1966; Streten, 1980) when the Indian Ocean Anticyclone is displaced eastward towards the Australian side of the Ocean (Fig. E-3). In mid-winter the Indian Ocean Anticyclone lies closer to Africa. It has been argued that convection in winter is inhibited as a consequence of intensified atmospheric descent accompanying the westward displacement of the Indian Ocean Anticyclone. At the same time the flux of moisture from the surrounding oceans into the interior is restricted by the subtropical inversion which frequently lies below the level of the raised central plateau of the subcontinent. Alternatively during the summer the influence of anticyclonic subsidence is reduced and the subtropical inversion weakens and lifts, permitting both the influx of moisture onto the plateau and the development of convective clouds.

Although many of the basic features of the seasonal rainfall cycle may be explained by the above exposition some aspects of the theory are inconsistent with observation and there are additional details of the cycle that remain to be elucidated. For example, the distinct summer rainfall maximum and winter minimum is present along the east coast in regions where inversions may not restrict the influx of moisture. Limitations on convection exerted by subsidence inversions might explain the winter rainfall minimum but these inversions develop less frequently at Durban in winter than in summer (Preston-Whyte *et al.*, 1977). Observations also indicate that the centre of the Indian Ocean Anticyclone migrates *no further west than* 60°E *in winter* (Fig. E-3) at which longitude it is too distant to exert the climatic influence postulated on a country which extends only to about 33°E. According to Streten (1980) a second anticyclone, independent of the Indian Ocean Anticyclone, develops over *the far western parts of the ocean during the* months *April* to September and it is this cell which is prominent in the low-level circulation over the subcontinent. Maximum pressures over the central interior of South Africa are achieved in mid-winter only below 700 mb above which level the annual pressure wave reverses (*Fig. 4-2c*). *The phase reversal* is consistent with the south-east to north-west tilt with height of upper-level waves over the region (Hofmeyr and Gouws, 1964; Newell *et al.*, 1972) and the seasonal latitudinal migration of the systems. Yet the variances of geopotential heights at all levels of the troposphere, in addition to those of the surface pressure and of the temperature above 600 mb, also reach maxima in mid-winter (Fig. B-1), indicating that disturbances of greater amplitude pass over the region in winter than during summer. The presence of large-amplitude waves may not be readily reconciled with the concept of steady subsidence in the downward branch of the winter-hemisphere Hadley Cell producing an inversion above a low-level diabatic cold high. Further difficulties arise in the detailed study of the annual rainfall cycle over the Orange Free State. The apparently simple cycle over this region results from a complex of contributions from several types of synoptic systems in which inter-month variations in the absolute and proportional rainfall contributions are present. Other unexplained aspects of the cycle include the December rainfall hiatus and the late season rainfall peak over the western regions.

In this chapter models of the annual rainfall cycle over the central interior of South Africa will be formulated in terms of seasonal adjustments in the general circulation in the African region, and in particular in the general circulation of the tropics. The models are based on the results of the harmonic analyses of rainfall, of the thermodynamics and kinematics of the circulation and of the meridional fluxes of momentum. The models are developed upon the momentum budget models for tropical-temperate troughs (Fig. 6-5) and the no rain circulation (Fig. 6-6). Results from the harmonic analyses are summarised in Appendix F where it is concluded that the phases of the annual rainfall and rain earth angular momentum flux cycles are closely synchronous and that the turning points of the former cycle occur contemporaneously with turning points of the semi-annual cycle of the rain transient flux.

FREQUENCIES OF SYSTEMS OVER SOUTH AFRICA

In order to develop a background for investigation of the circulation controls on the development of rain-bearing systems the mean frequencies with which the various types of systems affect South Africa have been derived (Fig. 7-1). It is possible that not all the cloud patterns sustained by particular circulation types provided rainfall over the land mass. Many of the disturbances included amongst the coastal depressions, for example, were probably coastal lows which rarely produce more than localised drizzle. All cases of cloud signatures appropriate to the various types of systems in the classification have, however, been included in the statistics in Figure 7-1.

Distributions for the tropical systems through the year are similar to those over the Orange Free State (Fig. 3-4). Tropical-temperate troughs

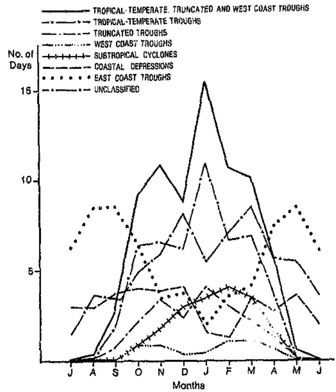


Figure 7-1. Mean number of days per month during which each type of rainfall system was present over South Africa as a whole during the period 1967 to 1977 (cf. system frequencies over the Orange Free State in Figure 3-4).

are most commonly situated across the country in January with a second frequency mode in November. A reduced frequency of troughs in December, suggested as the cause of the rainfall hiatus in that month, is present in the net statistics for the subcontinent. Subtropical cyclones are also distributed in time similarly over the country as over the Orange Free State. Major differences in the distributions appear for the temperate systems. Over the Orange Free State coastal depressions are distributed according to a six-month cycle with peaks in the transition seasons. For the subcontinent as a whole coastal depressions are present with quasi-constant frequency through most of the year apart from January and February. The reduction in the froquencies of coastal depressions in January and February is mirrored in the results for the Orange Free State. East coast troughs affect the subcontinent most frequently in May and September but the Orange Free State in March/April and October. Distributions for unclassified systems over the subcontinent are perhaps more alike those over the Orange Free State than for the other types of temperate systems. Differences in the distributions of the frequencies of the temperate systems over the subcontinent and over the Orange Free State reflect changes in the circulation such that these disturbances penetrate more frequantly into the interior of the country during the periods of the dominant Ferrel Circulation in the transitional seasons. Tropical systems are not affected by such constraints so that distributions for these systems for the Orange Free State and for the subcontinent are similar although on only about one-half of the days that tropical systems are present over the country do they provide significant rainfall (as defined in Chapter 3) to the western Orange Free State.

TROPICAL-TEMPERATE TROUGHS AND THE GENERAL CIRCULATION OF THE TROPICS

Two important properties of the circulations sustaining cloud band formation and determining the course of the seasonal rainfall cycle over the western Orange Free State have been identified. First, heat release in the tropics is a necessary condition for band formation along a tropical-temperate trough. Standing waves of the Southern Hemisphere are also predominantly forced by tropical heat release rather than by orography and evidence that the cloud bands mark the standing waves is presented in Appendix G. Secondly, the cloud bands develop in regions of interaction between circulations of the low and middle latitudes and mark channels of poleward energy and momentum transfer by the mean meridional circulation. Major controls on the intra-annual changes in the frequency of formation of tropical-temperate troughs over South Africa are thus the seasonal displacements of the region of tropical heat release and the attendant adjustments to the dynamics of the tropical/temperate circulation interactions.

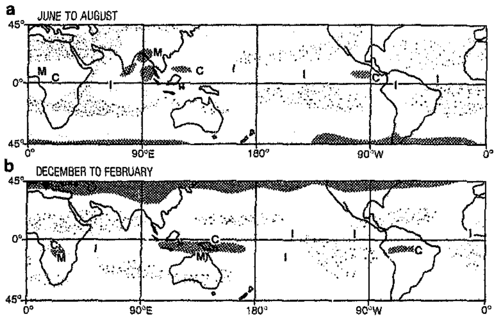


Figure 7-2. Seasonal distributions of the IR effective temperature for the period 1974 to 1978 for a) June to August and b) December to February adapted from Webster (1983) after Liebmann and Hartmann (1982). Temperatures denoted by shading: darkest areas <230°K; stippled areas <250°K; clear areas <270°K and grey areas >280°K. Locations of the Inter-Tropical Convergence Zone, the semi-permanent equatorial convective zones and the seasonal monsoon regions are marked as 'I', 'C' and 'M' respectively.

Three dominant areas of tropical heat release are present in the austral summer (darkest areas in Figure 7-2a - see also Figure 8 of Barton, 1983), all of which lie over continental areas including the Indonesian Archipelago which act as source regions for the main cloud bands (cf. Fig. 2-6). During winter only two primary regions of heat release are present, the major one of which resides within the Asian monsoon (Fig. 7-2b). A minor region of heat release occurs over tropical north Africa. The heat source relevant to tropical-temperate troughs over southern Africa is the region of convection along the African Inter-Tropical Convergence Zone and thus the seasonal cycle of rainfall from the troughs is related to the annual cycle of the latitudinal movements of the Zone.

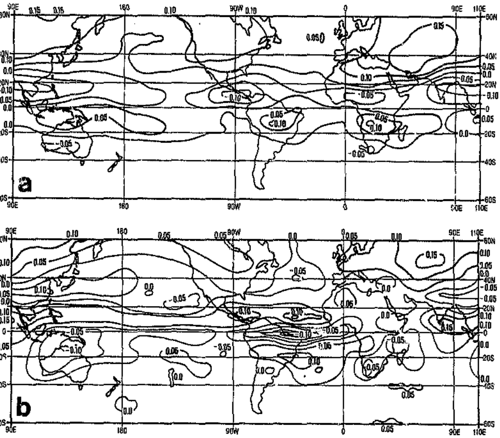


Figure 7-3. Fields of the first two eigenvectors of outgoing long-wave radiation for the period June 1974 to February 1978 after Heddinghaus and Krueger (1981). Positive areas are stippled; negative areas are hatched. Physical interpretations of the positive and negative areas are given in the text.

Details of the movements of the continental tropical cloud masses have been deduced in a principal component analysis of satellite outgoing long-wave radiation measurements for the period June 1974 to February 1978 by Heddinghaus and Krueger (1981). Globally-uniform seasonal movements of the continental portions of the Inter-Tropical Convergence Zone are reflected in the first component (Fig. 7-3a) for which maximum cloudiness over Africa at 10°S is attained in either January or February. Maximum cloudiness over the south-western portions of Africa is reached

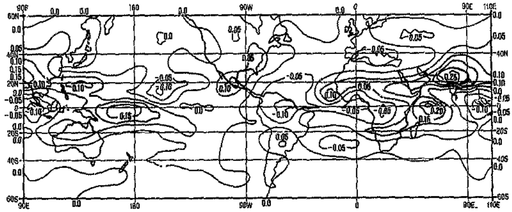


Figure 7-4. As Figure 7-3 but for the third eigenvector.

in either July or August on the first component and thus this component reflects the variations in the seasonal rainfall cycle across the subcontinent. Annual fluctuations of outgoing long-wave radiation are also depicted on the second component (Fig. 7-3b) and indicate that maximum cloudiness over the western parts of South Africa occur in April in conjunction with the delayed rainfall maxima over those regions.

Dominant latitudinal displacements of the region of African convection are limited to latitudes 10°N and S and so do not cover 20°S, the latitude at which the generation of momentum and heat transported poleward along the troughs appears to take place. At 20°S over Africa the outgoing long-wave radiation follows a semi-annual cycle (Fig. 7-4) such that minima occur in either January or February and in July or August. Outgoing long-wave radiation minima in summer are linked to the convective cloudiness maxima and in winter to emissions from the cold continental surface through a predominantly dry, cloud-free atmosphere. Emissions from the relatively warm surface through a cloud-free (compared to the summer) atmosphere account for the outgoing long-wave radiation maxima in the transitional seasons. Appropriate semi-annual cycles are present in several climate parameters including rainfall and hours of sunshine at Lusaka at 15°S (Nieuwolt, 1971). Poleward mean flow in a Hadley Circulation over the central interior of South Africa accompanies the minima in the outgoing long-wave radiation at 20°S and equatorward flow in a Ferrel Circulation the maxima.

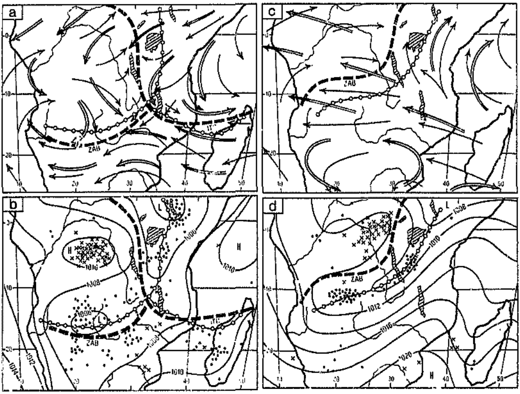


Figure 7-5. Mean locations of the Inter-Tropical Convergence Zone and Zaire Air Boundary (heavy dashed lines) during January and February 1958 (a) and b)) and July and August 1958 (c) and d)). In a) and c) single arrows illustrate low-level flow and double arrows 3 km flow; linked circles mark locations of the major surface troughs. In b) and d) crosses and dots mark centres of individual closed low and high pressure systems respectively and thin lines give mean sea surface pressure in mb. Adapted from maps for the International Geophysical Year by Taljaard (1972).

During January the Inter-Tropical Convergence Zone is oriented meridionally across tropical East Africa but becomes zonal across the Indian Ocean at around 15°S (Figs. 7-5a and b). According to Taljaard (1972) there is a secondary branch of the Zone which crosses the continent at about 18°S and which marks the confluence between the easterly flow from the Indian Ocean to the south and the westerly flow from the

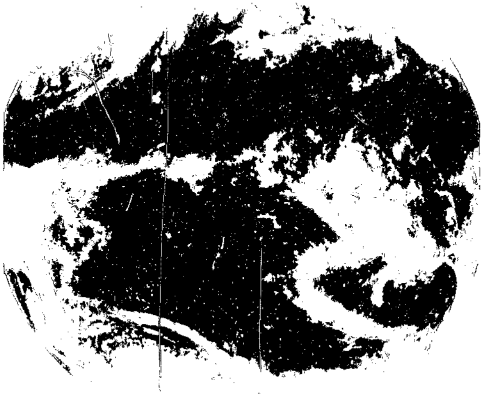


Figure 7-6. METEOSAT Infra-red Image at 1659 GMT on 23 February 1979 Illustrating the Inter-Tropical Convergence Zone and Zaire Air Boundary across tropical Africa following Taljaard (1972) linked to a cloud band across South Africa.

Atlantic Ocean to the north. Taljaard refers to this feature as the Congo Air Boundary but it should now be called the Zaire Air Boundary. An example of a cloud band which formed contemporaneously with cloud along the Zaire Air Boundary and the Inter-Tropical Convergence Zone across Africa and the adjacent oceans in a pattern consistent with that in Figure 7-5b is given in Figure 7-6. Although few lows developed along the climatological axis of the Zaire Air Boundary itself during the International Geophysical Year numerous systems were recorded both to the south and to the north of the feature (Fig. 7-5b). It is those lows at about 20°S that form the links between the tropical-temperate troughs and the region of tropical convection. During the austral winter the African Inter-Tropical Convergence Zone lies at about 15°N and so no longer directly influences the flow over southern Africa. The Zaire Air Boundary may, according to Taljaard (1972), still be traced as a boundary across tropical Africa between the easterly flow from the Indian Ocean and the Atlantic equatorial westerlies (Figs. 7-5c and d).

Seasonal shifts of the Inter-Tropical Convergence Zone are in part controlled by changes in the disposition of the global heat sources and sinks. The zonally-averaged subtropical atmospheric temperature cycle in the Southern Hemisphere is controlled by sea surface temperatures and the oceanic regions of tropical convective cloudiness tend to collocate with the regions of highest sea surface temperatures. Thus the zonally-averaged Inter-Tropical Convergence Zone is furthest south in February (Riehl, 1979) in conjunction with the highest sea surface temperatures over the greater part of the southern oceans (Panfilova, 1972). Over southern Africa, however, the surface and atmospheric temperature cycles are controlled directly by heating of the continent with resulting complex seasonal temperature gradient distributions around the land mass. If the latitude of the region of tropical convection may be deduced from the rainfall cycle over central Africa then the African Inter-Tropical Convergence Zone is furthest south in January according to estimates of the location of the 'centre of gravity' of African rainfall (Kidson, 1977) and to the results of harmonic analyses of the rainfall (Hsu and Wallace, 1976a). The lag between the latitudinal cycles of the sun and of the Inter-Tropical Convergence Zone, two months in the zonal average (Riehl, 1979), is therefore closer to one month over southern Africa.

Seasonal latitudinal displacements of the African Inter-Tropical Convergence Zone thus account for the changes in the location of the region of heat release over Africa such that tropical-temperate troughs form most and least frequently when the Zone is furthest south and north respectively. Latitudinal displacements of the Zone also affect the chances that interaction between the tropical disturbances and southern westerly waves will occur. Present theories of tropical/temperate circulation interactions based on Rossby wave dynamics have been reviewed by Webster (1983). According to these theories extra-tropical troughs in one hemisphere may penetrate deeply into the tropics and may perhaps even generate waves in the circulation of the temperate latitudes of the other hemisphere only in regions where the tropical flow is westerly. Such is the case in the austral summer over the Amazon Basin, the Atlantic Ocean and the central Pacific Ocean (Fig. 7-7b), all regions in which tropical-temperate interactions as marked by cloud bands occur. The south-eastern Atlantic Ocean is one of the regions over which the equatorward penetration of extra-tropical disturbances is a maximum (Webster and Curtin, 1975) and thus westerly troughs intruding equatorward over the ocean may subsequently be incorporated into tropical-temperate troughs across South Africa. Alternatively troughs are reflected back into their own hemisphere in regions over which the equatorial flow is easterly. Equatorial easterlies cover both the Atlantic Ocean and Africa during the austral winter (Fig. 7-7d) and thus no links between the tropical disturbances at 15°N and the southern troughs may be expected except within a highly perturbed flow. Recent modelling studies (e.g. Schneider and Watterson, 1984) have however challenged the validity of the applicability of the above results, which were based on an assumption of zero mean meridional velocity, in regions of non-negligible meridional currents and have indicated that responses to westerly forcing possibly do occur in the other hemisphere across easterly currents under certain flow regimes. In addition evidence also exists that gravity inertia waves forced by tropical convection may cross zones of easterlies (Paegle and Paegle, 1983). It is possible therefore that some responses in the circulation over southern Africa to waves generated in the disturbances along the Inter-Tropical Convergence Zone at 15°N may exist but in view of the rarity of cloud bands in winter (Fig. 7-1) it will be assumed that these responses may be neglected.

The basic annual cycle of the frequency of formation of tropical-temperate troughs over South Africa may therefore be explained simply in terms of seasonal movements of the zone of heat release along the African Inter-Tropical Convergence Zone. These movements alone do not, however, account for the semi-annual cycle in the meridional flow across the central interior of South Africa and, in particular, the winter poleward flow when the easterly tropical flow inhibits forcing of a Hadley Circulation across southern Africa by heat release at 15°N. An alternate source of the forcing of the Cell exists.

The African Inter-Tropical Convergence Zone is both a heat and a momentum source which is situated on the eastern side of the monsoonal Indian Ocean, the region which accounts for the greater part of the global cross-equatorial momentum flux (Newton, 1972). Atmospheric angular momentum is lost to the planet in the tropical monsoon westerlies. In order to compensate for this loss westerly momentum is effectively transferred into the summer hemisphere, in which the monsoonal westerlies are largely contained, through the transport of easterly momentum from the summer to the winter hemisphere (Johnson, 1969). During the austral summer the prime area of tropical surface westerlies forms with the 'winter' monsoon of the Indonesian region, but westerlies are also found over Angola and Peru. At 850 mb a cyclonic centre is located over northern Namibia in the vicinity of the average location of the Zaire Air Boundary (Fig. 7-7a). Westerly momentum is transferred to the atmosphere in the easterly flow to the south, east and north-east of the cyclonic centre and to the planet in the westerly flow to the north and north-west. Tropical-temperate troughs are associated with an intensified easterly flow. An outflow anticyclone is located above the low-level cyclone and easterly momentum is transferred towards the Northern Hemisphere along its northern flank to compensate for the loss to the planet in the Angolan westerlies (Fig. 7-7b). A similar outflow anticyclone is present over the west coast of South America. The major cross-equatorial flow occurs in response however to the westerlies of the winter monsoon which, according to Figure 7-7a, extend only as far west as 60°E but according to Ramage (1971), Lettau (1974) and Semyonov (1978) cover the tropical Indian Ocean. Easterly momentum is transferred into the Northern Hemisphere across the entire Indian Ocean (Fig. 7-7b). None of the westerly momentum generated over central Africa appears to be exported poleward across 30°S by the mean flow in Figure 7-7b but the result is a consequence of the cancelling effect of the six-month cycle in the meridional winds at this latitude. Conditions during the northern summer are similar in reverse to those of the austral summer with easterly momentum being transferred southward across the equatorial Indian Ocean (Fig. 7-7d). The cross-equatorial flux in July is rather stronger than in January as a result of the far more extensive region of surface a

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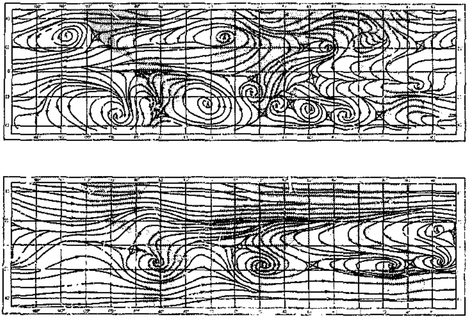


Figure 7-7. Streamlines in December to February at 850 mb (a) and 200 mb (b) and in June to August at 850 mb (c) and 200 mb (d) adapted from Newell et al. (1972).

westerlies associated with the Indian than with the winter monsoon (Fig. 7-7c). The efflux from the monsoon region covers southern Africa and is possibly the origin of the winter poleward flow across the interior of the subcontinent.

CONTROLS ON THE SEASONAL RAINFALL CYCLE

Models of the controls on the seasonal rainfall cycle over the central interior of South Africa may now be formulated which incorporate the major circulation changes on both the annual and semi-annual cycles (Figs. 7-8 and 7-9). The seasons are defined on the basis of the phases of the semi-annual cycle. Three models are presented, one for each of the c

d

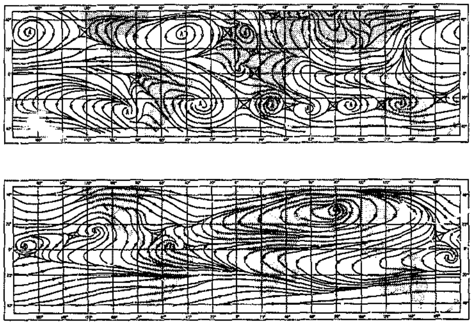


Figure 7-7 continued

summer and winter seasons and a single model for the transitional seasons.

The January to March summer season

The Inter-Tropical Convergence Zone reaches its southernmost location in January. Minima occur in the outgoing long-wave radiation at 10°S on the annual cycle and at 20°S on the semi-annual cycle in January. Convection over tropical southern Africa acts as a heat source capable of forcing standing waves and a Hadley Circulation across South Africa. Heat and momentum generated at 20°S are transported poleward across South Africa by the mean flow. Toroidal circulations for all rainfall systems apart from subtropical cyclones, east coast troughs and unclassified systems are that of the Hadley Cell. The mean vertical motion is

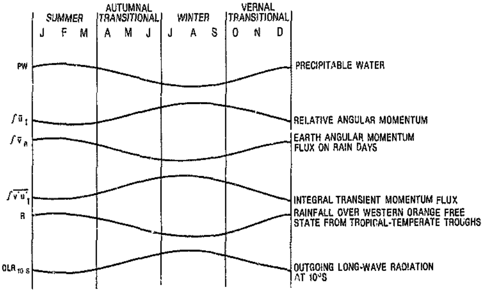


Figure 7-8. Schematic representation of annual cycles of circulation parameters over the central interior of South Africa as deduced through harmonic analyses.

possibly anomalously upwards and baroclinicity is at minimum in the semi-annual cycle (Fig. 7-9).

Given that tropical-temperate troughs are most likely to form when moisture concentrations are highest and the Inter-Tropical Convergence Zone is furthest south, i.e. that the westerly waves are most likely to penetrate sufficiently far equatorward to link with the tropical lows when the latter features themselves are displaced in the mean further poleward, then cyclone band frequency should reach a peak in January as observed. Cyclones in the southern Atlantic Ocean are also displaced further *equatorward* in January than in any other month according to the analyses of Howarth (1983) such that the formation of tropical/temperate links may be facilitated in this month. Confirmation that tropical-temperate troughs form at the time of peak momentum generation in the tropics is given by the synchroneity of the annual cycles of rainfall from the troughs and of the rain earth angular momentum flux (see Appendix F).

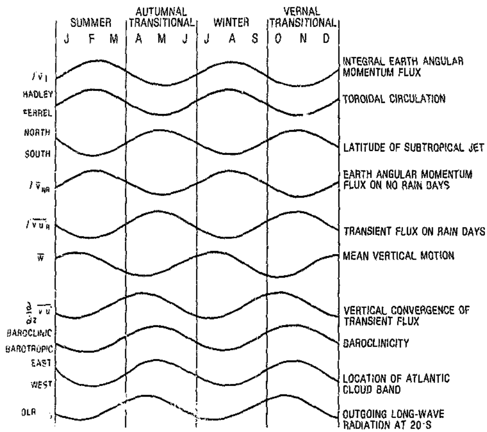


Figure 7-9. As Figure 7-8 but of semi-annual cycles.

The period of peak frequency of tropical-temperate troughs occurs close to the time of highest precipitable water in the atmosphere. Moisture concentrations reach a summer peak at about the same time as the appropriate maxima on the six-month cycle of the anomalous anticyclonic flow over the eastern parts of the subcontinent (Fig. 4-7) and of the depth of the 20°C isotherm over the western equatorial Indian Ocean (Quadfasel, 1982). Conditions are then optimised for the transport of moisture from the Indian Ocean along the northern flanks of high pressure systems over the east coast of the subcontinent as proposed by Taljaard (1958). Confirmation that the Indian Ocean source supplies moisture to the atmosphere over Zimbabwe was obtained by McNaughton and Wurzel (1972) but this study also revealed that the tropical Atlantic Ocean, and possibly that part of the ocean in the Northern Hemisphere, may also act as a moisture source under certain flow conditions. A similar conclusion had earlier been drawn in a study of moisture fluxes over Namibia (Gellert, 1962). Both oceans may therefore contribute moisture to the tropical heat source and to the atmosphere over the central interior of South Africa.

The Atlantic wave, forced by heat release over the Amazon Basin (Kalnay and Paegle, 1983), is displaced westward on the semi-annual cycle in the summer. In addition the forcing of the wave is weaker than in the transitional seasons because of the inverse phase of the semi-annual cycle in the outgoing long-wave radiation over the Basin in comparison to that over Africa at 20°S (Fig. 7-4). Maximum rainfall from tropical-temperate troughs coincides with the minimum in the transient flux on rain days (see Appendix F) resulting from the change in the structures of the westerly waves associated with the westward displacement of the Atlantic wave. Inspection of satellite wind analyses prepared by the South African Weather Bureau indicates that there are at least three modes of the circulation over the South Atlantic Ocean. In the first mode the wave is located such that equatorward flow to the west of southern Africa re-curves and becomes poleward immediately to the west of the African standing wave; in the second mode there is no re-curvature of the flow in the Atlantic wave so that the flow passes to the south of Africa; in the third mode the wave is not present. Relative frequencies of these three modes are unknown.

