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THE DYNAMICS AND ENERGETICS OF TROPICAL-TEMPERATE TROUGHS OVER SOUTHERN AFRICA

Peter Charles D'Abreton

Thesis submitted to the Faculty of Science,
University of the Witwatersrand, Johannesburg
for the Degree of Doctor of Philosophy.

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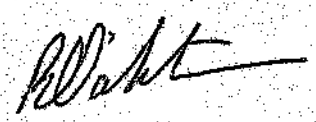
ABSTRACT

Water vapour content and transport over southern Africa and adjacent oceans are examined. Early summer rainfall over the northern and central interior of South Africa tends to be associated with baroclinic controls whereas late-summer rainfall is barotropic in origin. This is reflected in the northwesterly water vapour transport from an Atlantic Ocean source by middle and upper tropospheric westerly waves in early summer. A thermally indirect Ferrel cell, indicated from energetics, confirms the temperate nature of the early-summer atmosphere over southern Africa. Late summer water vapour transport, in contrast, is strongly from the tropics, with a reduced eddy component, indicating an important tropical control on late summer rainfall especially in terms of fluctuations in the position of the ascending limb of the Walker cell over southern Africa. The Hadley cell is of importance to the late summer rainfall in that dry (wet) years are associated with an anomalous cell over eastern (central) South Africa such that low level vapour transport is southerly (northerly). The anticyclone over the eastern parts of southern Africa, coupled with a trough over the interior (especially at the 700 hPa pressure level), is important for the introduction of water vapour over the subcontinent in wet and dry years and for tropical-temperate trough case studies. Water vapour source regions differ from early summer (Atlantic Ocean) to late summer (Indian Ocean), which reflects the temperate control on early and the tropical control on late summer circulation. The convergence of water vapour over southern Africa in wet years and during tropical-temperate troughs is not only important for cloud formation and precipitation, but also for latent heat release associated with convergent water vapour. Diabatic heating decreases the stability of the tropical atmosphere thereby resulting in increased vertical motion. It also forces an anomalous Hadley circulation during wet late summers and tropical-temperate trough cases as a result of complex energy transformations. Heating increases eddy available potential energy which is converted to zonal available potential energy by a thermally indirect circulation found in the tropics. The zonal potential energy is then converted to kinetic energy by the thermally direct Hadley cell. Water vapour and its variations are thus important for the precipitation, heating and subsequent energy of the subtropical southern African atmosphere.

I declare that this thesis is my own, unaided work,
and that it has not been submitted previously
as a dissertation or thesis for any degree
at any other University.



University of the Witwatersrand, 1992

To my Mother and Father

The general aim in the thesis is to examine the relationship between water vapour transport over the subcontinent and adjacent oceans and the rainfall over the summer rainfall region of the South African interior. More specific aims are:

i) to investigate the relationship between water vapour transport over southern Africa and adjacent oceans in mean wet and dry early, mid and late summer months,

ii) to determine the water vapour source regions for South Africa,

iii) to ascertain the degree of thermal forcing of the subtropical atmosphere through latent heat release, and

iv) to gain a better understanding of the synoptics, the hydrodynamics, and the energetics of one of the most important rain-producing systems over southern Africa.

The thesis is divided into eight chapters. **Chapter 1** provides an overview of previous work relevant to this study. A brief description of the climate of South Africa is given. Finally, an explanation is provided of the most important rain-producing system over the summer rainfall region of South Africa. In **Chapter 2** the data and and methods used in studying the hydrodynamics and energetics of the southern African atmosphere are described. **Chapter 3** describes the inter- and intra-annual variability of the water vapour fields over southern Africa. Thermodynamic aspects of the water vapour fields are investigated. The pressure fields are examined over southern Africa and adjacent oceans in **Chapter 4** in order to better understand the mechanisms of water vapour transport and the dynamics of tropical-temperate troughs. In **Chapter 5** the water vapour transport over southern Africa and adjacent oceans is investigated. Hydrodynamic variability is examined for wet and dry early, mid, and late summer months. A circulation model is proposed, linking global-scale circulations to water vapour availability over southern Africa. Divergence and convergence of water vapour over southern Africa and adjacent oceans is presented in **Chapter 6** in order to contribute to an understanding of the various sources of water vapour. This may serve to explain remote links between sea

PREFACE

South Africa, by virtue of its position within the subtropical belt of high pressure, is characterized by a semi-arid to arid climate. Unreliable rainfall coupled with a rapidly increasing population and urbanization has placed severe stress on the agricultural sector and the economy of the region as a whole. The sustained drought of the 1980s to present, interspersed with localized severe flood episodes, has resulted in widespread crop failure in the main maize-producing region of South Africa, and consequently the vagaries of the southern African climate have become the focus of much attention in recent years.

Over the last two decades increased knowledge has been gained of climatic, and more particularly rainfall variability over southern Africa. Many studies have been conducted into the statistical reliability and cyclicity of rainfall over the region. Explanation for southern African rainfall variability has been sought in terms of local pressure and sea surface temperature variations as well as planetary-scale controls. In the case of the latter, a relationship has been found between remote sea surface temperatures (the Southern Oscillation) and rainfall over South Africa through the teleconnections known to exist between tropical and extra-tropical latitudes. Identification of cloud bands linking tropical to extra-tropical latitudes as a major source of rainfall over the summer-rainfall region of South Africa has focused increasing attention on the tropical circulation as a determinant of summer rainfall.

Tropical-temperate troughs, as these systems linking the tropical and temperate latitudes are called, have been identified synoptically and the poleward energy and momentum transports associated with them have been assessed. Evidence suggests that the tropical diabatic heating realized through latent heat release is a critical forcing mechanism of these important rain-producing systems. Besides forcing the tropical circulation, water vapour is also essential for cloud band formation and precipitation; as South Africa is largely semi-arid to arid the water vapour over the country must be imported from elsewhere. To date, little information has been available on regional water vapour transport or the link between the water vapour transport and convergence fields and the formation/dissipation of tropical-temperate troughs.

surface temperatures and rainfall over South Africa. In Chapter 7 the limited-region energetics are examined for the southern African region in order to understand the changes in energy between wet and dry years, and also during tropical-temperate trough cases. The role of water vapour on the energetics is also assessed. Finally, in Chapter 8 the results of the study are summarized and the relationship between water vapour sources, transport, content and rainfall over South Africa is assessed for wet and dry years as well as for tropical-temperate trough cases.

Part of Chapter 5 has been accepted for publication in the *International Journal of Climatology*. Chapter 3 has been submitted for publication in the *South African Journal of Science*; Chapter 6 has been submitted to the *Journal of Geophysical Research*; and Chapter 7 has been submitted to the *Journal of Climate*. Aspects of chapters 3, 4, 6 and 7 have been included in a paper submitted to *Theoretical and Applied Climatology*. Furthermore, presentations have been made at conferences. Parts of chapters 4 and 5 were presented at the 1990 and 1991 annual conferences of the South African Society of Atmospheric Sciences. Aspects of chapters 5 and 6 have also been presented at the IGU Commission on Climatology meeting held at Pennsylvania State University in 1992.

Data used in the research were obtained from the South African Weather Bureau and from the United States Department of Commerce - *Monthly Climatic Data for the World*. The European Centre for Medium-Range Weather Forecasts (ECMWF) FGGE-IIIb dataset was also used in the research. Monthly mean outgoing longwave radiation were kindly supplied by Dr P. Aceituno. The cartographical work of Mrs W. Job and Mr P. Stickler is acknowledged. Dr R.J. Allan and Dr D. Meyer are thanked for their help. Special thanks are extended to Dr J. Lindesay for invaluable assistance and encouragement during the course of the work. The supervision of Prof. P.D. Tyson is gratefully acknowledged. The research was funded by the Foundation for Research Development and forms part of the Programme on Southern African Climatic Change: Analysis, Interpretation and Modelling (SACCAIM).

CONTENTS

Abstract iii
Declaration v
Dedication vii

1 BACKGROUND 1
Introduction 1
Southern African climate 2
Tropical-temperate troughs 7
Inter-annual rainfall variability 13
Hypotheses 17

2 DATA AND METHODS 21
Introduction 21
Data Source and characteristics 21
Methodology 25
Thermodynamics 25
Energetics 28
Statistics 31

3 WATER VAPOUR CONTENT 35
Introduction 35
Precipitable water 37
Variability of Precipitable water 40
Latent Heat 43
Latent heat and tropical-temperate troughs 46
Discussion 59

4 WATER VAPOUR AND SYNOPTIC CONDITIONS 69
Introduction 69
Water vapour and synoptic Conditions 70
Mean wet and dry synoptic conditions 72
The synoptics of tropical-temperate troughs 79
Discussion 86

5 WATER VAPOUR TRANSPORT 93
Introduction 93
Vertically integrated vapour fluxes 94
Vertical structure of the vapour fluxes 106
Outgoing Longwave Radiation anomalies 112
Water vapour transport variability 116
Early summer 116
Mid-summer 117
Late summer 117
Discussion 120

6 DIVERGENT AND NON-DIVERGENT VAPOUR TRANSPORT 133
Introduction 133
Divergent and non-divergent vapour transport 135
Circulation transport 135
Eddy transport 140
Non-divergent and divergent flow and tropical-temperate troughs 145
Discussion 160

7 ENERGY PROCESSES 171
Introduction 171
Inter-annual variability of energetics 173
Tropical Atlantic Ocean 173

Tropical Africa 176
Tropical Indian Ocean 177
Sub-tropical southern Africa 179
The energetics of tropical-temperate troughs 180
Discussion 184

8 **SUMMARY AND CONCLUSIONS** 191

APPENDICES 199

REFERENCES 217

CHAPTER 1

BACKGROUND

Introduction

South Africa, situated in the regions of descent beneath the Hadley and Ferrel cells, is characterized by a generally semi-arid to arid climate. Rainfall in subtropical southern Africa is strongly seasonal, with a well defined summer (December-March) maximum over most of the subcontinental interior (Lindesay, 1992; Nicholson *et al.*, 1988). Relatively small areas along the eastern and southern coasts receive year-round rainfall, and the south-western tip of the subcontinent has a winter (June-September) rainfall maximum (Tyson, 1986). Rainfall variability is greatest over the arid western parts of South Africa, decreasing over the wetter eastern parts (Tyson, 1986). Although the eastern part of the continent generally receives sufficient rainfall, it too is subject to periods of above- or below-normal rainfall. The rainfall over the summer rainfall area of southern Africa is particularly vulnerable to non-seasonal rainfall variations, since below-normal summer rainfall is not likely to be made up during the dry winter season (Lindesay, 1988a). Rainfall variability over southern Africa has been the subject of increasing attention over the last decade (Tyson *et al.*, 1975; Dyer, 1982; Harrison, 1986a; Lindesay, 1988a; Tyson, 1981, 1986; Tyson and Dyer, 1978; 1980). Temporal aspects of the rainfall variability have been considered (Tyson *et al.*, 1975; Tyson and Dyer, 1978; Tyson, 1981), as have the spatial aspects on a regional scale (Tyson, 1981, 1984; Miron and Tyson, 1984; D'Abreton and Lindesay, 1992), and on a hemispheric scale (Dyer and Tyson, 1978; Dyer, 1979; Harrison, 1986a; Nicholson, 1986; Lindesay, 1988a). Investigation of the spatial aspects of rainfall variability has involved the circulation changes between wet and dry periods (Tyson, 1981; Miron and Tyson, 1984; Lindesay, 1988a) as well as for specific rainfall events (Estie, 1981; Taljaard, 1981; Lindesay and Jury, 1991).

The effects of systematic circulation changes on rainfall over southern Africa have been examined only recently (Harangozo and Harrison, 1983; Harrison, 1983, 1986a; Lindesay and Jury, 1991; Matarira and Jury, 1992). The most important of these for summer rainfall over South Africa are the tropical-temperate troughs and their associated cloud bands linking tropical to temperate circulation regimes (Harrison, 1984). In this thesis these two terms will be used interchangeably. These cloud bands have been found to be the result of standing waves, forced by diabatic heating in the tropics (Krishnamurti, 1979; Peagle *et al.*, 1983; Harrison, 1986a). The linkages between diabatic heating in the tropics and cloud bands over South Africa require the investigation of inter-annual and event-scale transport of water vapour over the southern African region.

The climate of southern and South Africa has been well documented by, among others, Taljaard (1953, 1958, 1972, 1982), Tyson (1986) and Lindesay (1992). Consequently, only a brief overview will be given of the major features of the southern African climate.

Southern African Climate

South Africa's climate, by virtue of its physical setting (20°-35°S, 18°-30°E) is controlled by a number of physical factors. The orography is the most important feature, creating temperature anomalies and affecting rainfall (Tyson, 1986; Lindesay, 1992) (Fig. 1.1). Temperatures over the interior plateau are generally higher than the zonal average (Lindesay, 1992), whereas isohyets assume an approximate north-south alignment with highest precipitation values occurring over the eastern coastal regions and lowest values along the arid west coast (Jackson, 1961; Tyson, 1986). Highest rainfall values occur along the seaward (eastern) slope of the escarpment, decreasing on the leeward slope and to the west thereof.

The second important factor affecting South Africa's climate is the oceanographic setting. The southern African subcontinent is affected by the warm Mozambique and Agulhas currents, which are part of the western

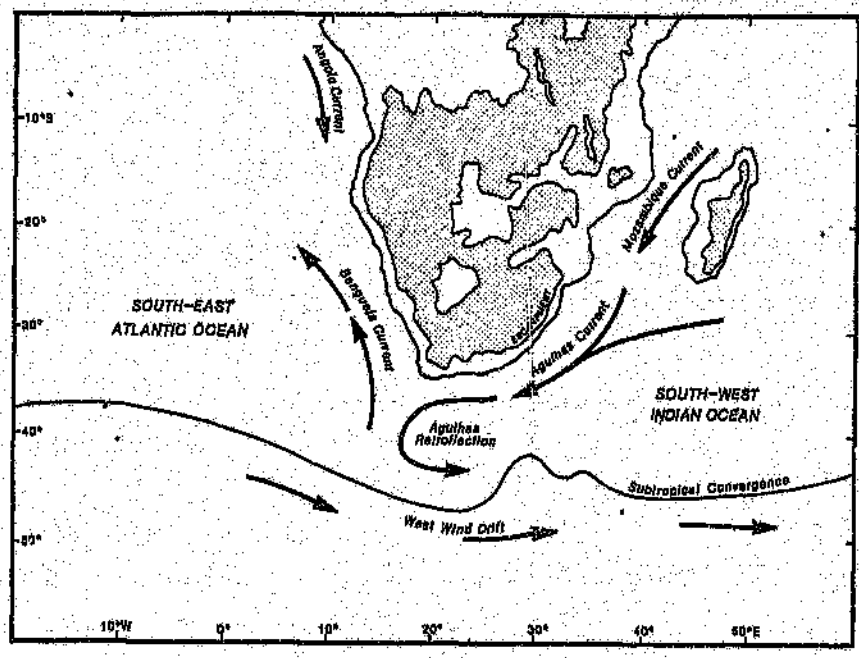


Figure 1.1: Physical features of southern Africa. Shading indicates relief greater than 1000 m and major oceanographic currents are indicated (after Lindesay, 1992).

boundary current of the Indian Ocean to the east, and the cold Benguela Current system along the west coast (Walker, 1989; Lindesay, 1992). Sea surface temperatures along the east coast vary between 22 and 28°C in summer, whereas sea surface temperatures in the Benguela system seldom exceed 16°C (Shannon, 1985; Lindesay, 1992). These currents influence air temperatures as well as moisture characteristics over South Africa (Lindesay, 1992), through the combined sensible and latent heat fluxes from the surrounding oceans. Heat flux from the warmer southwest Indian Ocean (150 $W.m^{-2}$) greatly exceeds that from the colder Atlantic Ocean (< 25 $W.m^{-2}$) (Hofflich, 1984; Taljaard and van Loon, 1984; Walker, 1989). This has an important effect on moisture availability, with the highest precipitation occurring along the eastern coast where sea surface temperatures and evaporation are high, and the lowest rainfall over the west coast where the sea surface temperatures and evaporation are lower (Walker, 1989).

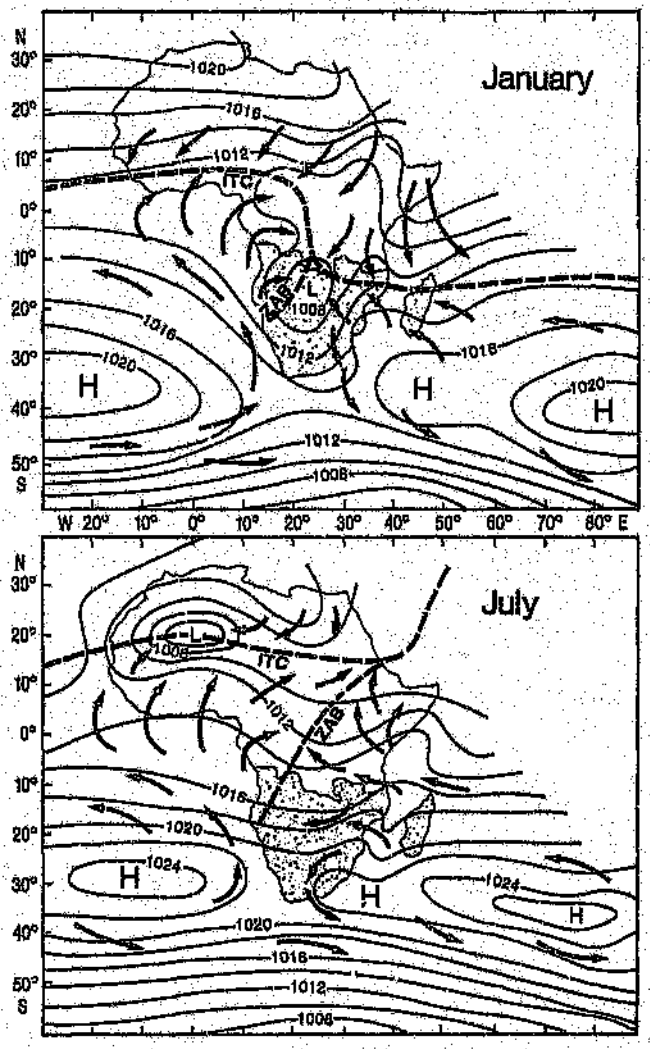


Figure 1.2: Schematic representation of the mean surface pressures; the Inter-Tropical Convergence (ITC) and mean wind directions in January (summer) and July (winter) (after Lindesay, 1992).

The third important factor affecting southern African climate is its position in relation to the tropical, subtropical and mid-latitude pressure systems (Lindesay, 1992). South Africa lies within the influence of the semi-permanent subtropical high pressure belt, and more particularly the two high pressure cells, the South Atlantic anticyclone to the west and the South Indian anticyclone to the east of the subcontinent (Fig. 1.2) (Lindesay, 1992). The anticylones are the result of the hemispheric mean circulation of the atmosphere (Lindesay, 1992).

The thermally direct Hadley cell, with ascending air in the tropics and descending air in the subtropics, combines with the thermally indirect Ferrel cell, with descending air in the subtropics, to create the quasi-stationary anticyclones which dominate the southern African climate. The position of the anticyclones adjacent to southern Africa is important in explaining the variability of rainfall over South Africa (Tyson, 1981, 1984). The South Atlantic and Indian anticyclones vary in position throughout the year. The South Atlantic anticyclone varies in latititudinal position from 25°S in May to 31°S in February and in longitudinal position from 16°W in August to 2°W in December (McGee and Hastenrath, 1966; Tyson, 1986) (Fig. 1.3 left top and bottom). The South Indian anticyclone shifts in latitude from 29°S in June and October to a southernmost position of 33°S in February (Fig. 1.3 right top. A large longitudinal shift of the South Indian anticyclone (24°) occurs from an easternmost position in December (88°E) to the westernmost position in June (64°E) (van Loon, 1972; Tyson, 1986; Lindesay, 1992). The anticyclone affecting the climate of southern Africa (Fig. 1.2) has been attributed to an independent cell of high pressure (Streten, 1980), resulting from subsiding air originating in the monsoon system of Asia in winter (Harrison, 1986a; 1990; Lindesay, 1992; Tyson, 1986), and from budding of the South Atlantic Anticyclone in summer (Lindesay, 1992). Tyson (1984), correlated principal component scores of various pressure indices at 850 hPa and at 500 hPa with rainfall series and found that anticyclonic ridging south of South Africa accounted for 16 to 25 per cent of the variance in the correlation analysis for the region (Tyson, 1984).

The southern limit of the subtropical high pressure belt indicates the transition between the tropical, subtropical and the midlatitude types of climate. The weather south of the anticyclone belt is dominated by transient mid-latitude depressions imbedded in the circumpolar westerly flow (Lindesay, 1992). The seasonal variation in the position of the subtropical anticyclones is reproduced by that of the mid-latitude depression track, such that the mid-latitude cyclones track 5° to 10° further south in summer than in winter (van Loon, 1972; Trenberth, 1981; Lindesay, 1992). Mid-latitude depressions mainly affect the southwestern regions of South Africa in winter, although on occasions cut-off low pressure systems are displaced equatorward (Tyson, 1986). These baroclinic, cold-cored systems are associated with most of the flood events over South Africa

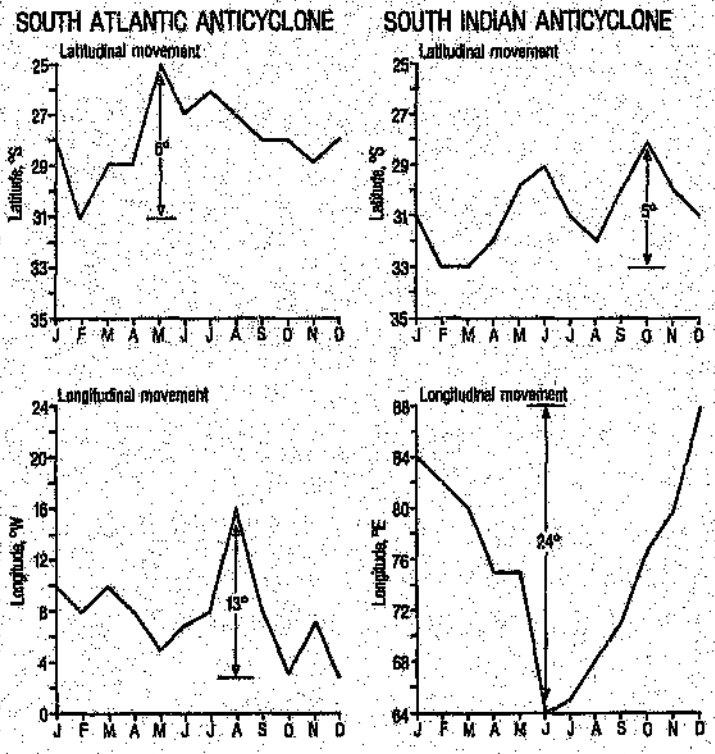


Figure 1.3: Annual variation of latitude and longitude of the South Atlantic and Indian anticyclones (after Tyson, 1986, modified after Vowinckel, 1956; McGee and Hastenrath, 1966).

(Estie, 1981; Taljaard, 1982). These systems display a maximum frequency of occurrence during the vernal and autumnal transition seasons, with lowest frequencies between December and February (Taljaard, 1982).

Three major airstreams converge over tropical southern Africa into the near-equatorial trough or Inter-Tropical Convergence (ITC) in summer (Taljaard, 1972; Tyson, 1986; Lindesay, 1992): these are the recurved southwesterly South Atlantic air at 12°S, the northeasterly monsoon air from the northeast, and the tropical easterlies from the South Indian Ocean (Torrance, 1972, 1979) (Fig. 1.2). The ITC migrates with the seasons, lying north of the equator in the austral winter and south in the austral summer, when it is aligned in a roughly north-south direction (Taljaard, 1972; Dhonneur *et al.*, 1974; Lindesay, 1992). Furthermore, another convergence zone, the Zaire Air Boundary

(ZAB), occurs where the tropical easterlies from the South Indian Ocean converge with the recurved southwesterly airstreams from the South Atlantic Ocean over southern Angola and northern Namibia and Botswana (Fig. 1.2) (Taljaard, 1972). This confluence zone, like the ITC, is a convective region of high latent heat release (Webster, 1972; Tyson, 1986) where depressions form (Taljaard, 1972). These quasi-stationary depressions sometimes move westward to northern Botswana, where easterly waves (troughs) extending southward from them may result in high rainfall over the summer rainfall areas of South Africa (Tyson, 1984, 1986; Lindesay, 1992). Tropical easterly waves/lows at the 850 and 500 hPa levels account for 16 to 49 per cent of the variance of the rainfall over the northeastern interior regions of South Africa (Tyson, 1984).

The penetration of mid-latitude disturbances plays an important role in tropical rainfall generation over southern Africa (Webster, 1983; Harrison, 1986a; Lyons, 1991), and the effects of tropical disturbances on mid-latitude systems cannot be ignored (Horel and Wallace, 1981; James and Anderson, 1984; Hastenrath, 1985; Harrison, 1986a). In recent years increased attention has been given to tropical-temperate interactions over southern Africa (Harrison, 1984a, 1986a; Harangozo, 1989; Lindesay and Jury, 1991). The system in which tropical and temperate synoptic systems interact to form a conduit (indicated by a cloud band) for the extraction of energy and momentum from the tropics has been classified as a tropical-temperate trough (Harrison, 1986a).

Tropical-temperate Troughs

Cloud bands and their attendant synoptic systems have been found to exist in various parts of the world and have been studied in Australia (Tapp and Barrell, 1984; Bell, 1986; Wright, 1988; Kuhnel, 1989), South America (Gray and Clapp, 1978; Kousky, 1979; Peagle and Kalnay, 1983; Virji and Kousky, 1983), western North Pacific (McGuirk *et al.*, 1987) and South Africa (Harrison, 1984a, 1984b, 1986a; Harangozo, 1989). The consensus among meteorologists and climatologists is that cloud bands form in conjunction with semi-stationary long waves in the atmosphere, due to orographic (Palmen and Newton, 1969; Mechoso, 1981) or thermal forcing (Webster and Holton, 1982; Webster, 1983).

The northwest Australian and North Pacific cloud bands occur predominantly during the cooler months with the statistical modes occurring in May and April respectively (Tapp and Barrel, 1984; Bell, 1986; Wright, 1988), whereas the South American cloud band occurs predominantly during the summer months (Kousky *et al.*, 1983). The Australian cloud band differs from the South American band due to the former resulting from a strongly baroclinic environment whereas the latter is the result of Hadley cell amplifications. Enhanced tropical convection in the easterly wave north of Australia, with strengthened intertropical convergence over the north Pacific results in atmospheric forcing and interaction between the temperate and tropical latitudes (McGuirk *et al.*, 1987). The Australian cloud band is associated with a strongly baroclinic region which develops when tropical air is advected southwestward in the easterly wave and subpolar air northward in the westerly wave (Tapp and Barrel, 1984). The cloud band results from gradual ascent of moist air along the isentropic surfaces associated with the baroclinic zone (Bell, 1986; Wright, 1988). The absence of significant cloud bands over Australia in the summer is possibly the result of decreased thermal contrasts between sub-polar and tropical air, which reduces baroclinicity (Tapp and Barrel, 1984). This points to an orographically forced wave being responsible for cloud band formation over Australia. The South American cloud band, in contrast, is thought to form when deep convection in the ITC, initiated by the penetration of mid-latitude troughs into low latitudes, generates accelerations of upper-air flow and hence kinematic divergence. This leads to enhanced low-level convergence and convection over the tropical regions, and a strengthening of the meridional flow (McGuirk *et al.*, 1987). The cloud bands in these regions represent local amplifications of the Hadley circulation and serve to transport mass, momentum and energy poleward (Virji and Kousky, 1983; McGuirk *et al.*, 1987). The South American cloud band is thought to be thermally forced (Peagle *et al.*, 1983; Peagle and Kalnay, 1983).

Tropical-temperate troughs and their associated cloud bands have also been studied over southern Africa (Harangozo and Harrison, 1983; Harrison, 1984, 1986a; Harangozo, 1989). These weather systems, with their associated cloud bands linking tropical cloud masses to temperate cyclones, have been found to be the one of the most important contributors to rainfall over the interior of South Africa and Zimbabwe during summer (Harrison, 1984; Smith, 1985).

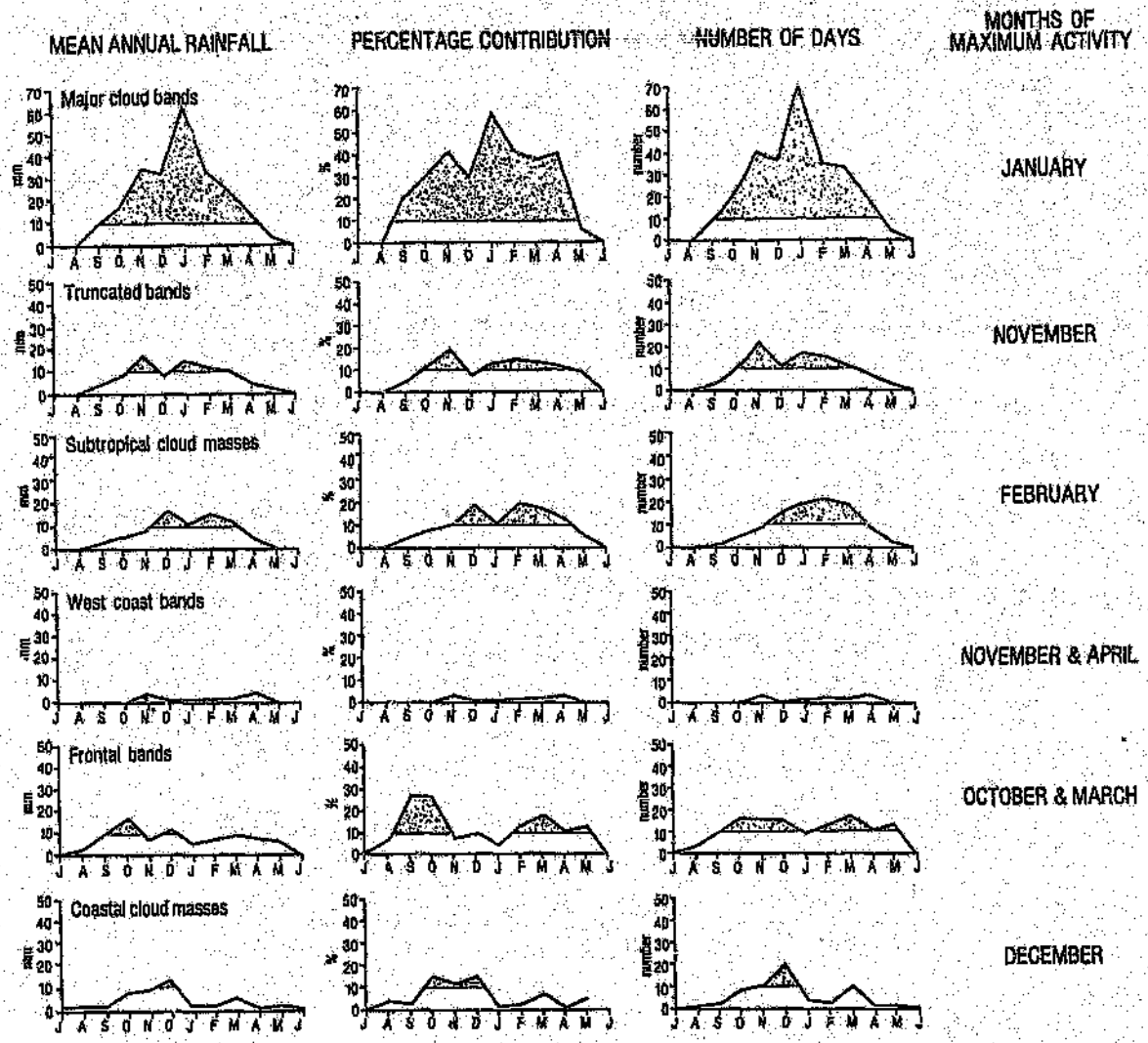


Figure 1.4: Annual cycles of significant rainfall, of percentage contribution and of frequency of significant raindays for the different cloud-producing circulation types (after Tyson, 1986, modified after Harrison, 1984)

Percentage rainfall contributed by these systems amounts to 30 per cent of the October and December total, 60 per cent of the January total, and 39 per cent of the annual total of rainfall over the eastern Orange Free State (Harrison, 1984, 1986a) (Fig. 1.4). Although tropical-temperate troughs have been found to be the most important contributors to October and December rainfall, other

cloud-producing systems contribute significantly during those months. In October (early summer), frontal bands (Figs 1.4, 1.5) contribute as much to the monthly total as do tropical-temperate troughs, which is indicative of a more baroclinic westerly circulation (Harrison, 1984, 1986a) (Figs 1.4, 1.5). During December, subtropical cloud masses contribute significantly to that month's total, and represent cold-cored upper-air depressions imbedded in the easterly flow over southern Africa (Harrison, 1984, 1986a; Tyson, 1986). The decrease in the contribution of tropical-temperate troughs in December (Fig. 1.4) may represent an hiatus when the barotropic late summer circulation replaces the early summer baroclinic westerly circulation.

Tropical-temperate troughs form when a tropical disturbance, such as an easterly low or wave at the surface, combines with a westerly wave or low in the upper atmosphere to form a connection between the tropical and mid-latitudes (Harangozo and Harrison, 1983; Harrison, 1984, 1986a). Major cloud bands form in conjunction with the tropical-temperate troughs (Fig. 1.5 *top left*), and variations thereof with different synoptic combinations (Fig. 1.5) (Harrison 1984, 1986a). Cloud bands mark a region of strong baroclinicity with convergence at the surface and divergence in the upper atmosphere (Harrison, 1986a), and serve to transfer energy and momentum poleward along the leading edge of the upper trough. This is important for the maintenance of the Hadley circulation (Riehl, 1979; Webster, 1983; Harrison, 1986a; Lindesay, 1992).

Evidence for the southward transport of momentum has been found by Harrison (1986a) in that mean earth angular momentum over South Africa is *poleward* on raindays, with tropical-temperate troughs accounting for the major contribution (Fig. 1.6a). Mean earth angular momentum is *equatorward* for all no-rain days, except for the winter months of July and August (Fig. 1.6a) (Harrison, 1986a). On dividing the mean flux into circulation and transient components, Harrison (1986a) discovered that the circulation flux of earth angular momentum is poleward in all raindays except October, although circulation transport for tropical-temperate troughs is poleward (Fig. 1.6b). Rainday transient angular momentum fluxes are poleward with a minimum during December, and a maximum during the transitional seasons (Fig. 1.6c) (Harrison, 1986a). This is indicative of a baroclinic structure of the atmosphere

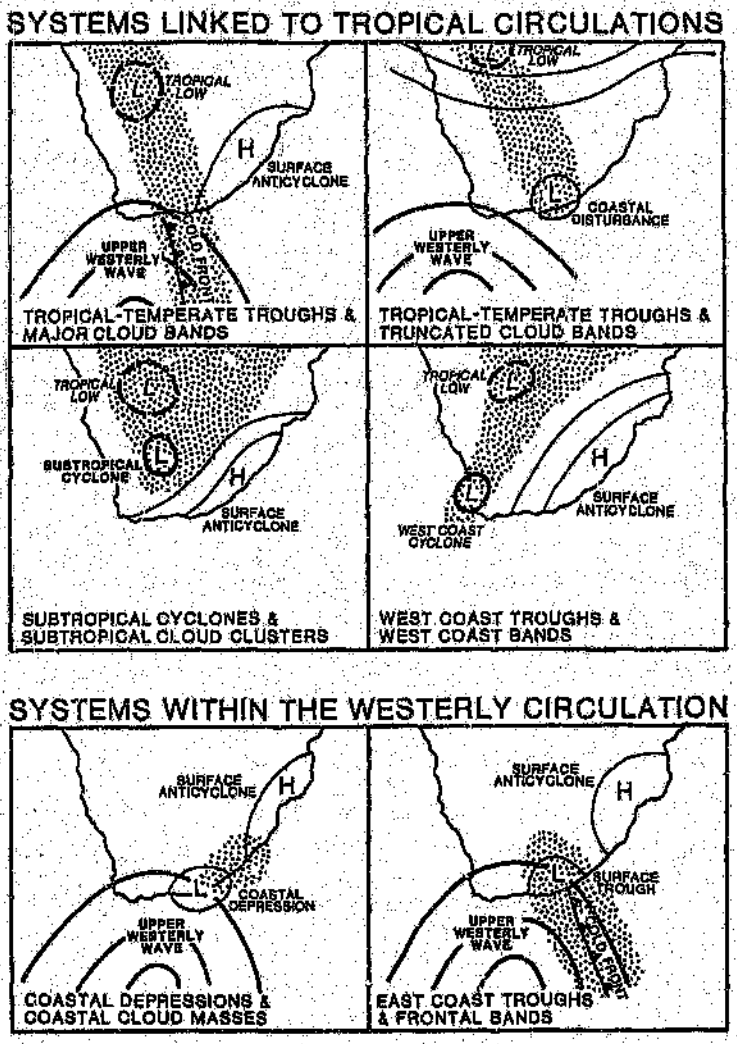


Figure 1.5: A generalized classification of circulation types and their corresponding cloud systems (after Harrison, 1986a). Low-level, upper-level circulation and cloud cover are depicted by light and heavy lines, and stippling respectively.

in the transitional seasons and a hiatus during December before the atmosphere becomes barotropic in late summer (Harrison, 1986a, 1986b). During the transitional seasons the bulk of the transport of the transient flux is carried by the tropical-temperate troughs (Harrison, 1986a). Easterly winds at 20°S result in the generation of momentum with southward transport across South Africa on rain days (Harrison, 1986a). The increase in the poleward transport of earth angular momentum during rain days has been attributed to the westward tilt of

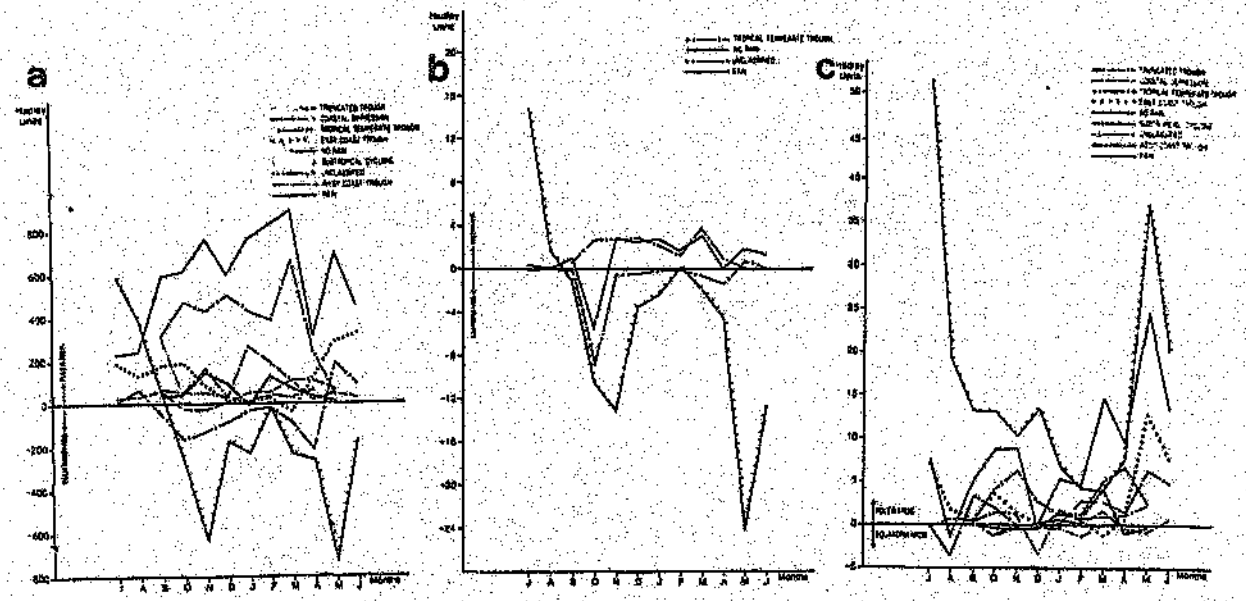


Figure 1.6: Monthly mean values of the vertically-integrated relative angular momentum of: a) earth angular momentum; b) contribution of circulation fluxes; and c) contribution of transient fluxes (modified after Harrison, 1986a).

the trough, with its corresponding higher momentum transport (Godske *et al.*, 1957; Harrison, 1986a). This poleward transport of westerly momentum during wet years has been corroborated by increased westerly winds in wet years at Marion Island (47°S, 37°E) (Harrison, 1986a; Tyson, 1986).

The South African cloud band, like its South American counterpart, is associated with a stationary wave, thermally forced by latent heat release over the tropics (Vonder Haar, 1968; Kalnay *et al.*, 1983; Harrison, 1986b). Application of the Eliassen-Palm relationship over southern Africa supports this theory in summer (Harrison, 1986b), when the relationship does not hold. In the transitional season, however, the Eliassen-Palm relationship does hold, implying an orographically forced, eastward moving wave (Eliassen and Palm, 1960; Harrison, 1986b).

Evidence therefore suggests that higher rainfall in summer is related to an intensification of the Hadley cell over southern Africa due to forcing by latent energy release over tropical Africa (Rind and Rossow, 1984; Harrison, 1986a). In the transitional seasons, rainfall is associated with a Ferrel cell and eastward-moving waves over southern Africa, although tropical-temperate troughs are still related to an intensification of the Hadley cell (Harrison, 1986a).