Dominant features of the circulation in summer on rain days deduced in the preceding are summarised in Figure 7-10. Easterly flow and heat release at 20°S provide suitable conditions for tropical-temperate trough formation and rainfall over southern Africa. The first and second modes of the circulation over the South Atlantic Ocean defined above are depicted as 'A' and 'B' respectively. On the no rain days the pattern shifts eastward such that the equatorward arm of the wave represented by mode 'A' overlies the central interior of South Africa.

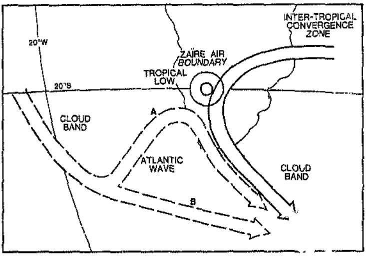
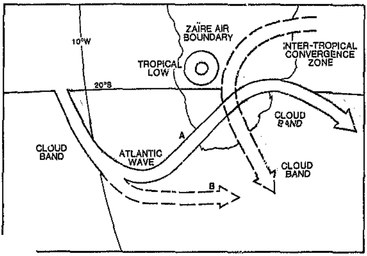


Figure 7-10. Schematic representation of the major features of the circulation over southern Africa during the summer season. The dominant 200 mb flow across tropical Africa and subsequently across South Africa is shown by the full line; 200 mb flows related to the Atlantic standing wave are shown by dotted lines for two of the three known modes (see text). The flow of mode A is displaced eastward such that the equatorward arm of the wave crosses the subcontinent on no rain days.

The vernal (October to December) and autumnal (April to June) transitional seasons

The Inter-Tropical Convergence Zone lies further north than in the summer season and there is a maximum on the semi-annual cycle of the outgoing long-wave radiation at 20°S. Compared to the summer season the region at 20°S is therefore an energy sink. The dominant circulation is that of the Ferrel Cell associated with the eastward displacement of the Atlantic wave (Fig. 7-11) forced by the heat source over the Amazon Basin. With the shift of the Atlantic wave the baroclinic stability of the atmosphere decreases and the transient flux on rain days increases. The Ferrel Circulation is directly reflected in the vernal transitional season circulations of the truncated troughs, coastal depressions and unclassified systems in addition to of the no rain days (Harangozo, 1986).



-11. As Figure 7-10 but for the transitional sea. The dominant 200 mb flow (solid line) is that associated with Atlantic wave. Flow along the African wave at 200 mb is shown by the dotted line.

Rainfall from the tropical-temperate troughs is lower than in the summer because of the reduced frequency of troughs resulting from the northward displacement of the Inter-Tropical Convergence Zone. As in summer at least three behavioural modes of the Atlantic wave occur and troughs sometimes develop in the Madagascar region when the equatorward flow of the wave overlies South Africa (Fig. 7-11). The vernal transitional season is the period of reduced rainfall over the western as compared to over the eastern Orange Free State and of the rainfall hiatus in December. Both of these aspects of the seasonal rainfall cycle are considered in Appendix H.

The July to September winter season

Rainfall is at a minimum in winter over the central interior of South Africa. The Atlantic wave is displaced westward and the degree of baroclinicity is reduced in comparison to that of the transitional seasons.

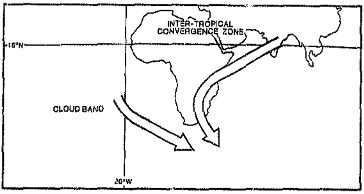


Figure 7-12. As Figure 7-10 but for the winter season when the dominant flow is the cross-equatorial flow forced by heat release in the Indian monsoon.

The dominant circulation is that of the Hadley Cell. A zone of equatorial easterly flow interposes between the relatively weak region of tropical energy release at 15°N and southern Africa (Fig. 7-7d) and inhibits interaction between the southern westerly waves and the region of convection. It is postulated that outflow from the Indian monsoon, which covers tropical Africa (Fig. 7-1 i), accounts for the dominant poleward flow across southern Africa (Fig. 7-12) The outgoing long-wave radiation over the Indian subcontinent is strongly modulated by a semi-annual cycle in phase with that over Africa at 20°S (Fig. 7-4 - see also Prasad and Verma, 1985). Similar reasons for the cycle obtain over India and over Africa, i.e. seasonal variations in heavy cloudiness and warm and cold surfaces below cloud-free atmospheres. Maxima in the cloudiness occur, however, in inverse seasons over the two regions. Desiccation of the air over the Indian subcontinent accounts in part for the dryness of the air over southern Africa. A second plausible cause of the dryness is that much of the moisture evaporated from the western Indian Ocean during the winter is carried into the Northern Hemisphere and to the Indian monsoon by the low-level jet over the western parts of the Ocean during that season (Findlater, 1969) rather than towards the African continent. Steady subsidence within the flow from the Indian monsoon, together with the lack of any upper-level easterly winds over Africa south of 10°S, account for the rainfall minimum achieved despite the maxima in the amplitudes of the westerly disturbances crossing the subcontinent.

CONCLUSIONS

New models of the controls on the annual rainfall cycle over the central interior of South Africa have been formulated which are consistent with many aspects of the annual and semi-annual cycles of both the thermodynamics and the kinematics of the flow. Summer season rainfall accompanies tropical heat release and consequent development of standing waves with attendant cloud bands over Africa. Development of standing waves from the African source is controlled by the seasonal latitudinal movements of the Inter-Tropical Convergence Zone which reaches a southernmost location in January when tropical-temperate troughs develop across South Africa most frequently. The seasonal movements of the Inter-Tropical Convergence Zone are the prime control on the rainfall cycle. Longitudinal displacements of the standing wave over the South Atlantic Ocean account for many aspects of the observed circulation changes on the semi-annual cycle. The longitudinal location of the wave is modulated such that the associated equatorward earth angular momentum flux over the central interior of South Africa is stronger in the transitional than in the high seasons. Cross-equatorial upper-level flow originating in the Indian monsoon account may for the poleward mean meridional circulation over the central interior of South Africa during the high winter season and subsidence of this flow is possibly responsible for the predominantly dry weather of this season. The models may be used as a foundation for future studies of the circulations governing the seasonal rainfall cycle and the rainfall variations over southern Africa and form the bases of the analyses presented in the third section of this thesis.

PART III

RAINFALL AND CIRCULATION VARIATIONS OVER THE CENTRAL INTERIOR OF SOUTH AFRICA

CHAPTER 8

RAINFALL AND CIRCULATION VARIATIONS

INTRODUCTION

Models of major modes of the circulation variations associated with rainfall departures over southern Africa may be evolved in parallel manner that models of the annual rainfall cycle were developed in Part II. Inter-annual changes in the thermodynamic and kinematic structures of the atmosphere and in the momentum fluxes over the central interior of South Africa will be interpreted within the framework of the classification of circulation types in the derivation of the models. A common method of studying circulation differences between wet and dry periods is through the superposed epoch technique whereby circulation parameters such as rainfall totals are used to stratify circulation data into groups for above- and below-normal periods. Examples of applications of the superposed epoch approach based on rainfall include the analyses of Lamb (1978) and Nicholson (1981) for west Africa, Chu (1983) for north-east Brazil and Kininmonth (1983) for northern Australia. The superposed epoch technique has also been applied to study circulation differences over South Africa between wet and dry periods over a few days (Triegaardt and Kits, 1963; Hofmeyr and Gouws, 1964), over a few months (Rubin, 1956, and over one or more years (Tyson, 1981). Certain circulation adjustments have appeared consistently in all of these analyses and have become accepted as standard manifestations of the changes associated with the rainfall variations by South African meteorologists. These changes include a strengthening of the poleward meridional flow and a lowering of the surface pressure over the country during wet in comparison to during dry spells. Lower pressures are associated with a deepening of the trough commonly located across the western interior of the country during the summer months and with the formation or intensification of the cyclonic system over the western subcontinent at about 20°S. Over the north-western Transvaal, and presumably over the remainder of the summer rainfall region, lower pressures and higher rainfall are accompanied by reduced surface temperatures but raised dew-point temperatures (Hofmeyr and Gouws, 1964). In addition upper-air geopotential heights tend to be anomalously low over the west coast and anomalously high over the east coast with the development of a climatological mean westerly wave with its axis in the vicinity of the west coast in wet as opposed to in dry periods (Triegaardt and Kits, 1963; Hofmeyr and Gouws, 1964).

A simple alternative to the superposed epoch approach in the study of interrelated rainfall and circulation changes is to calculate correlations between rainfall and circulation parameters. Often principal component analysis is applied to the rainfall data prior to the calculation of the correlations (e.g. Kidson, 1975; Pittock, 1980). Statistical models of rainfall variations over South Africa using indices of the latitude of the high pressure system off the east coast of Australia and of the Southern Oscillation have been developed through calculation of appropriate correlations with rainfall component scores (Dyer, 1976c, 1979a). Correlations between rainfall and circulation parameters over the central interior of South Africa are calculated by month in this Chapter to formulate an overview of the systematic trends in the circulation accompanying varying rainfall. Essentially similar results to those from a superposed epoch analysis are obtained but the correlation technique has one major advantage in that the temporal structure of the circulation and rainfall interrelationships through the year may be readily deduced.

The study of the circulation changes accompanying rainfall variations is achieved in three steps. First, correlations are calculated between rainfall and the circulation parameters. Secondly, harmonic analysis is applied to the correlations to identify any temporal organisation that may exist. The annual rainfall cycle over the central interior of South Africa is controlled by circulation changes regulated on both annual and semi-annual cycles and the harmonic analyses reveal systematic circulation variations on these cycles. Finally, the inter-annual phase stability of the annual and semi-annual cycles of the circulation is investigated by calculation of harmonics on annual (July to June) bases. The objective is to identify those aspects of the circulation which remain of stable phase between years. Controls on the circulation associated with the cycles of stable phase are more readily identified than those associated with variable-phase cycles and will form the foundations for the required models of the circulation variations. The technique permits discrimination of systematic tendencies on time scales ranging from one month to one year. Shorter and longer periods of systematic variations, such as the seven day cycle in the frequency of passage of Southern Hemisphere westerly waves at a point first detected by Defant (1912) and confirmed to occur over western Australia by Wright (1971) and over the coast of southern Africa (Preston-Whyte and Tyson, 1973), the *quasi-biennial* oscillation present in Southern Hemisphere zonal wind fields (Trenberth, 1980a), in tropical cloud cover (Zerefos and Repapis, 1979) and in South African secular rainfall variations (Tyson *et al.*, 1975) and the 18-year cycle in rainfall over South Africa (Tyson, 1981), may not be treated here.

DATA

Monthly mean values of the temperature, pressure or geopotential height, specific humidity, dry and total static energy and zonal and meridional wind components at the surface and at the 850, 800, 700, 600, 500, 400, 300, 200, 150 and 100 mb levels, calculated from the Bloemfontein radiosonde data, have been used. Monthly mean values of the precipitable water and of a thermodynamic stability index have also been estimated. Calculations of correlations between rainfall and the above circulation parameters have been made both with parametric and with non-parametric measures. Essentially similar results are obtained from either set of calculations but only the non-parametric (Spearman) results will be presented as these are more representative of trends for non-normally distributed data as is the case with monthly rainfall totals during the winter season.

Temperature decreases in the boundary zone with increasing rainfall in all months (Table 8-1). Above the boundary zone the relationship between rainfall and temperature is inverse at most levels in May, August, October and December but in the remaining months it is often direct,

*Table 8-1. Values of Spearman rank correlation coefficients between rainfall in the western Orange Free State and temperature at various levels in the atmosphere at Bloemfontein (in the columns) for each month of the year (in the rows) for the period 1968 to 1977. Negative correlations, indicating decreased temperatures in wetter months, are stippled. Asterisks indicate significance levels: * - better than 10 per cent; ** - better than 5 per cent; *** - better than 1 per cent.*

MONTHS	SUR	850	800	700	600	500	400	300	200	150	100
J	-0.70**	-0.60*	-0.48	0.08	0.32	0.47	0.45	0.45	0.38	-0.07	[illegible]
A	-0.30	[illegible]	-0.67**	-0.35	[illegible]	-0.37	[illegible]	0.04	0.18	0.16	0.15
S	-0.62*	-0.44	-0.31	-0.01	0.39	[illegible]	0.21	[illegible]	0.13	0.35	0.25
O	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.10
N	[illegible]	[illegible]	[illegible]	[illegible]	0.09	0.37	0.60*	0.44	0.32	0.60*	0.30
D	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.07	[illegible]	0.01	[illegible]	[illegible]
J	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.70**	0.78***	0.75**	[illegible]	[illegible]	[illegible]
F	[illegible]	[illegible]	[illegible]	[illegible]	0.56*	0.64**	0.67**	0.72**	0.30	0.01	[illegible]
M	[illegible]	[illegible]	[illegible]	[illegible]	0.12	0.33	0.19	0.33	0.16	[illegible]	0.02
A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.01	0.08	0.24	0.22	0.25
M	[illegible]	[illegible]	-0.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.31	0.09
J	[illegible]	[illegible]	0.09	0.41	[illegible]	0.28	0.12	[illegible]	[illegible]	[illegible]	[illegible]

particularly in the barotropic zone. The year may be split into two halves in terms of correlations between pressure and rainfall. During the second half of the year, from July to December, pressure decreases with increasing rainfall at most levels in most months (Table 8-2). From January to June, however, the relationships between pressure and rainfall are generally direct. Comparison of Tables 8-1 and 8-2 indicates that above the boundary zone thermodynamic changes are quasi-barotropic in that rainfall correlations with both heights and temperatures tend to be of the same sign but in the first half of the year in the boundary zone the changes are primarily baroclinic. Specific humidity and precipitable water increase with rainfall in all months (Table 8-3). It has been suggested that the relative humidity might be underestimated by the instrument flown on the radiosondes used at Bloemfontein since June 1974 (Taljaard,

Table 8-2. As Table 8-1 but for pressure (at the surface) and geopotential heights (at all other levels). Stippling denotes decreased pressure in the wetter months.

PRESSURE LEVEL

MONTHS	SUR	850	800	700	600	500	400	300	200	150	100
J	-0.35	[illegible]	-0.67	[illegible]	[illegible]	-0.57	0.07	0.27	0.33	0.30	0.07
A	-0.25	-0.27	-0.27	-0.34	[illegible]	[illegible]	[illegible]	[illegible]	-0.31	[illegible]	[illegible]
S	0.01	0.02	[illegible]	[illegible]	[illegible]	0.06	0.08	0.08	[illegible]	0.14	0.05
O	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.47
N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.21	0.31	0.26	0.43	0.42
D	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J	0.72	0.72	0.59	0.12	[illegible]	0.05	0.28	0.62	0.54	0.27	[illegible]
F	0.13	0.10	[illegible]	[illegible]	[illegible]	0.15	0.32	0.59	0.70	0.55	0.21
M	0.43	0.26	[illegible]	[illegible]	[illegible]	[illegible]	0.07	0.32	0.21	0.15	0.14
A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.10
M	0.31	0.23	0.28	0.09	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J	0.27	0.22	[illegible]	0.04	0.08	0.14	0.07	0.02	[illegible]	[illegible]	[illegible]

Table 8-3. As Table 8-1 but for specific humidity and precipitable water. Stippling denotes decreased specific humidity in the wetter months.

MONTHS	SUR	850	800	700	600	500	400	300	PW
J	0.10	0.37	0.08	0.10	0.10	0.13	0.28	0.07	0.03
A	0.52	0.44	0.40	0.63	0.75	0.54	0.52	0.46	0.56
S	0.33	0.39	0.37	0.21	0.33	0.53	0.22	0.27	0.37
O	0.45	0.20	0.16	0.41	0.32	-0.15	0.08	-0.21	0.39
N	0.47	0.62	0.62	0.36	-0.03	0.03	0.43	0.10	0.42
D	0.41	0.42	0.42	0.21	0.15	0.18	0.02	0.13	0.28
J	0.92	0.94	0.92	0.75	0.73	0.76	0.75	0.56	0.89
F	0.43	0.42	0.30	0.18	-0.09	0.33	0.22	0.20	0.18
M	0.82	0.79	0.71	0.61	0.50	0.36	0.32	0.15	0.75
A	0.02	0.14	0.25	0.01	-0.03	-0.09	0.52	0.38	0.12
M	0.84	0.74	0.75	0.77	0.38	0.49	0.21	0.20	0.84
J	0.71	0.59	0.37	-0.05	-0.25	0.07	0.02	-0.21	0.18

1983). The later part of the 1968 to 1977 period was, however, generally wetter than the earlier part and thus an underestimation of the moisture content in the later period would have tended to weaken the values of the correlations of Table 8-3.

As rainfall increases so dry static energy in the boundary zone decreases and in the barotropic zone (in most months) *increases* (Table 8-4). In terms of atmospheric energy contents, therefore, the boundary zone increases in pressure with rainfall in the first half of the year are more than offset by the temperature *decreases*. *Patterns of* the correlations between rainfall and the dry static energy reflect those for correlations with temperatures rather than those with heights indicating that temperature changes are not *fully compensated by appropriate* thickness changes. Correlations between rainfall and total static energy (Table

Table 8-4. As Table 8-1 but for dry static energy. Stippling denotes decreased energy in the wetter months.

PRESSURE LEVEL

MONTHS	SUR	850	800	700	600	500	400	300	200	150	100
J	[illegible]	[illegible]	[illegible]	0.08	0.25	0.33	0.35	0.42	0.28	[illegible]	[illegible]
A	[illegible]	[illegible]	-0.72*	[illegible]	-0.44	-0.32	[illegible]	[illegible]	0.04	[illegible]	0.19
S	[illegible]	[illegible]	-0.34	[illegible]	0.39	0.02	0.05	[illegible]	0.19	0.44	0.33
O	[illegible]	[illegible]	[illegible]	-0.36	[illegible]	-0.46	-0.50	[illegible]	-0.38	[illegible]	[illegible]
N	[illegible]	[illegible]	[illegible]	[illegible]	0.09	0.28	0.47	0.42	0.32	0.54	0.42
D	[illegible]	[illegible]	[illegible]	[illegible]	-0.32	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.57**	0.78***	0.76***	0.10	[illegible]	[illegible]
F	[illegible]	[illegible]	-0.72	[illegible]	0.42	0.62*	0.67**	0.72**	0.31	0.02	[illegible]
M	[illegible]	[illegible]	[illegible]	-0.38	[illegible]	0.30	0.18	0.33	0.20	[illegible]	[illegible]
A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.01	0.07	0.13	0.24	0.20
M	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.46	[illegible]	[illegible]	0.05
J	[illegible]	[illegible]	0.09	0.26	0.19	0.35	0.22	-0.07	[illegible]	[illegible]	0.05

8-5) in the boundary and lower barotropic zones in most months are positive rather than negative as for the corresponding correlations with the dry static energy. Total energy content thus increases in these levels with rainfall.

Westerly components of the zonal winds in the boundary zone at Bloemfontein weaken in most months as rainfall increases indicating that low-level easterly winds become more common in the wetter months throughout the year (Table 8-6). Above the boundary zone signs of the correlations vary such that in the summer months of January to March and in May, September and October wind speeds are normally inversely correlated with rainfall whereas in the remaining months the relationships are direct at most levels.

Table 8-5. As Table 8-1 but for total static energy. Stippling denotes decreased energy in wetter months.

PRESSURE LEVEL

MONTHS	SUR	850	800	700	600	500	400	300	200	150	100
J	-0.43	-0.20	-0.15	-0.15	0.03	0.35	0.45	0.50	0.28	-0.08	-0.27
A	[illegible]	-0.20	-0.27	0.19	-0.09	-0.36	[illegible]	[illegible]	0.04	-0.17	0.19
S	0.03	0.10	0.72	0.20	0.43	0.53	0.25	-0.10	0.19	0.44	0.33
O	-0.03	-0.41	-0.45	-0.21	-0.38	-0.40	[illegible]	-0.53	[illegible]	[illegible]	-0.06
N	0.35	0.43	0.38	0.10	0.13	0.28	0.59	0.43	0.32	0.54	0.42
D	-0.30	-0.02	0.03	0.25	-0.13	-0.13	-0.06	[illegible]	[illegible]	[illegible]	[illegible]
J	0.76	0.77	0.75	0.62	0.61	0.92	0.90	0.81	0.10	[illegible]	[illegible]
F	0.08	0.09	0.09	0.12	0.25	0.50	0.53	0.72	0.31	0.02	[illegible]
M	0.22	0.61	0.56	0.25	0.28	0.37	0.31	0.24	0.20	[illegible]	[illegible]
A	-0.20	-0.28	-0.13	-0.41	-0.35	-0.10	0.01	0.07	0.13	0.24	0.20
M	0.76	0.38	0.40	0.07	-0.32	-0.38	[illegible]	[illegible]	[illegible]	[illegible]	0.05
J	0.15	0.31	0.30	0.04	[illegible]	0.27	0.21	[illegible]	[illegible]	[illegible]	0.05

One of the fundamental tenets of South African meteorology is that the poleward flow across the country is stronger in wet than in dry periods. Direct calculations of the correlations between the meridional wind speed and rainfall over the western Orange Free State confirm the validity of the tenet but only for certain levels during specific periods of the year (Table 8-7). Above the boundary zone poleward flows intensify in the wetter months centred on February and August when the flow is poleward (Fig. 4-6) but weaken in the months centred on May and November when the mean flow is equatorward. In the boundary zone itself the poleward component of the flow increases with rainfall in most months as expected according to the tenet but correlations are weak in most months and negative in four including the summer months of February and March.

Table 8-6. As Table 8-1 but for zonal wind speeds. Stippling denotes decreased westerly components in wetter months.

PRESSURE LEVEL

MONTHS	SUR	850	800	700	600	500	400	300	200	150	100
J	-0.12	-0.30	-0.30	0.50	0.17	0.53	0.67	0.65	0.63	0.25	0.22
A	-0.10	-0.36	-0.27	0.07	0.13	0.07	0.07	0.25	0.05	0.04	0.01
S	-0.26	-0.45	-0.47	0.37	-0.30	-0.13	-0.38	-0.02	[illegible]	0.05	[illegible]
O	-0.35	[illegible]	[illegible]	0.13	-0.46	-0.27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
N	[illegible]	0.04	[illegible]	0.30	0.01	0.18	0.42	0.20	0.18	[illegible]	[illegible]
D	[illegible]	-0.22	[illegible]	0.13	0.37	0.42	0.32	0.50	0.30	0.05	[illegible]
J	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F	-0.67	[illegible]	-0.47	[illegible]	[illegible]	-0.44	[illegible]	0.12	[illegible]	[illegible]	[illegible]
M	-0.42	[illegible]	[illegible]	[illegible]	[illegible]	-0.27	[illegible]	[illegible]	0.04	[illegible]	0.09
A	0.04	-0.01	0.19	0.31	0.25	0.25	0.33	0.36	0.31	0.39	0.31
M	-0.30	-0.21	-0.40	[illegible]	-0.35	-0.26	[illegible]	-0.26	[illegible]	0.12	[illegible]
J	-0.21	0.42	0.47	0.25	0.22	0.26	0.13	0.02	[illegible]	[illegible]	[illegible]

HARMONIC ANALYSES OF THE CORRELATION FIELDS

Positive and negative correlations between rainfall and temperature, pressure, dry and total static energy and meridional component are clustered in the high and transitional seasons respectively, particularly in the barotropic zone. The second harmonics of the distributions of the temperature correlations with rainfall contribute between 15 and 60 per cent of the variances at all levels above 600 mb (Fig. 8-1b). In the barotropic zone highest positive correlations between temperature and rainfall occur in late January/early February and late July/early August at the times of the poleward meridional wind maxima (Fig. 4-6). Only at 200 mb does the second harmonic explain a major proportion of the variance of the mean temperature itself (Fig. 4-2b) with a phase con-

Table 8-7. As Table 8-1 but for meridional wind speeds. Stippling denotes increased equatorward components in wetter months (cf. Figure 4-6).

PRESSURE LEVEL

MONTHS	SUR	850	800	700	600	500	400	300	200	150	100
J	-0.17	0.00	-0.30	-0.36	-0.32	0.13	[illegible]	0.05	-0.32	-0.15	-0.27
A	0.41	0.13	[illegible]	0.41	0.40	0.47	0.71	0.61	0.27	0.51	0.33
S	0.15	0.25	0.18	0.33	0.41	0.09	0.32	0.09	0.06	0.07	0.60
O	-0.18	-0.19	-0.42	-0.66	[illegible]	[illegible]	0.13	0.04	0.32	[illegible]	[illegible]
N	0.36	0.09	0.44	-0.36	-0.30	[illegible]	0.19	[illegible]	[illegible]	[illegible]	[illegible]
D	0.22	0.31	0.14	0.49	-0.12	[illegible]	0.07	0.38	0.36	0.48	[illegible]
J	0.54	0.71	0.48	0.52	0.35	0.65	0.88	0.27	[illegible]	[illegible]	0.14
F	-0.06	-0.40	[illegible]	0.18	0.27	0.53	0.37	0.59	0.44	0.28	0.22
M	-0.15	-0.36	[illegible]	0.36	0.25	0.55	0.62	0.47	0.71	0.25	0.21
A	0.02	0.64	0.22	0.18	0.39	[illegible]	0.03	[illegible]	-0.25	-0.12	[illegible]
M	0.02	0.08	0.26	0.05	-0.04	0.04	0.04	[illegible]	-0.10	[illegible]	[illegible]
J	0.18	0.20	0.03	0.02	0.07	-0.01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

sistent with that of the second harmonic of the temperature correlations at the same level. At *all levels in the barotropic zone* the half-year cycle in the temperature correlations is approximately in phase with that at 200 mb. In the boundary zone the maximum of the first harmonic is in winter as *a result of the* statistically significant *negative* correlations of the summer months but the phase reverses into the barotropic zone such that a summer maximum is present at 300 mb (Fig. 8-1a). *Above 200 mb*, in the stratospheric jet-stream zone, phase angles of the first two harmonics reverse from those in the barotropic zone, as also occurs for the corresponding harmonics of the *temperature* itself at these levels (Fig. 4-2a and b). Thus whereas mean temperature is modulated primarily on a dominant annual cycle correlations of te[illegible] es with rainfall *in* the *barotropic* and jet-stream zones [illegible] ed on large-amplitude semi-annual in addition to annual cy[illegible] possible therefore that

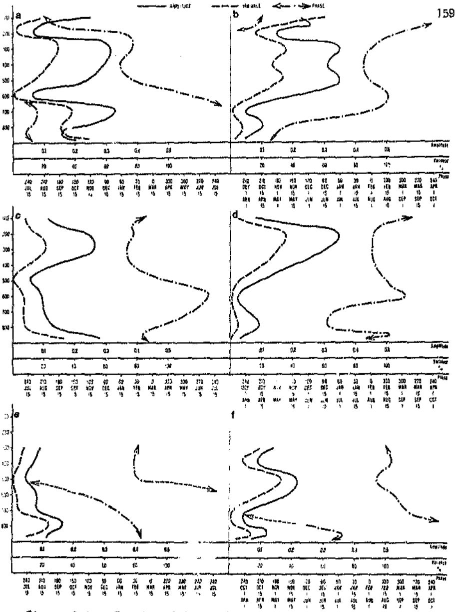


Figure 8-1. Results of harr..nic analyses of Spearman correlations with rainfall of monthly mean temperature, geopotential height and specific humidity at Blo..nfontein: a) 1st. harmonic of temperature; b) 2nd. harmonic of temperature; c) 1st. harmonic of geopotential height; d) 2nd. harmonic of geopotential height; e) 1st. harmonic of specific humidity; f) 2nd. harmonic of specific humidity.

large-amplitude modulations of temperature on semi-annual cycles occur in individual years.