Inter-annual Rainfall Variability

South Africa's rainfall, by virtue of its position in relation to tropical, sub-tropical and temperate circulation systems, displays inter-seasonal as well as inter-annual variations. Rainfall variability over southern Africa has been examined on a regional scale in terms of mean surface pressures on a short time-scale (King and van Loon, 1958; Triegaardt and Kits, 1963; Miron and Tyson, 1984). On a longer time-scale Tyson (1981) and Miron and Tyson (1984) compared mean surface pressures for an extended wet period (1954-1962) with that of an extended dry period (1963-1972). The overall results of the studies indicate that wet spells/periods/years occurred with decreased pressures over southern Africa at the surface and at 500hPa and increased pressure (surface and 500 hPa) over the South Atlantic Ocean. Relationships between sea surface temperatures (SSTs) and southern African rainfall have also been investigated (Nicholson and Entekhabi, 1987; Walker, 1989; Mason, 1990). Sea surface temperatures over the southwest Atlantic Ocean have been found to be positively correlated with rainfall south of the equator as far south as 20°S (Nicholson and Entekhabi, 1987). Correlations between sea surface temperature departures and area average rainfall for the summer rainfall region of South Africa have revealed significant positive correlations adjacent to South Africa in the South Indian and Atlantic oceans in late summer (January to March) and only over the South Indian Ocean in early summer (October to December) (Walker, 1989). Further evidence for sea surface temperature influence on southern African rainfall variability has been obtained from spectral and cross-spectral analysis of sea surface temperatures, where results suggest coherence between sea temperature and rainfall spectra (Nichoson and Entekhabi, 1987; Mason, 1990; Lindesay, 1992).

Increased attention has been focused on the effects of hemispheric interactions on southern African climate (Harrison, 1986a; Lindesay, 1988a; Van Heerden, Terblanee and Schulze, 1988). This research has been based on the inter-annual fluctuation of the ocean-atmosphere system, the Southern Oscillation, and its teleconnections around the globe (Bjerknes, 1969; Horel and Wallace, 1981; Philander and Rasmusson, 1985; Cane, 1986; Philander, 1990). The effects of inter-annual fluctuations of the Southern Oscillation on southern African climate has been extensively documented by Lindesay (1988a). Generally, the Southern Oscillation high (low) phase has been related to increased (decreased) precipitation over southern Africa (Lindesay, 1988a, 1988b; Nicholson, 1989), and decreased (increased) geopotential heights and temperatures at 700 and 200 hPa (Lindesay, 1988a). This is in accordance with earlier findings of decreased (increased) temperatures over Southern Hemisphere continental regions during the high (low) phase (Angell, 1981; Aceituno, 1988). Winds become anomalously westerly and northerly over the subcontinent during the high phase, reversing during the low phase (Lindesay, 1992). The zonal Walker Circulation is the most important mechanism whereby the Southern Oscillation influences southern African rainfall (Lindesay, 1988a, 1992). High phase years are characterized by major convection over Indonesia, and secondary convection over South America and Africa (Vonder Haar, 1968; Webster, 1983). Low phase (El Nino) years are characterized by reduced convection over Indonesia, resulting in shifts or intensity changes, such that wet (dry) years are characterized by anomalous westerly (easterly) winds at low levels and easterly (westerly) winds aloft (Lindesay, 1988a, 1992) (Fig. 1.7). Development of the African heat source is partially controlled by the Walker Circulation. This circulation is characterized by the ascending limb of the Walker Circulation being situated over tropical Africa in the high phase, leading to strong convection and an intensified Hadley cell over southern Africa (Harrison, 1986a). The intensified tropical convection and subsequent enhanced Hadley cell is considered necessary for cloud band development (Figs 1.7a, 1.7b) (Harrison, 1986a; Lyons, 1991; Lindesay, 1992). In contrast, the low phase of the Southern Oscillation is characterized by an eastward shift of the ascending limb of the Walker Circulation with a concomitant shift of strong convection, thereby reducing the meridional flux of energy over the subcontinent and increasing convection over

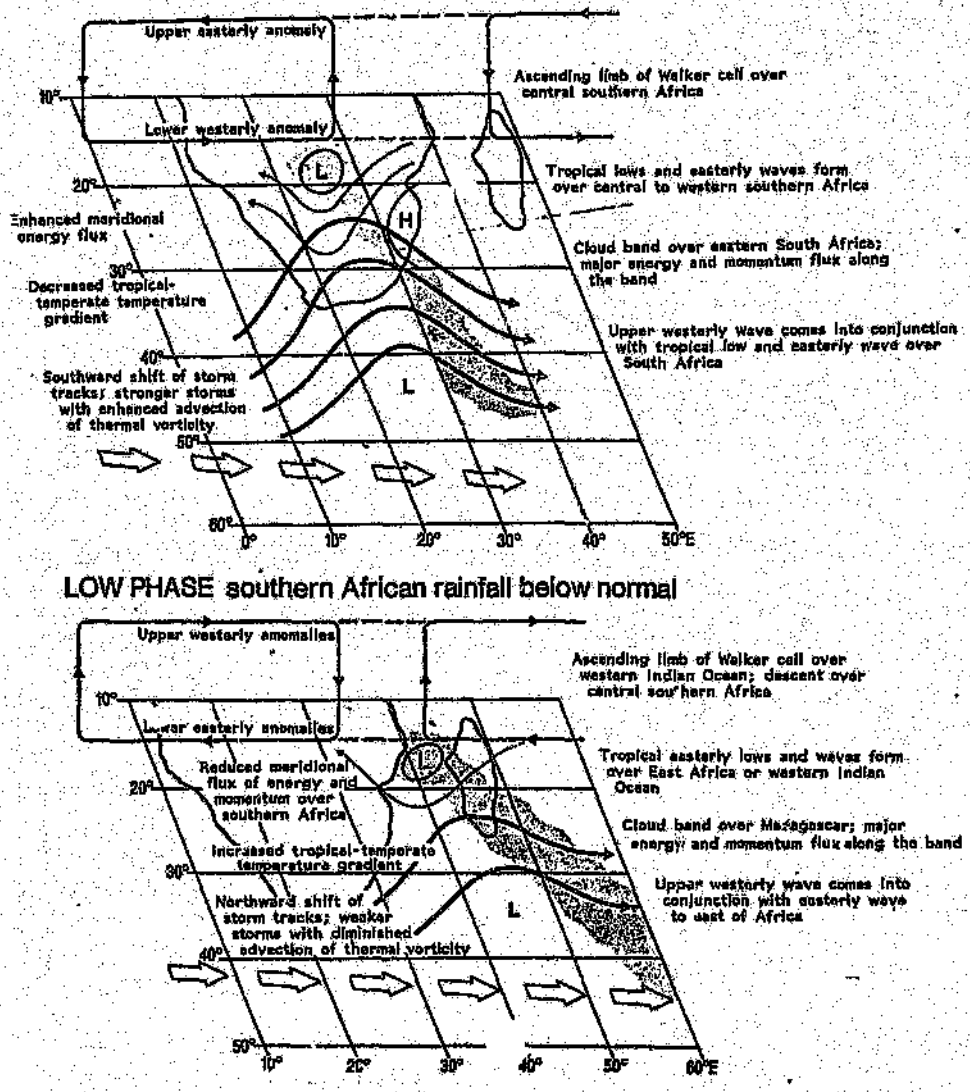


Figure 1.7: a) The Walker Circulation during the high and low phase of the Southern Oscillation, and b) Walker Circulation anomalies during the high phase (*upper*) showing the flow resulting in above-normal rainfall over southern Africa, and the low phase (*lower*) with associated flow resulting in below-normal rainfall (after Harrison, 1986a; Tyson, 1986). Light and heavy lines denote surface and upper-tropospheric flow respectively.

Madagascar, hence the increased frequency of cloud bands over that region during dry years over southern Africa (Harrison, 1986a) (Figs 1.7a, 1.7b).

Tropical heat release over Africa is weakest over Africa (Vonder Haar, 1968; Harrison, 1986a; Tyson, 1986). The development of the African heat source is therefore dependant on circulation generated elsewhere (Harrison, 1986a; Tyson,

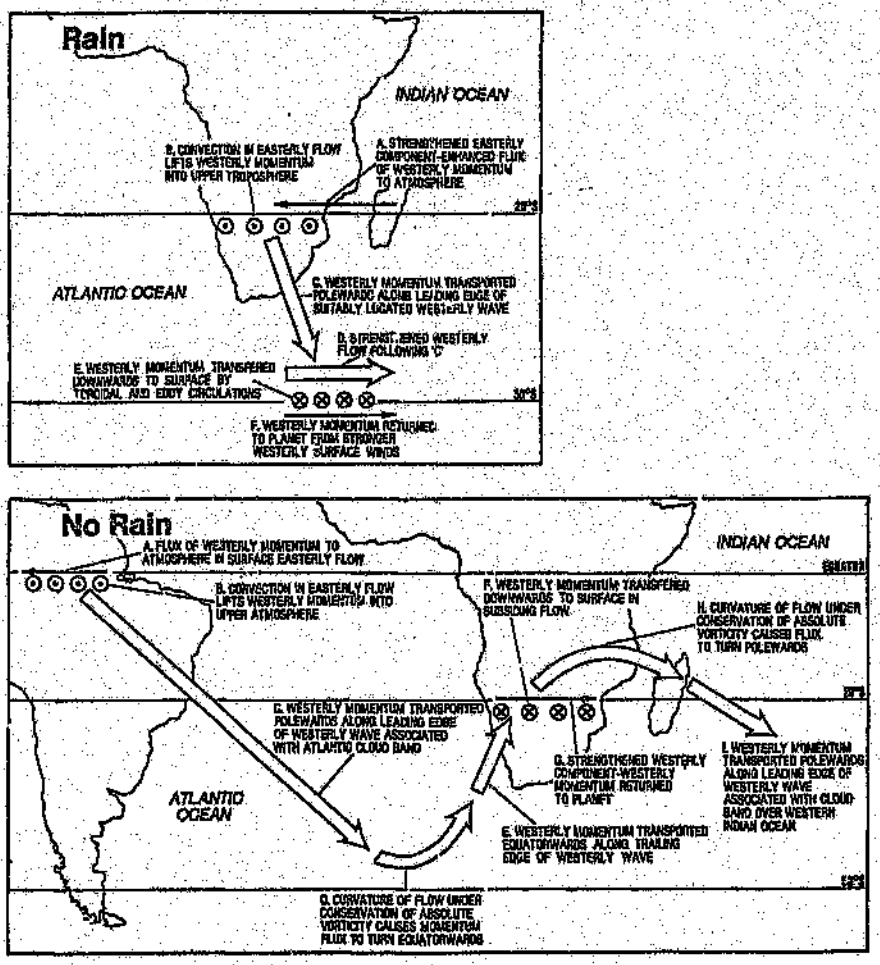


Figure 1.8: Schematic model of mean summer circulation associated with rainfall (*top*), and with no rainfall over southern Africa (*bottom*) (after Tyson, 1986, modified after Harrison, 1986a). Double arrows represent upper tropospheric flows and single arrows surface flow; dots within circles represent ascent and crosses in circles descent.

1986). One such mechanism is the Walker cell (discussed previously), and the South Atlantic standing wave. When conditions over southern Africa are dry, the westerly momentum generated over the tropics is lifted by convection over the Amazon and carried poleward along the leading edge of a westerly wave, after which it recurves and returns equatorward over South Africa (Fig. 1.8) (Harrison, 1986a). During wet conditions the Atlantic wave moves westward or weakens. The strong Intertropical Convergence (ITC) over tropical southern Africa acts as a heat source, capable of forcing standing waves and a Hadley circulation across South Africa (Fig. 1.8) (Harrison, 1986a, 1986b). Heat and momentum

generated in the tropics are transported poleward when westerly waves penetrate the ITC, thereby establishing a conduit for momentum and energy transport (Harrison, 1986a).

Hypothesis

Previous studies have focused on examination of the synoptic situations resulting in tropical-temperate trough formation over southern Africa and the large-scale forcing mechanisms resulting in the cloud bands. Emphasis has been placed on circulation changes and momentum transport in wet and dry years and during cloud band cases. Although the importance of water vapour variations over Africa for rainfall variability and cloud band formation has been emphasised previously, little is known about this important meteorological parameter over southern Africa. It is the intention, in this thesis, to investigate the inter-seasonal, inter-annual, and event-scale variations of this parameter on the general rainfall and for cloud band formation and dissipation over southern Africa. The influence of water vapour on the energetics will also be examined, both inter-annually and for cloud bands.

The hypotheses to be tested in the thesis are that:

i) cloud bands are local, thermally-induced amplifications of the Hadley Circulation;

ii) moisture, advected from the tropical Indian and Atlantic Oceans over tropical Africa, is then advected southward over southern Africa as a cloud band;

iii) moisture availability over subtropical Africa is essential for the development of a semi-stationary low pressure system over the subtropical latitudes of southern Africa;

iv) water vapour availability is dependent on the sea surface temperatures of the adjacent tropical Oceans as well as the large-scale transport and convergence of water vapour;

v) water vapour convergence results in a build-up of potential en. . y (from the release of latent heat) and the potential energy is converted to kinetic energy by symmetric overturning;

vi) the potential and kinetic energy, and latent heat is transported poleward by the tropical-temperate trough (cloud band); and

vii) tropical-temperate troughs differ in characteristics between early and late summer months.

Furthermore,

i) the importance of circulation and eddy water vapour transport during wet and dry early, mid, and late summer months;

ii) the characteristics of the circulation during the transition month between baroclinic and barotropic circulation systems (December);

iii) the relationship between the synoptic situation and precipitable water over southern Africa;

iv) changes in water vapour transport over southern Africa for the period preceding, during, and after cloud bands; and

v) the general synoptic situation preceding, during, and after cloud bands

will be assessed in order to bring about a better understanding of this important rain-producing system.

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Tropical-temperate troughs are an important rain-producing system over the summer rainfall region of South Africa, marking regions of poleward transport of energy and momentum along the leading edge of an upper level westerly wave. The hypotheses outlined will be tested by examining inter-seasonal and inter-annual variations of water vapour content and transport over southern Africa. Water vapour transport and divergence fields will be examined in order to investigate relationships between cloud bands and energy fluctuations and transformations over the African region. The methodology to be used is described in the following chapter.

CHAPTER 2

DATA AND METHODS

Introduction

The mean vapour transport and synoptics during wet and dry early, mid, and late summer months and the formation, displacement and dissipation of tropical-temperate troughs, and the energy transfers associated with them, form the basis of this thesis. The sources of the data and the analysis applied to them in order to investigate and characterize these important weather-producing systems are outlined below.

Data Sources and Characteristics

Monthly rainfall data used to define anomalously wet or dry months in the summer rainfall region of the South African interior are district rainfall data supplied by the South African Weather Bureau. Rainfall districts have been compiled based on similarity of annual march of rainfall, topographical features and comparable size (Weather Bureau, 1972).

Monthly rainfall for seven contiguous districts over the summer rainfall interior of South Africa (Fig. 2.1), inclusive of the areas used in the studies conducted by Harrison (1983, 1984, 1986a), have been averaged o give an area mean. Anomalies have been calculated from the long-term area means for the 25-year period 1965-1989, and the wettest and driest months selected for analysis (Table 2.1).



Figure 2.1: Upper air stations used for the climatological study. The rainfall region used in the study is indicated by shading.

No continuous upper air data are available for the entire study period from a single source, thereby necessitating use of various data sets. Mean upper air data for a 20-year period (1965-1984), including monthly means of vector winds and dewpoint temperatures at 850, 700, 600, 500, 400, and 300 hPa, were obtained from *Monthly Climatic Data for the World* (United States Department of Commerce, various dates) for all 22 stations in the southern African region with good data availability for the period (Fig. 2.1). The European Centre for Medium Range Weather Forecasts (ECMWF) III-b Global Analysis Data Set, consisting of daily 12:00 UT data, has been used for the period 1980 to 1989. The ECMWF datasets are therefore used independently throughout the study to calculate daily as well as transient values of various parameters and to compare

Table 2.1. Significantly wet and dry Octobers, Decembers and Januaries over the summer rainfall region of South Africa. Significance levels at better than the 95 per cent level and 90 per cent level are indicated by double and single asterisks respectively.

WET			DRY		
Month	Year	Rainfall (mm)	Month	Year	Rainfall (mm)
October	1988	117**	October	1981	33 *
October	1976	100**	October	1989	32 *
October	1969	100**	October	1973	31 *
October	1982	97**	October	1975	31 *
October	1985	91**	October	1968	27**
October	1986	88**	October	1980	13**
October	1984	78 *	October	1965	13**
December	1975	135**	December	1982	33**
December	1985	106 *	December	1984	32**
December	1966	105 *	December	1972	31**
December	1973	99 *	December	1965	31**
December	1981	99 *			
January	1974	178**	January	1988	66 *
January	1976	172**	January	1983	66 *
January	1967	172**	January	1973	59**
January	1981	163**	January	1984	49**
January	1978	145 *	January	1968	47**
January	1972	139 *	January	1969	37**
January	1975	138 *			

these values with the 25-year means obtained using the United States Department of Commerce dataset. Although the ECMWF data field underestimates eddy transport due to model smoothing, an underestimation of eddy transport is preferable to an overestimation, especially in the tropics where eddy transport is relatively unimportant.

Details of tropical-temperate troughs and their associated cloud bands have been obtained from NOAA2 and NOAA5 polar orbiting satellite imagery (published by the Environmental Data Service of the United States Oceanic and

Atmospheric Administration). The cloud band has to fulfil the following criteria to be classified as a tropical-temperate trough (Harrison, 1986a; Kuhnel, 1989). It must:

i) have its origin equatorward of 20°S,
ii) have a length of at least 25°,
iii) have a maximum width of 5°, and
iv) have a more or less homogeneous texture.

The tropical-temperate troughs have been categorized according to the classification of Harrison (1986a), with particular emphasis being placed on major cloud bands, as they are the systems most likely to result in precipitation over the central interior of southern Africa (Harrison, 1984).

Monthly means of outgoing longwave radiation (OLR) on a 5°x5° grid, from the NOAA satellite AVHRR, are also available and have been used to identify areas of convective activity in the mean and for anomalously wet/dry months. Although the OLR data were for a 10 year period, they include four wet and four dry Octobers (out of seven wet and dry), two wet and two dry Decembers (out of five wet and four dry), and two wet and two dry Januaries (out of seven wet and six dry), and it was decided that they represent a fair sample of the population and could thus be used to indicate areas of convection during anomalously wet and anomalously dry years during that period.

Wind vectors were resolved into zonal and meridional components, with westerly zonal components positive and *northerly meridional components positive.* Several thermodynamic parameters were calculated from the available data in order to examine the characteristics of water vapour over southern Africa.

Methodology

Thermodynamics

Data limitations have necessitated the implementation of two methods for calculating specific humidity. In the absence of relative humidity from the Monthly Climatic data set, specific humidity has been obtained using the method described in McGee (1971) to derive vapour pressure (E) from dewpoint temperature (T_d)(Appendix A) using

$$E = 6.11 \times 10^{(7.5T_d/237.3 + T_d)} \tag{2.1}$$

The specific humidity was then calculated using E from

$$q = 623 \times E/(p - 0.377E) \tag{2.2}$$

where E is vapour pressure, Td is dewpoint temperature and p the pressure. Relative humidity, given in the ECMWF dataset, has been used to calculate vapour pressure directly from the relationship

$$\frac{E}{E_s} = RH \tag{2.3}$$

Precipitable water, defined as the amount of surface rainfall which would result were all the moisture in an atmospheric column condensed and rained out (Harrison, 1988), was calculated as follows:

$$W = g^{-1} \int_{850}^{300} q dp \tag{2.4}$$

where g is gravitational acceleration, q is mean specific humidity (after Rathor *et al.*, 1989).

The following equations describe the total water vapour transport in the zonal and meridional planes:

$$Q_\lambda = \overline{uq} + u'q' \tag{2.5}$$

$$Q_\phi = \overline{v}\overline{q} + \overline{v'q'} \tag{2.6}$$

(after Hutchings, 1961), where g is gravitational acceleration, q is mean specific humidity, and u and v the mean zonal and meridional wind components respectively. The superscripts () and (') refer to time mean and deviation from the time mean. The first term on the right hand side of equations (2.5) and (2.6), thus refers to the circulation (or advective) transport while the second term refers to eddy transport. The vertically integrated total zonal (Q_λ) and meridional (Q_ϕ) vapour fluxes are obtained by integrating equations (2.5) and (2.6) between 850 hPa and 300 hPa using the trapezoidal rule.

$$Q_\lambda = g^{-1}\int_{850}^{300} \overline{q}\overline{u}dp + g^{-1}\int_{850}^{300} \overline{q'u'}dp \tag{2.7}$$

$$Q_\phi = g^{-1}\int_{850}^{300} \overline{q}\overline{v}dp + g^{-1}\int_{850}^{300} \overline{q'v'}dp \tag{2.8}$$

(after Rosen *et al.*, 1979; Salstein *et al.*, 1983; Rathor *et al.*, 1989).

Vertically integrated total vapour flux is calculated from the equation

$$Q = g^{-1}\int_{850}^{300} \overline{q}\overline{V}dp + g^{-1}\int_{850}^{300} \overline{q'V'}dp \tag{2.9}$$

(after Hastenrath, 1966), where V is the vector mean wind obtained from the equations (after Giles, 1963):

$$V = N^{-1}[(\sum V_u)^2 + (\sum V_v)^2]^{\frac{1}{2}} \tag{2.10}$$

for magnitude, and

$$\tan\alpha = \frac{\Sigma V_v}{\Sigma V_u} \tag{2.11}$$

for direction, where V_u is the zonal component and V_v the meridional component of the wind. The water vapour transport thus obtained from ECMWF and

radiosonde data have also been visually compared to Meteosat water vapour channel photographs (where available) to provide some validation of calculated results.