Neither of the first two harmonics account for more than 40 per cent of the variance of the pressure correlations at any level (Figs. 8-1c and d). Maxima at levels at which in excess of 10 per cent of the variance is captured by either harmonic generally occur in February such that at 200 mb height increases with rainfall on the second harmonic occur in the periods of peak poleward flow. No reversal of the phase of either of the higher two harmonics of the height correlations, as of the mean heights themselves (Fig. 4-2c and d), occurs into the stratosphere. As for temperatures semi-annual cycles of pressure may therefore occur in individual years. Both the annual and semi-annual cycles of the variations are baroclinic in both the boundary and stratospheric jet-stream zones but quasi-barotropic in the barotropic zone (Fig. 8-1a to d).

At most levels much of the varian[illegible] the distribution of the correlations between rainfall and specific h[illegible], resides in the higher harmonics (Fig. 8-1e and f) but it is [illegible]ear whether this is a reflection of real phenomena or of noise in the signal. In the boundary zone mid-February maxima occur on the first harmonic. Around 500 mb the second harmonic explains over 30 per cent of the variance such that higher moisture contents occur in the periods of mean poleward flow. Semi-annual cycles therefore probably also occur in the moisture distribution as in those of temperature [illegible] pressure in individual years. Close to 55 per cent of the variance [illegible]he precipitable water correlations distribution is captured by the fifth harmonic. Less than one per cent resides on the second harmonic and only seven per cent on the first with a maximum on 1 February, the date of the maximum of the annual precipitable water cycle.

Results of the harmonic analyses of the [illegible] static energy correlations (Fig. 8-2a and b) resemble those of the temperature rather than those of the height correlations. No phase re[illegible]al from the boundary to the barotropic zone of the first harmonic [illegible] total static energy occurs such that midsummer maxima in the corr[illegible] between rainfall and total static energy are present throughout t[illegible] posphere (Fig. 8-2c). In the barotropic zone phase angles of the [illegible]ond harmonics of both dry and total static energy are such that maxima occur in the months of peak

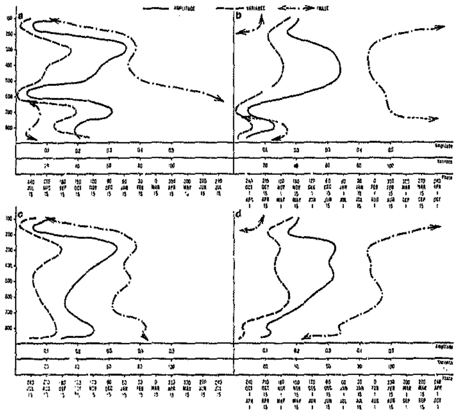


Figure 8-2. As Figure 8-1 but for: a) 1st. harmonic of dry static energy; b) 2nd. harmonic of dry static energy; c) 1st. harmonic of total static energy; d) 2nd. harmonic of total static energy.

mean poleward flow (Figs. 8-2b and d). There appear therefore to be important modulations of all thermodynamic parameters in the barotropic and jet-stream zones on semi-annual cycles in individual years, modulations which are approximately in phase and are possibly related to meridional circulation changes on the cycle.

No marked second harmonic in the correlations between rainfall and the zonal component is present at most levels (Fig. 8-3a and b). Only at 850 mb is in excess of 30 per cent of the variance explained by the second harmonic with a corresponding rainfall season maximum on 1 December. On the first harmonic maxima occur in the winter months, i.e. the

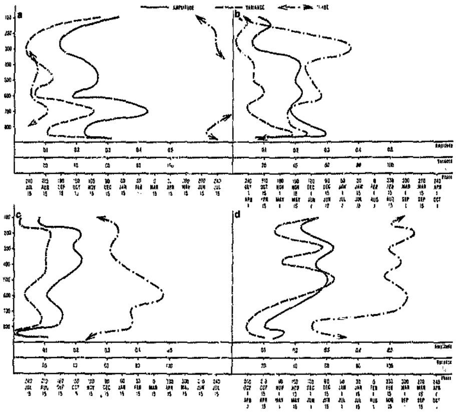


Figure 8-3. As Figure 8-1 but for: a) 1st. harmonic of zonal component; b) 2nd. harmonic of zonal component; c) 1st. harmonic of meridional component; d) 2nd. harmonic of meridional component.

strongest negative correlations indicative of stronger easterlies in the wetter months were present in the rainfall season. The major portion of the variance is accounted for by the third harmonic throughout the atmosphere. In excess of 8 per cent of the variances of the meridional component correlations is accounted for by the second harmonics at all levels and in excess of 60 per cent at 500 mb (Fig. 8-3d). A phase reversal occurs between the boundary and barotropic zones but above 700 mb maximum positive correlations occur in mid-February and mid-August in phase with the equivalent wave on the meridional component itself. In the wetter high seasons the poleward flow is thus intensified but in the wetter transitional seasons the equatorward flow intensifies. These changes are in phase with those of the thermodynamic parameters on the semi-annual cycle. Maximum correlations on the first harmonics indicating increased poleward flow, which account for up to 23 per cent of the variance (at 200 mb), occur generally in the rainfall season (Fig. 8-3c).

STABILITY OF THE ANNUAL AND SEMI-ANNUAL CYCLES

The stability of the phases of the annual and semi-annual cycles of several circulation parameters have been inspected. Results help determine whether the phase angles given in Figures 8-1, 8-2 and 8-3 are representative for all years and indicate whether inter-annual changes in the meridional component on the semi-annual cycle may account for the similar changes in the thermodynamic parameters. Harmonic analyses of 200 mb meridional components and 200 and 300 mb temperatures made on annual bases will be discussed in detail. The phase angles of the annual 200 mb temperature cycles vary across about 180° or six months such that yearly maxima occur throughout the warmer months of the year (Fig. 8-4). Between 3 and 63 per cent of the variances are explained by the first harmonics in individual years. Phase angles of the second harmonics, with one exception, vary across only 60° or one month with rainfall season maxima between 10 January and 10 February. Explained variances are in the range 0 to 63 per cent. The large-amplitude second harmonic in the mean data (Fig. 4-2b) results therefore from the stability of the phase of the second in relation to that of the first harmonic rather than from the dominance of the second harmonic in all years. Below 200 mb only a weak second harmonic is present in the mean data whereas the harmonic explains up to 35 per cent of the variance of the correlations with rainfall (Fig. 8-1b). In individual years the temperature at 300 mb is subjected to marked half-year cycles, the amplitudes of which increase in the wetter years. Phase angles of the first harmonics of 300 mb temperature cycles vary only across 30° or one month with maxima centred at 20 January and of the second harmonics across 90° or one-and-a-half months with rainfall season maxima between 20 January

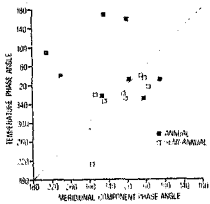
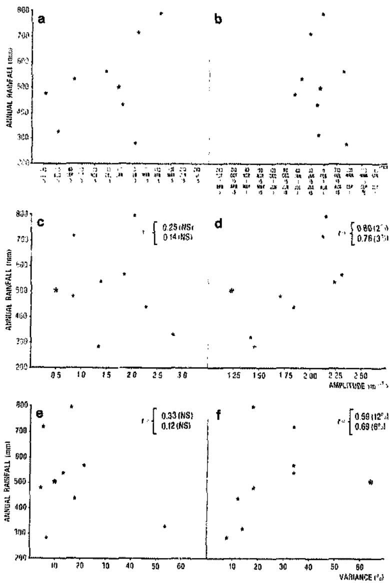


Figure 8-4. Phase angles of the annual (solid blocks) and semi-annual (open blocks) cycles of the 200mb temperature (ordinate) and meridional wind speeds (abscissa) for the July to June years from 1968/69 to 1976/77. The diagonal line marks the locus of equal phase angles. Dates corresponding to the maxima are as for Figures 8-1, 8-2 and 8-3.

and 10 March. Up to 28 per cent of the variance is explained by the second harmonics as opposed to between 66 and 91 per cent by the first harmonics. The relative stability of the phases of the annual cycles ensure their dominance in the mean data and conceal the presence of

Figure 8-5 (opposite). Phase angles of, amplitudes of (ms^{-1}) and variances explained (per cent) by the first (a), c) and e) respectively) and second harmonics (b), d) and f) respectively) of the 200 mb meridional wind speed at Bloemfontein for each of the July to June years between 1968 and 1977 against corresponding annual rainfall over the western Orange Free State. Phase angles are marked with the dates of maxima (annual) or summer maxima (semi-annual). Circled crosses opposite the 500 mm ordinate mark corresponding values for the integral 10-year period. Values of the Pearson (upper) and Spearman (lower) correlation coefficients (r) are given in c) to f). Significance levels of the coefficients are given in brackets ('NS' is Not Significant).

modulations of the temperature on semi-annual cycles in individual years. Similar inferences apply to pressure, specific humidity and dry and total static energy at levels at which the first harmonics are dominant in the total period but large amplitude second harmonics are present in the correlations with rainfall.



Phase angles of the annual waves of 200 mb temperature and meridional wind speed vary markedly between years so that in some years the two agree to within a few degrees but in others differ by almost 180° (Fig. 8-4). With one exception phase angles of the semi-annual waves, on the other hand, agree to within 60° (one month) in all years. The exception occurs in a year in which the amplitude of the second harmonic of temperature is relatively small so that a possibly inaccurate estimate of the phase angle has been made. Close similarities in the phase angles of the second but not of the first harmonic indicate that thermodynamic changes on the former but not on the latter harmonic are related to changes in advection resulting from a modified meridional circulation. Phase angles for either harmonic are not distributed in any systematic manner as rainfall varies (Figs. 8-5a and b) but there are affiliated systematic changes in the amplitudes and variances explained by the second harmonics (Fig. 8-5c to f). Correlations (both Pearson and Spearman) have been calculated between rainfall and the amplitudes and the explained variances of the higher two harmonics of both t[illegible]rature and meridional wind speed at 200 mb. Both the amplitude [illegible] the variances explained by the first harmonics of the temperat[illegible] tend to decrease in the years of higher rainfall although the co[illegible]ions are not statistically significant. Similarly weak negative trends are present between rainfall and both the amplitudes of and the variances explained by the first harmonics of the meridional component (Fig. 8-5c and e). Rainfall is, however, significantly positively correlated with the amplitudes of, and at a lower level of significance with the variances explained by, the second harmonics of the meridional wind speed (Fig. 8-5d and f). Positive but non-significant tendencies also occur between rainfall and the parameters of the second harmonics of temperature. The amplitudes of the semi-annual cycles of temperature and of the meridional component thus increase with rainfall. Inspection of data for individual years indicates that the amplitude of the semi-annual cycle of the meridional component is greater than that of the annual cycle in the wetter years whereas the relationship reverses in the drier years.

DISCUSSION

Systematic circulation changes with varying rainfall are both temporally dependent through the year and dependent on the level in the atmosphere over the central interior of South Africa. Some of the directions of the circulation changes indicated by the present results are inconsistent with those revealed in the earlier superposed epoch analyses. Based upon results of the earlier analyses in the lower atmosphere it may be expected that higher rainfall over the central interior of South Africa is accompanied by decreased temperatures and pressures, increased moisture and intensified poleward flows (Rubin, 1956; Triegaardt and Kits, 1963; Hofmeyr and Gouws, 1964). Temperatures in the boundary zone at Bloemfontein decrease in the wetter years in all months (Table 8-1) but pressures increase in the January to June months (Table 8-2). Poleward components increase with rainfall in eight months only (Table 8-7). In wet months the flow becomes increasingly anticyclonic over the north-eastern regions of South Africa according to Hofmeyr and Gouws (1964), Miron and Lindesay (1983) and Miron and Tyson (1984). Wet period circulation over the western Orange Free State is thus anomalously northerly and easterly, anomalies consistent with low-level circulations of rain-bearing systems (Fig. 2-15). Easterly components increase with the rainfall in most months (Table 8-6) as do northerly components (Table 8-7), results supportive of the concept of an intensified anticyclonic circulation. Higher pressures in the wetter months of the first half of the year may be the result of the anomalous anticyclonic circulation. Confirmed positive surface pressure anomalies developed over the eastern subcontinent in the wet months of January to March 1974 (Taljaard, 1981a - his Figures 22 to 24) and of January 1978 (Miron and Tyson, 1984 - their Figure 2). Moisture originating over the western Indian Ocean and carried in the flow around the high pressure cell accounts for the increased specific humidity values (Table 8-3). Systematic cooling of the air during its passage over the subcontinent through evaporation of precipitation and through injection of cool mid-tropospheric air by thunderstorm downdraughts in addition to radiative effects may account for the lower temperatures. Poleward flows are, however, weaker in the wetter months of February, March, July and October, changes not directly indicative of an intensified anticyclonic circulation. Circulation changes in the boundary zone thus involve variations in the locations and intensities of the major features of the circulation, including the high pressure system over the east coast and the central trough, which may not be resolved with data from a single station.

In the upper troposphere poleward components increase with the rainfall according to Triegaardt and Kits (1963), Hofmeyr and Gouws (1964), Miron and Lindesay (1983) and Miron and Tyson (1984) and the moisture content is unrelated to rainfall according to Hofmeyr and Oelschig (1965) and McGee (1970). Moisture increases with rainfall (Table 8-3) and only in the high seasons is the poleward component stronger in the wetter months. The anomalous flow is equatorward in the wetter transitional seasons (Table 8-7). If the ageostrophic flow in the boundary zone is ignored then the changes in the meridional circulation are indicative of intensified Hadley and Ferrel Cells in the wetter high and transitional seasons respectively. Changes in the toroidal circulations of similar senses to those in the integral circulation are also found in the mean circulations of both the rain and the no rain days in the wetter periods (see Appendix J). Frequency adjustments of the rain and no rain days may therefore not account alone for the changes in the toroidal circulation. Rather there are systematic changes to the circulation such that there is a stronger Hadley Circulation on a daily average in the wetter than in the drier high seasons and a stronger Ferrel Circulation on a daily average in the wetter than in the drier transitional seasons. Two important modes of circulation variations over the central interior of South Africa have therefore been identified. First, the sense of the dominant toroidal circulation cell associated with higher rainfall varies on a semi-annual cycle through the year. Changes remain of stable phase in all years. Consequently the atmospheric dynamics linked to the rainfall variations are seasonally dependent. Secondly, within any season the dominant meridional cell is intensified in the wetter years and thus so are those aspects of the general circulation forcing a particular cell. Changes in the toroidal circulation cells result in changes to the thermodynamic parameters in the barotropic zone such that increased temperatures, geopotentials and moisture concentrations occur with an anomalous Hadley Circulation.

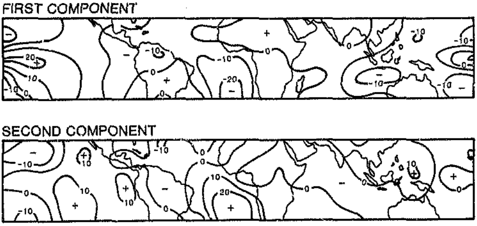


Figure 8-6. Fields of the first two principal components of tropical rainfall after Kidson (1975).

The differences in the sense of the wet-period anomalous toroidal circulation between seasons denote an unusual feature of circulation changes over South Africa associated with above-normal rainfall. Augmentation of the Hadley Circulation does not normally result in increased subtropical rainfall in longitudes close to that of the heat source because of the consequent amplified subsidence in the latitude 15 to 30° zones. The opposition of equatorial and subtropical anomalies over the central Pacific Ocean and over South America is illustrated in Kidson's (1975) first two principal components of low-latitude rainfall (Fig. 8-6). Opposition of anomalies also occurs in the Australian region on the second component but on neither component are anomalies over any two regions of Africa south of 10°S (the region which includes the heat source related to the African bands) reversed. Nicholson (1986) has confirmed that anomalies over the subcontinent south of 20°S are coherent. Positive subtropical rainfall departures tend to be associated with weaker Hadley Circulations, a situation which occurs over the central interior of South Africa only in the transitional seasons. Rainfall over tropical Australia, for example, was exceptionally high in January 1974 in association with a Ferrel Circulation anomaly at 130°E. Alternatively in January 1973 and January 1975, when rainfall was close to average, a Hadley Cell anomaly was present along the same meridian (Allan, 1983). Further, the dry month of February 1965 in northern Australia was associated with a strengthened

Hadley Circulation but the toroidal circulation anomaly reversed during the following unusually wet month (Kininmonth, 1983). For South America modelling studies have indicated that drought over north-east Brazil results from descent within a Hadley-type circulation cell (Moura and Shukla, 1981), inferences supported by direct observations (Chu, 1983). The intensification of the Hadley Circulation across southern Africa in the wetter high seasons is thus an uncommon feature of the circulation variations.

Because of the differences in the dynamics of the toroidal circulation between seasons and because of the stability of the phase of the semi-annual cycle of the barotropic zone meridional flow circulation changes forcing the semi-annual cycle represent major components of the controls on the rainfall variations over the subcontinent. Appropriate features include energy and momentum generation over tropical Africa and the location of the Atlantic standing wave (Figs. 7-10, 7-11 and 7-12). A simple test of the relevance of changes in the location of the Atlantic standing wave to the observed toroidal circulation changes over the central interior of South Africa may be made by inspecting changes in the phase angles and amplitudes of the first two harmonics of 200 mb heights at the coastal stations of Alexander Bay and Durban in relation to rainfall over the western Orange Free State. Phase angles in all cases were stable between years. Amplitudes of the first harmonics at both stations and of the second harmonics at Durban are not significantly correlated with rainfall (Fig. 8-7a, c and d). At Alexander Bay, however, amplitudes of the second harmonics are significantly correlated with rainfall such that amplitudes increase in the wetter years (Fig. 8-7b). Enhanced longitudinal displacements of the Atlantic wave therefore occur such that the wave is displaced anomalously westward and eastward, with consequently reduced and increased influences on the circulation over the central interior of South Africa, in the wetter high and transitional seasons respectively. Heights at Alexander Bay tend to be higher than those at Durban in the dry periods and lower in the wet periods in accord with the positioning of a trough over the west coast in the latter periods first detected by Triegaardt and Kits (1963) and Hofmeyr and Gouws (1964).

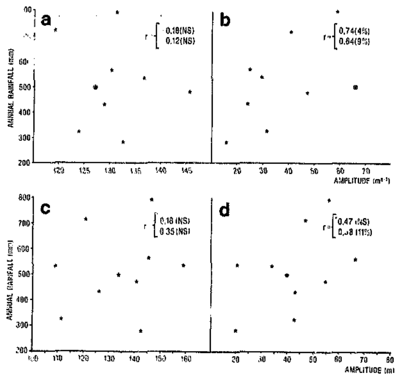


Figure 8-7. As Figure 8-5 but for the amplitudes of the first two harmonics of 200 mb heights at Alexander Bay (a) and b) respectively) and Durban (c) and d) respectively).

Adjustments to the thermodynamic structure of the barotropic zone result in changes to the stability of the atmosphere indicated by adjustments to the vertical profiles of the dry and total static energies. In terms of the vertical bipolar nature of the dry static energy correlations (Table 8-4) the atmosphere becomes increasingly statically *stable* in the wetter months. An example of the change in the vertical energy structure for two months of January, one wet and one dry, is given in Figure 8-8. In all months therefore, with the possible exceptions of May, August, October and December in which the energy content decl'ne with increasing rainfall at all levels up to at least 300 mb, the mean atmosphere becomes more characteristic of that of the temperate rather than that of the tropical latitudes during the wetter periods. Thus the majority of the disturbances providing rainfall over the western Orange Free State are baroclinically unstable. Baroclinic structures are present in the mean

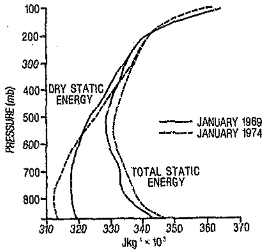


Figure 8-8. Vertical profiles of dry and total static energy for the dry month of January 1969 and the wet month of January 1974 over the western Orange Free State.

fields of rain-bearing systems (Harangozo, 1986) and were associated with several tropical-temperate troughs studied in detail.

Vertical profiles of the total static energy are useful as indicators of the degree of thermodynamic stability of the atmosphere and indices derived from the profile have been employed to aid forecasting of severe convective storms. Severe storms tend to develop in atmospheres with relatively low values of the total static energy in the mid-troposphere above high values in the lower atmosphere and hence one such index is the difference between values of the total static energy at 850 (above the boundary layer in the Great Plains of the United States) and 500 mb (Darkow, 1968). Equivalent but more sophisticated measures of thermodynamic instability have been proven efficacious in discriminating between atmospheric structures associated with dry weather and with varying types of convective clouds and rainfall in several areas of the World including Venezuela (Betts, 1974) and eastern Canada (Zawadzki *et al.*, 1981). At Bloemfontein in January values of the total static energy increase at most levels such that no immediately evident adjustment in conditional stability occurs in wet as opposed to dry months (Fig. 8-8). Changes in the stability with varying rainfall have therefore been determined using a Darkow index modified to allow for the high elevation of the western Orange Free Stat The index used is the difference between the energy values at 800 and 500 mb. During most rainfall season months and May and June correlations between the modified index and rainfall are positive indicating that enhanced conditional instability accompanies higher rainfall totals. In the remaining months the atmosphere tends to become additionally stable as rainfall increases. Harmonic analysis of the correlations between rainfall and the Darkow index reveals that highest positive correlations on the first harmonic occur on 23 February and on the second harmonic in summer on 23 January. Maxima in the correlations occur at the time of peak poleward flow in the barotropic zone and the dates correspond with that of the peak thermodynamic instability in the integral cycle (20 January). Higher summer rainfall accompanies therefore both decreased thermodynamic and baroclinic stability.

CONCLUSIONS

Details of the circulation changes accompanying the rainfall variations over the central interior of South Africa differ both between the distinct levels of the atmosphere and between the individual seasons of the year. In the boundary zone temperature decreases, specific humidity increases and westerly components weaken in the wetter months throughout the year. Pressure decreases in the second half of the year only whereas the direction of the meridional component anomalies varies through the year. In the barotropic and jet-stream zones signs of circulation anomalies in wetter months are seasonally dependent. Harmonic analyses indicate that correlations with rainfall are modulated on both annual and semi-annual cycles. Phase angles of the second harmonics of the correlations are consistent for all of the thermodynamic parameters and for the meridional circulation in the barotropic zone. Further the phases of the second harmonics of these parameters remain stable between years independent of rainfall but amplitudes of the harmonics increase in the wetter years. Phase angles are such that values of the thermodynamic parameters increase in the wetter months when the poleward flow is intensified, a result indicative of close associations between the thermodynamic parameters and the meridional circulation related to changes in advection.

Changes in the stability of the atmosphere resulting in part from the differences in the advection of heat are such that both baroclinic and thermodynamic instability increase in the wetter *rainfall season months*.

One important consequence of the quasi-stable phase of the semi-annual cycle of the toroidal circulation is that higher rainfall is associated with an intensified Hadley Circulation in the high seasons and an intensified Ferrel Circulation in the transitional seasons. Neither anomalous circulation results simply from frequency changes of rain and no rain days but also from appropriate intensifications of either circulation type on *both rain and no rain* days. The dynamics of the Hadley and Ferrel Circulations are somewhat different and therefore the vacillations between the anomalies of the two circulations indicates that the atmospheric dynamics forcing the *rainfall variations change through the year. Longi*tudinal displacements of the standing wave over the Atlantic Ocean in part force the changes in the meridional components.

An overview of the circulation changes associated with varying rainfall over the central interior of South Africa has been developed. It has been demonstrated that the circulation and rainfall interrelationships vary according to season and thus models of the controls on the rainfall variations must be developed for each season. In particular the models must take into account circulation changes on the semi-annual cycle of the meridional circulation. Adjustments in features of the general circulation *forcing the semi-annual cycle in the meridional component,* together with those features controlling the annual cycle of the circulation and of the rainfall, are of major importance in the determination of rainfall anomalies across the subcontinent.

CHAPTER 9

TROPICAL-TEMPERATE TROUGHS AND THE SOUTHERN OSCILLATION

INTRODUCTION

Circulation differences between wet and dry periods over the central interior of South Africa may be forced by changes at either or both of tropical and temperate latitudes. On the basis of observed reduced pressures Rubin (1956) proposed that the subtropical anticyclones retreat from South Africa during the wet summers and that higher rainfall results from an increased influence from westerly troughs. This concept of *temperate circulation controls* on the rainfall was extended by Tyson (1981). Alternatively Hofmeyr and Gouws (1964) provided evidence that the prime circulation changes associated with the summer rainfall variations occur to the north of the country in the tropical belt. Results from the most comprehensive relevant investigation to date indicate that the dominant *circulation changes controlling the rainfall* fluctuations vary spatially across the country with tropical controls prevailing over the northern parts and either subtropical or temperate controls elsewhere (Tyson, 1984). Over the central interior of South Africa the bulk of the rainfall in the October to April period comes from tropical-temperate troughs. The circulations at both *tropical and temperate latitudes* participate in the formation of these troughs and hence the inferences by both Rubin (1956) and Hofmeyr and Gouws (1964) may be correct.

Certain features of the circulation anomalies over the central interior of South Africa in the wetter months do not conform, however, with the models on which the propositions of increased tropical and temperate circulation influences were based. These features include increased surface pressures in the first half of the year and reduced poleward components in certain months. Comparison of deviations from the mean circulation at Bloemfontein associated with tropical-temperate troughs

(Harangozo, 1986) with the departure fields developed in Chapter 8 *reveals that broad similarities exist in most rainfall season months.* Changes in frequency of and hence in rainfall from the tropical-temperate troughs may thus account for many aspects of the associated total rainfall and circulation changes over southern Africa.

Rainfall departures over many parts of the globe are modulated with the Southern Oscillation (Kidson, 1975; Wright, 1977). A review of the properties and causal mechanisms of and of the global circulation teleconnections with the Southern Oscillation is given in Appendix K. Rainfall over the central interior of South Africa is affected such that it is above normal in Southern Oscillation high phase periods (Stoeckenius, 1981; Schulze, 1983; Lindesay *et al.*, 1986; Lindesay, 1986). High phase periods are marked by decreased and increased pressures in the *Indonesian region and South Pacific Ocean anticyclone respectively. The* longitudinal location of the major cloud band in the South Pacific Ocean is modulated according to the phase of the Oscillation such that it lies further west in high phase periods (Streten, 1975; Trenberth, 1976; Webster, 1981; Pazan and Meyers, 1982; Liebmann and Hartmann, 1982; Lau and Chan, 1983a). Similar longitudinal displacements of the tropical-temperate troughs and their associated cloud bands in the southern Africa region also occur (Fig. 2-6) such that they are displaced westward in the wetter periods over South Africa and thus in high phase periods. Shifts of the troughs and hence of the standing waves between southern Africa and Madagascar may therefore represent a major mode of behaviour of the atmosphere related to the rainfall fluctuations and may in turn be associated with circulation changes linked to the Southern Oscillation. *In this Chapter the importance of rainfall anomalies from* tropical-temperate troughs in the determination of departures over the central interior of South Africa will be examined. Statistics of trough locations in the southern African and Madagascan regions are also developed and rainfall anomalies studied within a framework of locations over either region. Finally, statistical relationships between rainfall and trough locations with an index of the Southern Oscillation are calculated to determine if rainfall anomalies and trough displacements may be linked to circulation changes between the high and low phases of the Oscillation. In order to facilitate interpretation calculations are made for the vernal transitional and summer periods, i.e. October to March, only.

SYSTEM CONTROLS ON RAINFALL VARIATIONS

Principal component analysis is used to identify those types of systems in each month whose rainfall is most closely correlated with the monthly totals. Rainfall from these systems is dominant in the determination of monthly anomalies whereas that from other systems is randomly distributed in time and represents noise in the signal. Matrices have been developed by month with total and system significant rainfall for each of the years across the rows. Rainfall data for which satellite images were missing have been excluded from the analyses except for incorporation into the monthly totals. Problems associated with linear associations between variables (Kendall, 1975) are reduced by exclusion of the missing data - in the present case the monthly totals would otherwise be linear sums of the systems' totals. The analyses were run on the correlation matrices and Varimax rotation has been applied. Following Kaiser (1960) only components with eigenvalues in excess of unity were retained for subsequent rotation. In most cases the retained components explain in excess of 90 per cent, and in all cases in excess of 80 per cent, of the variance of the monthly totals. Only systems with loadings above |0.6| (i.e. 36 per cent of the variance) on any component with monthly total loadings also above |0.6| after rotation are considered to control monthly totals. The limit of |0.6| is arbitrary but is similar to that used in a principal component analysis of circulation changes associated with rainfall variations over southern Africa (Tyson, 1984).

Only rainfall from tropical-temperate troughs is heavily and directly loaded with monthly totals in the summer season (Table 9-1). In February rainfall decreases as that from truncated troughs increases. Rainfall from several systems is heavily loaded with monthly totals throughout the vernal transitional season. In October monthly totals are heavily loaded on two components. One component represents controls from tropical-temperate troughs and subtropical cyclones and the other controls from the temperate east coast troughs and unclassified systems. Only tropical systems control totals in November. Tropical-temperate troughs do not control totals in December. Rainfall from truncated troughs, subtropical cyclones and unclassified systems determine anomalies in this month. Circulation controls on the formation of

Table 9·1. Systems (identified by an 'X') heavily loaded with monthly totals on any component after rotation (see text for details). A bar on an 'X' indicates inverse loadings. In October monthly totals were heavily loaded on two components - respective heavily-loaded systems are connected by lines. Systems are identified as tropical-temperate troughs (TTT), truncated troughs (TRT), west coast troughs (WCT), subtropical cyclones (STC), east coast troughs (ECT), coastal depressions (CLD) and unclassified systems (UNC).

	TTT	TRT	WCT	STC	ECT	CLD	UNC
October	X			X	X		X
November	X	X					
December		X		X			X
January	X						
February	X	$\bar{X}$					
March	X						

tropical-temperate troughs are therefore the prime determinants of rainfall anomalies in the summer season whereas controls on the formation of several types of systems including the tropical-temperate troughs are similarly decisive in the vernal transitional season.

STATISTICS OF TROUGH LOCATIONS OVER THE WESTERN INDIAN OCEAN

In order to develop a data base to study longitudinal displacements of tropical-temperate troughs a daily catalogue of cloud band types associated with the troughs over the western Indian Ocean has been developed for the period 1967 to 1977. Four types of Indian Ocean band have been incorporated into the catalogue. Bands were classified as Indian Ocean bands only when no portion overlay any part of South Africa and when some portion lay west of 60°E. Missing data have been ignored in the development of the catalogue and in the estimation of the associated statistics. The four categories of Indian Ocean bands are:

a) Tropical band: a band rooted in convection over the eastern parts of southern tropical Africa and extending through the Madagascar region to a temperate cyclone in the southern Indian Ocean - a satellite image of a tropical band is given in Figure 9-1;

b) Tropical band (embedded cyclone): as a tropical band but with a tropical cyclone embedded within the band;

c) Malagasy band: as a tropical band but rooted in convection over Madagascar without any cloud link across the Mozambique Channel to the African continent;

d) Tropical cyclone band: as a tropical band but rooted in either a tropical cyclone (most common in the later summer months) or in an oceanic tropical cyclonic vortex (most common in the winter months) over the low-latitude Indian Ocean - a satellite image of a tropical cyclone band associated with a cyclone on the east coast of South Africa is given in Figure 2-14.

The term African bands will also be used to include bands associated with tropical-temperate, truncated and west coast troughs.

Bands of all types are present on more days in January than in any other month after a relative decline in frequency in December (Fig. 9-2a). The December minimum is also present in the percentage frequency of all days with bands that bands are present over South Africa (Fig. 9-2b). October, rather than January, is the month in which this percentage reaches its annual maximum. Indian Ocean bands develop most frequently in December and are unimodally distributed throughout the year (Fig. 9-2c). Thus the December minimum results from a reduction in the frequency of African bands and from an eastward displacement of the bands, and thus of the troughs, into the Indian Ocean. Of the different types of Indian Ocean bands only the Malagasy bands develop most frequently in December with other maxima in March and September (Fig. 9-2c).

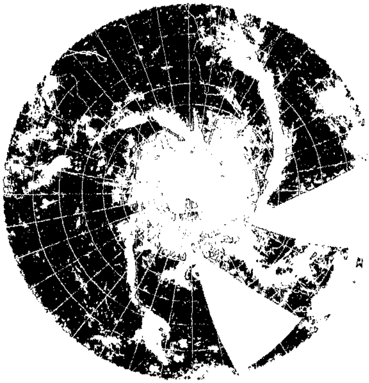


Figure 9-1. NOAA-2 polar-orbiting satellite hemispheric infra-red mosaic at 21L showing a tropical band across the Indian Ocean on 13 January 1973.

Tropical bands are the most common type of Indian Ocean band and are bimodally distributed with maxima in April and November. Tropical cyclone bands are also distributed according to a semi-annual cycle but, with highest frequencies in March and August, of opposite phase to that of the tropical bands. Tropical bands (embedded cyclone) alone are unimodally distributed with the maximum in January. On the majority of days only one trough, if any, is present in the African region. On a small proportion of days, reaching maxima in January and March, relatively short wavelength circulations develop in which troughs form both across South Africa and across the western Indian Ocean (Fig. 9-2d). The December hiatus is present in the frequency of days on which only one trough, across South Africa, is present as is the December maximum

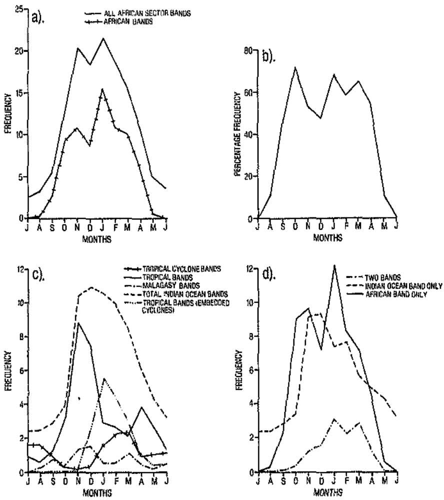


Figure 9-2. Mean frequency statistics of cloud bands in the southern African region for the period 1967 to 1977. a) Monthly mean frequencies of total and of African bands as defined in the text - the African band curve is taken from Figure 7-1. b) Monthly percentage frequency of days with bands on which African bands were present. c) Monthly mean frequencies of total and individual types of Indian Ocean bands. d) Monthly mean frequencies of days with a single band, either an African or an Indian Ocean band, and with bands in both locations.

in the frequency when the single trough is situated over the Indian Ocean.

WESTERN ORANGE FREE STATE RAINFALL IN RELATION TO TROUGH LOCATIONS

On days on which an Indian Ocean band is present rainfall over the western Orange Free State is generally light and predominantly cloud-free conditions as in Figure 9-1 affect South Africa as a whole. Mean daily rainfall over the western Orange Free State for four classes of days, those on which either none or two troughs are present or those on which only one trough is present across either South Africa or the Indian Ocean, during the rainfall season are listed in Table 9-2. Corresponding rainfall distributions for January are illustrated in Figure 9-3. In all months rainfall is lowest when Indian Ocean bands are present and highest, apart from in October, with the occurrence of African bands. Rainfall is also higher in all months when there are two rather than when there are no bands.

Daily rainfall exceeds 15 mm in January only on days with African bands (Fig. 9-3). The highest frequency of dry days occurs when Indian Ocean bands are present and only on 10 per cent of days with Indian Ocean bands does significant rain, as defined in Chapter 3, fall. Unclassified systems supply rainfall on about 50 per cent of the days on which Indian Ocean bands are present. Distribution changes between the four categories of Figure 9-3 are significant at better than the 1 per cent level according to a χ^2 test (Table 9-3). Highest cell contributions to the χ^2 value come from the high frequency of dry days when Indian Ocean bands are present and the low frequency of dry days and the high frequency of daily falls between 5.1 and 10.0 mm when African bands are present.

Results for other rainfall season months are basically similar to those for January although, except in December, rainfall in excess of 15 mm also occurs on other than days with African bands. Tests for the differences

Table 9-2. Mean rainfall (mm) over the western Orange Free State in the 1967 to 1977 period rainfall season months for days on which (in columns 2 to 5 respectively) there was an African band, an Indian Ocean band, on which there were no bands and on which there were bands across both Africa and the Indian Ocean. In the case of African and two bands means have been calculated across all days regardless of whether or not a band overlay the western Orange Free State.

	African	Indian	None	Two
OCT	1.8	0.9	2.0	8.0
NOV	2.8	0.4	1.2	1.9
DEC	3.1	1.0	1.7	3.0
JAN	4.4	0.7	2.5	2.9
FEB	4.9	1.5	2.8	3.5
MAR	4.7	1.0	2.3	3.3

between the frequency of falls in categories similar to those of Table 9-3 rev : that the differences in all months are significant at the 1 per cent level. Various non-parametric distribution tests, including the non-parametric ANOVA and Kruskal-Wallis tests, have also been run on the daily rainfall totals for the four band classes. In all months the null hypothesis of no difference in the rainfall distributions of the categories is rejected at better than the 1 per cent level. Thus circulations suitable for the formation of Indian Ocean bands normally result in minimal, if any, rainfall over the western Orange Free State.

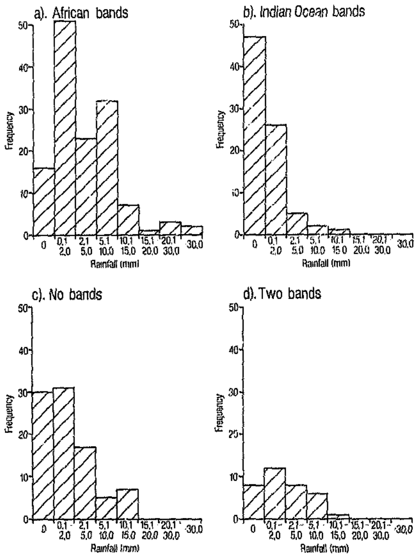


Figure 9-3. Frequency distributions of daily rainfall over the western Orange Free State in January for a) days with an African band only, b) days with an Indian Ocean band only, c) days with no bands and d) days with both an African and an Indian Ocean band.

Table 9-3. Contingency table for five categories of daily rainfall in January against the four band categories of Figure 9-3. In all groups the top figure represents the observed frequency, the second figure the expected frequency and the third figure the cell contribution to the χ^2 value given in the lower right-hand corner.

	Rainfall (mm)				
	0	0.1-2.0	2.1-5.0	5.1-10.0	>10.0
African	16	51	23	32	13
	40.0	47.5	21.0	17.8	8.7
	14.4	0.3	0.2	11.3	2.1
Indian	47	26	5	2	1
	24.0	28.5	12.6	10.7	5.2
	22.1	0.2	4.6	7.1	3.4
None	30	31	17	5	7
	26.7	31.7	14.0	11.9	5.8
	0.4	0.0	0.6	4.0	0.2
Two	8	12	8	6	1
	10.4	12.3	5.4	4.6	2.3
	0.5	0.0	1.2	0.4	0.7

$\chi^2 = 73.8$
12 Degrees of Freedom

LONGITUDINAL DISPLACEMENTS OF THE TROUGHS

Principal component analysis has been employed to investigate the associations between the frequency of African and Indian Ocean bands. In order to test the supposition that the frequency of troughs over Africa is inversely related to that over the western Indian Ocean matrices have been set up by month with frequencies of single African bands, single

Indian Ocean bands, two bands and no bands in the columns. In all cases the analysis was run on the correlation matrix and only parameters loaded in excess of |0.6| on any component after Varimax rotation are considered to be associated.

In the three months November to January frequencies of African and Indian Ocean bands are inversely heavily loaded (Fig. 9-4). Months of higher frequencies of troughs over southern Africa are thus months of lower frequencies over Madagascar, and *vice versa*. Frequencies of no bands and of two bands are also oppositely loaded in the three months. In October the frequency of African bands is indirectly related to the frequency of no bands and directly to that of two bands. Indian Ocean band frequencies are loaded on a component separate from that of the other types of bands. Thus the dominant mode of action in October is related to the formation or non-formation of African bands rather than to longitudinal vacillations of the locations of the bands as in November, December and January. In February the frequency of African bands is inversely loaded with that of no bands as in October indicating that a similar mode of the variations is present in the two months. Indian Ocean band frequency is inversely related to that of two bands in February, possibly indicative of a mode representative of longitudinal band displacements. The frequency of African bands in March is loaded separately from that of the other types of bands. The frequencies of Indian Ocean bands and of two bands are loaded together in March and both are inversely loaded with the frequency of no bands. Thus a major mode in March is represented by the inverted frequencies of no bands and of Indian Ocean bands.

THE SOUTHERN OSCILLATION AND SOUTH AFRICAN RAINFALL

Associations between rainfall from and locations of tropical-temperate troughs and the Southern Oscillation may now be investigated. Interpretations of teleconnections based on linear correlations with a Southern Oscillation index may potentially be misleading (Ramage, 1983; Pittock, 1984), especially when used *a priori* to determine statistically-significant

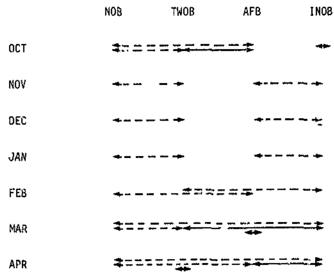


Figure 9-4. Results of the principal component analyses of band frequencies for the rainfall season months - for no bands (NOB), two bands (TWOB), African bands (AFB) and Indian Ocean bands (INOB). Band frequencies loaded in excess of |0.6| on the same component are connected by solid (if loadings are of similar signs) or dashed (if loadings are of opposite signs) double-headed arrows. Frequencies loaded in excess of |0.6| independently of any other frequencies are identified by a short double-headed arrow.

circulation links. In the present case, however, this process is reversed in that partial validation of hypothesised circulation links is sought in the correlations. The index of the Southern Oscillation used is the non-seasonal surface pressure difference between Tahiti and Darwin which has been recommended for diagnostic studies of links with the Southern Oscillation (Chen, 1982). Data were recorded at Tahiti from 1935 and thus the available index series covers the period 1935 to 1977. Correlations are calculated at zero lag only despite the established lags between responses of the circulation over distant parts of the globe to changes over the Pacific Ocean (Pan and Oort, 1983). Further, correlations are calculated by month rather than by integrated three-month seasons recommended by several authors as a technique for reducing the noise level in the index series (e.g. Trenberth, 1976). In order to partially remove noise inherent in the Southern Oscillation index time series a smoothed series was developed through application of a three-term binomial filter, centred on the month under study, to the index series.

Correlations have been calculated in all months from October to March for the 1935 to 1977 period between the smoothed index and scores of all components retained during the development of the classification in Chapter 2. Sums of the scores, weighted by the appropriate loadings, for those components inferred to represent the tropical-temperate and truncated troughs closely simulate the estimated time series of rainfall from the troughs for the period 1967 to 1977 (Harrison, 1984d) and thus these sums have also been correlated with the index. Time series for the troughs' rainfall include those for the first two October to December components and those for the first two and the fifth January to March components.

Correlations are not significant at the 5 per cent level in October and November (Table 9-4). Few regions across South Africa over which integral October and November rainfall is statistically significantly correlated with the index have been detected by Lindesay (1986). December to March correlations significant at the 5 per cent level are present between the time series of the first component and of the total rainfall from tropical-temperate troughs and the index. Higher rainfall occurs in the Oscillation's high phase. Time series of several higher components are also significantly correlated with the index in all months but no interpretation of any of these components was offered in Chapter 2. The results reinforce the inference of Lindesay *et al.* (1986) that trough rainfall is responsible for the north-west to south-east alignment of the region of highest statistically-significant differences in rainfall obtained in a superposed epoch analysis based on the phases of the Southern Oscillation.

Principal component analysis has been used to investigate the supposition that troughs form more frequently over the central interior of South Africa in high phase periods of the Southern Oscillation. Matrices have been developed by month with rainfall from the troughs as simulated by the principal component scores, the Southern Oscillation index and the frequencies of single African bands, single Indian Ocean bands, two bands and no bands in the columns. The analyses follow the same format as that for the examination of the longitudinal displacements of the troughs above. In October cloud band rainfall is indirectly related to the Southern Oscillation index (Fig. 9-5). Time series of both the first October component and the total cloud band rainfall are also negatively but non-significantly correlated with the Southern Oscillation index (Ta-

*Table 9-4. Correlations between the smoothed Southern Oscillation index and scores of the components developed in Chapter 2 for the rainfall season months - except for component 1 and for total trough rainfall only linear correlations significant at better than the 10 per cent level are listed. In the column headed 'Troughs' are correlations with scores of components inferred to represent rainfall from tropical-temperate and truncated troughs. In the column headed 'Total troughs' are correlations with the appropriately weighted sums of the scores of components inferred to represent trough rainfall. In the column headed 'Other' are correlations with scores of retained components. Component numbers are given in brackets and significance levels are indicated by asterisks: * better than 10 per cent; ** - better than 5 per cent; *** - better than 1 per cent.*

	Troughs	Total troughs	Other
OCT	-0.15(1)	-0.06	0.27*(3)
NOV	0.05(1)	0.08	-0.33**(6)
DEC	0.47***(1)	0.48***	
JAN	0.30**(1) 0.29*(2)	0.36**	-0.44***(11) 0.29*(13)
FEB	0.33**(1)	0.33**	0.33**(13)
MAR	0.31**(1)	0.30**	0.32**(6) -0.26*(7) -0.30**(10)

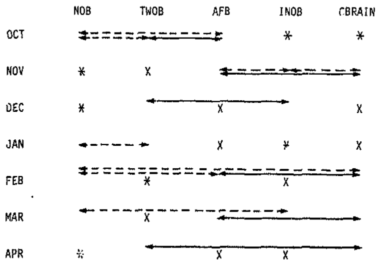


Figure 9-5. As Figure 9-4 but for band frequencies and western Orange Free State cloud band rainfall (CBRAIN) with the smoothed Southern Oscillation index. Parameters loaded in excess of |0.6| together with the Southern Oscillation index are identified with an 'X'. Opposing signs of loadings in excess of |0.6| with the Southern Oscillation index are marked by a bar across the 'X'.

ble 9-4). Frequencies of Indian Ocean bands are indirectly loaded with the Southern Oscillation index. African band frequencies are not loaded on the same component as either cloud band rainfall or the Southern Oscillation index but are loaded directly and indirectly with frequencies of two and of no bands respectively. African band frequencies and cloud band rainfall are directly related and both are indirectly related to the frequency of Indian Ocean bands in November. Cloud band rainfall is not, however, loaded with the Southern Oscillation index. Instead the index is directly related to the frequency of two bands and indirectly to the frequency of no bands.

December is the earliest month in which the Southern Oscillation index is loaded directly with the frequency of African bands and with cloud band rainfall in addition to being indirectly loaded with the frequency of no bands. Indian Ocean band frequencies are heavily loaded with the frequency of two bands. January is the only month in which African band frequency and band rainfall are directly and Indian Ocean band frequency is indirectly loaded with the Southern Oscillation index. No band and two band frequencies are also indirectly related. Frequencies of Indian Ocean and two bands are indirectly loaded in February but on the same component as the Southern Oscillation index such that the frequency of Indian Ocean bands increases in the high phase months. Cloud band rainfall is directly loaded with African band frequency but not with the index despite the high direct correlations obtained for this month (Table 9-4). In March cloud band rainfall is loaded with the frequency of African bands but the Southern Oscillation index itself is loaded, directly, only with the frequency of two bands. No bands and Indian Ocean bands are indirectly loaded.

In a final test of the association between trough locations and the phases of the Southern Oscillation band locations have been stratified according to the December to February anomalous flow patterns in the tropical Pacific Ocean following Arkin (1982). The stratification is based on the sense of the anomalous circulation over the Pacific Ocean in the vicinity of the date line which frequently takes the form of a cyclonic or an anticyclonic couplet to either side of the Equator. Cyclonic couplets are normally associated with the high phase of the Oscillation and anticyclonic couplets with the low phase, the physical significance of which has been discussed by Keen (1982). In all months (Table 9-5) the highert mean rainfall totals are associated with cyclonic and the lowest with anticyclonic couplets. Frequencies of African bands are higher in periods with a cyclonic rather than an anticyclonic couplet whereas the reverse applies (except in February) for the frequencies of Indian Ocean bands. Days without bands also tend to be more frequent when there is a cyclonic couplet and days with two bands when there is an anticyclonic couplet.

DISCUSSION

The suppositions that rainfall anomalies over the central interior of South Africa are dependent upon variations in rainfall from tropical-temperate troughs, upon longitudinal displacements of the troughs between the

Table 9-5. Mean western Orange Free State rainfall (Rain - mm) and frequencies of African bands (Afr), Indian Ocean bands (In), no bands (No) and two bands (Two) for the months December, January and February in the period 1968 to 1977 stratified according to the presence of an anticyclonic (A) or a cyclonic (C) couplet or neither (N) across the central Pacific Ocean according to Arkin (1982).

	DEC			JAN			FEB		
	A	C	N	A	C	N	A	C	N
Rain	28.1	80.5	61.6	42.9	143.4	92.2	71.1	123.3	88.6
Afr	4.7	8.5	7.5	11.7	14.8	11.5	9.3	10.0	6.0
In	12.0	9.0	11.0	7.7	4.8	10.0	7.0	8.0	6.5
No	12.0	12.0	11.5	7.3	8.8	6.0	7.7	8.8	12.5
Two	2.3	1.5	1.0	4.3	2.8	3.5	4.0	1.8	3.0

southern African and Madagascan regions and upon circulation changes related to the Southern Oscillation have all been verified. The suppositions do not apply, however, in all months from October to March. Rainfall from tropical-temperate troughs uniquely determines anomalies in the summer season when the Hadley Circulation is intensified in the wetter months. Close correspondence may be noted between the wet period circulation departures derived in Chapter 8 and those for the tropical-temperate troughs obtained by Harangozo (1986) in confirmation of the importance of frequency changes of the troughs in the determination of the anomalies. Higher rainfall in the summer season is associated with stronger forcing of the Hadley Circulation across southern Africa and therefore with enhanced energy and momentum generation over the African tropics.

In the wetter vernal transitional seasons the Ferrel Circulation across southern Africa intensifies and toroidal circulations for some of the types of systems which determine rainfall anomalies, including the truncated troughs and the unclassified systems, are of the Ferrel Cell type. Rainfall from tropical-temperate troughs also determines anomalies in October and November and thus both enhanced energy and momentum generation over the African tropics together with enhancement of the forcing mechanisms of the Ferrel Circulation occur in the wetter months. Thermodynamic and kinematic structures for few of the systems as derived by Harangozo (1986) correspond with the departures determined in Chapter 8 and thus circulation variations may not be interpreted in terms of frequency changes of particular systems. Marked changes in the structures of the systems also occur between years. Circulation variations are thus more complex in the vernal transitional than in the summer season. Correspondence between the toroidal circulations of those types of systems determining the rainfall anomalies and the dominant toroidal circulation cell indicates that the changes in the details of the variations between the two seasons are closely related to the circulation adjustments on the semi-annual cycle.

Outgoing long-wave radiation over Africa at 20°S is modulated on a semi-annual cycle (Fig. 7-4) such that it is a minimum in summer when energy generation at 20°S is a major determinant of rainfall anomalies. The standing wave over the Atlantic Ocean is displaced westward in summer, a displacement which is enhanced in the wetter seasons. Equally it is displaced eastward in the wetter vernal transitional seasons when energy generation at 20°S is reduced. Evidence for the eastward displacement of the wave is afforded by the high frequencies of tropical bands in April and November (Fig. 9-2c), frequencies consistent with the concept of tropical bands forming in the second poleward arm of the wave (Figs. 6-7 and 7-9). Circulation departures on the semi-annual cycle are thus suitable for forcing intensified Hadley and Ferrel Circulations in the wetter summer and vernal transitional seasons respectively. The inverse semi-annual cycle of the frequency of tropical cyclone bands to that of tropical bands is such that highest frequencies occur at times of maximum depths of the 20°C isotherm over the western Indian Ocean (Quadfasel, 1982). These are the times of most suitable conditions in terms of sea surface temperatures for the formation of tropical cyclonic vortices. Similarly tropical bands (embedded cyclone) formed most frequently near the time of warmest sea surface temperatures.