Water vapour transport may be separated into non-divergent (rotational) and divergent (irrotational) components, and may be expressed in terms of streamfunction (ψ) and velocity potential (χ) following the methods of Salstein *et al.*, 1980; Chen, 1985; Chen *et al.*, 1988; Chen and Tzeng, 1990; Allan, pers comm., 1992). The vertically-integrated vapour flux, Q, is given by

$$Q = Q_\psi + Q_\chi = \hat{k} \times \nabla \overline{\psi} + \nabla \overline{\chi} \tag{2.12}$$

where Q_ψ is the rotational (or non-divergent) part of Q, Q_χ the divergent part of Q, $\hat{k}$ the unit vector, and ∇ the del operator (Salstein *et al.*, 1980). The streamfunction and potential fields from which Q_ψ and Q_χ are related to Q are defined by the relationship

$$\nabla^2 \chi = \nabla \cdot Q \tag{2.13}$$

$$\nabla^2 \psi = k \cdot \nabla \times Q \tag{2.14}$$

where ∇^2 is the Laplacian operator, $\cdot$ the dot product, and $\times$ the cross product.

The ψ and χ fields are obtained from the solution of the following equations:

$$-\nabla^2 \chi = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} - \frac{v \tan \phi}{r} \tag{2.15}$$

$$\nabla^2 \psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + \frac{u \tan \phi}{r} \tag{2.16}$$

where u is the zonal component and v the meridional component of the wind, r the radius of the earth, and ϕ the latitude. The non-rotational and non-divergent components of vertically integrated total (Q), circulation ($\overline{Q}$) and eddy (Q') water vapour transport have been calculated following the method adopted by Chen (1985) and Chen and Tzeng (1990). The sign convention is that transport is cyclonic around ψ maxima and anticyclonic around ψ minima in the Southern

Hemisphere. Convergence (positive χ) at lower levels is usually accompanied by divergence (negative χ) at upper levels. This implies ascending vertical motion in intermediate levels (see Appendix D). Divergent transport is toward higher values of χ and is perpendicular to the contours (Knutson and Weickmann, 1987). The divergent component of water vapour is also related to the water vapour budget through the equation

$$\nabla^2 \overline{\chi} \approx \overline{E} - \overline{P} \tag{2.17}$$

where E is evaporation and P is precipitation. Equation (2.17) is therefore an indicator of water vapour sources (evaporation exceeds precipitation) and sinks (precipitation exceeds evaporation) (Salstein *et al.*, 1980; Chen *et al.*, 1988). A more complete derivation of the velocity potential and streamfunction equations as well as the boundary correction technique is addressed in Appendix B.

The link between convergence of water vapour, cumulus convection and diabatic heating (Chen, 1985; Chen *et al.*, 1988) has necessitated the inspection of total latent heat for mean wet and dry early, mid, and late summer months. Latent heat in the atmosphere has been calculated using following Gordon's (1982) method from

$$Lh = q \times L \tag{2.18}$$

where L = 2500 J/g and is the latent heat of vapourization at 0°C

Energetics

Studies on energetics of a limited region have been studied by, among others, Smith (1969), Norquist *et al.* (1977), Brennan and Vincent (1980), Robertson and Smith (1983), Michaelides (1987) and Rajamani and Sikdar (1989). In these studies it has been emphasised that the available potential energy refers to the contribution of the area to the global available potential energy (Michaelides, 1987) and that the conversion of energy does not preclude the possibility of production of a form of energy within the region at the expense of any other form of energy outside the region (Smith, 1969). Energy budget calculations have been

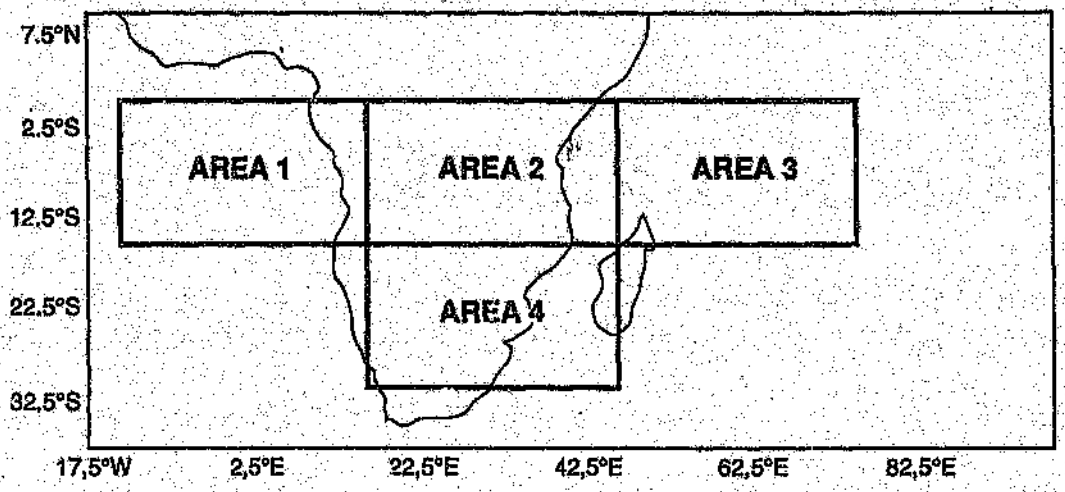

Figure 2.2: The areas of study for energetics and the conversions thereof.

performed for regions 15° of latitude wide and 30° of longitude in length. Four regions have been chosen on the basis of geographical homogeneity: one bounded by the 15°W and 15°E meridians and the 0° and 15°S latitudes over the tropical Atlantic Ocean; one over the tropical Indian Ocean (45°E - 75°E, 0° - 15°S); one over tropical Africa (15°E - 45°E, 0° - 15°S); and one over subtropical southern Africa (15°E - 45°E, 15°S - 30°S) (Fig. 2.2). Horizontal integrations have been performed over the areas using the averaging operators following the method of Meunch (1965), Reiter (1969) and Brennan and Vincent (1980), where

$$[(\ )] = \frac{1}{\lambda_e - \lambda_w} \int_{\lambda_w}^{\lambda_e} (\ )\, d\lambda \tag{2.19}$$

is used to calculate the zonal average, and

$$\overline{(\ )} = \frac{1}{\sin \phi_n - \sin \phi_s} \int_{\phi_s}^{\phi_n} [(\ )] \cos \phi \, d\phi \tag{2.20}$$

the area average. The symbols ϕ_n and ϕ_s represent northern and southern latitude of the area respectively and λ_e and λ_w the eastern and western longitude of the area respectively.

In order to expand the available potential and kinetic energies into zonal and eddy components, the following definitions have been used:

$$( )' = ( ) - [( )]$$

for deviation from zonal mean, and

$$( )^* = [( )] - \overline{( )}$$

for deviation from the area mean (Oort, 1964; Brennan and Vincent, 1980).

The four energy terms are therefore

$$A_z = \int_{p_2}^{p_1} \frac{T^{*2}}{2\sigma} dp \tag{2.21}$$

$$A_e = \int_{p_2}^{p_1} \frac{T'^2}{2\sigma} dp \tag{2.22}$$

$$K_z = \frac{1}{2g} \int_{p_2}^{p_1} [u^2] - [v^2] dp \tag{2.23}$$

$$K_e = \frac{1}{2g} \int_{p_2}^{p_1} (u'^2 - v'^2) dp \tag{2.24}$$

where T is temperature, g is gravitational acceleration and σ the static stability parameter

$$\sigma = g\left[\frac{R_d T}{C_p p} - \frac{\partial T}{\partial p}\right] \qquad (2.25)$$

C_p is specific heat, R is the gas constant and p is atmospheric pressure (Brennan and Vincent, 1980). The partial derivative with respect to pressure has been estimated as centred finite differences at midpoint $(\frac{P_1 + P_2}{2})$.

According to Rajamani and Sikdar (1989), energy budget studies cannot be performed reliably over limited areas. The energy conversions are thus calculated to determine the direction of energy conversions between the different forms of energy in order to facilitate a better understanding of the energy processes operating over tropical and subtropical Africa. Data constraints have restricted the energy conversion calculations to:

$$KZ - AZ = -\int_{P_2}^{P_1} \frac{R}{p} \omega^* \overline{T}^* dp \qquad (2.26)$$

$$AE - KE = -\frac{1}{g}\int_{P_2}^{P_1} \frac{R}{p} \omega' \overline{T}' dp \qquad (2.27)$$

where KZ-AZ (CZ) is the conversion between zonal available potential and kinetic energy and AE-KE (CE) the conversion between eddy available potential and kinetic energy.

Statistical methodology.

A number of statistical procedures have been used in analyses on a climatological time-scale. To test whether rainfall in a certain year differed significantly from the 20 year mean, it was necessary to test for autocorrelation and normality in order to determine whether a parametric or non-parametric significance test could be used. Autocorrelation was tested using the Durbin-Watson d-statistic; normality was tested using the Shapiro-Wilk W-statistic (SAS, 1982). Results of the tests for the October, December and

January rainfall showed near-normal distributions. Consequently, it was decided to use the Z-test for single observations to assess if an individual year differed significantly from the 25 year mean. Significantly wet and dry years were selected as those differing from the mean at better than the 90 per cent level.

Mean vertically-integrated meridional and zonal vapour transport for anomalously wet and anomalously dry Octobers, Decembers and Januaries were tested for significant differences for selected stations in southern Africa. Since the data were not normally distributed, it was decided to use the non-parametric Mann-Whitney U-test to determine significant differences between zonal as well as meridional vapour transport in wet and dry Octobers, Decembers and Januaries.

Linear relationships between variables have been examined using Pearson product-moment or Spearman rank correlation. Although Ramage (1983) has cautioned against the use of correlation in climatology, Lindesay (1988a) and Lyons (1991), among others, have demonstrated the usefulness of such techniques as statistical indicators of relationships for which physical explanations must be sought. As with the Durbin-Watson and Shapiro-Wilk tests, correlations have been calculated using the Statistical Analysis System (SAS) software package.

Harmonic analysis was performed on the 20-year monthly means of precipitable water for selected stations to establish if annual, semi-annual, or any other cycles exist for water vapour over the African subcontinent. Harmonic analysis is the process of fitting Fourier series to data and calculating the amplitudes and phase angles of the waves which describe an array of data, usually a time series in terms of a series of sine functions (Rayner, 1971). The variance of any time series about its mean value can be broken down into the components contributed by each frequency element along its length (Bennett, 1979). These frequency elements can be described by a number of parameters, namely wavelength, amplitude, and phase, where wavelength is the distance between maximum, amplitude the relative height of the maximum, and phase the distance between the first maximum and the origin (Bennett, 1979). The actual curve is therefore described by a series of sine functions with different wavelengths,

amplitudes and phase angles (Bennett, 1979), such that the variate X_t at time t is given by

$$X_t = \overline{X} + \sum_{k=1}^{n/2} a_k \sin\left(\frac{2\pi kt}{N} + \phi_k\right) \qquad (2.28)$$

where $\overline{X}$ is the mean of the series X_t (t=0 ,...,n-1) and a_k denotes the amplitude of the kth harmonic with phase angle ϕ_k (Tyson, 1969). The maximum number of harmonics is given by N/2. The amplitude ak and phase angle ϕ_k are calculated from:

$$a_k = (p^2k + q^2k)^{\frac{1}{2}} \qquad (2.29)$$

$$\tan \phi = \frac{pk}{qk}$$

where

$$pk = \frac{2}{N} \sum_{t=0}^{N-1} Xt \cos \frac{2\pi kt}{N} \qquad (2.30)$$

$$qk = \frac{2}{N} \sum_{t=0}^{N-1} Xt \sin \frac{2\pi kt}{N} \qquad (2.31)$$

Each of these functions (harmonics-k) is then assessed for the order of importance in describing the actual curve. This is done by calculating the variance contributed by each harmonic to the total variance,

$$\frac{a^2k}{2\sigma^2x} \qquad (2.32)$$

to give the relative importance of each harmonic in describing the fluctuating data. The phase angles are then converted to calendar dates (McGee and Hastenrath 1966).

All data manipulation and calculations were performed on the IBM 3081-K32 and SUN SPARCstation IPC at the University of the Witwatersrand, Johannesburg. Contouring has been performed using the SURFER plotting package.

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The calculations and methods described in this chapter provide the basis for the study of the water vapour characteristics and the limited area energetics over southern Africa and adjacent oceans. The results obtained from these calculations form the remainder of the thesis.

CHAPTER 3

WATER VAPOUR CONTENT

Introduction

The moisture content of the air is the most important parameter in the tropical atmosphere (Krishnamurti, 1979; Gaffen *et al.*, 1991), with the release of latent heat the primary thermal source in the tropics (Riehl and Malkus, 1958; Riehl, 1979). The zonal variation of latent heat release is the primary driving mechanism of the tropical circulation (Krishnamurti *et al.*, 1973; McIlveen, 1986; Hack and Schubert, 1990; Hack *et al.*, 1989), forcing zonal as well as meridionally orientated circulation cells. Precipitable water has also been found to play a major role in driving the 30 to 50-day oscillation in the upper troposphere. These thermally direct circulations, associated with the Indian monsoon, are coupled to the divergent component of water vapour, with convergence at the surface and divergence aloft (Chen *et al.*, 1988). The latent heat provides a feedback mechanism to enhance and maintain the divergence. Latent heat also serves to increase baroclinicity in mid-latitudes when transferred there from the tropics (Robertson and Smith, 1983; James and Anderson, 1984), due to the generation of eddy available potential energy by diabatic heating (Rao and Rajamani, 1972).

The effect of water vapour in the atmosphere is also more direct. Water vapour content (precipitable water) of the atmosphere, its variability and the relationship with rainfall have been studied in Europe (Angouridakis, 1977), North America (Reitan, 1960; Hastenrath, 1966), South America (Adedokun, 1983; Rathor *et al.*, 1989) and extensively in West Africa (Ojo, 1970; Adedokun, 1978; Anyadike, 1979, 1981). Strong relationships have been found to exist between precipitable water and precipitation over West Africa (Anyadike, 1979, 1981; Adedokun, 1983), where correlations of up to +0.88 have been found to

occur between the parameters over the Sahelian region (Anyadike, 1979; Adedokun, 1983).

In the southern African region, mean atmospheric water vapour content has been investigated over South Africa (McGee, 1970, 1986), as has the inter-annual variability (McGee, 1978). The relationship between precipitable water and rainfall has also received attention (Harrison, 1988). No simple relationship has been found to exist between precipitable water and rainfall over South Africa, although higher rainfall has been found to accompany raised moisture concentrations (Harrison, 1988). Rainfall has been found to occur only above a certain threshold value of precipitable water, with maximum rainfall within a certain value of precipitable water (Harrison, 1988). Increases in precipitable water have also been found to decrease static stability over South Africa on rain days (Harrison, 1988).

Precipitable water, apart from its role in supplying moisture for rainfall, has also been found to be important in the role it plays in forcing anomalies in the meridional Walker circulation over the tropics. Variations in latent heat release on an hemispheric scale force a reversal of the Walker Circulation over Africa (Harangozo and Harrison, 1983; Harrison, 1986a), causing an eastward shift of the convective regions and associated tropical lows and cloud bands from southern Africa (Harrison, 1986a), resulting in drought (Lindesay, 1988a). Apart from its role in forcing tropical circulations, latent heat transport has also been considered important in maintaining the energy balance (McIlveen, 1986). Poleward transport of latent heat in the southern African region has been thought to occur in cloud bands, with resultant increases in the baroclinicity in mid-latitudes (James and Anderson, 1984; Harrison, 1986a).

The importance of water vapour content over Africa and the variability thereof has been documented. In this chapter, the annual, inter-annual and daily variability of this important parameter and the latent heat associated with it will be further investigated.

Precipitable Water

The intra-annual variation of mean monthly precipitable water for stations over southern Africa has been examined using harmonic analysis. Results obtained reveal that the predominant variation of precipitable water over Africa south of approximately 15°S is best described by an annual cycle with percentage explained variances of approximately 80 to 99 per cent (Fig. 3.1). Further north and west over the tropics the percentage variance on the annual cycle decreases to 50 to 60 per cent over the west coast of tropical Africa (north of 15°S) and to values as low as 15 per cent over equatorial central Africa (Fig. 3.1). The importance of the semi-annual (6-month) cycle of precipitable water is negligible over southern Africa, but the semi-annual cycle is relatively important over the tropical regions where percentage variances range from 25 to 43 per cent (Fig. 3.1). Phase angles, converted to calendar dates following the method of Hastenrath and McGee (1966), indicate a date of maximum precipitable water over southern Africa varying from mid-January over the eastern interior and coastal regions to a late-January to early February maximum in the extreme south-west and south, and over Madagascar (Fig. 3.1). This implies a southward and westward shift in maximum precipitable water over the subcontinent as the summer progresses, and conforms with the westward progression of precipitation during the summer season (Tyson, 1986; Van den Heever and Lindesay, 1992).

The annual variation of precipitable water over Africa has been confirmed by the seasonal variation of the spatial distribution of precipitable water (Steyn and Taljaard, 1990). This distribution has been examined from September (early summer) to April (late summer). The early summer study month (October) revealed a precipitable water maximum over tropical west Africa, corresponding with the termination of the West African monsoon. Minima occur along the western and southern coast and interior regions of southern Africa. The mid-summer month of December is characterized by a southeastward shift of the area of maximum precipitable water to over the Zaire Basin with a concomitant decrease over West Africa. Precipitable water increases over subtropical southern Africa with minimum values found over the south-western semi-arid to arid regions of southern Africa. Januaries are characterized by a further southeastward shift of maximum precipitable water such that it occurs over

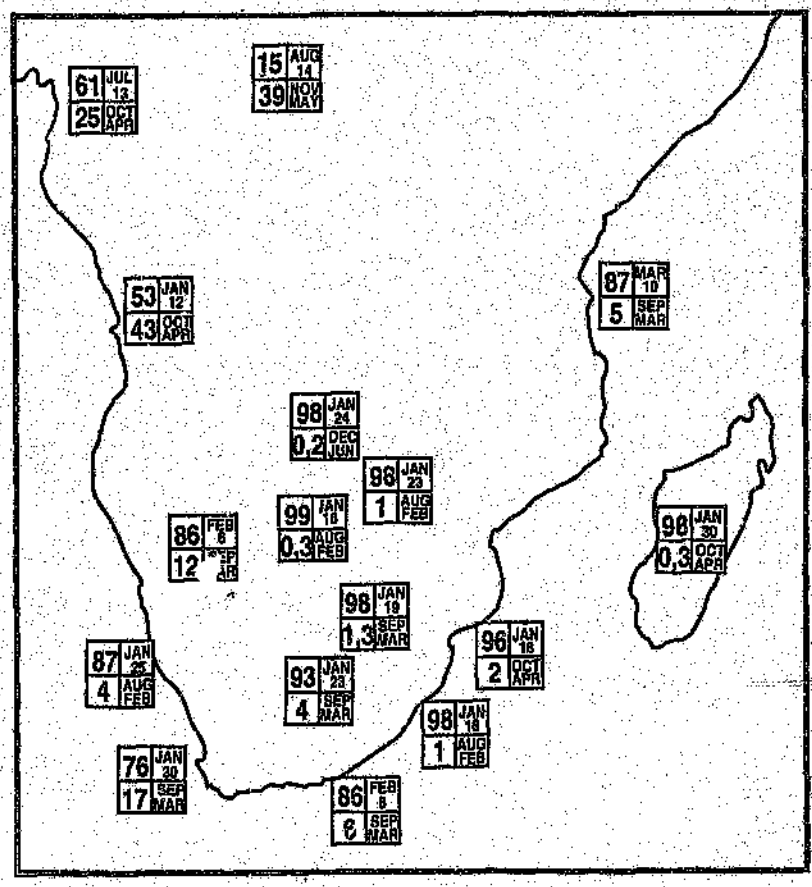


Figure 3.1: The annual and semi-annual cycles of mean precipitable water over Africa. At each station the top left figure denotes the percentage variance of the cycle captured by the first harmonic, and the top left figure the date of maximum amplitude. The lower left and right figures denote the percentage variance captured by the second harmonic and the dates of maximum amplitude respectively.

subtropical and tropical Africa centred on an area around 15°S and 30°E. Minimum values of precipitable water again occur over the southwestern regions of southern Africa.

Precipitable water has also been examined for the months of October, December and January that were significantly wetter or drier than the long-term (25-year) average. Comparison of precipitable water for wet and dry early summer months reveals a general decrease in precipitable water over the continent south of 10°S between wet and dry months of October (Fig. 3.2a, 3.2b).