Rainfall over the central interior of South Africa is reduced when troughs lie over the western Indian Ocean in all months. The concept of longitudinal displacements of the troughs causing the rainfall variations applies, however, only in the months November to January. Modes of action of the atmospheric circulation other than longitudinal displacements of the waves also occur in several months. Nor are displacements of the waves directly related to the Southern Oscillation in months other than January (Fig. 9-5). Longitudinal displacements of standing waves in the Southern Hemisphere are, nevertheless, associated with the Southern Oscillation. Longitudinal shifts in the location of wave 1 are linked to the Southern Oscillation according to Trenberth (1980b). Further, movements of cloud bands over the Indian and Pacific Oceans appear to be reflected in the field of the first eigenvector of tropical rainfall (Fig. 8-6 - cf. Fig. 2-7) according to Kidson (1975) - an interpretation supported by Heddinghaus and Krueger (1981) - the time series of which is significantly correlated with an index of the Southern Oscillation. Shifts in wave locations between phases of the Southern Oscillation are therefore important components of climatic change in the Southern Hemisphere but may not uniquely account for rainfall variations over southern Africa.

Only rainfall from tropical-temperate troughs is linearly correlated at zero lag to the Southern Oscillation index and only in the months December to March. Lindesay (1986) similarly noted that correlations between rainfall and the index are higher in the summer than in the vernal transitional season. Associations between the Southern Oscillation and South African rainfall are therefore stronger in the summer than in the vernal transitional season. Over Australia an inverse situation occurs with strongest associations with rainfall in spring (McBride and Nicholls, 1983). January to March is the period of strongest development of circulations associated with the Southern Oscillation (Rasmusson and Carpenter, 1982; Horel, 1982; Quiroz, 1983) and it may be postulated that these circulations influence the generation of energy and momentum over southern Africa in summer. December rainfall from tropical-temperate troughs is not, however, a determinant of rainfall anomalies (Table 9-1). There appears to be a marked adjustment in the circulation in December which may be associated with the rainfall hiatus (Appendix H) and which renders the circulation more complex than that of any other month. Origins of the stronger correlations with rainfall in December, detected in Table 9-4 and by Lindesay (1986), thus remain to be elucidated. The major impact of circulation changes related to the Southern Oscillation is therefore to the formation of tropical-temperate troughs across southern Africa in the summer season.

CONCLUSIONS

Several postulated modes of behaviour of the atmosphere resulting in rainfall variations over the central interior of South Africa have been examined. The postulates include that frequency changes of tropical-temperate troughs cause the variations, that the troughs are displaced eastward towards Madagascar in the drier months and that trough displacements and hence rainfall totals are determined by circulation variations associated with the Southern Oscillation. All of the postulates have been verified but none are applicable in all months October to March. Changes in the circulation on the semi-annual cycle in part account for differences in the modes of behaviour in the various months.

In the summer season, when the Hadley Circulation is intensified in the wetter months, rainfall from tropical-temperate troughs alone determines anomalies over the central interior of South Africa. Rainfall is well correlated with the Southern Oscillation index and it has been suggested that circulation changes related to the Southern Oscillation control the generation of momentum and energy over tropical Africa and hence the forcing of the Hadley Circulation across southern Africa. In the vernal transitional season, when the Ferrel Circulation is intensified in the wetter months, several systems including the tropical-temperate troughs determine anomalies. No evidence of control of the anomalies from the Southern Oscillation has been obtained for October and November. It is therefore possible that circulation links between the Pacific Ocean and southern Africa are modulated on a semi-annual cycle.

Further evidence for circulation changes on a semi-annual cycle, specifically for longitudinal displacements of the Atlantic standing wave, has been obtained in terms of frequencies of troughs in the Madagascar region. Displacements of the troughs between years may not, however, simply account for the rainfall variations. Behavioural modes of the atmospheric circulation are such that only in January is there a well-defined association between rainfall, locations of the troughs and the Southern Oscillation. Other modes are present in the remaining months. Thus the major identified cause of rainfall variations is the differences in frequency of formation of tropical-temperate troughs, and hence in the forcing of the Hadley Circulation across southern Africa. This forcing is most closely associated with circulation changes *related to the Southern* Oscillation in the summer months.

CHAPTER 10

RAINFALL, MERIDIONAL MOMENTUM FLUX VARIATIONS AND THE SOUTHERN OSCILLATION

INTRODUCTION

The hypothesis upon which this thesis has been based is that rainfall increases in periods of enhanced poleward momentum fluxes. This hypothesis was developed upon the assumption that tropical-temperate troughs form more frequently in the wetter months and that consequently the transient flux, which is greater in the vicinity of the cloud bands of the Southern Hemisphere than in the zonal average (Webster and Curtin, 1975), increases. Changes in the toroidal fluxes must also occur, however, as a result of inter-annual variations in the meridional components on the semi-annual cycle. Differences in both the mean and the transient atmospheric circulations between years may therefore be determinants of rainfall variations. Inter-annual flow changes over the Northern Hemisphere are resident primarily within the mean meridional flow and the corresponding momentum fluxes, whereas the zonal flow and the transient fluxes tend to be relatively constant between years (Gaut *et al.*, 1976). Confirmation of the relative stability of the zonal flow and of the significance of the inter-annual variations of the meridional flow was obtained in a detailed analysis of Northern ' nispheric flow changes between one normal and one dry summer over central India and the Sahel (Kanamitsu and Krishnamurti, 1978). Marked changes in the zonal spectra of the meridional wind field and of the poleward meridional fluxes of momentum between the Equator and 30°N were associated with changes in the locations of the regions of tropical heat release between the two years. In the Southern Hemisphere inter-annual circulation changes are also associated with differences in the mean flow in affiliation with longitudinal displacements of the standing waves, displacements which are possibly related to variations in the distribution of the tropical heat sources and to phase changes of the Southern Oscillation (Trenberth, 1980b). Inter-annual differences in the forcing of the Hadley Circulation by energy release over tropical Africa together with longitudinal displacements of the waves over the Atlantic Ocean and over Africa accompany the rainfall variations over the central interior of South Africa. As in the Northern Hemisphere adjustments to the mean flow and to the locations of tropical heating may thus be of greater importance in the determination of climatic anomalies over the Southern Hemisphere than adjustments in the transient circulation.

Two theories, summarised in Appendix L, have been forwarded to account for changes in tropical rainfall and hence in the forcing of the Hadley Circulation. In the first rainfall varies according to the latitudinal excursion of the Inter-Tropical Convergence Zone as determined by meridional temperature gradients across one or other hemisphere. In the second latitudinal excursions are considered secondary to the extent of convective overturning along the Zone. Observational evidence indicates that the second theory is of greater relevance over southern Africa than the first (Nicholson and Chervin, 1933). Convection over tropical Africa lies within the region of influence of the zonal circulation cell across the Indian Ocean, the Walker Circulation (see Appendix K). Zonal circulation cells lie around the globe and link the regions of tropical convection. In addition global variations in senses and locations of the Walker Circulations result from longitudinal displacements of the tropical heat sources which accompany phase changes of the Southern Oscillation. In the high phase the anomalous 200 mb zonal component across the Indian Ocean is easterly, an anomaly suitable for the development of convection over Africa. In the low phase the anomaly reverses. It is conceivable therefore that the Indian Ocean Walker Circulation represents a mechanism by which the Southern Oscillation signal is transmitted to southern Africa in such a way as to control energy release over the subcontinent. Subsequent changes to the Hadley Circulation result in modified poleward toroidal momentum fluxes and in part determine rainfall anomalies across southern Africa.

Changes to both the toroidal and the transient momentum fluxes with varying rainfall are examined in this Chapter to test the validity of the hypothesis that rainfall increases with the poleward flux. Circulation differences and changes to the Indian Ocean Walker Circulation between the two extreme phases of the Southern Oscillation are also inspected to determine the possible validity of the assertion that the Southern Oscillation signal is transmitted to southern Africa via the Walker Circulation in such a way as to control energy release at 20°S.

MOMENTUM FLUX CHANGES

Both the data and the analysis technique are identical to those used in the study of the associations between the circulation variations and rainfall in Chapter 8. Based on the mean and eddy wind component values at each level at Bloemfontein the monthly mean relative angular momentum of the atmosphere together with the poleward fluxes of earth angular momentum and relative angular momentum by the mean circulation, by the transient eddies and by the total circulation, integrated through the depth of the atmosphere to 100 mb, have been calculated. Spearman correlations have subsequently been calculated between rainfall and both the relative angular momentum and the various components of the meridional flux.

The relative angular momentum declines as rainfall increases in seven months (Table 10-1 - cf. Table 8-6). Earth angular momentum fluxes are directly related to rainfall in seven months, with strongest positive correlations (i.e. enhanced poleward flux with higher rainfall) in the summer and late winter months (cf. Table 8-7). Values of the correlations with the circulation flux are similar to those with the earth angular momentum flux except that the January correlation with the circulation flux is negative. Only in February, March, April and November is the poleward transient flux stronger in the wetter months. Total poleward relative angular momentum fluxes increase with rainfall in six months mainly during the rainfall season. Similar systematic changes to the relative angular momentum and to the meridional fluxes as rainfall varies also occur on the rain and the no rain days (see Appendix J). Variations of the fluxes are not dependent therefore simply on frequency changes of rain and no rain days but also on structural changes to the atmospheric

*Table 10-1. Values of Spearman rank correlation coefficients between rainfall and the vertically-integrated relative angular momentum of the atmosphere ($\int u$), the vertically-integrated flux of earth angular momentum ($\int v$) and the vertically-integrated circulation ($\int vu$), transient ($\int v'u'$) and total ($\int vu$) relative angular momentum fluxes. Negative correlations, indicating decreased relative angular momentum or poleward fluxes in wetter months, are stippled. Asterisks indicate significance levels: * - better than 10 per cent; *** - better than 1 per cent.*

MONTHS	$\int\bar{u}$	$\int\bar{v}$	$\int\bar{v}\bar{u}$	$\int\overline{v'u'}$	$\int\overline{vu}$
J	0.50	-0.25	-0.10	-0.42	-0.09
A	0.16	0.40	0.44	-0.20	0.35
S	-0.28	0.31	0.03	-0.31***	-0.08
O	-0.38	-0.01	-0.03	-0.10	-0.02
N	0.14	-0.27	-0.18	0.38	0.05
D	0.41	0.27	0.15	-0.31	0.26
J	-0.87***	0.77***	-0.04	-0.61*	-0.30
F	-0.41	0.44	0.30	0.25	0.47
M	-0.20	0.52	0.62*	0.03	0.30
A	0.36	0.05	0.10	0.12	0.01
M	[illegible]	[illegible]	-0.1?	-0.3?	-0.40
J	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

circulation on the two types of days such that poleward toroidal fluxes in summer and equatorward fluxes in the vernal transitional season on a daily average are stronger in wet than in dry months.

Table 10-2. Details of the first and second harmonics of the monthly correlations between rainfall and the components of the momentum flux. Amplitudes (Amp) are of the values of the correlations. Columns headed 'Var' give variances explained by harmonics while those headed 'Max' list approximate dates of maximum positive (i.e. poleward) correlation. For second harmonic dates are for the rainfall season maxima. In first column an 'I' indicates results for integral data, an 'R' results for rain days and an 'NR' results for no rain days.

	Annual Wave			Semi-annual Wave		
	Amp	Var	Max	Amp	Var	Max
Relative angular momentum - $\int \bar{u}\,dp/g$.						
I	0.21	15.7	15 Jul	0.15	8.0	1 Dec
R	0.21	15.8	5 Aug	0.04	0.5	5 Nov
NR	0.28	23.1	15 Jul	0.10	2.9	2 Jan
Earth angular momentum flux - $\int \bar{v}\,dp/g$.						
I	0.26	29.8	20 Jan	0.32	46.7	19 Feb
R	0.07	1.6	7 Jun	0.26	24.0	27 Feb
NR	0.20	14.2	21 Jan	0.27	24.5	5 Feb
Circulation relative angular momentum flux - $\int \bar{v}\bar{u}\,dp/g$.						
I	0.11	10.1	19 Feb	0.26	54.9	1 Mar
R	0.11	3.4	1 Aug	0.28	23.6	7 Mar
NR	0.33	25.5	28 Jan	0.41	38.7	10 Feb
Transient relative angular momentum flux - $\int \overline{v'u'}\,dp/g$.						
I	0.18	14.8	16 Feb	0.16	11.0	20 Oct
R	0.13	7.3	2 May	0.06	1.6	7 Mar
NR	0.15	23.1	18 Dec	0.01	0.0	1 Mar
Total relative angular momentum flux - $\int \overline{vu}\,dp/g$.						
I	0.13	12.4	25 Dec	0.21	32.0	28 Feb
R	0.08	2.5	7 May	0.18	13.9	5 Mar
NR	0.20	11.9	7 Jan	0.39	46.2	12 Feb

HARMONIC ANALYSES OF THE CORRELATION FIELDS

Together the first two harmonics of the relative angular momentum correlations account for only 24 per cent of the variance (Table 10-2), the cycle of the correlations being dominated by the third harmonic. Highest positive correlations (i.e. increased relative angular momentum in the wetter months) occur in mid-July on the first harmonic and on the second harmonic in early June and December. The second harmonic accounts for 47 per cent of the variance of the earth angular momentum flux correlation distribution with maximum positive correlations (stronger poleward fluxes in wetter months) in late February and August and the first for 30 per cent with a maximum in late January (Table 10-2). Similarly the distribution of the correlations for the circulation flux is dominated by the second harmonic with maxima a few days after those for the harmonic of the earth angular momentum flux correlations. Peak positive correlations on the first harmonics for the two fluxes are separated by one month. Results for both toroidal fluxes reflect the semi-annual cycle in the meridional component correlations with rainfall (Table 8-7). Seasonal cycles of the transient flux are dominated by the first harmonic (Table 5-1) but that of their correlation with rainfall by the third harmonic. Weak first and second harmonics have maxima in mid-February and late April/October respectively (Table 10-2). The phase of the latter harmonic is roughly inverse to that of the correlations between rainfall and the earth angular momentum flux.

STABILITY OF THE ANNUAL AND SEMI-ANNUAL CYCLES

Dates of the maxima on the first harmonics of the annual relative angular momentum distributions in individual July to June years vary between 15 and 25 August (Fig. 10-1) as compared to 15 August for the mean data (Table 5-1). In all years but one the first harmonic dominates the annual cycle of the relative angular momentum and thus the weak first harmonic of the correlations with rainfall (Table 10-2) is indicative of intra-annual adjustments in the response of the rainfall to changes in the atmospheric zonal circulation on higher frequencies than represented by the annual cycle. Second harmonics account for less than 10 per cent of the variance in five of the eight years but up to 31 per cent in the remaining three years. Phase angles of the harmonics tend to cluster

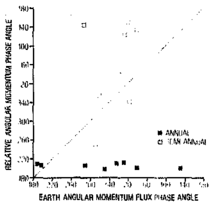


Figure 10-1. Phase angles of the annual (solid blocks) and semi-annual (open blocks) cycles of the vertically-integrated relative angular momentum (ordinate) and poleward flux of earth angular momentum (abscissa) for the July to June years from 1968/69 to 1976/77. The diagonal line marks the locus of equal phase angles. Phase angles of 360° indicate maxima on the first harmonic on 15 March and on the second harmonic on 1 February and 1 August.

such that rainfall season maxima are in either November or between 10 January and 10 February (Fig. 10-1). Cycles with maxima in these two periods are roughly anti-phase. Rainfall season maximum occur on 20 November in the 10-year data (Table 5-1). Large-amplitude semi-annual cycles in the zonal flow in individual years are consequently concealed in the overall results by the phase stability of the annual cycle and by the self-negation of the semi-annual cycles through phase reversals between years.

Phase angles of the first harmonics of the earth angular momentum fluxes are markedly variable from year to year (Fig. 10-1) although in five years maxima occur between 5 February and 5 May, maxima that probably account for the phase of the first harmonic of the correlations with rainfall (Table 10-2). Only in three years is the date of the maximum close to that of 15 October for the mean cycle (Table 5-1). Variances explained by the first harmonics range between 1 and 81 per cent. Phase angles of the second harmonics are quasi-stable with summer maxima varying between 10 January and 10 March, a slightly larger range than for the

200 mb meridional wind component (Fig. 8-4). Only four days separate the maxima of the integral data and of the correlations with rainfall on the second harmonics (Tables 5-1 and 10-2). Between 3 and 55 per cent of the variances is captured by the second harmonics indicating that the dominance of the harmonic in the integral cycle results from the phase stability of the second as compared to of the first harmonics rather than from uniformly large amplitudes of the former harmonics. Amplitudes of the second harmonics increase in the wetter years such that there is an accompanying anomalous poleward flux in the summer months and an anomalous equatorward flux in the vernal transitional months. Phase angles of the first harmonics of the transiant fluxes remain quasi-stable with dates of maxima ranging between 5 June and 15 August. The weak first harmonic of the correlations indicates therefore that links between rainfall and the transient flux are modulated on higher frequencies that of the annual cycle. Rainfall season maxima of the second harmonics generally occur in the vernal transitional months between 10 October and 20 December. Only in two years do maxima fall in the summer months.

Important modulations of all of the relative angular momentum of the atmosphere and of the various components of the meridional fluxes occur on annual and semi-annual cycles. Circulation modifications deduced above do not necessarily affect the circulations of the rain and no rain days uniformly (see Appendix J). In particular changes to the toroidal circulation on rain days as rainfall varies are modulated on the semi-annual in addition to on the annual cycle. Amplitudes of the second harmonics of the earth angular momentum fluxes increase in the wetter years. Changes to the mean meridional flow on the semi-annual cycle are therefore confirmed as an important determinant of rainfall variations over the central interior of South Africa.

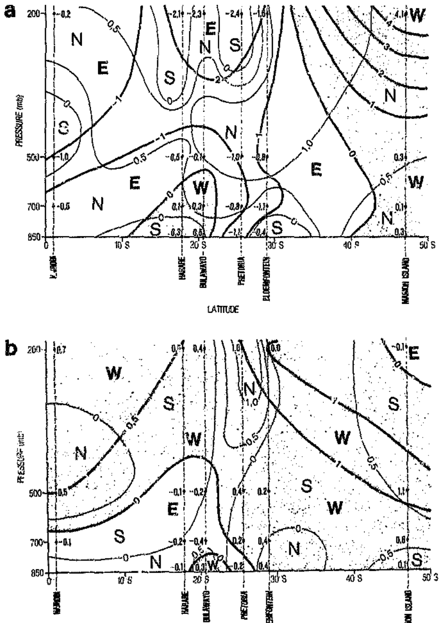
THE MOMENTUM BUDGET AND THE SOUTHERN OSCILLATION

The Hadley Circulation is intensified in periods of enhanced cumulus friction (Helfand, 1979) and tropical heat release (Schneider, 1984). Thus in terms of the modulations of the Hadley Circulation on the semi-annual cycle convection over tropical Africa at 20°S increases in the wetter summer months but decreases in the wetter vernal transitional seasons. Correlations between southern African rainfall and the Southern Oscillation index are also modulated on a semi-annual cycle such that associations are stronger in the summer than in the vernal transitional season (Table 9-4 and Lindesay, 1986). Cross sections of the zonal and meridional components along 30°E for the high and low phases of the So. .nern Oscillation in these two seasons have been prepared by Lindesay (1986). Seasons falling into the two phases have been identified as those with values of the Southern Oscillation index in the upper and lower quartiles across the period 1935 to 1984. These cross sections may be used to determine whether flow changes between phases of the Oscillation are cons[illegible] [illegible]th the changes between above- and below-normal rainfall period[illegible] [illegible]thern African regio[illegible] derived above and in Chapter 8 and wi[illegible] [illegible]ept of increased and reduced instability at 20°S in wetter summe[illegible] [illegible]nd vernal transitional seasons respectively.

Summer season

Zonal flow anomalies at Bloemfontein in summer are easterly in the high phase and westerly in the low phase (Fig. 10-2), anomalies consistent with those associated with increased and reduced rainfall respectively (Tables 8-6 and 10-1). Except in the boundary zone high phase meridional flow anomalies are poleward as occurs in the wetter months of February and March (Table 8-7). In the low phase those anomalies reverse except around 200 mb. Flow anomalies in the high and low phases thus correspond closely with those associated with increased or reduced rainfall over the western Orange Free State. Equivalently the anomalies are consistent with an increased frequency of tropical-temperate troughs in the wetter seasons, the only system for which the rainfall is correlated with the Southern Oscillation index at zero lag (Table 9-4).

High phase easterly anomalies extend southward from the Equator to beyond 30°S except in a region of the lower atmosphere around 20°S (Fig. 10-2a) and consequently there is an enhanced flux across Africa of moisture from the Indian Ocean. Conditions are thus suitable for the development of deep convection along the *Inter-Tropical Convergence* Zone with attendant *release of latent heat*, of lows at around 20°S, of



standing waves forced by the heat release and of tropical-temperate troughs across South Africa. Of the three types of instabilities possibly associated with the development of extensive convection at 20°S, namely barotropic instability, instability of the internal jet and instabilities related to the easterly flow at 200 mb, only two appear to be of importance. The low-level westerly anomaly indicates that the strength of the easterly jet at 20°S declines in wetter periods, a result consistent with that for North Africa obtained by Newell and Kidson (1984). The jet is unlikely to be of importance therefore in controlling the stability of the flow. The juxtaposition of easterly anomalies to the south of 20°S and of westerly anomalies to the north indicates that barotropic instability is increased in the 20 to 25°S zone in the wetter periods. At 200 mb and 20°S the easterly flow also intensifies in the high phase. Barotropic instability, rather than the instability associated with the low-level jet, and intensifications of the easterly 200 mb flow, therefore, represent mechanisms associated with the development of convection over southern tropical Africa.

The anomalous flux of westerly momentum generated through surface stresses is into the atmosphere everywhere north of 40°S except in a region between about 12 and 22°S. Momentum generated at around 20°S is lifted into the upper atmosphere in the convection over the subcontinent. Together with heat released in the convection the cumulus friction drives the intensified Hadley Circulation across southern Africa. The enhanced poleward energy flux is marked by the increased temperatur[illegible] and heights in the barotropic zone (Tables 8-1 and 8-2) while the tropi[illegible]

Figure 10-2 (opposite). Composite zonal and meridional flow anomalies along the 30°E meridian for the a) high and b) low phases of the Southern Oscillation for the 1957 to 1983 summer seasons adapted from Lindesay (1986). Heavy and light lines delineate isopleths of constant zonal and meridional flow anomalies respectively (units are ms^{-1}). Figures vertically above stations indicate zonal flow anomalies. Regions of westerly anomalies are stippled and identified by a 'W'. Regions of easterly, northerly and southerly flow anomalies are similarly identified by 'E', 'N' and 'S' respectively.

nature of the circulation adjustments over the central interior of South Africa is indicated by the three-layer temperature correlation structure of the summer months (Table 8-1) characteristic of tropical rainfall systems and of the tropical-temperate troughs (Harangozo, 1986). On dry days the temperature stratification is the reverse of that of the tropical-temperate troughs. In the low phase circulation anomalies reverse, stability at 20°S increases and hence the toroidal circulation anomaly is of the sense of the Ferrel Cell (Fig. 10-2b). In most respects, therefore, circulation changes between the high and low phases of the Southern Oscillation in the summer season are consistent with those observed during above- and below-normal rainfall periods over the western Orange Free State respectively. These results support the postulate that the Southern Oscillation represents a remote control on circulation variations over the southern African region.

The vernal transitional season

Circulation changes along the 30°E meridian between the high and low phases in the vernal transitional season are less consistent with corresponding results in Tables 8-6 and 8-7 than are summer season changes. High phase zonal anomalies at Bloemfontein are westerly above 700 mb, anomalies consistent with those in wetter months of November and December (Fig. 10-3a). Meridional anomalies are poleward throughout the troposphere in Figure 10-3a whereas equatorward anomalies occur in wetter vernal transitional seasons (Table 8-7). Low phase zonal and meridional anomalies are both generally of similar signs to high phase anomalies (Fig. 10-3b) The most marked differences in the circulation between the two phases occur in the upper-tropospheric zonal flow south of 10°S and in meridional flow north of 20°S and in the lower troposphere south of 20°S. Changes in other locations do not exhibit consistent reversals as do those in the summer season. Direct stratification of the circulation data by the phase of the Southern Oscillation is thus less apposite in the vernal transitional than in the summer season. The

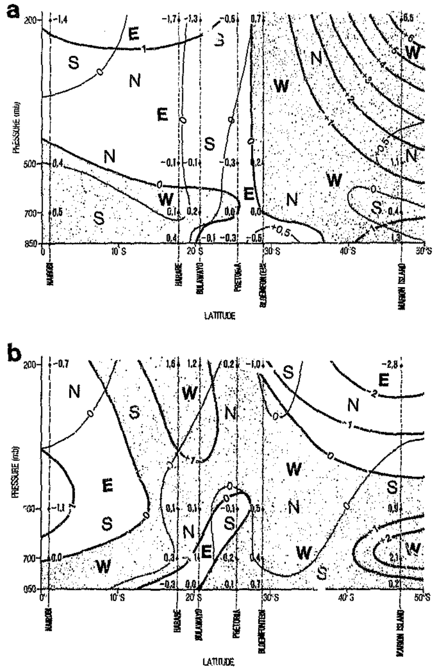


Figure 10-3. As Figure 10-2 but for the vernal transitional season.

control exerted by the Southern Oscillation on the circulation over southern Africa is weaker in the former than in the latter season.

SOUTH AFRICAN RAINFALL AND THE INDIAN OCEAN WALKER CIRCULATION

In order to test the supposition that the flow changes at 20°S depicted in Figures 10-2 and 10-3 are associated with reversals of the Indian Ocean Walker Circulation and with above- and below-normal rainfall respectively over the central interior of South Africa integral scores for tropical-temperate trough rainfall as used in Chapter 8 have been correlated with zonal components at Harare, Bulawayo and Cocos Island. Cocos Island is located in the equatorial Indian Ocean approximately 10°W of Djakarta and the station is thus well situated for the monitoring of the Walker Circulation over the ocean. Except in November and February signs of correlations between the Cocos Island 200 mb zonal component and rainfall from tropical-temperate troughs are opposed to those at 850 mb (Table 10-3), results indicative of the opposition of the flow anomalies in the lower and upper troposphere associated with the Walker Circulation. From December higher rainfall from tropical-temperate troughs is accompanied by strengthened 200 mb easterlies and, except perhaps in February, 850 mb westerlies. In October and November weaker 200 mb easterlies occur in the wetter months.