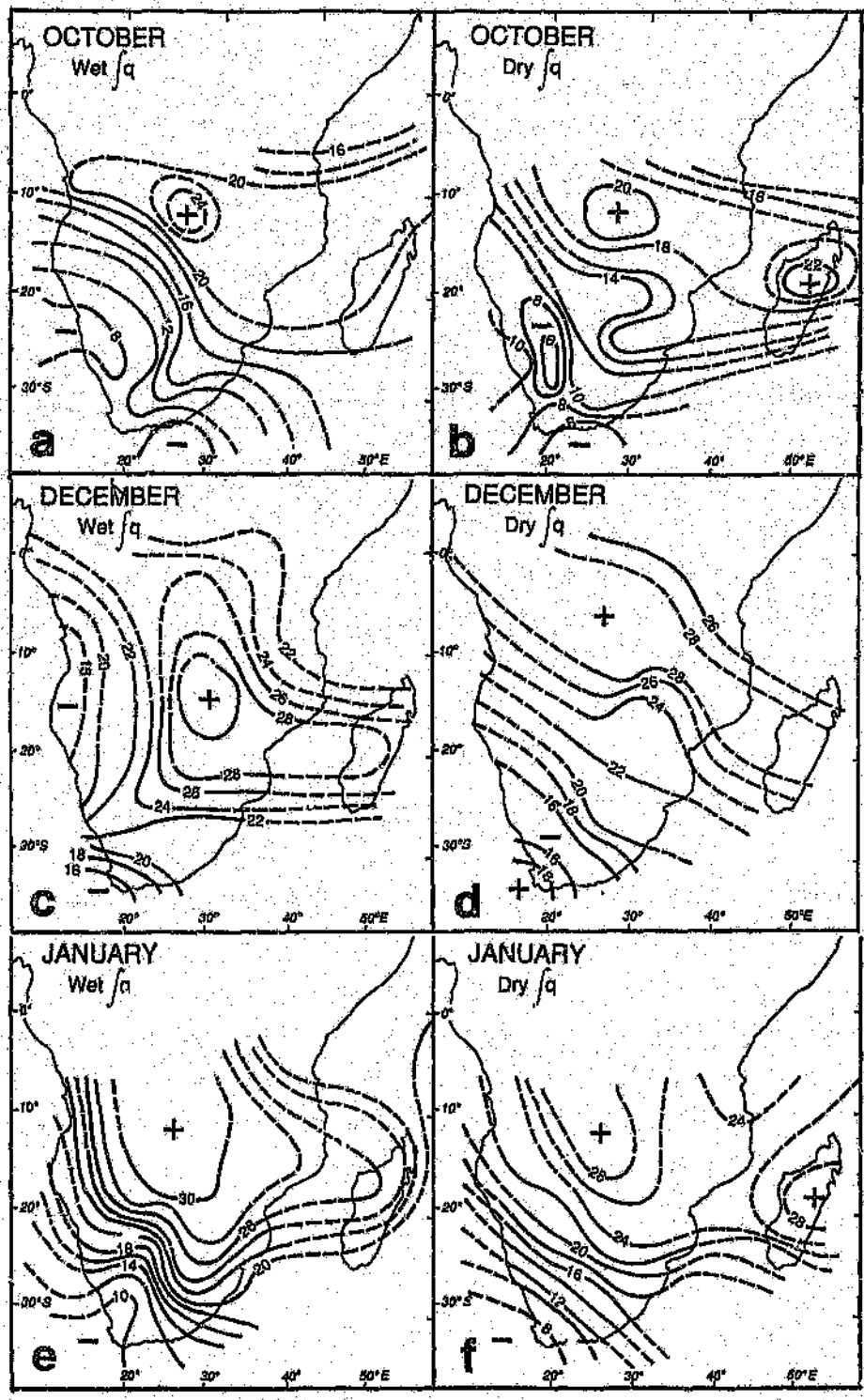


Figure 3.2: Mean precipitable water over southern Africa for: a) Mean wet Octobers; b) mean dry Octobers; c) mean wet Decembers; d) Mean dry Decembers; e) mean wet Januaries; f) mean dry Januaries. Plus signs indicate areas of relative maxima, and minus signs areas of relative minima. Units are mm.

Extremely low precipitable water occurs over the south-western interior regions (20°-30°S, 20°E) with an area of high precipitable water over Madagascar during dry early summers (Fig. 3.2a, 3.2b). In December precipitable water increases over southern Africa and subtropical Africa from early summer (Fig. 3.2c, 3.2d). Dry Decembers are characterized, as in early summer, by decreased precipitable water content over subtropical Africa from mean wet Decembers (Fig. 3.2c, 3.2d). Comparison of wet and dry late summers also reveal a decrease of precipitable water in dry summers. A secondary maximum occurs over Madagascar in dry summers whereas in wet summers a single maximum occurs over subtropical and tropical southern Africa (Fig. 3.2e, 3.2f). This may reflect the eastward shift of the cloud bands during dry years (Harrison, 1986a). Of note is the steep moisture gradient across South Africa extending from the north-east to south-west (20-35°S and 15 - 35°E) during wet Januaries, a feature less well defined during dry years (Fig. 3.2e,f).

Variability of Precipitable Water

Time-longitude sections of precipitable water have been constructed for a latitude band at 10°S and 25°S. These Hovmoller plots have been constructed in order to determine the nature of the convective systems over tropical and subtropical southern Africa (as in Jury *et al.*, 1991). The months analyzed below have been selected on the basis of the cloud bands that had occurred during those months. A wet early and a wet and dry mid and late summer month thus form the basis of the investigation into the variability of precipitable water over tropical and subtropical southern Africa.

The time-longitude plot for precipitable water (850-300 hPa) for the wet October of 1986 at 10°s reveals a quasi-stationary mode throughout the month, with high precipitable water over the western interior and low precipitable water over the northern Mozambique Channel (Fig. 3.3a). Small eastward pulses of moisture can be seen over the western part of the continent. Further south at 25°S, a similar quasi-stationary mode exists, although values of low precipitable water display a more transient nature in moving from west to east (Fig. 3.3b).

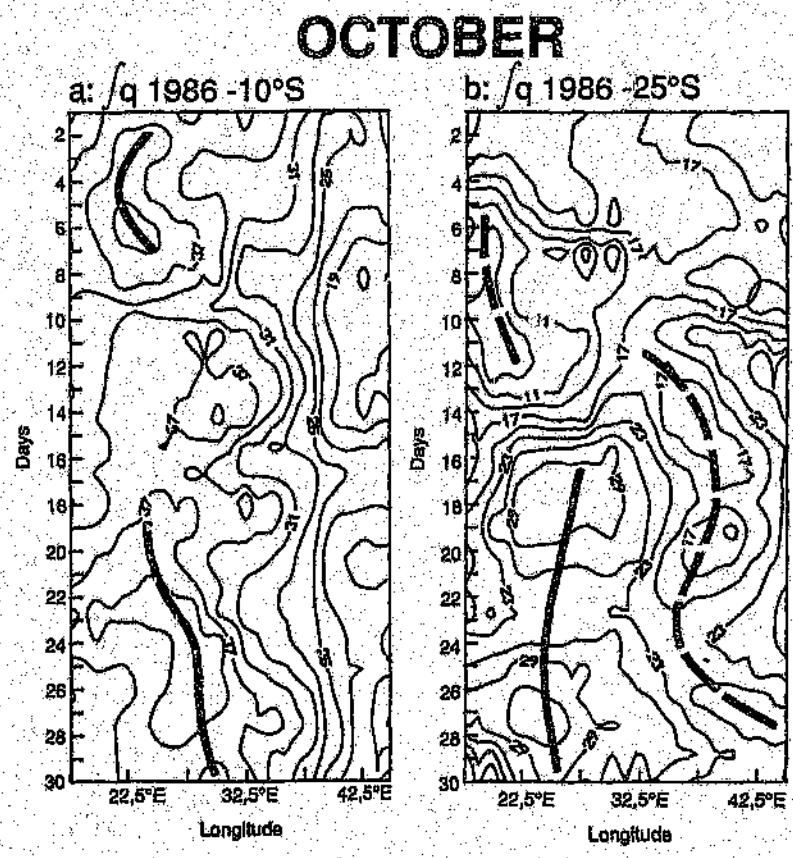


Figure 3.3: Time-longitude plot of precipitable water for October 1986 at: a) 10°S and b) 25°S. Units are mm; contour interval is 3mm. Heavy black lines indicate trends of relative maximum and dashed lines trends of minimum precipitable water.

The precipitable water Hovmoller analysis for a dry December at 10°S identifies relatively stationary maxima, with maximum values at approximately 27°E (Fig. 3.4a). The wet December (1985) reveals a quasi-stationary maximum of precipitable water situated further west over tropical Africa at approximately 25°E (Fig. 3.4b). Further south at 25°S the dry and wet Decembers are both characterized by a stationary convective system over the interior of South Africa (Fig. 3.4c, 3.4d). Values of precipitable water are generally lower during the dry

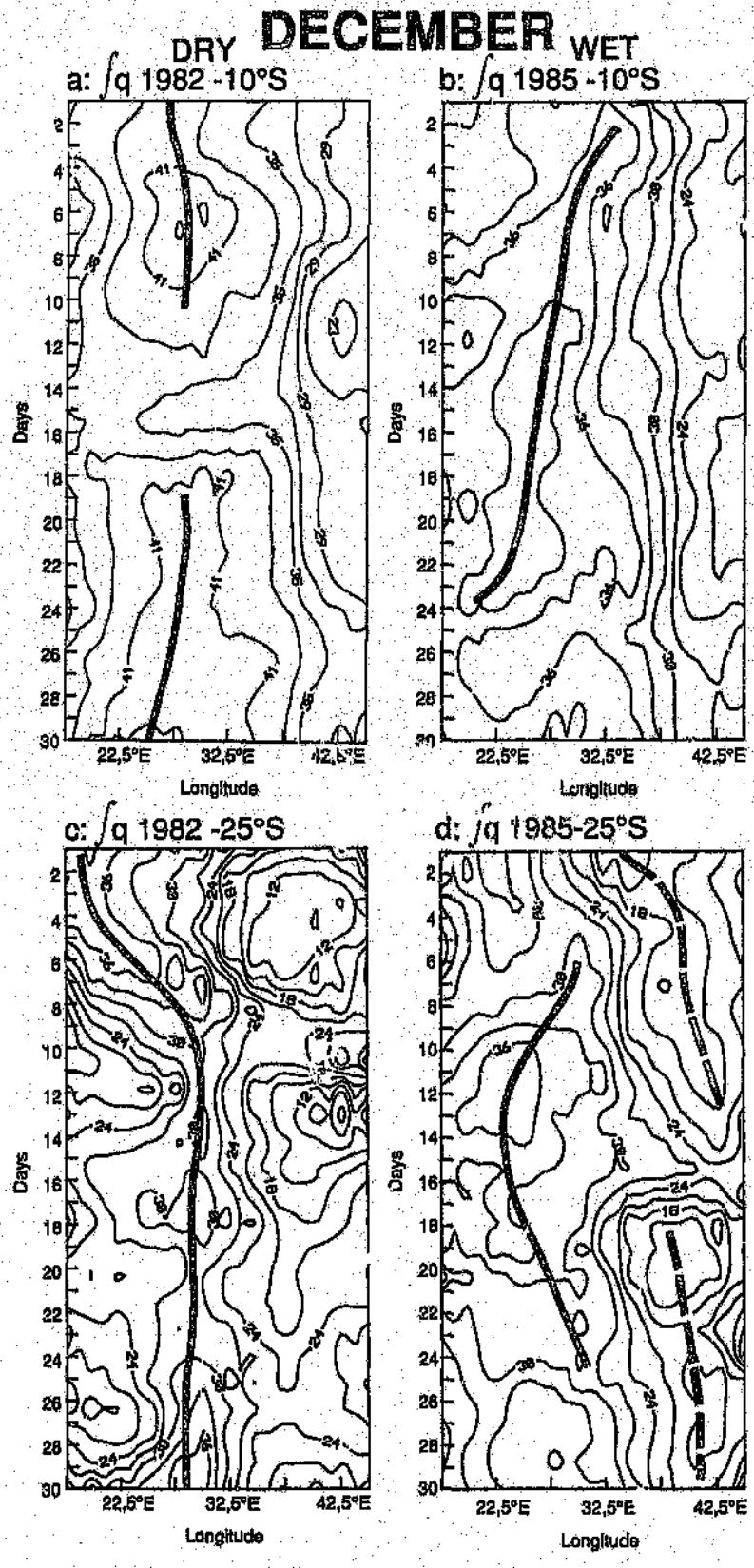


Figure 3.4: Time-longitude plot of precipitable water for: a mean dry December (1982) at a) 10°S and c) 25°S; and for a mean wet December (1985) at b) 10°S and d) 25°S. Units are mm; contour interval is 3mm. Heavy black lines indicate trends of relative maximum and dashed lines trends of minimum precipitable water.

month and the minimum values over the eastern region (corresponding with the southern Mozambique Channel) shift westward by approximately 2°.

Time-longitude sections have also been constructed for a relatively dry (1980) and a wet (1981) late summer month. At 10°S, both the wet and the dry January show a quasi-stationary mode of preciptable water although the region of maximum precipitable water occurred marginally to the east during the dry year (Fig. 3.5a,b). This was due to the intrusion of dry air over the western regions of tropical Africa, as between 12 and 15 January 1980 (Fig. 3.5a). The time-longitude sections at 25°S differ between the wet and the dry month. During the dry January convective systems (indicated by precipitable water maxima, as in Jury *et al.*, 1991)) were transient in nature, moving across southern Africa in an easterly direction (Fig. 3.5c), whereas during the wet January the convective systems were quasi-stationary over the subcontinent (Fig. 3.5d).

Latent Heat

Previous work undertaken on tropical-temperate troughs over southern Africa suggests that the systems are responsible for the exchange of energy and momentum between the tropics and mid-latitudes (Harrison, 1986a). This hypothesis of poleward energy transfer needs further investigation.

Mean latent heat has been examined for wet and dry early, mid, and late summers over a 10-year period from 1980 to 1989 using ECMWF gridded data. During the early summer, little difference occurs between mean wet and mean dry months. In both the mean wet and the mean dry October, maximum values of latent heat occur over the African tropics (approximately 7000 $J.cm^{-2}$ at 0°, 12 - 32°E) (Fig. 3.6a, 3.6b) in the region corresponding with the maximum precipitable water (cf. Fig. 3.2).

The mean mid-summer (December) latent heat patterns reveal differences between wet and dry years. Wet Decembers are characterized by a southward shift of the area of highest latent heat (8000 $J.cm^{-2}$) to subtropical southern Africa, to the general location of the low pressure system. Inter-tropical

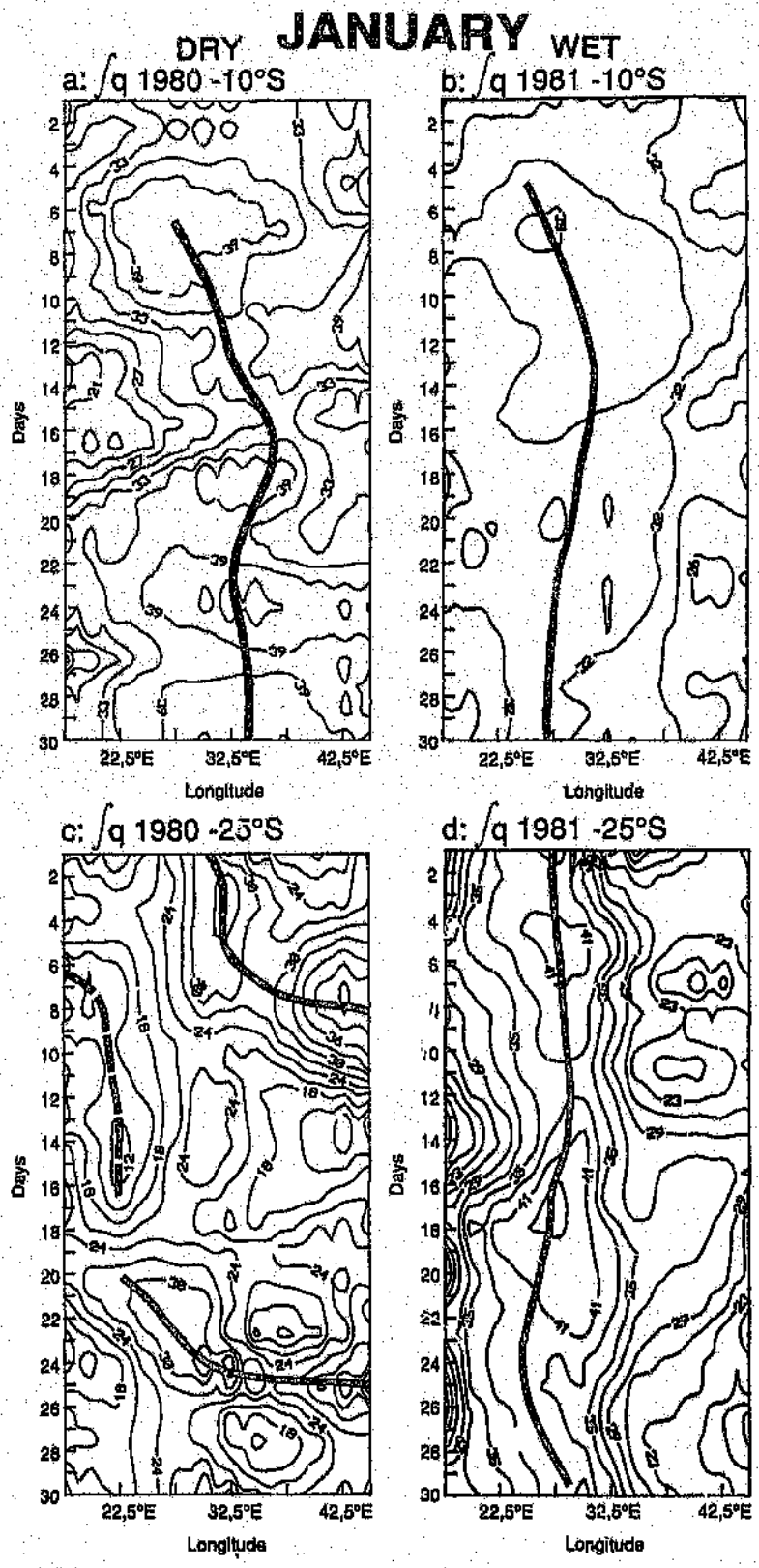


Figure 3.5: Time-longitude plot of precipitable water for: a mean dry January (1980) at a) 10°S and c) 25°S; and for a mean wet January (1981) at b) 10°S and d) 25°S. Units are mm; contour interval is 3mm. Heavy black lines indicate trends of relative maximum and dashed lines trends of minimum precipitable water.

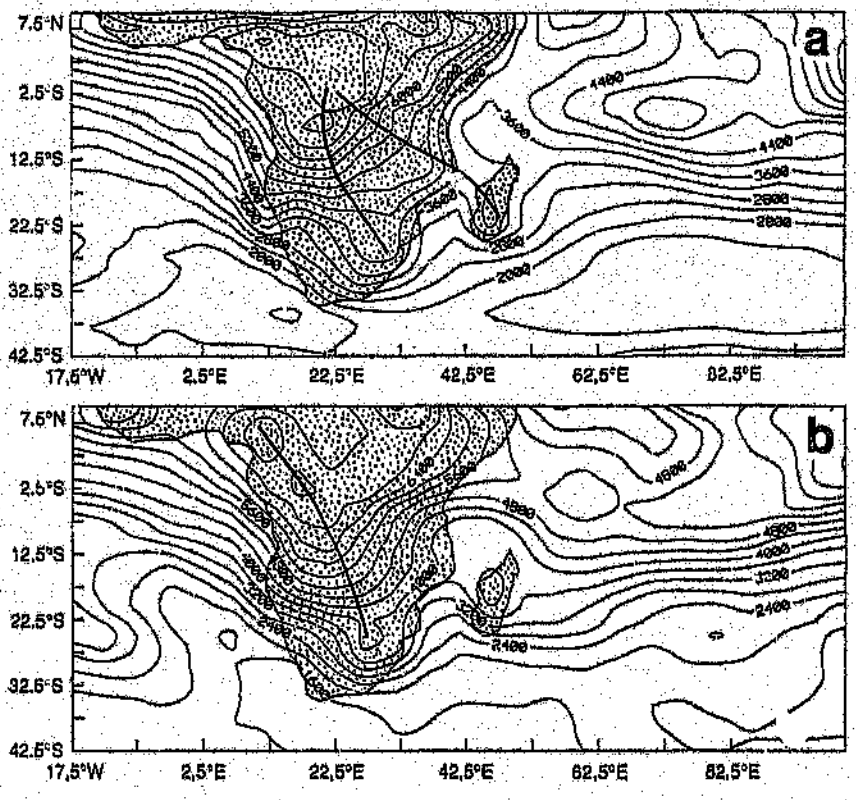


Figure 3.6: Latent heat for: a) Mean wet Octobers; b) mean dry Octobers. Units are $J.cm^{-2}$ and contour interval is 400. Heavy black lines indicate axes of relative maximum latent heat.

Convergence (ITC) (Fig. 3.7a). A tongue of relatively high latent heat extends southward over central southern Africa from the region of maximum to the north. A second tongue extends across Madagascar to the South Indian Ocean (Fig. 3.7a). Mean dry Decembers are different from wet Decembers in that the tongue of relatively high latent heat extending southward over southern Africa shifts eastward to lie over the extreme eastern regions of South Africa (Fig. 3.7b).