Magnitudes and signs of the correlations between the 200 mb winds and rainfall from tropical-temperate troughs are similar for data from both Harare and Bulawayo although the correlations tend to be stronger at Harare in the vernal transitional season and at Bulawayo in the summer season (Table 10-3). The correlations are in all cases negative from November. In October, as for Cocos Island, correlations for both Harare and Bulawayo components are positive. In general correlations with the 850 mb components at both Harare and Bulawayo are close to zero with both signs represented. Either station may lie within the region of low-level easterly or westerly anomalies depicted in Figures 10-2 and 10-3

Table 10-3. Values of Pearson correlations for the rainfall season months between integral western Orange Free State rainfall from tropical-temperate troughs and the zonal component at the 850, 700, 500 and 200 mb levels at Cocos Island, Harare and Bulawayo. All available data for the 1957 to 1977 period are used in the calculation of the correlations but the periods vary for the different stations - see Lindesay (1986). Positive correlations indicate strengthened westerly components at times of higher rainfall.

	OCT	NOV	DEC	JAN	FEB	MAR
Cocos Island						
200	0.14	0.13	-0.76***	-0.51*	-0.53*	-0.47
500	0.19	0.31	-0.48*	0.63**	-0.09	0.09
700	0.43	0.51*	0.40	0.77***	-0.04	0.30
850	-0.05	0.04	0.39	0.84***	-0.03	0.36
Harare						
200	0.32	-0.5[illegible]*	-0.58**	-0.52*	-0.31	-0.53*
500	0.67**	0.11	0.07	0.10	0.15	-0.40
700	0.78***	0.28	0.17	0.10	0.05	-0.67**
850	0.32	0.15	0.00	-0.53**	-0.08	-0.05
Bulawayo						
200	0.32	-0.06	-0.37	-0.43*	-0.71***	-0.42
500	0.29	0.44*	0.23	0.17	0.05	-0.14
700	0.53**	0.60**	0.20	0.58**	0.16	0.36
850	0.14	0.28	0.03	-0.05	-0.32	-0.29

and thus weakly-defined trends of zonal components with rainfall may occur. Regions with zonal component anomalies at 850 mb of opposite sign to those at 200 mb in both the high and low phases of the Southern Oscillation are, nevertheless, indicative of the extension of the Walker Circulation across tropical Africa to the 30°E meridian. The results in Table 10-3 and Figures 10-2 and 10-3 are therefore consistent with the concept of changes in the Walker Circulation forcing variations in convection over southern tropical Africa in the summer but not in the vernal transitional season. Differences in the relationship between the Southern Oscillation and southern African circulation changes in the two seasons are related to the semi-annual cycle of the tropical circulation. At Cocos Island strongest correlations occur in the December to March period in which correlations with rainfall from tropical-temperate troughs is strongest (Table 9-4). The 200 mb zonal component across the tropical Indian Ocean is anomalously westerly on the semi-annual cycle in the vernal transitional season (Fig. 4-[illegible]) and the control of the Walker Circulation on the circulation over tropical Africa is accordingly reduced. Magnitudes of correlations between the Southern Oscillation Index and South African rainfall consequently decline in the vernal transitional season (Lindesay, 1986).

Evidence has also been obtained for responses of rainfall over South Africa to perturbations in the Indian Ocean Walker Circulation on shorter time scales than represented in the preceding analyses. Locations of the heat release over the western Pacific Ocean are controlled to an important extent by the disposition of sea surface temperatures across the tropical Pacific Ocean but the amount and the timing of the release is dependent on other factors which may locally modify the structure of the atmosphere in the Indonesian region. Enhanced monsoonal convection occurs in conjunction with surges of cold air from the Asian continent across the South China Sea (Chang *et al.*, 1979; Chang and Lau, 1980, 1982; Lau *et al.*, 1983). Responses in the equatorial plane of the circulation to tropical heat sources take the form of eastward-propagating Kelvin waves and westward-propagating Rossby waves (Gill, 1980; Lau and Lim, 1982; Lim and Chang, 198[illegible]; Webster, 1983). Westward Rossby wave propagation excited by surges in the monsoon convection results in intensification of the Indian Ocean Walker Circulation as made manifest by an increase in the 200 mb easterly component across the ocean (Chang and Lau, 1982) and enhanced upper-level convergence above equatorial East Africa (Chang and Lau, 1980). The response time of the zonal flow across the western ocean to the surges is of the order of one to two days. Tropical-temperate troughs may form across South Africa in association with these intensifications of the Indian Ocean Walker Circulation. Results of a test of this supposition are given in Figure 10-4 in which the

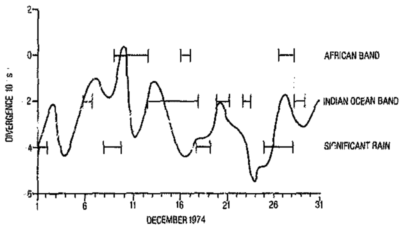


Figure 10-4. Time series of 200 mb divergence over east Africa (15°N to 15°S and 35°E to 55°E) for December 1974 after Chang and Lau (1980). Marked on the curve are periods with an African band, an Indian Ocean band and of significant rainfall as defined in Chapter 3 over the eastern Orange Free State. Periods of significant rainfall over the western Orange Free State are similar. Bands that shifted from Africa into the Indian Ocean are indicated by light dashed lines linking the appropriate marks.

divergence field over East Africa during December 1974 is illustrated. African bands are conjectured to form at times of upper-level divergence minima (i.e. convergence maxima) over East Africa in association with the strengthened easterly flow whereas, by inversion, Indian Ocean bands may be expected to form at times of divergence maxima. The first two African bands of the month developed at divergence minima but the third developed several days after a minimum and close to a maximum. Similarly the association between divergence maxima and the formation of Indian Ocean bands is clearer for the first two than for the final independent band. Also shown in Figure 10-4 are the periods of all days of significant rainfall over the eastern Orange Free State during the month. These periods all begin close to minima in the divergence field. These results may be tentatively accepted as providing further evidence of an association between the Indian Ocean Walker Circulation and rainfall from tropical-temperate troughs and as suggestive of a link between equatorial

Rossby wave propagation over the Indian Ocean and tropical-temperate trough formation across South Africa.

THE SOUTHERN OSCILLATION AND THE TEMPERATE CIRCULATION IN THE SOUTHERN AFRICAN REGION

Differences in the meridional momentum fluxes between the high and low phases of the Oscillation as across southern Africa occur in other regions of the globe. It has been suggested that enhanced tropical convection over the central Pacific Ocean in low phase periods and resultant increased poleward earth angular momentum fluxes result in a strengthened subtropical jet stream in the longitudes of the heat source (Bjerknes, 1966a, 1969). Observational evidence, however, does not fully support the postulate of increased toroidal fluxes in the Northern Hemisphere (Chiu and Lo, 1979; Chiu *et al.*, 1981). Stronger mid-latitude westerlies at Marion Island in the high phase (Fig. 10-2) are however consistent with the concept of strengthened winds resulting from the enhanced poleward earth angular momentum fluxes. The inverse relationship between westerly components at tropical and middle latitudes is well established (Trenberth, 1980b) and is consistent with the distribution of westerly components in Figure 10-2. Temperature gradients between the southern African subtropics and the middle latitudes weaken in high phase periods (Lindesay, 1986), a result attributed to enhanced poleward transient heat fluxes by van Loon and Rogers (1981). Most of the meridional energy transport in the Southern Hemisphere is achieved by the shorter moving waves as the standing waves are quasi-barotropic (van Loon and Jenne, 1972; van Loon *et al.*, 1973). The relationship between temperature gradients and the transient flux is indirect (Lorenz, 1979) and thus the reduced gradient is perhaps indicative of an intensified transient flux in high phase periods. Consequently the westerlies are displaced southward together with the tracks of temperate cyclones. Cyclone tracks were displaced southward in January 1974 (exceptionally wet over South Africa) by comparison to in January 1973 (generally dry over South Africa) (Harrison, 1981).

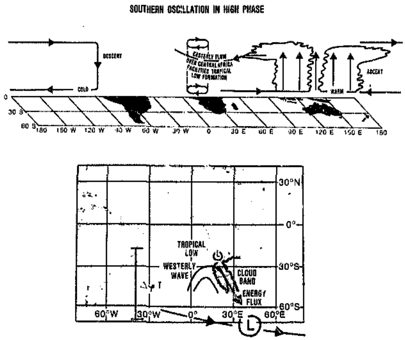


Figure 10-5. Schematic representation of a) the anomalous Walker Circulations of the tropical Pacific and Indian Oceans during the high phase of the Southern Oscillation and of b) the derived flow across South Africa resulting in above-normal rainfall.

A MODEL OF THE CONTROL ON SOUTH AFRICAN SUMMER RAINFALL BY THE SOUTHERN OSCILLATION

A model of the control on South African summer rainfall exerted by heat release in the Indonesian region and transmitted to southern Africa via the Indian Ocean Walker Circulation may now be proposed. During the high phase of the Oscillation sea surface temperatures are relatively warm in the Indonesian region and cold off the Peruvian coast (Fig. 10-5a). Extensive convection develops in the northern Australian region and heat release in the convection drives the Walker Circulations of opposing senses across the Pacific and Indian Oceans. The upper tropospheric flow over southern tropical Africa at 20°S is anomalously easterly and thus conditions are suitable for the development of convection and hence

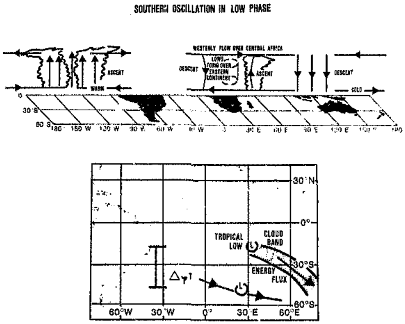


Figure 10-6. As Figure 10-5 but for the low phase of the Southern Oscillation resulting in below-normal rainfall.

of heat release (Fig. 10-5b). Cloud bands forming along suitably-located westerly waves bring rainfall to the summer rainfall region of South Africa and mark channels of momentum and energy efflux from the tropics by the mean meridional circulation. Temperature gradients decrease and cyclone tracks are displaced south. Alternatively during the low phase there is a marked change in the zonal gradient of sea surface temperatures across the equatorial Pacific Ocean with warm water off the Peruvian coast (Fig. 10-6a). Sea surface temperatures in the Indonesian region may not necessarily decrease but the major heat source migrates toward the date line and descent occurs over Indonesia. The Walker Circulations over the Indian and western Pacific Oceans reverse with consequent westerly anomalies at 200 mb across tropical Africa. As observed by Harangozo and Harrison (1983) the tropical lows over southern Africa migrate northward and eastward towards the Indian Ocean. Tropical-temperate troughs then tend to form in the Madagascar region

(Fig. 10-6b) and below normal rainfall affects the central interior of South Africa.

PROSPECTS FOR LONG-TERM RAINFALL FORECASTING OVER SOUTH AFRICA

One of the motivations for undertaking the work described in this thesis was to develop an improved understanding of the underlying mechanisms of the circulation vacillations responsible for the rainfall variations across southern Africa with the ultimate objective of developing long-range rainfall forecasting techniques for the region. The identification of the Southern Oscillation as representative of a major mode of the rainfall variations represents a potentially valuable step towards this objective. In a review of the status of long-range prediction techniques Nicholls (1980) discussed various methods including the use of persistence of anomalies, of extrapolation of the cyclic portions of climate time series and of numerical modelling but concluded that the most viable methods presently available are based on teleconnections with low-frequency variations of sea surface temperatures. Use of teleconnections with features of the circulation other than sea surface temperatures but related to them is not new having formed the basis of Walker's (1923) attempts to predict Indian monsoon rainfall. Reviews of early attempts to extend and improve the techniques of monsoon rainfall prediction, and to apply them to the rainfall of other regions, have been supplied by Namias (1968) and Ramage (1971) while updated syntheses have been provided by Barnett and Somerville (1983) and Namias (1985). Attempts to foreshadow rainfall using the Southern Oscillation and/or sea surface temperatures either in the tropical Pacific or other oceans include those for the eastern equatorial Pacific islands (Quinn and Burt, 1970, 1972), for the Peruvian coast (Quinn, 1974), for Indonesia (Nicholls, 1981), for north-east Brazil (Hastenrath *et al.*, 1984), for the United States of America (Lanzante and Harnack, 1982; Kung and Tanaka, 1985) and for the region of the Asian summer monsoon (Khandekar, 1979; Kung and Sharif, 1982; Nicholls, 1983; Shukla and Paolino, 1983). Preliminary attempts to forecast rainfall over South Africa using techniques developed on the basis of the links between the rainfall and the Southern Oscillation have provided an encouraging start to attempts to employ teleconnections in long-range prediction over the subcontinent (Harrison *et al.*, 1985). Recognition of a mechanism by which the Southern Oscillation signal is transmitted to southern Africa provides confidence that models for long-range prediction based on links with the Southern Oscillation may be formulated on physically-sound foundations.

CONCLUSIONS

Signs of systematic tendencies of poleward momentum fluxes as rainfall increases vary through the year. Poleward transient fluxes decrease as rainfall increases in eight months whereas earth angular momentum fluxes are directly related to rainfall in seven months. The annual cycle of the transient fluxes and the semi-annual cycle of the toroidal fluxes are of quasi-stable phase between years. The amplitude of the latter cycle increases with the rainfall such that in the wetter high seasons there is an anomalous poleward flux and in the wetter transitional seasons an anomalous equatorward flux. Increased poleward earth angular momentum fluxes in the wetter summer months result from stronger forcing of the Hadley Circulation across southern Africa by cumulus friction and energy release in the vicinity of 20°S over tropical Africa. Forcing of the Hadley Circulation declines in the wetter vernal transitional seasons.

Summer zonal and meridional component anomalies along the 30°E meridian in the high and low phases of the Southern Oscillation are consistent with anomalies over the central interior of South Africa in wetter and drier seasons respectively. High phase 200 mb easterly components at 20°S are indicative of increased tropical convection. Barotropic instability also appears to increase. The easterly anomaly extends across the Indian Ocean as part of the Walker Circulatio· ·-·ed by heat release in the Indonesian region. Anomalies and ·' Ocean Walker Circulation reverse in the low phase. Differ. sense of the Indian Ocean Walker Circulation caused by changes mount and location of heat release over the western tropical Pacific Ocean therefore influence the extent of the convection over tropical Africa and hence the toroidal circulation and rainfall over South Africa. Vernal transitional season anomalies are not consistent in similar manner to summer season anomalies with flow changes between wet and dry periods over the central interior of South Africa. The Indian Ocean Walker Circulation is a weaker link between circulation variations over southern Africa and over the Pacific Ocean than in the summer season.

Circulation changes associated with the Southern Oscillation are the first recognised control on southern African rainfall variations for which the sequence of cause and effect has been defined. Statistically only a fraction of the variance of the circulation and rainfall variations may be explained through the Southern Oscillation index and then only in part of the rainfall season. Physically a model has been developed in which rainfall variations are associated with changes in the distribution of sea surface temperatures over an ocean on the opposite side of the Hemisphere to southern Africa. It is perhaps remarkable that values of the correlations are as high as they are. The model provides an incentive for the exploration of associations between rainfall over southern Africa and sea surface temperature over the remaining two southern oceans. Part of the unexplained rainfall variance may reside in these associations. Recognition of mechanisms through which sea surface temperature anomalies are translated to rainfall anomalies are a desirable but not an essential step prior to the incorporation of statistical associations between the anomalies into long-range rainfall prediction models for the subcontinent.

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CHAPTER 11

CONCLUSIONS

Models of global-scale circulation controls on the annual rainfall cycle and on the inter-annual rainfall variations over the central interior of South Africa have been developed. Prime components of the controls are intra-annual and inter-annual changes in the generation of energy and momentum over southern tropical Africa. Rainfall over the central interior of South Africa is typically associated with a toroidal circulation of the sense of the Hadley Cell forced by tropical energy and momentum generation. Maximum forcing of the Hadley Circulation, and hence maximum rainfall, occurs in January when the region of tropical energy release in the Inter-Tropical Convergence Zone is furthest south. Periods of above-average energy release along the Inter-Tropical Convergence Zone are periods of higher rainfall. Further important components of the controls are inter-seasonal circulation changes on a semi-annual cycle. *Outgoing long-wave radiation budgets of the three regions of energy* release over the tropical continents are all modulated on semi-annual cycles. Maximum energy release over Africa on the semi-annual cycle occurs at the time of maximum rainfall. Circulation variations over the equatorial Pacific Ocean related to the Southern Oscillation are an important remote control on energy release over tropical Africa. The signal from the Pacific Ocean is transmitted to Africa, in part, via the Walker Circulation across the tropical Indian Ocean. Control on African energy release is strongest in summer as a result of circulation changes on the semi-annual cycle. Changes of the circulation in the Southern Hemisphere on the annual and semi-annual cycles therefore contribute towards the determination of both the intra-annual and the inter-annual temporal rainfall distributions over the central interior of South Africa.

Specific conclusions may be listed as follows:

A. Properties of rain-bearing systems over the central interior of South Africa

1. Eight major types of synoptic systems supply rainfall to the central interiorof South Africa. Tropical-temperate troughs are marked in satellite images by cloud bands linking the tropical cloud masses at a tropical low along the leading edge of a westerly wave to a temperate cyclone in the southern Indian Ocean. Truncated troughs are similar to tropical-temperate troughs except that the cloud band terminates at a coastal depression. West coast troughs are systems for which the cloud band terminates at a cyclone on the west coast of the subcontinent. Subtropical cyclones are cyclonic vortices embedded in the tropical easterly flow. Tropical cyclones and depressions mainly affect the east coast regions. East coast troughs are overland extensions of frontal systems. Coastal depressions are cyclonic vortices forming ahead of cold fronts which on occasion influence inland regions. Cut-off lows are independent cyclonic vortices embedded in the temperate westerly flow. The first five types are referred to as tropical systems and the remainder as temperate systems.

2. Tropical-temperate troughs account for about 35 per cent of the rainfall over the central interior of South Africa and for about 60 per cent in January. Tropical-temperate, truncated and west coast troughs account for 50 per cent of the rainfall and 90 per cent in January. No single type of system other than the tropical-temperate troughs provides more than 17 per cent of the mean annual rainfall.

3. Rainfall from tropical systems, and in particular from tropical-temperate troughs, primarily accounts for the amplitude and the phase of the annual rainfall cycle over the western Orange Free State. Rainfall from the tropical-temperate troughs decreases in

December relative to in November and January and causes the rainfall hiatus of December.

4. The apparent semi-annual cycle in rainfall detected in earlier studies is a consequence of the mathematical techniques applied to temporally non-symmetrically-distributed data. Rainfall from several of the temperate systems is distributed according to well-defined semi-annual cycles. These semi-annual cycles are in-phase with the semi-annual cycle of the circulation at temperate latitudes of the Southern Hemisphere.

5. Rainfall departures in the January to March summer season are determined primarily by variations in rainfall from tropical-temperate troughs. In the October to December vernal transitional season variations from several types of systems, both tropical and temperate, determine departures.

B. Properties of the circulation over the central interior of South Africa

1. Three zones of the atmosphere, each withindividual properties, are present. In the boundary zone (surface to 700 mb) the mean flow is ageostrophic and the thermodynamic structure baroclinic. In the barotropic zone (700 to 300 mb) the mean flow is geostrophic and the thermodynamic structure quasi-barotropic. Geostrophic flow is also present in the baroclinic jet-stream zone (300 to 100 mb).

2. The annual cycles of temperature and pressure are determined by the cycle of insolation and are typical of continental atmospheres. Equivalent cycles elsewhere over South Africa are determined to varying degrees by interactions with the oceanic atmosphere. Resultant changes in the zonal geopotential gradient across South Africa at 30°S are modulated on a semi-annual cycle. Barotropic and jet-stream zone meridional winds are modulated on the semi-annual cycle with strongest poleward components in February and August.

The zonal flow is modulated on the annual cycle of the meridional *geopotential gradient*.

3. The sense of the toroidal circulation across the central interior of South Africa varies with the seasons. In the transitional seasons (the vernal transitional season is centred on November and the autumnal transitional season on May) the sense of the circulation is that of the Ferrel Cell with poleward flow below and equatorward flow above 500 mb. In the high seasons (summer centred on February and winter on August) the sense is that of the Hadley Cell although the flow is poleward at all levels. Dynamics of the toroidal circulation therefore vary between the high and transitional seasons. Baroclinicity is stronger in the transitional than in the high seasons.

4. *At 200 mb the temperature is modulated on a semi-annual cycle.* Phase consistencies between the temperature and meridional component semi-annual cycles provide evidence for the presence of the subtropical jet-stream throughout the year, the latitude of which is modulated on the semi-annual cycle. In February and August the jet lies to the south of Bloemfontein.

5. At Gough Island the semi-annual cycle of the meridional flow is anti-phase to that at Bloemfontein, implying that a standing wave lies over the subtropical South Atlantic Ocean and that its longitudinal location is modulated on a semi-annual cycle. The wave lies further west in the high seasons.

6. *In the boundary zone temperature decreases, specific humidity increases* and easterly components strengthen in wetter months throughout the year. Pressure decreases only in the second half of the year and poleward components intensify only in eight months as rainfall increases. In the barotropic zone signs of circulation anomalies in wetter months are seasonally dependent. Increased temperatures, geopotential heights, specific humidities and poleward components occur in the wetter high season months.

7. As rainfall increases so amplitudes of the first harmonics of most thermodynamic parameters and of the meridional component tend to

decrease while those of the second harmonics increase. The phase of the second harmonic of the meridional component remains quasi-stable in all years. In the barotropic and jet-stream zones the poleward flow (i.e. the Hadley-type circulation) intensifies in the wetter high seasons. The equatorward flow (i.e. the Ferrel-type circulation) is stronger in the wetter vernal transitional seasons. Increased longitudinal displacements of the Atlantic standing wave in the wetter months account in part for the changes in the meridional circulation.

8. Close phase coherence is present in individual years between the temperature and the meridional component on the semi-annual but not on the annual cycles indicating that the two are related by advection on the former though not on the latter cycle. Changes in the structure of the atmosphere are such that as rainfall increases so both the static and the thermodynamic stabilities of the atmosphere decrease in most rainfall season months.

9. Mean kinematic structures of the atmosphere on rain and no rain days vary systematically with rainfall in similar manners to the overall structure of the atmosphere. Circulation changes between wet and dry periods do not result, therefore, simply from frequency changes of rain and no rain days but also from structural changes on all days. Thus in summer the Hadley Circulation is intensified on a daily basis in the wetter months.

C. Properties of the relative angular momentum and of the meridional momentum flux across the central interior of South Africa

1. The earth angular momentum flux is poleward in all months apart from May and ismodulated on a semi-annual cycle with peak poleward fluxes in the high seasons. The circulation flux is modulated on a semi-annual cycle with poleward fluxes in the high seasons and equatorward fluxes in the transitional seasons. The magnitude of the circulation flux is comparable with that of the transient flux.

The transient flux remains poleward throughout the year and is modulated on an annual cycle with a maximum flux in winter.

2. The earth angular momentum flux on rain days is always poleward in the mean and is modulated on an annual cycle with maximum transport in summer. The no rain earth angular momentum flux is equatorward except in winter and is modulated on a semi-annual cycle. Transient fluxes on both types of days are poleward throughout the year (except in August and December on rain days) with that on no rain days modulated on an annual cycle and that on rain days on both an annual and a semi-annual cycle. This latter semi-annual cycle is anti-phase to that of the toroidal fluxes and of an amplitude such that in the transitional seasons the poleward transient flux on rain days is counterbalanced by the equatorward circulation flux on no rain days.

3. In excess of 50 per cent of the poleward earth angular momentum flux is carried in the vicinity of tropical-temperate t[illegible]hs in the rainfall season months. The bulk of the transport [illegible]nsient flux on rain days is carried on the tropical-temperate [illegible]n the transitional seasons. No system dominates the trans[illegible] in the summer months.

4. Westerly components are stronger on rain than on no rain days, a feature associated with the marked tilt of westerly troughs over southern Africa. Rainfall is therefore associated with generation or convergence of momentum to the north of the troughs.

5. The relative angular momentum is not modulated on a large-amplitude semi-annual cycle despite the presence of the cycle in the Coriolis torque. The cycle of generation by the Coriolis torque is probably negated by an anti-phase cycle in the latitudinal transient flux convergence.

6. Several other components of the momentum budget undergo semi-annual cycles. These include the mountain torque, with maximum transfer of westerly momentum to the atmosphere in the high seasons, and, possibly, the vertical transports by the mean flow and

by the transients. That by the mean flow is anomalously upward in the high seasons whereas the phase is reversed for the transients. Surface stresses in the African region undergo semi-annual cycles in phase with the cycle of the toroidal flux.

7. Generation of momentum through surface stresses transported poleward across the central interior of South Africa by the mean flow on rain days takes place across Africa in the vicinity of 20°S and destruction across the oceans at 50°S. Surface stresses over tropical South America account for generation of some of the westerly momentum transported equatorward across Bloemfontein on dry days. The semi-annual cycle in the latter flux derives from the cycle in the longitudinal location of the Atlantic wave and possibly from an equivalent cycle in the generation of momentum over the Amazon Basin. Adjustments in the wavelengths of the troughs over the subcontinent following the longitudinal movements of the wave account for the existence and the phase of the semi-annual cycle of the transient flux on rain days.

8. The amplitudes of the second harmonics of the toroidal fluxes increase in the wetter years. The fluxes are anomalously poleward in the high seasons and anomalously equatorward in the transitional seasons. Poleward transient fluxes are stronger in the wetter months of February, March, April and November.

9. Phase angles of the first harmonics of the relative angular momentum and of the transient flux are stable between years as are phase angles of the second harmonics of the toroidal fluxes. Only changes on the semi-annual cycle affect toroidal fluxes on rain days.

D. Determinants of the annual rainfall cycle and of rainfall variations

1. Tropical-temperate troughs form at times of interaction between the tropical and temperatecirculations and mark channels for the poleward export by the mean meridional circulation of momentum and energy

generated along the Inter-Tropical Convergence Zone. The troughs develop most frequently when the region of active tropical convection, the Inter-Tropical Convergence Zone, is furthest south in January. Momentum and energy generation over Africa in the vicinity of 20°S is a necessary condition for the formation of tropical-temperate troughs. Interaction between the Inter-Tropical Convergence Zone over North Africa and Southern Hemisphere westerly troughs is inhibited in winter by the presence of equatorial easterlies interceding between the systems. Hence tropical-temperate troughs rarely form in winter.