The late wet summer (January) latent heat patterns reveal an area of maximum latent heat over subtropical southern Africa with a tongue of relatively high latent heat extending southeastward from it over the Indian Ocean (Fig. 3.8a). In contrast, in dry late summers a northwestward shift of the area of

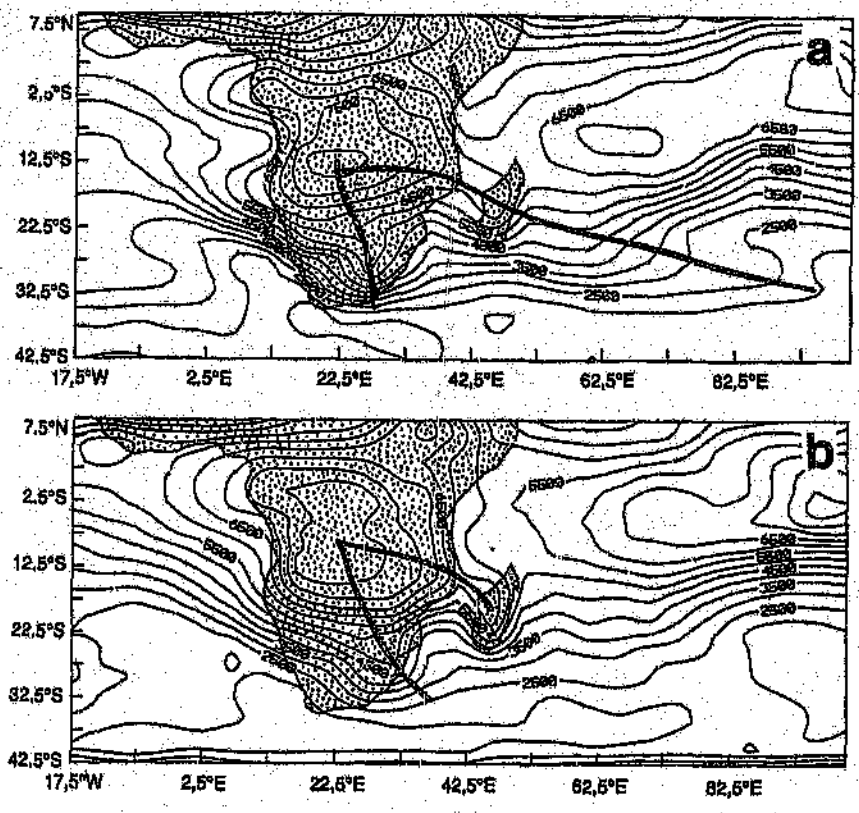


Figure 3.7: Latent heat for: a) Mean wet Decembers; b) mean dry Decembers. Units are $J.cm^{-2}$ and contour interval is 500. Heavy black lines indicate axes of relative maximum latent heat.

maximum latent heat takes place towards central Africa. The southward extending tongue of high latent heat shifts eastward to occur over Madagascar, with a secondary tongue over South Africa (Fig. 3.8b).

Latent Heat and Tropical-temperate Troughs

Tropical-temperate troughs and their associated major cloud bands have been visually selected from satellite data. Using the criteria necessary for a cloud mass to be classified as a cloud band (as outlined in Chapter 2, after Harrison, 1986a; Kuhnel, 1989), a number of case studies have been selected.

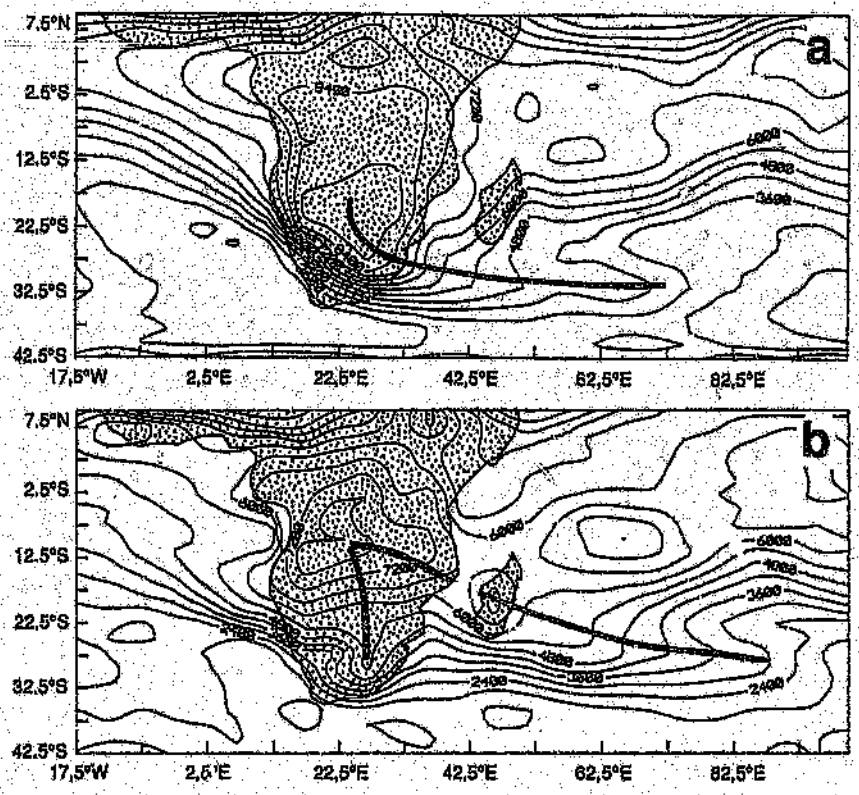
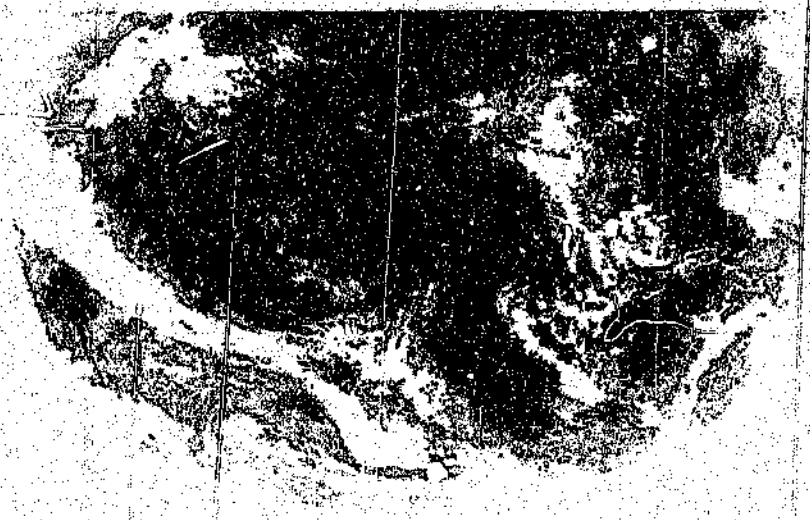


Figure 3.8: Latent heat for: a) Mean wet Januaries; b) mean dry Januaries. Units are $J.cm^{-2}$ and contour interval is 600. Heavy black lines indicate axes of relative maximum latent heat.

The early summer case study is for the period 15 to 17 October 1986. Pre-cloud band conditions on 15 October (Plate 3.1a) were characterized by considerable convection over Africa south of the Equator. By 16 October the cloud band had formed (Plate 3.1b), linking the tropical African latitudes with the mid-latitudes to the southeast. Although *disconnection* of the cloud band occurred on the following day over the South Indian Ocean/southern Mozambique Channel, large masses of cloud persisted over the eastern parts of southern Africa (Plate 3.1c).

The spatial distribution of latent heat for 15 October 1986 (Plate 3.1a and Fig. 3.9a) reveals high values of latent heat over tropical and subtropical Africa with

a



b





Plate 3.1: Meteosat infra-red satellite imagery for: a) 15 October; b) 16 October; and c) 17 October 1986 of image is 1200 UT.

a southeastward projecting tongue of high values over South Africa. A secondary area of high latent heat occurs off the southeast coast of Madagascar. The region of high latent heat had moved southward by 16 October (cloud band conditions), such that values of latent heat in excess of 700 $J.cm^{-2}$ existed over the eastern parts of South Africa (cf. Plate 3.1b and Fig. 3.9b). The tongue of high latent heat had extended further southeastward over the South Indian Ocean to approximately 42°S, 65°E (Fig. 3.9b). This tongue of high latent heat protruding southeastward corresponds closely with the cloud band position (cf. Plate 3.1b). The latent heat distribution for the following day reveals an eastward shift of the southeastward protruding high latent heat to a position from southeastern Madagascar to 42°S, 75°E. (cf. Plate 3.1c and Fig. 3.9c). This is again reflected in the eastward shift of the cloud band. High latent heat values continued over South Africa, but did not extend further south as on the previous day.

Cloudband case studies have been conducted for wet and dry Decembers. A cloud band occurred between 4 and 7 December 1982 (Plate 3.2). The pre-cloud

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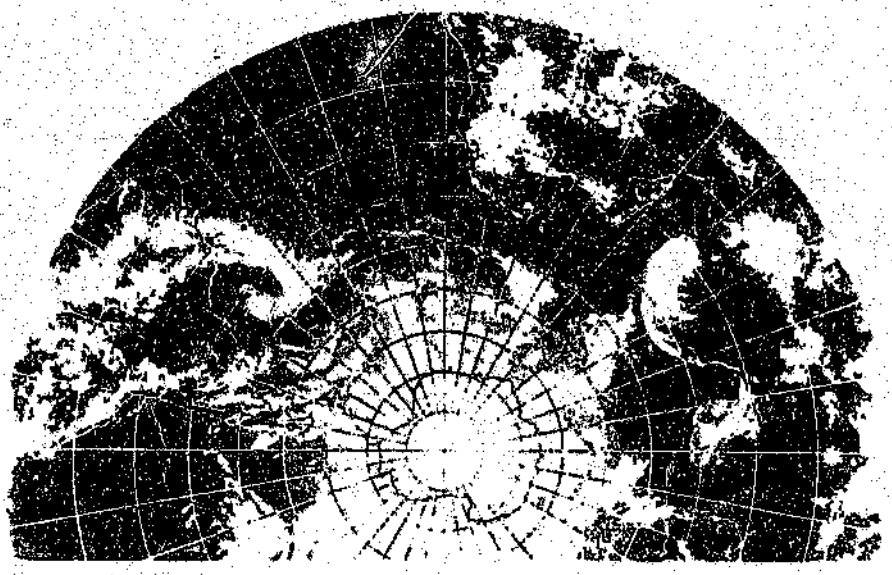

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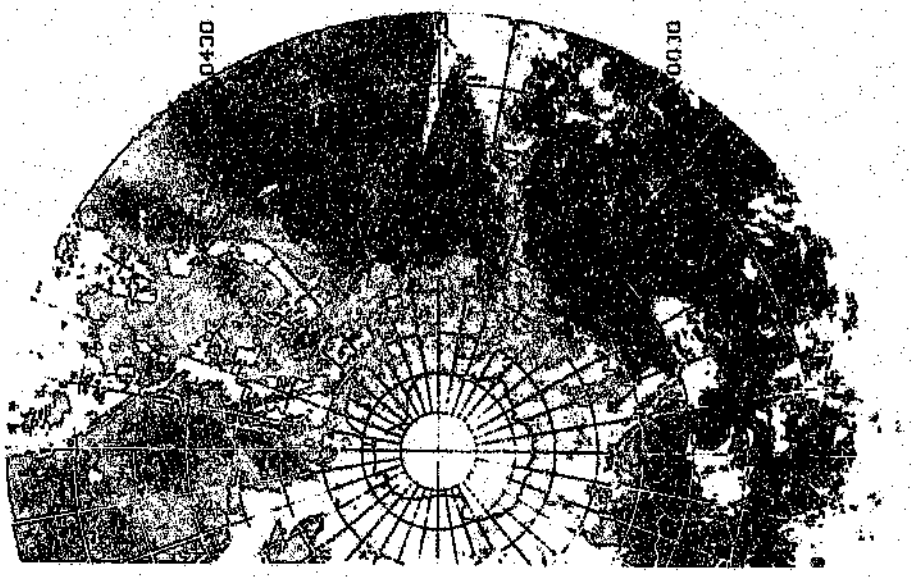


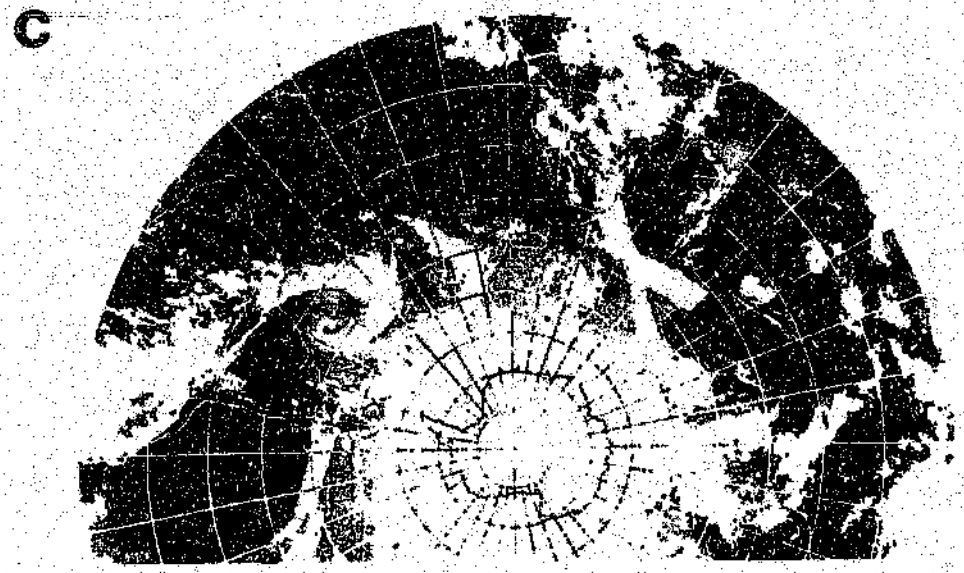
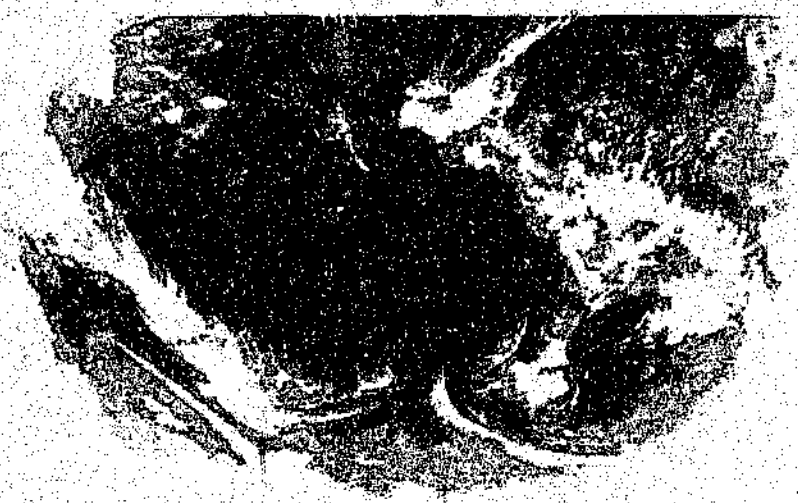


Plate 3.2: NOAA infra-red satellite imagery for: a) 4 December; b) 5 December and c) 7 December 1982. Time of image indicated on plate in UT.

band conditions of 4 December were characterized by convection over tropical and subtropical southern Africa (Plate 3.2a). By 5 December the cloud band had formed over central South Africa, linking the convection over tropical Africa to the mid-latitudes (Plate 3.2b). The cloud band had shifted eastward and partially dissipated by 7 December, leaving the study area over South Africa relatively cloud-free (Plate 3.2c). A cloud band during a wet December occurred from 1 to 3 December 1985 (Plate 3.3). Extensive convection occurred over tropical and subtropical Africa on 1 December, with a truncated cloud band extending southward from the tropical convection to approximately 35°S, 20°E (Plate 3.3a). A well-developed cloud band was visible on the following day, extending from the cloud mass over tropical and subtropical eastern Africa southward to the mid-latitudes (Plate 3.3b). By 3 December, the cloud band had been displaced from southern Africa to the southern Mozambique Channel (Plate 3.3c).

The spatial distribution of latent heat reveals that high latent heat extended from tropical Africa southward in the general region of the cloud band during 1

a



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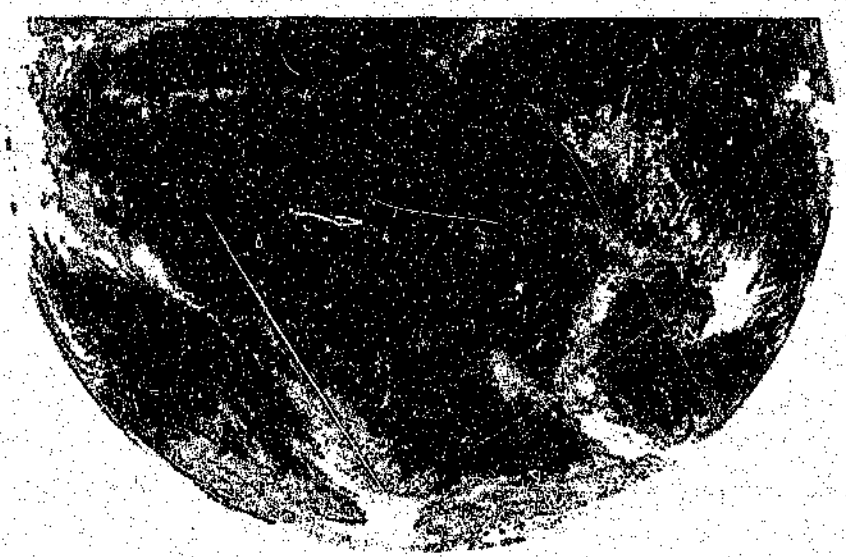


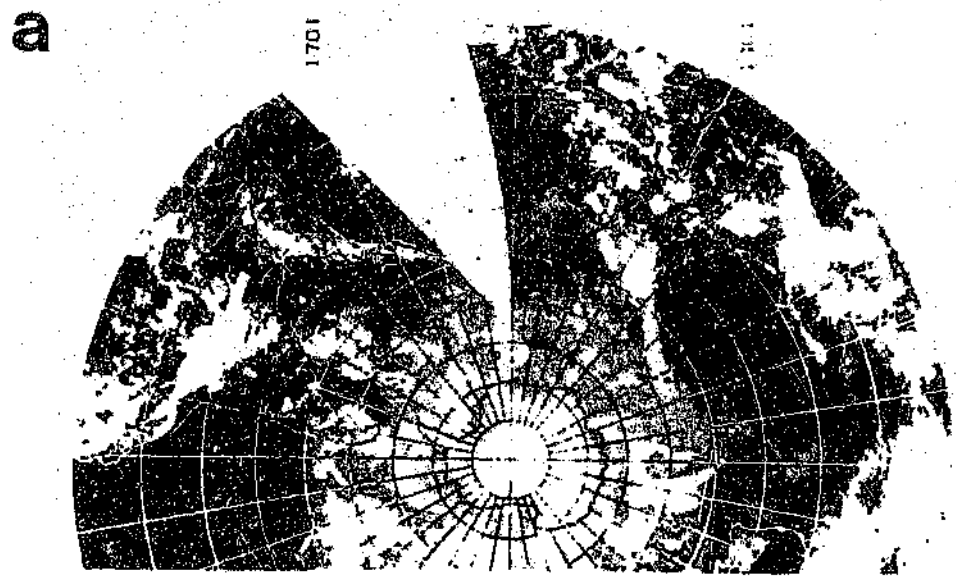
c



Plate 3.3: Meteosat infra-red satellite imagery for: a) 1 December; b) 2 December and c) 3 December 1985. Time of image is 1200 UT.

to 3 December 1985 (cf. Plate 3.3 and Figs 3.10a-c). Increased area and magnitude of latent heat occurred over southern Africa from the pre-cloud band day to the cloud band day on 2 December (Fig. 3.10a, b). A decrease in the latent heat (from 8000 to 7000 $J.cm^{-2}$) occurred over South Africa from 2 to 3 December, indicating a partial dissipation of the cloud band (cf. Plate 3.3c). A further reduction in latent heat occurred on 4 December (not shown here), when the cloud band had dissipated.