2. Higher rainfall in the summer season accompanies an intensified Hadley Circulation and enhanced momentum and energy generation over tropical southern Africa. Higher rainfall in the vernal transitional season accompanies an intensified Ferrel Circulation although the Hadley Circulation is intensified on rain days. Both enhanced momentum and energy generation over tropical southern Africa and increased impacts from the circulation of the standing wave over the Atlantic Ocean occur in the wetter months.

3. Rainfall over the central interior of southern Africa is normally nil or light when tropical-temperate troughs overlie Madagascar rather than the subcontinent. Patterns of directly inverted frequencies of troughs over South Africa and Madagascar occur only from November to January. Thus longitudinal displacements of the standing waves and hence of the tropical energy sources alone do not account for the rainfall variations.

4. The Southern Oscillation is a major mode of the inter-annual circulation variations forcing climate anomalies over South Africa. Rainfall from the tropical-temperate troughs alone is correlated with an index of the Southern Oscillation at zero lag.

5. One mechanism by which the Southern Oscillation signal is transmitted to southern Africa is via the Indian Ocean Walker Circulation. Increased rainfall in the Oscillation's high phase in summer results from enhanced heat release in the convection over tropical southern Africa caused by zonal circulation adjustments in the Walker Circulation and

hence from an above-normal frequency of tropical-temperate troughs across South Africa. In the low phase of the Oscillation the sense of the Indian Ocean Walker Circulation reverses and consequently fewer bands form across South Africa.

6. The association between the Southern Oscillation and South African rainfall is weaker in the vernal transitional than in the summer season. The sense of the anomalous Indian Ocean Walker Circulation in the vernal transitional high phase is opposed to that in summer. Thus the control on the African source from circulation changes over the Pacific Ocean is reduced by comparison to during the summer season and the Southern Oscillation is a weaker determinant of rainfall anomalies.

Water is a major component of and a link between the atmospheric, ecological and economic environments of southern Africa. Consequences of excesses or deficiencies of water to the ecology of the subcontinent and to the economies of the countries in the region are well appreciated so it is pertinent to note that the periodic floods and droughts are themselves results of changes in rainfall over other parts of the globe. Latent energy released by condensation of atmospheric water vapour is in part responsible for the forcing of the atmospheric circulation across the globe. Latent energy released over tropical Africa forces the Hadley Circulation across southern Africa which is associated with rainfall over the interior of South Africa. Latent energy released in the Indonesian region forces the Walker Circulation across the tropical Indian Ocean and in turn forces a circulation over tropical Africa suitable for the formation of extensive convection and for the release of latent energy. A decline in the rainfall and in the energy release in the Indonesian region leads to a consequent decline in energy release over tropical Africa and to drought over southern Africa. Rainfall over the central interior of South Africa is thus a result of a chain of interacting modes of the circulation across the Southern Hemisphere in which rainfall itself acts as a major link. The chain may not simply stop with rainfall over South Africa as further latent energy is released which may reinforce the existing circulation or force new modes to develop.

The global nature of the controls on South African rainfall requires that the causes of the rainfall variations be studied on appropriate spatial scales. The Southern Oscillation is only one large-scale mode of operation of the atmosphere, albeit a major one. It is important that other modes of operation be examined to determine their relationships to the circulation over southern Africa so that dynamics of the rainfall variations in the region may be fully absorbed in all respects into models of the global circulation. To date the atmosphere over southern Africa has received less detailed study than the atmospheres over the remaining continental regions of the Southern Hemisphere. Only through exhaustive examination of the circulation dynamics over the subcontinent may interactions between the local and the global circulations be defined so that local rainfall variations may be interpreted within the context of the general circulation of the atmosphere. Improved comprehension of the dynamics of the rainfall, in addition to the possible development of techniques for long-range prediction, would be the outcome of such a study and would represent an important contribution by meteorologists to the understanding and the utilisation of the environment of the southern African subtropics.

APPENDICES

APPENDIX A

PRINCIPAL COMPONENT AND HARMONIC ANALYSES

PRINCIPAL COMPONENT ANALYSIS

Only the calculation of principal components from the n by n correlation matrix, R, of an m by n data matrix, X, will be considered.

The eigenvalues (λ_i, $i = 1$ to n) of R are obtained from solutions to the characteristic equation

$$|R - \lambda_i I| = 0 \qquad \text{A-1}$$

where I is the n by n identity matrix.

The eigenvectors of R may then be obtained from solutions to the series of equations

$$(R - \lambda_i I)v_i = 0 \qquad i = 1 \text{ to } n \qquad \text{A-2}$$

where the v_i are the eigenvectors.

To obtain the principal components n linear combinations of the elements of R must be formed subject to the constraints of orthogonality, i.e.

$$s_{ij} = e_{i1}r_{1j} + e_{i2}r_{2j} + \ldots \qquad (i = 1 \text{ to } m,\ j = 1 \text{ to } n)$$

such that the first combination captures the maximum possible variance, the second the maximum possible of the remaining variance, etc.

or $$S = RE \tag{A-3}$$

where S is the m by n matrix of component scores and E is identical to the n by n matrix of eigenvectors, V.

The orthogonality constraint is

$$V^tV = I. \tag{A-4}$$

To calculate the variance captured by each component multiply both sides of A-3 by their transposes (denoted by a ^{t})

$$S^tS = E^tX^tXE \tag{A-5}$$

$$= V^tX^tXV.$$

Form a diagonal n by n matrix D of the eigenvalues from Equation A-1 then, after standardisation of the variables X, by definition

$$R = X^tX = VDV^t. \tag{A-6}$$

Substituting in A-5 from A-6

$$S^tS = V^t(VDV^t)V = D. \tag{A-7}$$

Hence the total variance of the components is equal to trace(D) and the percentage of the variance captured by component i is given by $(\lambda_i/\text{trace}(D))\times 100$.

To obtain the loadings (in the matrix L) we need to calculate the correlations between the scores and the original variables. For observation 1 of variable i the correlation is

$$l_{i1} = (d_1)^{\frac{1}{2}}v_{i1}$$

or $$L = VD^{\frac{1}{2}}$$

i.e. the loadings are obtained by scalar multiplication of the eigenvectors by the square roots of the eigenvalues.

HARMONIC (FOURIER) ANALYSIS

A stationary function, $f(t)$, in the range of t from $-\pi$ to π may be written as the sum of a series of sine and cosine functions of the form

$$f(t) = a_0/2 + \sum_k a_k \cos kt + \sum_k b_k \sin kt \qquad \text{A-8}$$

where k is the l'th of $n/2$ harmonics, a_0 is the amplitude of the zeroth harmonic (the mean) and a_k and b_k are the coefficients of the terms of the k harmonics.

Alternatively let

$$a_k = A_k \cos\phi_k$$

$$b_k = A_k \sin\phi_k.$$

Then

$$f(t) = a_0/2 + \sum_k A_k(\cos kt \cos\phi_k + \sin kt \sin\phi_k)$$

$$= a_0/2 + \sum_k A_k \cos(kt - \phi_k)$$

where $A_k = (a_k^2 + b_k^2)^{\frac{1}{2}}$ is the amplitude of the k'th harmonic and $\phi_k = \tan^{-1}(b_k/a_k)$ is the phase angle of the k'th harmonic.

To obtain the values of a_k muitiply A-8 by cosst and integrate from $-\pi$ to π.

Then

$$\int f(t)\cos st \, dt = (a_0/2)\int \cos st \, dt + \sum_k \int a_k \cos kt \cos st \, dt + \sum_k \int b_k \sin kt \cos st \, dt.$$

All terms in the third summation are zero for any k and s and in the second summation except for $k = s$ when the value of the integral is π. The first term is zero except when $s = 0$ when its value is $a_0\pi$. Hence

$$\int f(t)\cos st \, dt = a_k \pi$$

or

$$a_k = (\int f(t)\cos st \, dt)/\pi. \qquad \text{A-9}$$

The series $f(t)$ has n points in the interval $-\pi$ to π, hence for the k'th harmonic

$$s = 2\pi k/n.$$

Setting $\Delta t = 2\pi/n$ and writing A-9 as a finite summation

$$a_k = (2/n) \sum_n f(t)\cos(2\pi kt/n).$$

Similarly by multiplying by $\sin st$ we obtain

$$b_k = (2/n) \sum_n f(t)\sin(2\pi kt/n).$$

In all cases in the text of this thesis $n = 12$, hence $2\pi/n = 30°$.

The variance captured by each harmonic k is given by

$$A^2(k)/(\Sigma A^2(k)) \times 100$$

where the summation is from 1 to $n/2$.

APPENDIX B

HARMONIC ANALYSES OF THE STANDARD DEVIATIONS OF TEMPERATURE, PRESSURE, ZONAL AND MERIDIONAL COMPONENTS AT BLOEMFONTEIN

Thermodynamic parameters

Maxima on the first harmonics of the standard deviations of both temperatures and heights occur during the winter months (Figs. B-1a and c). For the heights the maxima occur in mid-July at most levels concurrently with minima of the temperatures and heights themselves (cf. Figs. 4-2a and c). Apart from in the lowest layers the maxima in temperature variances occur about 15 days earlier than those in heights. Continental controls on the geopotential height variances are indicated by the phases of the harmonics. In the stratosphere the phase reverses toward that of the pressure wave itself. Only in the vicinities of the 600 to 400 and 200 to 150 mb layers do the phase angles of the first harmonics of the standard deviations of temperature match that of the continental atmosphere. Apart from lesser deviations at around 300 and 100 mb the phase angles shift markedly from those of the temperature in the region of the surface to 600 mb levels, with the largest departure at the surface. Deviations on the annual thermodynamic wave have a mixed barotropic and baroclinic structure.

Throughout the layer 700 to 300 mb maxima in the height variances on the second harmonics (Fig. B-1d) occur synchronously with minima in the heights in mid-May/November (cf. Fig. 4-2d). Only near the surface and in the highest levels of the troposphere do the phases correspond. The second harmonic of the standard deviation of temperature explains a major portion of the variance in the lower troposphere and at 300 mb,

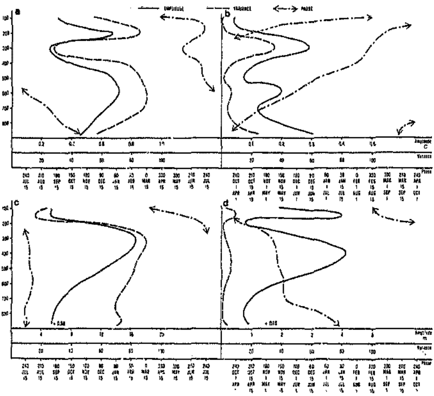

Figure B-1. Results of harmonic analyses of standard deviations of temperatures and geopotential heights at Bloemfontein: a) 1st. harmonic of standard deviation of temperature; b) 2nd. harmonic of standard deviation of temperature; c) 1st. harmonic of standard deviation of geopotential height; d) 2nd. harmonic of standard deviation of geopotential height. In c) and d) surface values refer to harmonics of the pressure itself using the amplitude abscissa scale in units of mb x 10^{-1}.

where it is dominant (Fig. B-1b). The phase angle of the harmonic changes constantly with height. It is similar to that of the second harmonic of the temperature only near the surface and in the vicinities of 300 and 150 mb (cf. Fig. 4-2b). It is out of phase with that of the height variations except around 600 and 100 mb. Thus while the annual and six-month thermodynamic waves and the disturbances on the annual wave have a quasi-barotropic structure in the upper-troposphere, the disturbances on the six-month wave are baroclinic throughout the layers between the surface and 100 mb.

Kinematic parameters

Amplitudes of first harmonics of the standard deviations of the zonal wind are approximately one-half of those of the wind itself at all levels to about 300 mb (Figs. B-2a and 4-5a). Above 700 mb the maximum variation in the zonal winds occurs about one month before the maximum wind speeds at the same time as the maximum variation of geopotential heights (Fig. B-1c). The first harmonic is dominant in the deviations of the zonal wind at all levels except 150 mb. Whereas the phase of the first harmonic of the meridional wind changes constantly with altitude (Fig. 4-5c) that of the first harmonic of the standard deviation of the meridional wind remains quasi-constant (Fig. B-2c). Largest amplitude atmospheric disturbances occur in mid-winter synchronously with maxima of the variances of the zonal components, temperatures and geopotential heights. Amplitudes at all levels are of similar magnitude to those of the zonal means (Newell *et al.*, 1974).

The second harmonics of monthly standard deviations of the zonal components explain more than 10 per cent of the variance only at 150 mb (Fig. B-2b), at which level they also explain their maximum variance in the zonal winds themselves (Fig. 4-5b). The phase of the harmonic of the deviations changes rapidly between the surface and 600 mb, above which level maxima occur in early June and December. Between 600 and 300 mb the peaks in the standard deviations occur up to two months after, but from 300 mb upwards within a few days of, the wind maxima. Amplitudes of the second harmonics of the standard deviations of the meridional winds (Fig. B-2d) are, in the levels around 200 mb, approximately double those for the zonal means (Newell *et al.*, 1974). The phase angles of the harmonics are variable except above 500 mb, where the peak dates shift from December to mid-November. Above 300 mb the peaks turbances on the six-month wave are baroclinic throughout the layers between the surface and 100 mb.

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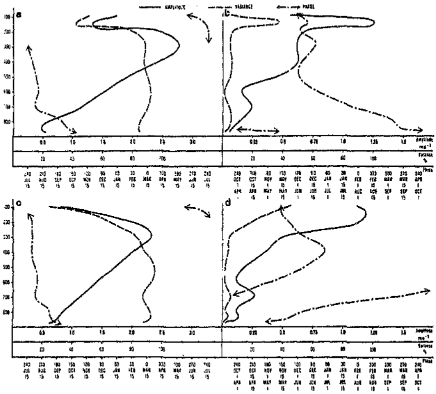

Figure B-2. As Figure B-1 but for: a) 1st. harmonic of standard deviation of zonal component; b) 2nd. harmonic of standard deviation of zonal component; c) 1st. harmonic of standard deviation of meridional component; d) 2nd. harmonic of standard deviation of meridional component.

occur about 15 days before the corresponding peaks on the standard deviation of the zonal winds (Fig. B-2b). Above 500 mb the second harmonic of the standard deviation of the meridional winds is closely anti-phase to the second harmonic of the meridional wind itself. Thus the maximum variation in the meridional wind occurs around the times of maximum equatorward flow at upper levels, i.e. at the time of the strongest Ferrel Circulation. Conversely the minima occur around the times when the mean flow throughout the troposphere is directed poleward. Maximum variability on the annual wave (Fig. B-2a) occurs with the winter peak poleward flow on the semi-annual cycle.

APPENDIX C

ATMOSPHERIC ZONES AT BLOEMFONTEIN

Based on the harmonic analysis results in Chapte.· 4 and Appendix B four zones of the atmosphere over Bloemfontein may be defined (Fig. C-1). In the *boundary zone*, which stretches from the surface to the 700 mb level, the annual temperature and pressure waves are anti-phase (Fig. C-2) and both reflect continental rather than oceanic controls. Thermodynamic processes in the zone are primarily baroclinic. Meridional winds in the boundary zone are always poleward in the mean with strongest poleward components in November. Mean meridional and zonal components are ageostrophic.

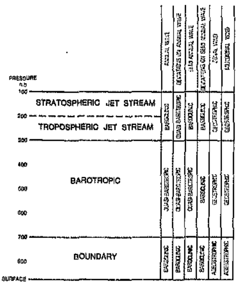

Figure C-1. Approximate limits of the major atmospheric zones over Bloemfontein and their major thermodynamic and kinematic properties.

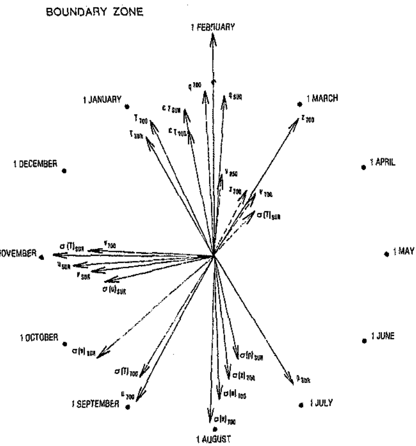

Figure C-2. Summary of the properties of the boundary zone: phases of the annual and semi-annual waves of temperature (T), surface pressure (p), geopotential height (z), specific humidity (q), total static energy (ε_T), zonal (u) and meridional wind speed (v) and appropriate standard deviations (σ). Subscripts denote the level of the data, either the surface (SUR) or a standard pressure level in mb; solid lines represent maxima on the first harmonics and dashed lines summer maxima on the second harmonics. Only harmonics explaining more than 10 per cent of the varlanc. are plotted. Note that lengths of the lines in no way reflect amplitudes of the harmonics.

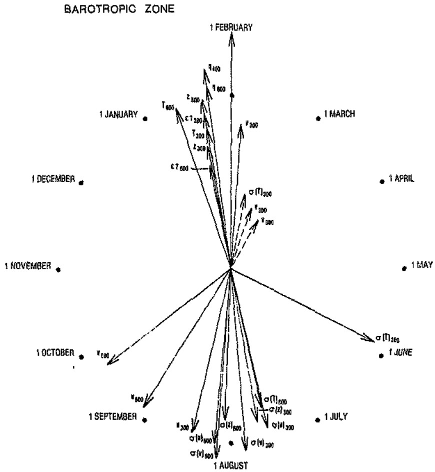

Figure C-3. As Figure C-2 but for the barotropic zone.

The *layers between* 700 *and* 300 *mb* may be referred to as the *barotropic zone* in view of the quasi-barotropic nature of both the annual and semi-annual thermodynamic waves in this region. First harmonics dominate cycles of all parameters apart from that of the meridional winds in which second harmonics are dominant (Fig. C-3). Both zonal and meridional winds are geostrophic above 700 mb. Continental controls on the thermodynamic cycle are present but the zonal winds are in phase with those of the hemisphere and do not reflect local continental controls.

JET STREAM ZONE

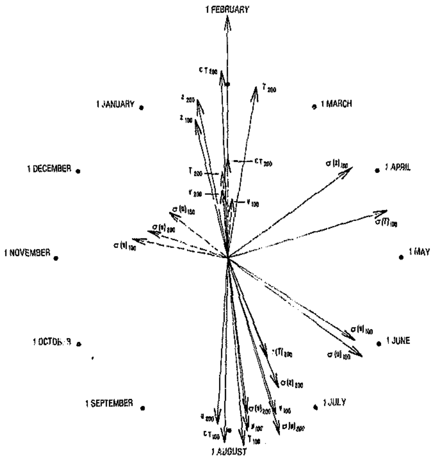

Figure C-4. As Figure C-2 but for the jet-stream zone.

The region above 300 mb, the *jet-stream zone,* may be split into two sub-regions - the *tropospheric jet-stream zone* below 200 mb and the *stratospheric jet-stream zone* between 200 and 100 mb. *Disturbances on* the second *harmonics throughout* and on the first harmonics of the thermodynamic wave in the stratospheric jet-stream zone are baroclinic. The second harmonics make important contributions to the cycles of several parameters with maxima at 200 (*temperature*) *or* 150 mb (*e.g.* deviations of the zonal wind) and are dominant for the meridional wind throughout the zone (Fig. C-4).

APPENDIX D

THE MERIDIONAL CIRCULATION AND THE SUBTROPICAL JET-STREAM OF THE SOUTHERN HEMISPHERE

MERIDIONAL WINDS OF THE SOUTHERN HEMISPHERE

Few studies of meridional components over the Southern Hemisphere have been attempted because of the difficulties of accurate measurement of winds over the oceanic regions. Using observational data obtained during the International Geophysical Year Obasi (1963b) calculated values of mean meridional wind speeds across the hemisphere at a number of levels but only for averages over six-month periods. On the basis of Obasi's data and periods Gilman (1965) estimated the zonal mean meridional velocity from hemispheric balance requirements. Both sets of calculations suggest that no change occurs in the direction of the 200 mb flow at 30°S between the summer and winter seasons. There appears to be a seasonal reversal of the meridional wind over the ocean at 30°S to the east of Africa according to the Eulerian analyses of Newell *et al.* (1972) in which averages were calculated across three-month seasons, but no similar reversal occurs at that latitude over Australia (Newell *et al.*, 1974). Evidence for a seasonal reversal in the zonal mean meridional wind directions was provided by Lagrangian data from the GHOST, EOLE and TWERLE constant-level balloon experiments (Solot and Angell, 1969, 1973; Angell, 1972, 1974; The TWERLE Team, 1977). In particular a six-month cycle in zonal-mean meridional winds at 200 mb and 30°S with a phase displaced by one month (maximum poleward flow in March) from that at Bloemfontein (Fig. 4-5d) is present in the GHOST data (Solot and Angell, 1969, 1973; Angell, 1972). An apparent reversal of the phase of the cycle between the 200 and 100 mb levels (Solot and Angell, 1973) is not repeated in the Bloemfontein data. The GHOST results may not be reliable, however, as a consequence of inaccuracies in the estimation of Eulerian quantities from Lagrangian data (Dyer, 1973; Webster and Curtin, 1974). New studies of the meridional winds in the Southern Hemisphere may become possible using results from the Australian numerical analyses (Trenberth, 1981) and from the FGGE data set (Bengtsson *et al.*, 1982) but it appears that the Bloemfontein data (Fig. 4-6), with the possible exception of the GHOST data, present the first conclusive evidence of a six-month oscillation in the meridional winds at any location in the Southern Hemisphere.

Harmonics of the 200 mb meridional components have been calculated at all stations in South Africa and Namibia (Fig. D-1). Second harmonics are dominant at Port Elizabeth, Cape Town and Pretoria in addition to at Bloemfontein. At Port Elizabeth the maximum on the harmonic corresponds to within 12 days of that at Bloemfontein, at Cape Town the summer peak is delayed slightly by comparison but at Pretoria it occurs somewhat earlier. The amplitude of the second harmonic is negligible at Windhoek and is relatively small at the coastal stations of Alexander Bay and Durban. Except at Windhoek all summer maxima occur in January or February. Dates of maxima on the first harmonics vary markedly between stations. Inspection of Figure 7.14 of Newell and Kidson (1979) (quantitative analysis is not possible for the published data) suggests that a semi-annual cycle in the 200 mb meridional flow may be present over the Indian Ocean at 30°S and 40°E but is probably absent over the Atlantic Ocean at 30°S and 0°E. Reversals of the meridional flow are primarily limited, therefore, to the central parts of the subcontinent with no, or at most a weak, counterpart over the surrounding subtropical oceanic regions. This fact may explain why the phenomenon has not been detected before and why the amplitude of the second harmonic of the standard deviations of the meridional wind at 200 mb is double that of the zonal mean (see Appendix B). Equivalent calculations for the 200 mb temperature reveal that the peak of the annual wave of temperature moves northward and eastward during the summer months while that of the semi-annual wave moves in the opposite direction (Fig. D-2). Further the annual cycle is stronger over the western parts and the semi-annual cycle over the eastern parts of the country, changes related to the varying continental and maritime influences. Only a few days separate the maxima of the second harmonics of the temperature and meridional components at all stations. Rather longer periods separate the maxima

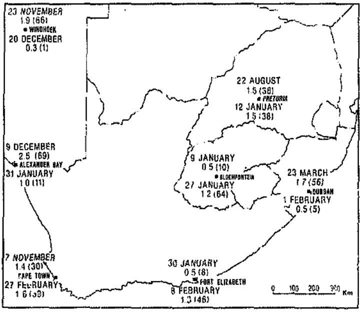

Figure D-1. Dates of (summer) poleward maxima of the annual (upper values) and semi-annual (lower values) 200 mb meridional component waves at South African and Namibian radiosonde stations. Figures give amplitudes of waves in ms^{-1} and, in brackets, explained variances.

of the first harmonics, particularly at the northern stations. Temperatures are related, therefore, to changes in advection resulting from reversals of the meridional component on the semi-annual but not on the annual cycle.

THE SUBTROPICAL JET-STREAM OF THE SOUTHERN HEMISPHERE

The half-yearly oscillations in zonal mean upper-tropospheric temperature at 30°S appear to be related to shifts in the mean latitude of the subtropical jet-stream (van Loon and Jenne, 1970b). Over Australia, where it is best developed and has been studied in detail (Weinert, 1968; Brook,

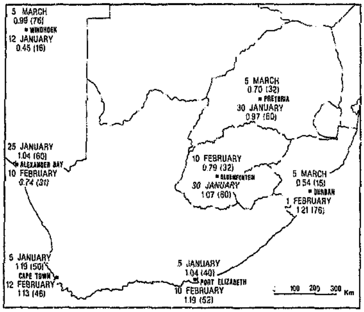

Figure D-2. As Figure D-1 but for 200 mb temperatures. Amplitudes in °C.

1982), the mean latitude of the jet undergoes a six-month oscillation with northerly extremes in May and November. No equivalent studies of the jet in the South African region have been undertaken. According to Taljaard (1981b) the jet does not appear in the mean monthly circulation fields even in the winter months, perhaps because it is either too weak or too variable in location. Nevertheless it is clearly defined at 25 to 30°S in winter meridional cross-sections at 20°E (Hofmeyr, 1961, 1970) and over the southern parts of the subcontinent in the 200 mb July geostrophic zonal wind field presented by van Loon *et al.* (1971). Under the assumption that the jet behaves similarly over South Africa to over Australia then, following Weinert (1968), it should be located in the mean to the north of Bloemfontein during May and November and to the south of the city in August and February. This postulate is consistent with the observed meridional winds (Fig. 4-6) and with the analyses of locations of the jet in the southern African region of Phillpot (1962). ...e of the zonal flow are at a higher level in the transitional months ... the meridional flow is equatorward than in the peak seasons when it is poleward (Katsiambirtas, 1979). Higher levels of the wind maximum also occur to the south of the jet over Australia (Fig. 6 of Brook, 1982). Latitudinal movements of the jet probably account for the variations in the level of the strongest zonal winds as reflected in the second harmonics of the zonal wind and of its deviations at 150 mb (Figs. 4-5b and B-2b), both of which reach maxima when the jet is to the north of Bloemfontein. No theory of the causes of the movements of the jet has been developed.

Directly equivalent reversals of the 200 mb meridional component to those at Bloemfontein also occur at Marion Island (Katsiambirtas, 1979). These reversals may be interpreted in terms of the location and strength of the jet near 45°S over the southern Indian Ocean (see charts of van Loon *et al.*, 1971) rather than of the subtropical jet itself. Marion Island lies close to the region of wind maximum in the jet (van Loon *et al.*, 1971). It may be inferred that there is a region between the southern coast of Africa and Marion Island over which the semi-annual cycle of the meridional component is anti-phase to that at Bloemfontein and Marion Island. The close phase correspondence of the harmonics at Bloemfontein and at Marion Island remains to be explained.