The cloudband case studies have also been conducted for late summer (January): one for a dry January case (1980); and one for a wet January case (1981). The dry January cloud band occurred from 6 to 8 January 1980. The pre-cloud band day was (as in early summer) characterized by extensive tropical cloud over southern Africa (Plate 3.4a). By the following day (7 January) the cloud band had formed, linking the tropics (at approximately 15°S, 35°E) to the mid-latitudes (Plate 3.4b). It had partially dissipated and moved eastward by 8 January, to overlie Madagascar, leaving South Africa cloud-free (Plate 3.4c). The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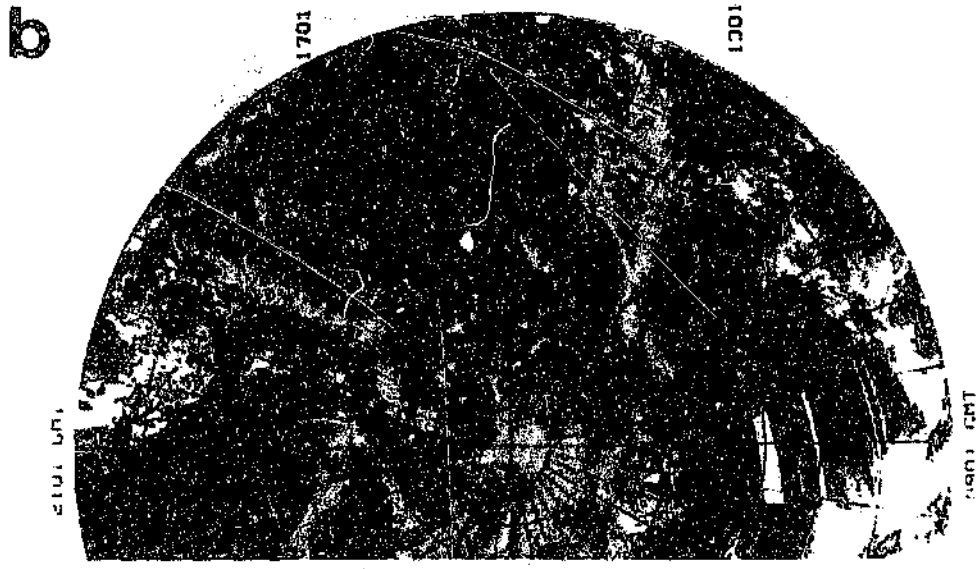
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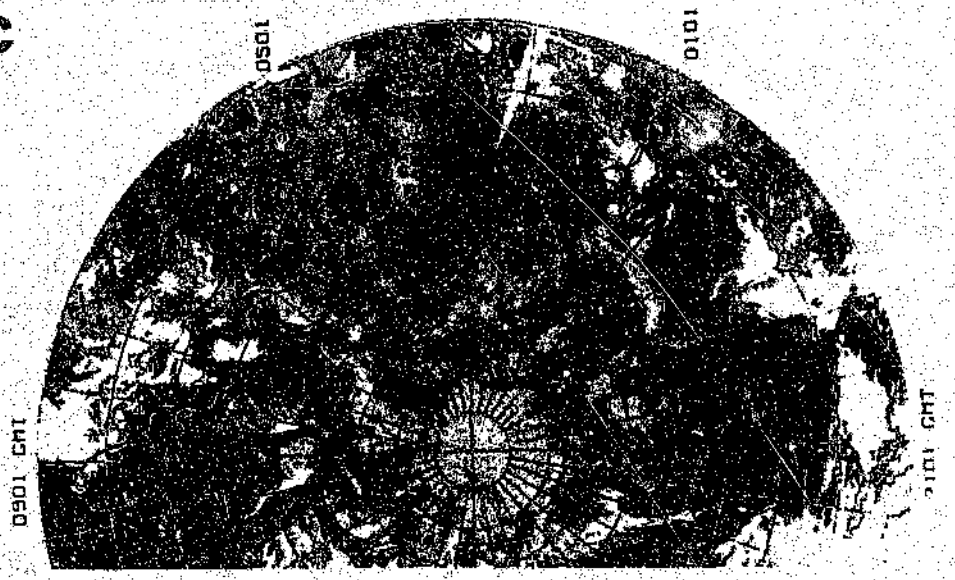

Plate 3.4: NOAA infra-red satellite imagery for: a) 6 January; b) 7 January and c) 8 January 1980. Time of image indicated on plate in UT.

wet January cloud band case study was that of 22 to 27 January 1981. Extensive tropical cloudcover again occurred on the pre-cloud band day on 22 January (Plate 3.5a). The cloud band had formed by the following day (23 January), extending southeastward across South Africa from the tropical convection to the mid-latitudes (Plate 3.5b). Partial dissipation of the cloud band occurred on 24 and 25 January (not shown), but by 26 January it had re-formed, extending southward across central southern Africa (Plate 3.5c). Partial final dissipation of the cloud band had occurred by 27 January (Plate 3.5d).

The spatial distribution of latent heat on 22 January 1981 reveals high values of latent heat over southern Africa, with a maximum of more than 9000 $J.cm^{-2}$ over South Africa (cf. Plate 3.5a and Fig. 3.11a). A tongue of high latent heat extended southeastward to the South Indian Ocean at approximately 42°S, 55°E (Fig. 3.11a). The cloud band conditions of the following day are reflected in the latent heat distribution, with an increased area of high latent heat over South Africa and a tongue extending southeastward over the South Indian Ocean (Fig.

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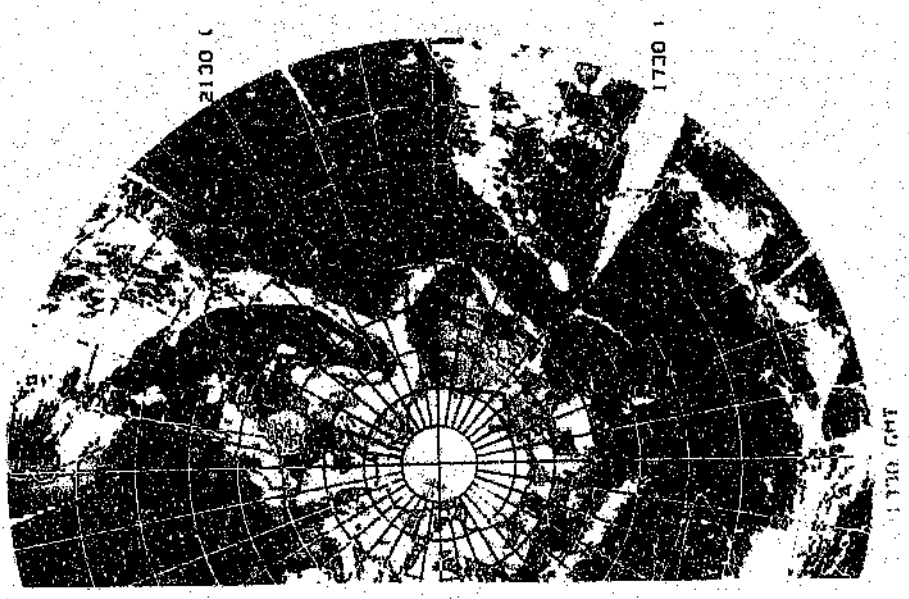

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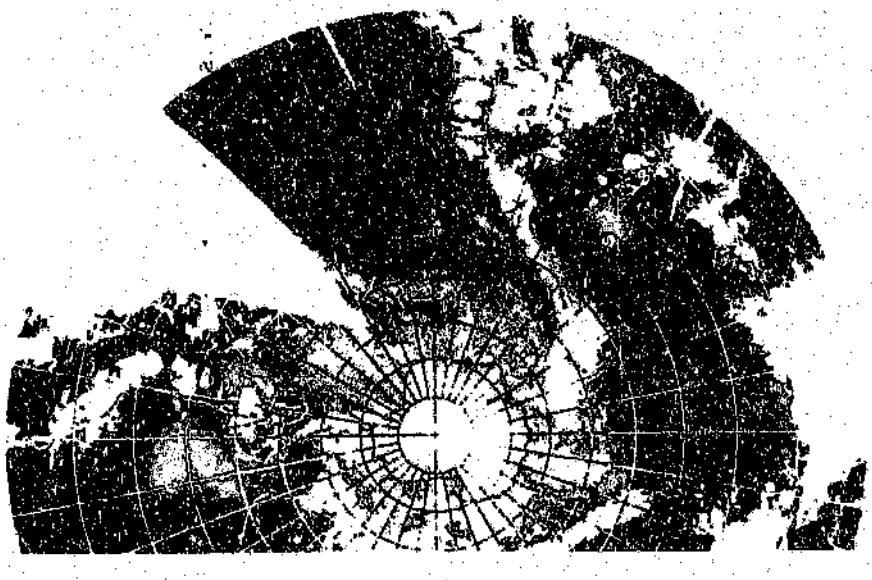

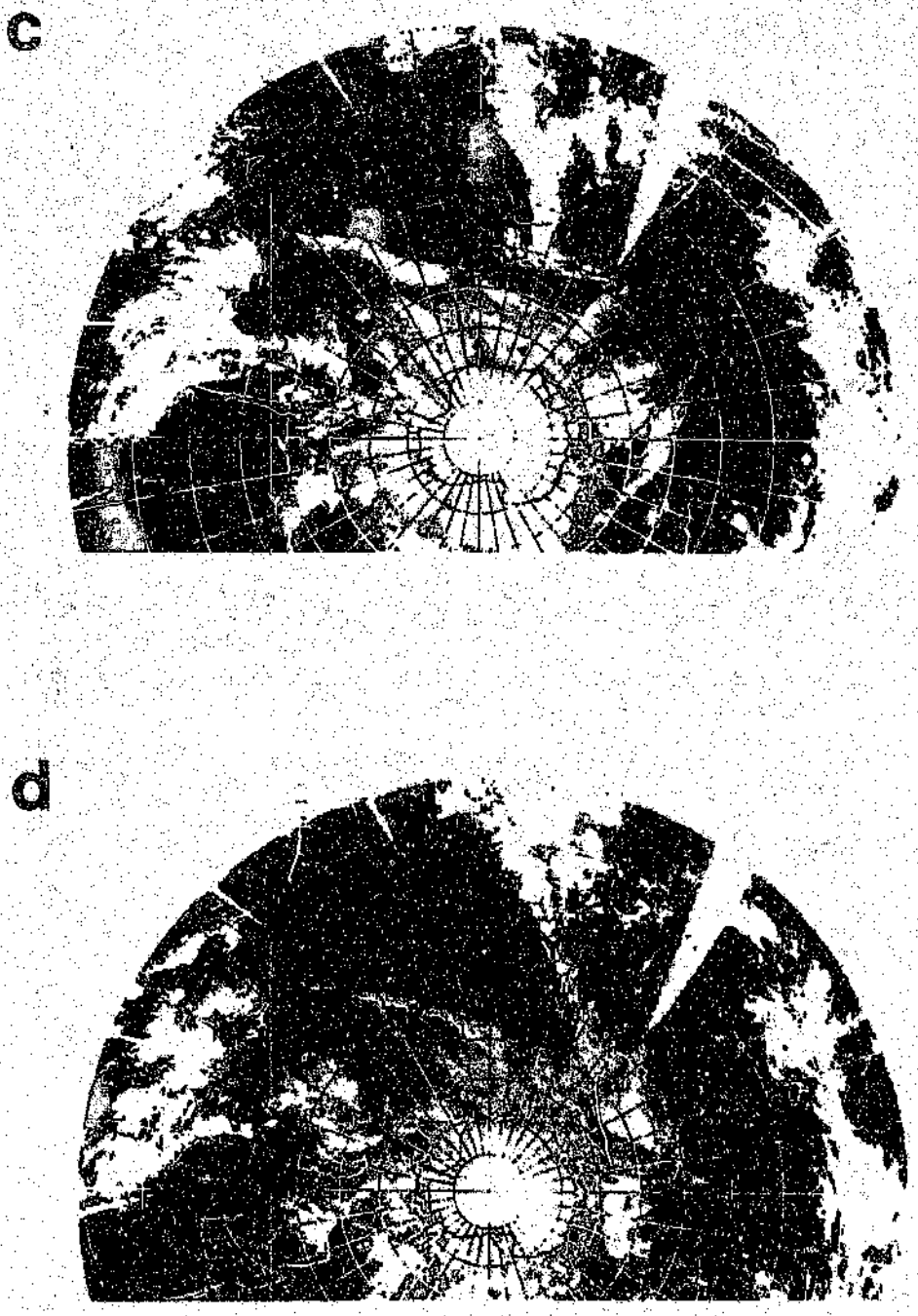

Plate 3.5: NOAA infra-red satellite imagery for: a) 22 January; b) 23 January; c) 26 January and d) 27 January 1981. Time of image indicated on plate in UT.

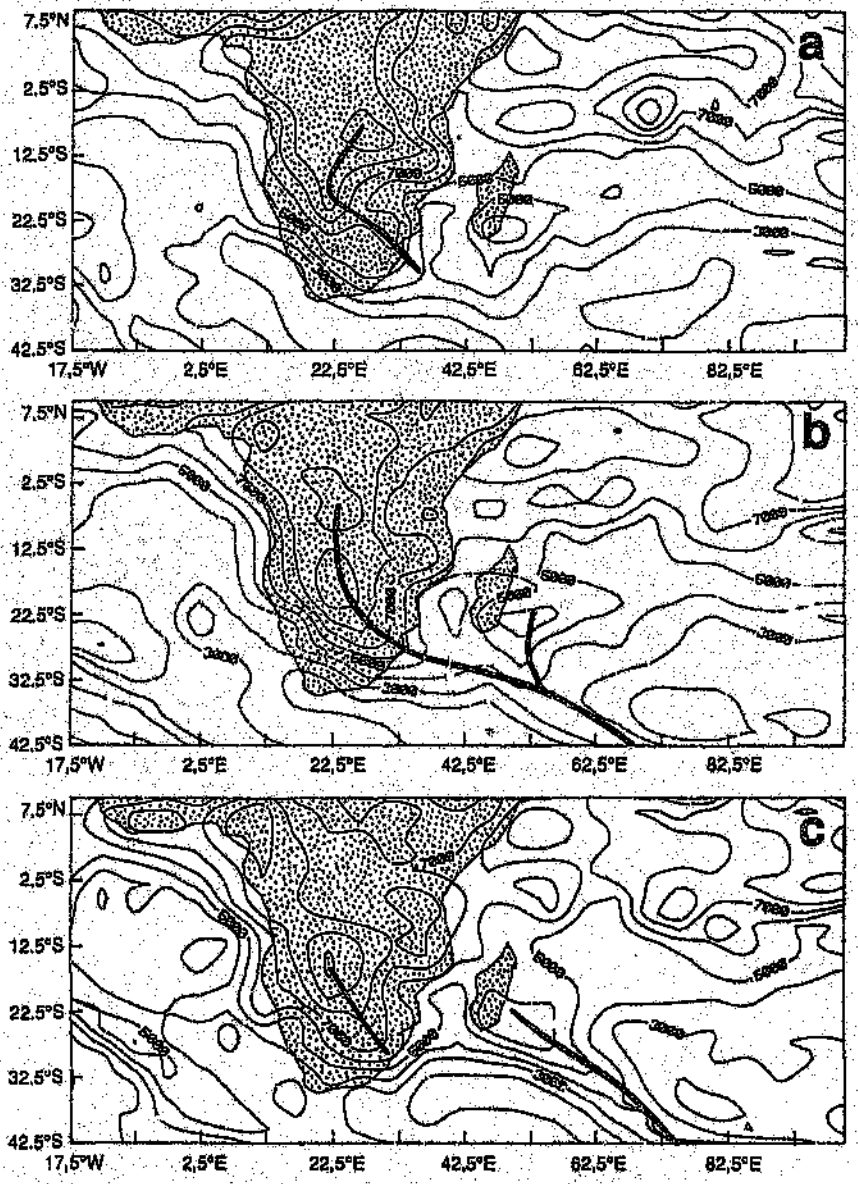

Figure 3.9: Total latent heat for: a) 15 October (pre-cloud band); b) 16 October (cloud band); and c) 17 October 1986 (post-cloud band). Units are $J.cm^{-2}$. Heavy line indicates axis of relative maximum latent heat.

3.11b). The high latent heat areas and southward extending tongue again corresponds closely with the cloud band on 26 January 1981 (cf. Plate 3.5c and Fig. 3.11c). A decrease in the latent heat over South Africa on 27 January reflects the partial dissipation of the cloud band, especially over the continent (cf. Plate 3.5d and Fig. 3.11d).

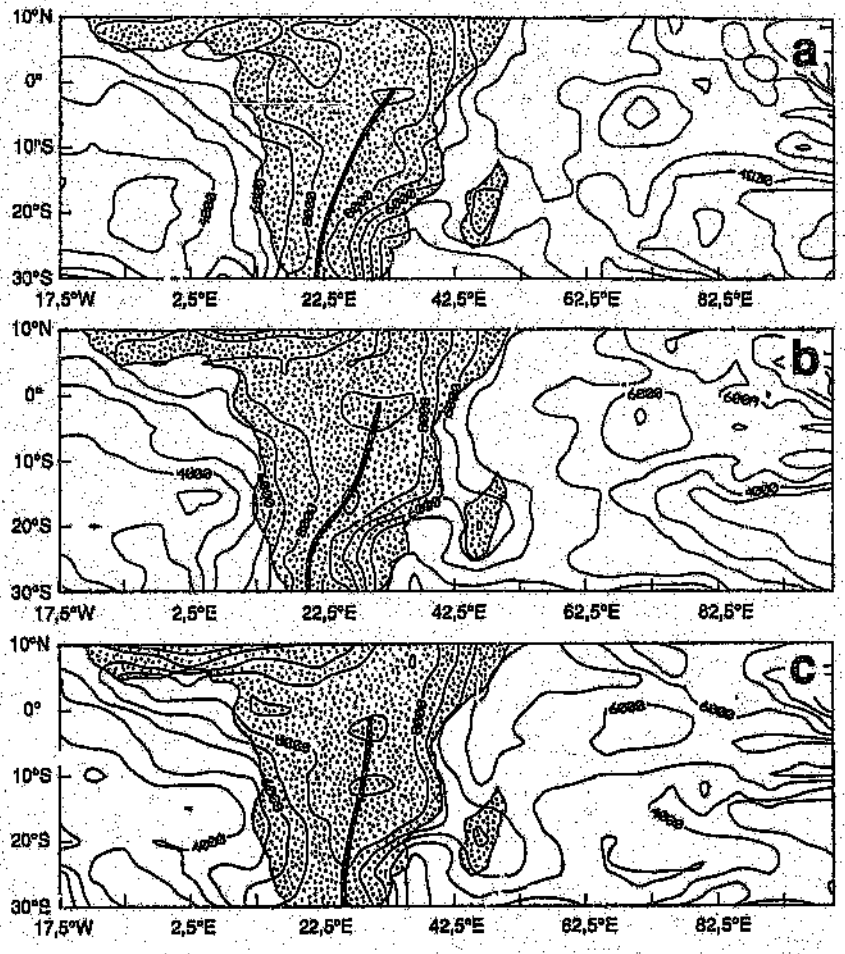

Figure 3.10: Total latent heat for: a) 1 December (pre-cloud band); b) 2 December (cloud band); and 3 December 1985 (post-cloud band). Units are J.cm^{-2}. Heavy line indicates axis of relative maximum latent heat.

Discussion

The water vapour content over South Africa is characterized by a general southeast-northwest decrease in precipitable water (Louw, 1983; Schulze, 1984; Tyson, 1986). The reason for this trend is the escarpment of 3000 m altitude along the eastern seaboard which restricts the advection of moist maritime air inland (McGee, 1986). Corroboration has come from studies showing that 75 per cent of the water vapour content of the air over coastal stations occurs below

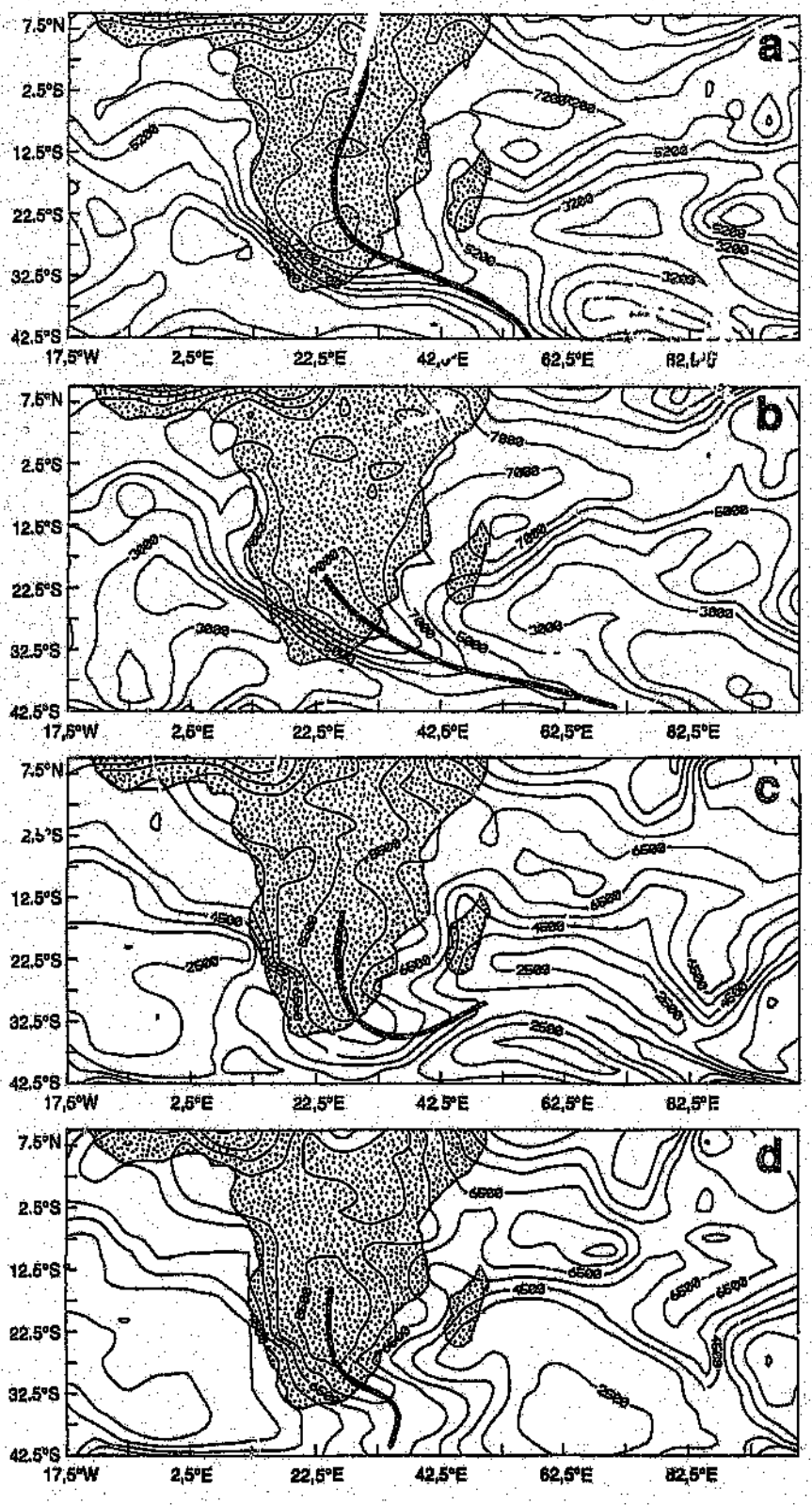

Figure 3.11: Total latent heat for: a) 22 January (pre-cloud band); b) 23 January (cloud band); c) 26 January (cloud band); and 27 January 1981 (post-cloud band). Units are $J.cm^{-2}$. Heavy line indicates axis of relative maximum latent heat.