Positions of the subtropical jet stream speed maxima in both hemispheres are longitudinally collocated with regions of tropical convection (Bjerknes, 1966a, 1969; Krishnamurti *et al.*, 1973; Murakami and Unninayer, 1977; Paegle *et al.*, 1979; Paegle and Paegle, 1983). Peaks of the standing wave kinetic energy of the 200 mb flow occur to the south-east of the southern continents during the high seasons and modelling studies have indicated that these peaks may be related to the continental tropical heat sources (Paegle *et al.*, 1983; Nobre, 1983). The direct association between tropical convection and locations of jet stream wind maxima has been confirmed in the Northern Hemisphere (Riehl, 1981; Chang and Lum, 1985). Thus during the summer the jet moves south when tropical-temperate troughs are present over southern Africa in similar manner to the jet in the vicinity of the Pacific cloud band (Vincent, 1982). Similar behaviour of the Northern Hemisphere jet occurs (Riehl, 1981). Frequent reversals of the meridional flow accompanying varying weather conditions over the central interior of South Africa thus result in rapid fluctuations of the latitude of the jet which consequently does not appear in the mean summer and transitional seasons circulation fields of the South African sector of the Southern Hemisphere. The poleward earth angular momentum flux in winter is relatively consistent and thus the jet lies quasi-constantly to the south of Bloemfontein and appears in the mean circulation fields of that season (Hofmeyr, 1961, 1970; van Loon, 1972d).

APPENDIX E

CIRCULATION VARIATIONS ON SEMI-ANNUAL CYCLES

The six-month wave is an important feature of the atmospheric circulation of the Southern Hemisphere, both in the tropics (van Loon and Jenne, 1969) and in the middle and high latitudes (van Loon, 1967b). In southern tropical latitudes the westerly component of the 200 mb zonal wind reaches maxima in May and November at the times of the peak equatorward flow in the barotropic and jet-stream zones over Bloemfontein (Fig. E-1). Global variations of the relative angular momentum on the semi-annual cycle also reach *maxima* in May and November (Rosen and Salstein, 1985). Over Africa the six-month wave in the zonal winds is dominant at Luanda (van Loon and Jenne, 1969) and at Nairobi (van Loon and Jenne, 1970b). Variations of the zonal wind are consistent with adjustments in the tropical-subtropical temperature gradients. At Nairobi, *for example*, the six-month wave in the 200 mb temperature is anti-phase to that at Pretoria such that the temperature *gradient* between the two stations undergoes a six-month oscillation with Nairobi warmer than Pretoria in May and November and *vice versa* in February and August (van Loon and Jenne, 1969).

At around 45°S the phase of the second harmonic of the zonal wind is anti-phase to that in tropical latitudes, i.e. maximum westerlies occur in February and August, although at 200 mb the harmonic only accounts for 20 per cent of the variance (van Loon *et al.*, 1968). South of Africa the variance accounted for rises above 25 per cent (van Loon and Jenne, 1969). Calculations *for* Marion Island indicate that the second harmonic accounts for 20 per cent of the variance of the cycle of the 200 mb zonal winds with westerly maxima in February and August, in accordance with the second harmonic of the temperature gradient across 40 to 50°S (van Loon, 1967b; Streten, 1980). The first harmonic accounts for 25 per cent with a maximum in November. Seasonal variations of the 200 mb

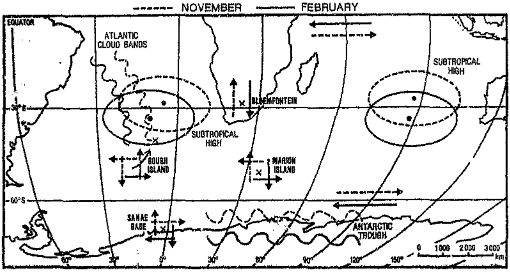

Figure E-1. Schematic illustration of some major surface and 200 mb features of the semi-annual cycle in the African sector of the Southern Hemisphere. Median locations are given for November (dashed) and February (full) of the: subtropical anticyclones from McGee and Hastenrath (1966); Atlantic cloud band between 30 and 40°S from Streten (1973); zonally-averaged sub-Antarctic trough from van Loon (1971a). 200 mb winds at Bloemfontein, Gough and Marion Islands and SANAE Base (marked with crosses) were taken from the present results while the tropical and polar zonal winds are based on van Loon et al. (1968). At polar latitudes the appropriate turning points fall in April and October rather than in February and August.

meridional component at Marion Island are dominated by the second harmonic (53 per cent of the variance) with a phase angle close to that of the wave in the meridional winds at Bloemfontein, a result that may not be interpreted in terms of contrasting oceanic and continental influences.

In the vicinity of the Antarctic continent the phase of the second harmonic of the 200 mb zonal mean wind (40 per cent of the variance) again reverses. Westerly maxima of the winds occur in April and October about one month prior to those in the tropics and are strongest during periods

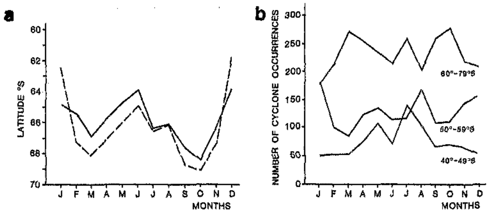

Figure E-2. a) Latitude of the zonally-averaged sub-Antarctic trough from van Loon (1971a) - solid line - and Streten (1980) - dashed line; b) frequencies of cyclones in three southern latitude belts during the period September 1973 to May 1975 from Howarth (1983).

when the sub-Antarctic trough, the latitude of which also undergoes a six-month cycle (Fig. E-2a), is furthest north (van Loon, 1967b, 1971a; Streten, 1980). Movements of the trough are quasi-coherent around the polar continent (van Loon and Rogers, 1984) but the trough is displaced some 2 to 4° north of its zonal mean latitude to the south of Africa and across the Indian Ocean, a consequence of the deeper equatorward extension of the Antarctic continent in that sector (Streten, 1980). At SANAE Base on the Antarctic coast a semi-annual cycle in the 200 mb meridional winds is present (19 per cent) with poleward maxima, synchronised with the wave in the polar zonal winds, in early January and July. During February and August, months in which the tropical meridional circulation is dominated by the winter Hadley Cells and the sub-Antarctic trough is to the south of its mean position, the flow over the eastern parts of southern Africa is anomalously anticyclonic at 200 mb (Fig. E-1). Inversely the flow is anomalously cyclonic in May and November when the Hadley Cells are uniformly distributed about the equator and the sub-Antarctic trough is displaced northward. Similarly the flow is anomalously anticyclonic over the South Atlantic Ocean in November and anomalously cyclonic in February.

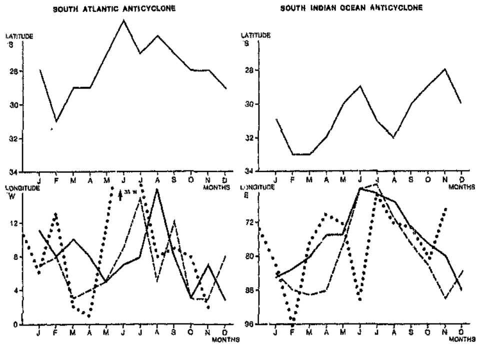

Figure E-3. , Latitudes and longitudes of the subtropical highs of the Atlantic and Indian Oceans from McGee and Hastenrath (1966) based on Vowinckel (1955b) - solid lines - Streten (1980) - dashed lines - and Streten and Pike (1980) for the FGGE year - dotted lines.

Locations of several features of the circulation in the vicinity of southern Africa undergo semi-annual cycles which are synchronised with those of the zonal and meridional winds. The Indian Ocean subtropical high lies furthest south while the South Atlantic subtropical high is furthest west in February and August (Fig. E-3) according to the analyses of McGee and Hastenrath (1966) based on data derived by Vowinckel (1955b) for the five-year period 1949 to 1953. Harmonic analyses of the locations of both cells reveals that the six-month cycle is dominant, accounting for 56 and 48 per cent of the variances respectively with maxima in February and August. A second harmonic in the latitudinal movements of the South Atlantic Anticyclone also occurs (10 per cent) with poleward displacements in March and September about one month prior to the maximum equatorward excursion of the sub-Antarctic trough. Similar longitudinal movements of the South Atlantic Anticyclone to those during the 1949 to 1953 period occurred during the five-year period 1972 to 1977 and during the FGGE year (Fig. E-3). The six-month cycle remained dominant but the anticyclone was closest to Africa in late April and October during the 1972 to 1977 period and in late March and September during the FGGE year. A marked semi-annual cycle was also present in the longitudinal movement of the Indian Ocean Anticyclone during the period 1972 to 1977 (23 per cent) such that the system was closest to Africa in early January and July. Six-month latitudinal and longitudinal oscillations of the subtropical anticyclones surrounding South Africa are present, therefore, during all years but changes in phase occur between years.

The cloud bands of the Atlantic Ocean and across Australia are furthest west in February and August (Streten, 1973). A semi-annual cycle in the longitudinal locations of the tropical-temperate troughs associated with cloud bands over southern Africa as for those over the South Atlantic and Australia may also occur. The existence of such a cycle is plausible in terms both of the semi-annual cycle in rainfall from tropical-temperate troughs over the western Orange Free State with a maximum in February (Fig. 3-5d) when the band may be displaced furthest westward and of the semi-annual cycle in the frequencies of troughs in the Madagascar region (Fig. 9-2).

At Gough Island the second harmonic dominates the seasonal variations of both the zonal (69 per cent) and meridional (44 per cent) components at 200 mb. Westerly maxima occur in early January and July and northerly maxima in mid-May and mid-November. The semi-annual cycle of the meridional wind at Gough Island is thus almost exactly *anti-phase* to that at Bloemfontein, a reversal suggestive of longitudinal modulations of a standing wave across the South Atlantic Ocean. These modulations are mirrored in the longitudinal displacements of the Atlantic cloud band. The wind is poleward when the median location of the cloud band is close to Gough Island and equatorward when the band is to the west (Fig. E-1). Gough Island receives more rainfall than most islands in the southern oceans as a result of its location close to the mean position of the Atlantic cloud band (Streten, 1977). No six-month cycle in the rainfall at the station is present with the second harmonic explaining less than one per cent of the variance. No wave occurs therefore in the frequency of frontal disturbances crossing the island. Harmonic analysis of the data of Howarth (1983) indicates that in the zone 40 to 49°S the monthly frequency of cyclones follows a prime annual cycle with a mid-winter peak at the time of maximum rainfall at Gough Island. Further south the frequency of cyclones undergoes six-month cycles consistent with the movement of the sub-Antarctic trough (Fig. E-2b). In the latitude belt 50 to 59°S cyclones are relatively infrequent in March and September when the trough is displaced southward (Fig. E-2a). Maxima of the second harmonic of cyclone frequencies, which explains 27 per cent of the variance, occur towards the end of June and December. Peak frequencies of cyclones in the belt 60 to 79°S occur in the same or adjacent months to the minima further north, the second harmonic accounting for 49 per cent of the variance with the phase closely anti-phase to that of the harmonic in the 50 to 59°S belt. Rainfall at stations in the South Atlantic Ocean and at Marion Island undergo consistent semi-annual cycles (van Loon, 1972a). Marked regional variations in the behaviour of the cyclones south of 50°S also occur (Howarth, 1983). In the South Atlantic Ocean the second harmonic explains 42 and 29 per cent of the variances of the mean central pressures and of the mean latitudes of the cyclones respectively with minimum pressures and southerly displacements in March and September. In the South Indian Ocean, where the sub-Antarctic trough is displaced further equatorward than at other latitudes, first harmonics dominate the annual cycles of both central pressures and latitudes (55 and 34 per cent respectively). Second harmonics, which explain 17 and 14 per cent of the respective variances, are in close phase coherence with those in the South Atlantic Ocean. Results conform with the fact that storm tracks in the South Indian Ocean are more clearly defined and subject to less seasonal latitudinal displacement than at any other longitude (Trenberth, 1982).

Proposed forcing mechanisms of the semi-annual cycles in the atmospheric circulation fall into two groups - those relating to atmospheric mechanisms only and those relating to atmosphere-ocean interactions. The double crossing of the rising branch of the Hadley Cell over the equator during the year has been suggested as the cause of the second harmonic in the temperature at the equator (van Loon and Jenne, 1970b; see also discussion in Newell *et al.*, 1974), the link being through seasonal variations in the release of latent heat (Dickinson, 1971). Maximum equatorial temperatures are achieved in May and November, the months in which the tropical meridional circulation is quasi-symmetric about the equator as opposed to being dominated by the winter Hadley Cell (Oort and Rasmusson, 1970). A parallel explanation for the semi-annual cycle of the tropical wind in terms of the opposition of the generation of westerly momentum through the Coriolis torque and the annihilation by the latitudinal eddy flux convergence, both of which are also modulated by the latitudinal movements of the Hadley Cells, has been given by Newell *et al.* (1969). Kinetic energy of the tropical circulation is strongly modulated on a semi-annual cycle (Rao, Bonatti and Santos, 1984) as is outgoing long-wave radiation over many tropical continental areas (Fig. 7-4) and surface insolation in the tropics (Reid and Gage, 1981). Changes in the tropical continental atmospheric heat budget may therefore account for the semi-annual cycle in the circulation and indicate that the semi-annual cycle is a derivative of the annual cycle. Support for this contention is given by the phase relationships between the annual and semi-annual cycles of the circulation over the central interior of South Africa. Turning points of the relative angular momentum on the annual cycle and of the earth angular momentum flux on the semi-annual cycle, for example, occur on the same days (Table 5-1).

Atmosphere-ocean interactions must nevertheless play an important role in the forcing of the circulation changes on the semi-annual cycle. Sea surface temperatures across all oceans are modulated in part on the semi-annual cycle (Panfilova, 1972; Weare *et al.*, 1976; Weare, 1977; Chiu and Newell, 1983) as is the rate of storage of heat in the ocean according to Reid and Gage (1981). Over the Pacific Ocean the strongest semi-annual cycle signal in sea surface temperatures occurs over the northern parts of the ocean (Weare *et al.*, 1976). At about 15°N, as a consequence of the double passage of the strongest north-easterly trade winds across that latitude (Wyrtki and Meyers, 1976), there is a semi-annual cycle in the surface easterly flow and in the surface stresses with maxima in June and December (Goldenberg and O'Brien, 1981). These phenomena are associated with resultant signals in the atmospheric circulation across the North Pacific Ocean (Lanzante, 1983, 1985). Various oceanographic and atmospheric circulation parameters in the equatorial Pacific Ocean including the equatorial surface easterly component (Meyers, 1979; Goldenberg and O'Brien, 1981; Busalacchi and O'Brien, 1981), the depth of the thermocline (Meyers *et al.*, 1982) and the height of sea level (Wyrtki and Leslie, 1980; Meyers, 1982) are modulated on a semi-annual cycle. According to Meyers (1982) the phases of the cycles of these parameters are inter-related and remain quasi-constant but amplitudes of the cycles vary in comparison to those of the corresponding annual cycles between years. Maximum amplitudes of the semi-annual cycles of sea level heights, in excess of those of the annual cycles, occur in high phase years of the Southern Oscillation. Alternatively the cycle of sea level heights is dominated by the annual cycle during years with an El Nino. It may be noted that the semi-annual cycle in the meridional flow is dominant across the central interior of South Africa in the wetter years but that the annual cycle is dominant in the drier, El Nino, years. The divergence of the equatorial zonal component on the semi-annual cycle in the Pacific Ocean is consistent, according to Meyers (1982), with the modulation of the convection in the Indonesian region as observed in the outgoing long-wave radiation field (Fig. 7-4) by Heddinghaus and Krueger (1981).

The atmospheric semi-annual cycle over the equatorial Indian Ocean is a monsoon signature of highest amplitude over the north-west of the ocean and decreasing amplitudes towards the south and the east (Ramage, 1974). As in the Pacific Ocean there are linked semi-annual cycles in several equatorial oceanographic and atmospheric parameters (Wyrtki, 1973; Quadfasel, 1982; McPhaden, 1982; Luyten and Roemmich, 1982; Hellerman and Rosenstein, 1983; Gent *et al.*, 1983). There are semi-annual cycles in several components of the heat budget over large areas of the northern Indian Ocean (Hastenrath and Lamb, 1979b). In part the cycles in the equatorial ocean are driven by the semi-annual cycle in the zonal winds across the ocean which at 700 mb at Dar es Salaam is of inverse phase to that at 200 mb at Cocos Island (van Loon and Jenne, 1970b). Maximum 200 mb Cocos Island easterlies occur in mid-February and mid-August (van Loon and Jenne, 1969). Thus there is a semi-annual cycle in the sense of the Indian Ocean Walker Circulation for which strongest easterlies occur with the minima in the outgoing long-wave radiation over both the Indonesian region and over Africa at 20°S (Fig. 7-4). Little is known of the semi-annual cycle in the circulation over the tropical Atlantic Ocean, should it exist. Semi-annual cycles in the heat budget of the ocean are present only over restricted regions (Hastenrath and Lamb, 1978).

At high latitudes seasonal variations in the oceanic heat budget have been proposed as the source of circulation changes on the semi-annual cycle (van Loon, 1967b). As in tropical latitudes the phase of the cycle remains quasi-stable as evidenced for the cycle of surface pressure (van Loon, 1972c) and surface zonal winds (van Loon and Rogers, 1984). It has been suggested that a link exists between the Southern Oscillation and the Southern Hemisphere temperate latitude semi-annual cycle (van Loon, 1983). Oceanic responses to the six-month cycles of the low-level winds in the Indian Ocean have been detected both at about 42°S, where the strength of the eastward current undergoes a semi-annual cycle with maxima lagging those of the winds by about three weeks (van Loon, 1971b).

APPENDIX F

SUMMARY OF THE HARMONIC ANALYSIS RESULTS

The following summarises the results of the harmonic analyses of rainfall in Chapter 3, of circulation parameters at Bloemfontein in Chapter 4 and of their standard deviations in Appendix B and of the meridional momentum fluxes in Chapter 5. There is a change in the period of the data base for the rainfall (1967 to 1977) and upper-air (1968 to 1977) analyses. Removal of the 1967 data from the rainfall set results in only minor changes to the results presented in Chapter 3 except for those for the east coast troughs for which the phase of the annual wave over the western Orange Free State shifts to a maximum in late January. Results presented below incorporate calculations for rainfall for the 1968 to 1977 period.

Rainfall. The first harmonic of the integral rainfall reaches its maximum in early February in close synchronism with those of the first harmonics of rainfall from most of the individual types of systems (Fig. F-1). Only the rainfall cycle of the tropical-temperate troughs has a large-amplitude second harmonic with a summer maximum close to that of the first harmonics. Other appreciable summer six-month wave maxima occur in late March or early October for the west coast troughs, coastal depressions and east coast troughs.

Thermodynamics. Values of several thermodynamic parameters reach maxima or minima around 1 February (Fig. F-2). Maximum surface temperatures are reached a month earlier than the rainfall peak in conjunction with the minimum surface pressures. Surface temperatures during the period of high rainfall may, of course, be affected by the, presumably, increased cloudiness but the temperature maximum at 500 mb occurs about 10 days prior to and at 200 mb 10 days later than the rainfall peak. Height maxima at 500 and 200 mb occur closely synchronously with the 500 mb temperature maximum. Although the surface specific humidity maximum ...rs a few days later than the rainfall peak and that at 500 mb some days before, the rainfall and precipitable water peaks occur nearly simultaneously. The clearest phase association on the first harmonics is thus between specific humidity, rather than between temperature and pressure, and rainfall. Maxima of the total static energy,

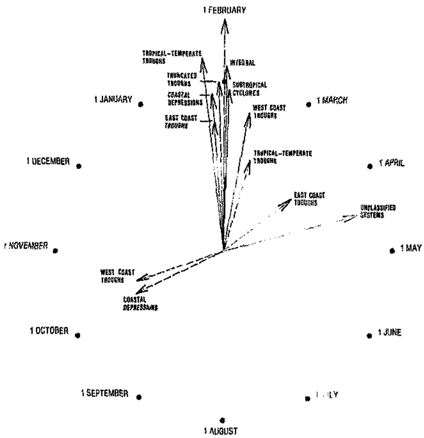

Figure F-1. Summary of the results of the harmonic analyses of the rainfall in the western Orange Free State. Solid lines represent maxima on the annual wave and dashed lines summer maxima on the semi-annual wave. Only harmonics explaining more than 10 per cent of the variance are plotted. Note that the lengths of the arrows in no way reflect amplitudes of the harmonics.

together with the highest thermodynamic instability of the atmosphere, occur some 10 days before the rainfall peak. Dates of maxima for rainfall for some of the systems such as the tropical-temperate troughs correspond more closely (to within five days) with those for several parameters including the total static energy. Highest variance of surface temperature occurs exactly three months prior to and of upper-air temperature

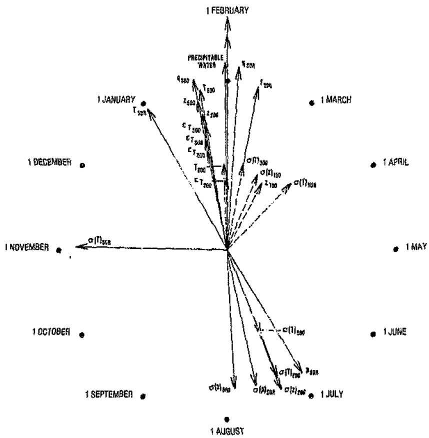

Figure F-2. As Figure F-1 but for the thermodynamic parameters of the atmosphere at Bloemfontein. Phase angles are marked for temperature (T), surface pressure (p), geopotential height (z), specific humidity (q), total static energy (ε_T) and appropriate standard deviations (σ) at the surface (SUR) and at standard pressure levels (mb).

five months later than the rainfall peak. Surface pressure and upper-level height distributions are approximately anti-phase to the rainfall wave. Of the thermodynamic parameters with appreciable second harmonics only those of the temperature and total static energy at 200 mb reach summer maxima around 1 February. Summer maxima for other parameters occur subsequent to the rainfall peak.

Kinematics. Phase angles of the first harmonics of the surface wind components are approximately 90° ahead of that of the rainfall cycle but maximum rainfall is associated with weakest westerly zonal flow at 200 mb (Fig. F-3). Meridional winds are subjected to only a weak annual cycle above the boundary zone with the phase varying markedly between levels such that the apparent correspondence between the waves of the rainfall and of the 200 mb meridional winds may be coincidental. No association between the annual cycles at the surface of the wind variances and rainfall is apparent but peak rainfall occurs with the minimum variances of the zonal wind at 500 mb (at 200 mb the minimum precedes the rainfall peak by about 15 days) and of the meridional wind throughout the upper troposphere. At 200 mb the time of the minimum variance of the meridional component corresponds closely with that of the maximum rainfall from the tropical-temperate troughs. Only the meridional wind had a major second harmonic throughout most of the depth of the atmosphere to 100 mb and at 200 mb the appropriate summer maximum poleward flow occurs at the same time as the rainfall peak.

Momentum. Highest values of the relative angular momentum of the atmosphere occur in August for all of the integral, rain and no rain groups indicating that the corresponding minima develop up to one month after the rainfall peak although that of the rain days occurs within 10 days of the rainfall maximum (Fig. F-4). The flux of earth angular momentum is modulated primarily on a semi-annual cycle with the summer maximum poleward (i.e. minimum equatorward) flux some 15 days after the rainfall peak. On rain days, however, the flux varies primarily on an annual cycle with the maximum 10 days before the rainfall peak at the time of highest rainfall from the tropical-temperate troughs. The corresponding minimum of the flux on no rain days occurs 15 days after the rainfall peak, almost synchronously with the summer maximum flux on the dominant second harmonic. The circulation flux on rain days has a first harmonic that explains more than 10 per cent of the variance but the maximum flux occurs about five weeks after the rainfall maximum. Phases of the second harmonics of the circulation flux are such that the summer peaks of both the integral and no rain fluxes develop almost synchronously a few days after the rainfall peak but that of the rain flux occurs about one month earlier. Over the year transient fluxes dominate the total transport. Phases of the first harmonics of these fluxes are such

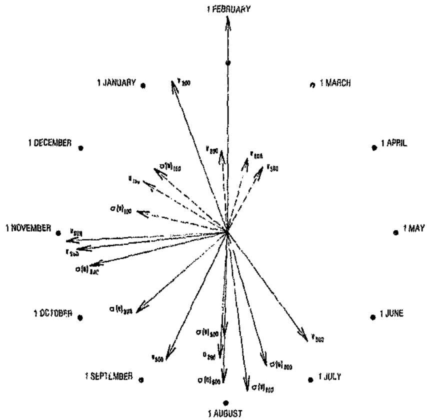

Figure F-3. As Figure F-1 but for the kinematic parameters of the atmosphere at Bloemfontein. Phase angles are marked for zonal wind speed (u), meridional wind speed (v) and appropriate standard deviations (σ) at the surface (SUR) and at standard pressure levels (mb).

that minima in the integral and no rain fluxes occur in late December and mid-January respectively while the maximum in the rain flux occurs in early May. Second harmonics of the integral and rain transient fluxes are about 160° out of phase such that summer maxima of the former and minima of the latter occur at the time of the maximum of the first harmonic

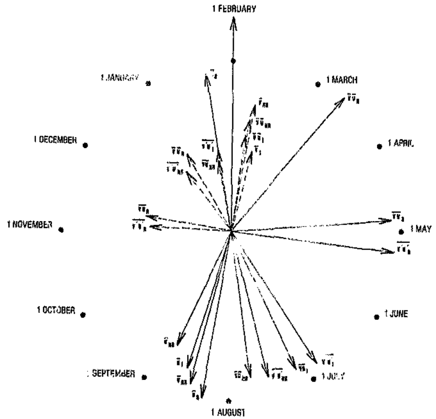

Figure F-4. As Figure F-1 but for the meridional momentum fluxes at Bloemfontein. Phase angles are given for the relative angular momentum of the atmosphere (u) and for the earth angular momentum (v), circulation relative angular momentum (vu), transient relative angular momentum (v'u') and total relative angular momentum (vu) fluxes for the overall circulation (I) and for the rain days (R) and the no rain days (NR).

of rainfall from the tropical-temperate *troughs*. Maxima of the corresponding *no rain* flux develop between those of the other two fluxes.

Phase angles of several of the fluxes correspond closely to those of the rainfall cycle. Fluxes for which the maxima or minima on the first harmonic occur around 1 February include the earth angular momentum flux on rain days (maximum) and the transient and total relative angular momentum fluxes on no rain days (minima). On the second harmonic late January/early February maxima occur for the integral and *no rain* earth angular momentum, integral and *no rain* circulation, integral transient and *no rain* total relative angular momentum fluxes and minima for the rain transient and total fluxes. The maximum of the annual rainfall cycle therefore occurs with that of the annual earth angular momentum flux and of the summer minimum of the six-month transient flux on rain days.