700 hPa (approximately 3000 m) (Howarth, 1983; McGee, 1986; Theron, 1990). The clear annual march of precipitable water coincides with earlier findings of an annual cycle over South Africa with peaks from mid-January to mid-February (Fig. 3.1) (Louw, 1983; McGee, 1986; Theron, 1990). This precipitable water maxima occur later than temperature maxima, indicating that moisture levels are determined primarily by the nature of the moisture advection (McGee, 1986; Theron, 1990; Theron and Harrison, 1990). Minima of precipitable water over the region coincide with the rainfall minimum during the dry winter season over the central plateau (McGee, 1986). Along the coast, the highest precipitable water occurs in late January to early February when oceanic evaporation is greatest because of maximum sea surface temperatures (Theron, 1990).

Further north, the precipitable water cycle is linked to the thermal cycle, corresponding closely with the thermal maximum (Leroux, 1983), such that the maximum precipitable water occurs with solar apex. A connection may also exist between the movement of the Inter-Tropical Convergence and Zaire Air Boundary (see Fig. 1.2) and precipitable water over subtropical and tropical regions. The significant semi-annual cycle present over tropical central Africa is the result of the biennial migration of the rainfall belt over the region (Krishnamurti, 1979). This is related to the Atlantic monsoon which effects the region between March and October (Leroux, 1983), hence the precipitable water maximum in November and May (Fig. 3.1).

Comparison of the spatial distribution of precipitable water over southern Africa between wet and dry early, mid and late summers reveals a general decrease in precipitable water (in space and magnitude) over southern Africa during dry summers (Fig. 3.2). This reduced precipitable water over subtropical southern Africa corresponds with reduced vapour transport (Peixoto *et al.*, 1981) and increased anticyclonic circulation over the region in dry summer months (Lindesay, 1988a). Increased precipitable water over Madagascar in dry years (Fig. 3.2b-f) conforms with the findings of Jury and Pathack (1991) where correlations of outgoing longwave radiation (OLR) revealed a southwest-northeast dipole over southern Africa (high OLR over southern Africa with low OLR over Madagascar and *vice versa*), indicating a mean tropospheric trough over the Mozambique Channel (Lyons, 1991). This relationship between

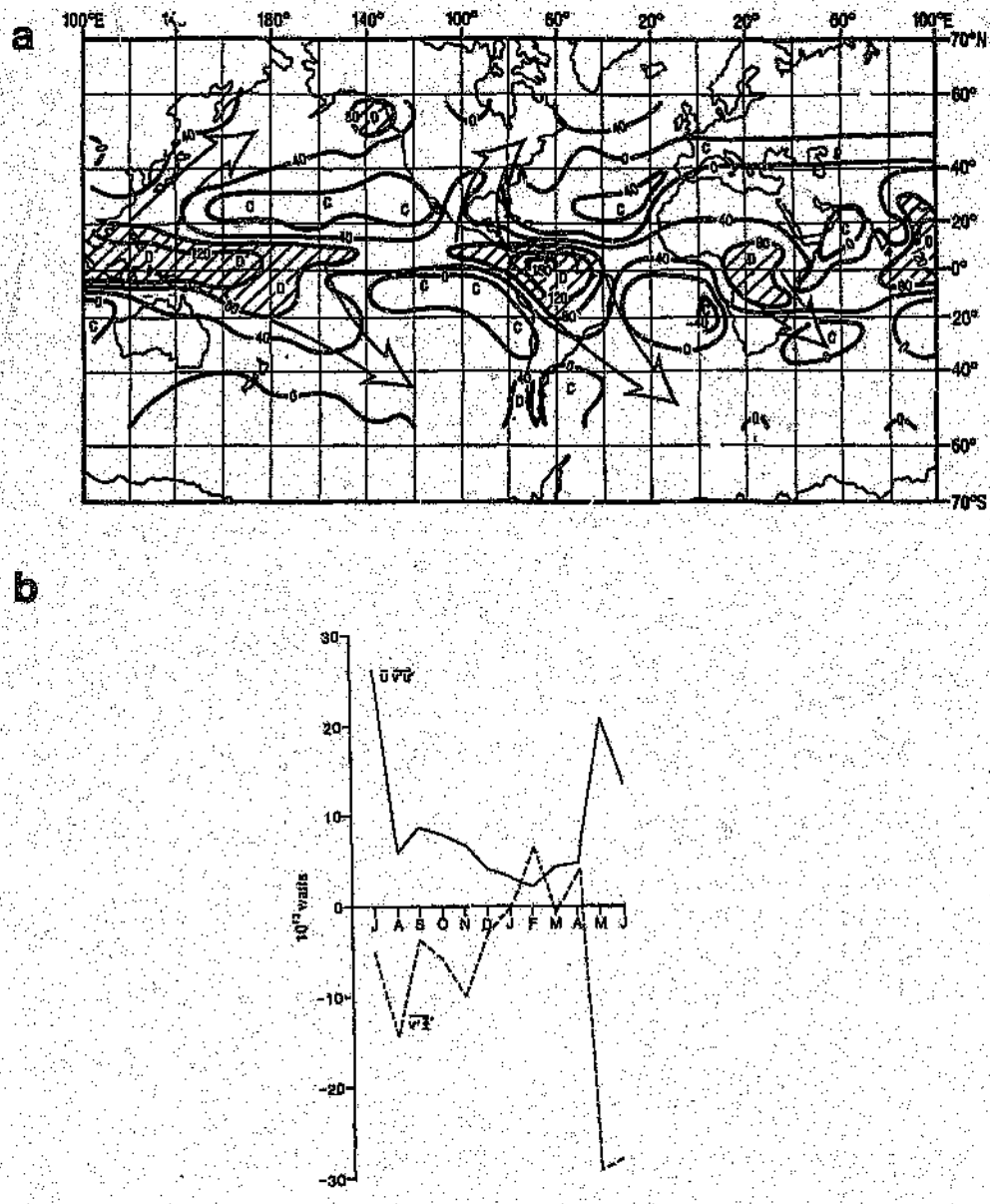

Figure 3.12: a) Divergence of energy in the annual mean atmosphere estimated from satellite by vonder Haar (1968). Units are kcal.cm^{-2}.year^{-1}. Shading indicates major areas of divergence and sources of energy export (modified after Tyson, 1986). b) Mean monthly momentum ($\bar{u}\,\overline{v'u'}$ - solid lines) and geopotential ($\overline{v'\Phi'}$ - dashed lines) fluxes across central South Africa. Poleward fluxes are positive. Momentum and geopotential fluxes of same (different) direction indicate thermal (orographic) forcing (after Harrison, 1986b).

high OLR (low convection) over southern Africa and low OLR (high convection) over Madagascar, coupled with the decreased (increased) precipitable water over southern Africa (Madagascar) corresponds with Harrison's (1986a) findings that cloudbands overlie Madagascar during dry years in southern Africa. The decrease in precipitable water over tropical and subtropical southern Africa is also related to the El Nino-Southern Oscillation phenomenon, which is considered the dominant climatic signal to water vapour in the tropics (Prabhakara *et al.*, 1985; Gaffen *et al.*, 1991). The effects of the Southern Oscillation on the pressure, temperature and wind fields and rainfall variability over southern Africa have been documented (Lindesay, 1988a). Increased rainfall during the high phase of the Southern Oscillation results mainly from enhanced latent heat release in the convection over tropical Africa, which in turn forces a Hadley circulation across southern Africa (Harrison, 1986a). The dominant forcing at low latitudes is diabatic heating (Webster, 1972), resulting in meridional circulation in the tropics (Gill, 1980; Rind and Rossow, 1984; Chen *et al.*, 1989; Hack *et al.*, 1989). The latent heat thus forces a standing wave over the tropics (Peagle *et al.*, 1983; Kalnay and Peagle, 1983) (Fig. 3.12a) when diabatic heating is at a maximum, namely in late summer (Fig. 3.8). Investigation of the Eliassen-Palm relationship over southern Africa has revealed the presence of a thermally forced standing wave in summer, when the relationship does not hold, and an orographically forced wave in the vernal and autumnal transition seasons when the Eliassen-Palm relationship does hold over the subcontinent (Harrison, 1986b) (Fig. 3.12b). Linkages between the upper tropospheric Atlantic wave and convection over southern Africa as hypothesized by Harrison (1986a) may play an important role in modulating early-summer precipitable water over the subcontinent with the leading edge of the wave over Madagascar during mean dry southern African months reflected in the eastward shift of the maximum precipitable water (see Fig 1.7).

Inspection of the total latent heat for mean wet and mean dry Octobers, Decembers and Januaries demonstrates the link between precipitable water and latent heat as well as the inter-seasonal and inter-annual variability of latent heat (Figs 3.6, 3.7, 3.8). Precipitable water and latent heat generally display a poleward shift and increased magnitude from early to late summer (Figs 3.2, 3.8a), pointing to the likelihood of increased tropical influences on the southern African

circulation in mean wet late summers (Gill, 1980; Rind and Rossow, 1984; Harrison, 1986a). The poleward transport of tropical latent heat suggested by Vonder Haar (1968), Webster (1983) and Harrison (1986a) is most apparent in late summer (Fig. 3.8). This latent heat transport is southeastward from the tropical heat source in both mean wet and dry late summers. The transport, inferred by geostrophic approximation, occurs over southern Africa in mean wet months, shifting eastward to occur over Madagascar during mean dry months (Fig. 3.8a,b). This conforms with the eastward shift of the standing wave and cloud band between wet and dry years (Harrison, 1986a; Lyons, 1991; Jury and Pathack, 1991). A similar pattern emerges between wet and dry Decembers (Fig. 3.7a, b), but is absent from the mean October study (Fig. 3.6a, b). This observation corresponds with the contention that inverse frequencies of troughs over South Africa and Madagascar only occur from November to January (Harrison, 1984, 1986a). The relative unimportance of latent heat release in transitional season (when orographically forced waves occur) is reflected in the similarity between the latent heat in mean wet and mean dry Octobers, with the insignificant poleward protrusion of latent heat in both (Fig. 3.6).

Case studies of cloud band sequences conform with the mean latent heat fields and the cloud band studies of Harrison (1986a). Total latent heat for the case studies corresponds closely to the position of the cloudbands in all instances (Plates 3.1 - 3.5 and Figs 3.9 - 3.11), implying a poleward transport of latent heat within the cloud bands (James and Anderson, 1984; Harrison, 1986a). Maximum latent heat occurs furthest south in mean wet years (Figs 3.6 - 3.8) and during cloud band days (Figs 3.9 - 3.11) again conforming with previous hypotheses that cloud bands only form when convection and latent heating is sufficiently far poleward and intense for interaction to occur with the mid-latitude systems (Rind and Rossow, 1984; Harrison, 1986a; Kuhnel, 1989). Dissipation of the cloud band subsequently corresponds with a decrease in the magnitude and spatial extent of the subtropical/tropical latent heat source (Figs 3.9c, 3.10c, 3.11c).

Precipitable water and latent heat release in the atmosphere exert a more local effect on the climate of southern Africa. Besides the role of precipitable water in water availability for rainfall (McGee, 1986; Harrison, 1988), steep moisture discontinuities play a role in thunderstorm development. Such a steep moisture

discontinuity, seen over southern Africa in the mean wet January (Fig. 3.2e), is important for line thunderstorm development over the interior of South Africa (Taljaard, 1958). Atmospheric moisture has also been found to decrease stability (Garstang *et al.*, 1987; Harrison, 1988; Theron, 1990). Mid-tropospheric energy increases as precipitable water increases, such that an isentropic energy profile occurs with precipitable water of 40 mm (Harrison, 1988). This decreased stability results in increased vertical motion and hence convective storm formation. Confirmation of the role of total static energy in rainfall over southern Africa has been obtained from Spearman rank correlations between mid-tropospheric energy and rainfall over the summer rainfall regions of South Africa (Table 3.1). Generally, the most significant positive correlations have been found over Bulawayo (Table 3.1), indicating that increased water vapour in the subtropical mid-troposphere is related to late-summer rainfall over South Africa. Increased static energy in the mid-troposphere is ideal for the development of large-scale convection and may even be indicative of widespread steady-state ascent associated with mean circulations (Riehl and Malkus, 1958; Riehl, 1979; Garstang, pers comm., 1991). Southern African summer rainfall is significantly positively correlated with the total static energy at 500 hPa over Bloemfontein, central South Africa (Table 3.1) and coupled with increased (decreased) meridional geopotential transport in wet late (early) summer indicates a thermally induced circulation in late-summer (Harrison, 1986a, 1986b) (Fig. 3.12b). This conforms with Riehl's (1979) observations that increased upper-tropospheric transport is indicative of a thermally direct circulation. Water vapour therefore not only supplies the moisture for rain, but also contributes toward atmospheric stability and circulation.

The importance of water vapour for the atmosphere over southern Africa has made it essential to investigate daily and inter-annual variations of convective systems. Precipitable water has been used as a proxy for the convective systems (Chen and Tzeng, 1990; Jury *et al.*, 1991). The time-longitude plots for precipitable water have revealed the quasi-stationary nature of convective systems over southern Africa (Figs 3.3 - 3.5), reflecting the contribution of the standing tropospheric waves and lows to the summer rainfall over southern Africa (Jury *et al.*, 1991). During the October and dry January case studies, precipitable water displayed a more transient nature at 25°S, generally moving

Table 3.1: Spearman rank correlation between total static energy and South African summer rainfall in late-summer (20 year period). * indicates significance at better than the 10% level, and ** at the 5% level. For location of stations refer to Fig. 2.1.

	700 hPa	500 hPa
Station	r	r
Dar Es Salaam	0.01	0.29
Kabwe	0.33	0.07
Bulawayo	0.69 **	0.70 **
Windhoek	0.26	0.07
Pretoria	0.03	0.42
Alexander Bay	0.51 **	0.19
Bloemfontein	0.36	0.53 **
Durban	0.27	0.32
Cape Town	0.47 *	0.37

from west to east (Figs 3.3b, 3.5c). This reflects the northerly location of the westerly winds and associated transient system activity during early-summer and dry late-summers (Harrison, 1986a, 1986b). The precipitable water generally increases during cloud band days at 25°S and at 10°S in December and January (Figs 3.4, 3.5), further indicating the importance of the tropics.

The largely quasi-stationary nature of the convective systems over southern Africa point to the relative unimportance of transient synoptic systems in supplying water vapour to the southern African subcontinent in late summer months. It has been suggested that the tropical energy source over the continent is supplied by inflow from the surrounding equatorial oceans, pulsed by standing and transient waves (Vowinckel, 1956; Taljaard, 1972; Tyson, 1986; Jury and Pathack, 1991). Recent evidence, however, shows that water vapour over the tropics is maintained by the large-scale divergent or global-scale atmospheric circulations (Chen *et al.*, 1988; Chen and Tzeng, 1990). Indications are therefore that southern Africa's late summer rainfall is triggered by synoptic weather systems, utilizing the available moisture largely supplied by the global-scale atmospheric circulation.

To summarize, water vapour over southern Africa is partially modulated with the annual temperature range. Differences in location and amount of precipitable water point to other controls of water vapour over southern Africa. The influence of transient synoptic systems on the water vapour supply over southern Africa appears to be more dominant in early than in late-summer months, when the systems tend to be quasi-stationary. This suggests that the global mean atmospheric circulation as well as movements of the Inter-tropical Convergence play a role in moisture availability over the region in late summer. Total latent heat increases (decreases) in intensity and occurs further poleward (equatorward) in wet (dry) years. Similarly, poleward extensions of the latent heat maximum occurs over southern Africa (Madagascar) during wet (dry) years and during cloud band cases. Water vapour, besides supplying moisture for precipitation, also decreases the stability of the atmosphere over southern Africa, and evidence suggests that the latent heat release over subtropical southern Africa may force a standing wave over the subcontinent in wet late-summer months.

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The water vapour and latent heat release over southern Africa has been examined inter-annually, intra-annually and daily. Evidence suggests that the latent heat release over subtropical and tropical Africa is transferred poleward and may force a standing wave over southern Africa in wet Decembers and Januaries, and over Madagascar in South African dry years. Latent heat transfer appears to be facilitated by tropical-temperate troughs and their associated cloudbands. The quasi-stationary nature of convective systems over southern Africa indicates that the water vapour (and energy source) is primarily introduced to the subcontinent by the mean atmospheric circulation and standing synoptic systems. This link between water vapour and pressure fields over southern Africa and adjacent oceans will be examined in Chapter 4 in order to assess the importance of atmospheric pressure variations on the rainfall, water vapour content and cloud band formation over southern Africa.

CHAPTER 4

WATER VAPOUR AND SYNOPTIC CONDITIONS

Introduction

In the previous chapter the annual and inter-annual variability of water vapour has been examined for the southern Africa region. The influence of precipitable water and latent heat over subtropical southern Africa has been found to be significant for late summer circulation and rainfall over South Africa. Most of the interior of South Africa is semi-arid to arid, and a marked rainfall gradient exists from the wetter east coast to the hyper-arid west coast (Tyson, 1986; Lindesay, 1992). Important features affecting atmospheric moisture over the region are the high potential evapotranspiration, exceeding 2000 mm yr^{-1} over the west-central interior in summer due to generally clear skies and high insolation, and low levels of available surface moisture from the arid, sparsely vegetated continental surface (Henning, 1989; Lindesay, 1992). Most of the moisture that contributes to precipitation over southern Africa must therefore be imported over the subcontinent from source regions elsewhere. A strong link has also been found to exist between precipitable water and cloud bands (Harrison, 1986a). Pressure is the force responsible for wind and therefore for converging and diverging flow, resulting in vertical motion, cloudiness and rain. The link between rainfall, precipitable water, and cloud bands has necessitated the investigation of pressure fields over the region in order to assess the circulation adjustments between wet and dry early, mid and late summer.

The relationship between pressure fields over southern Africa and adjacent oceans and rainfall over the interior of South Africa has been well documented (Triegaardt and Kits, 1963; Taljaard, 1981; Tyson, 1981, 1984; Miron and Lindesay, 1983; Miron and Tyson, 1984). Pressure fields for wet (dry) Decembers

and Januaries have shown decreased (increased) surface pressures over continental southern Africa and over the South Indian Ocean, and increased (decreased) pressure over the South Atlantic Ocean (Triegaardt and Kits, 1963; Tyson, 1981; Miron and Lindesay, 1983). A quasi-stationary trough over the west coast at 500 hPa has also been associated with wet conditions over the summer rainfall region (Triegaardt and Kits, 1963; Dyer, 1982). this trough is considered important for cloud band formation (Streten, 1973; Harangozo and Harrison, 1983; Harrison, 1984, 1986a). The importance of the surface pressure configuration in wet years is that the influx of humid air from the east and northeast is enhanced (Taljaard, 1981; Miron and Lindesay, 1983). Furthermore, the influence of changing circulation patterns on rainfall has also been assessed using geostrophic flow correlated with precipitation, using principal component analysis (Tyson, 1984, 1986).

The effect of synoptic systems on vapour content necessitates a closer inspection of mean low-level pressure fields over southern Africa and adjacent oceans in wet and dry years and for cloud band case studies. The relationship between precipitable water and geopotential height has been examined to determine the effect of synoptics on precipitable water content over southern Africa, and to provide a proxy for conditions suitable for cloud band formation. Area means of precipitable water for the area 15°-30°S, 22°-32°E have been correlated with 850 hPa and 700 hPa pressure heights using Spearman's rank correlation to assess relationships between synoptic patterns and water vapour content over the summer rainfall regions of southern Africa. Furthermore, the evaluation of collective significance of finite individual significance tests will be performed, according to the method outlined by Livezey and Chen (1983), to assess whether correlation patterns over space display field significance.

Water vapour and Synoptic Conditions

Correlations of precipitable water and pressure fields at the 850 and 700 hPa level have been conducted for a five year period for early, mid and late summer months. Correlations for the early summer (October) reveal that at the 850 hPa level correlations are relatively weak, with the strongest correlations (positive)

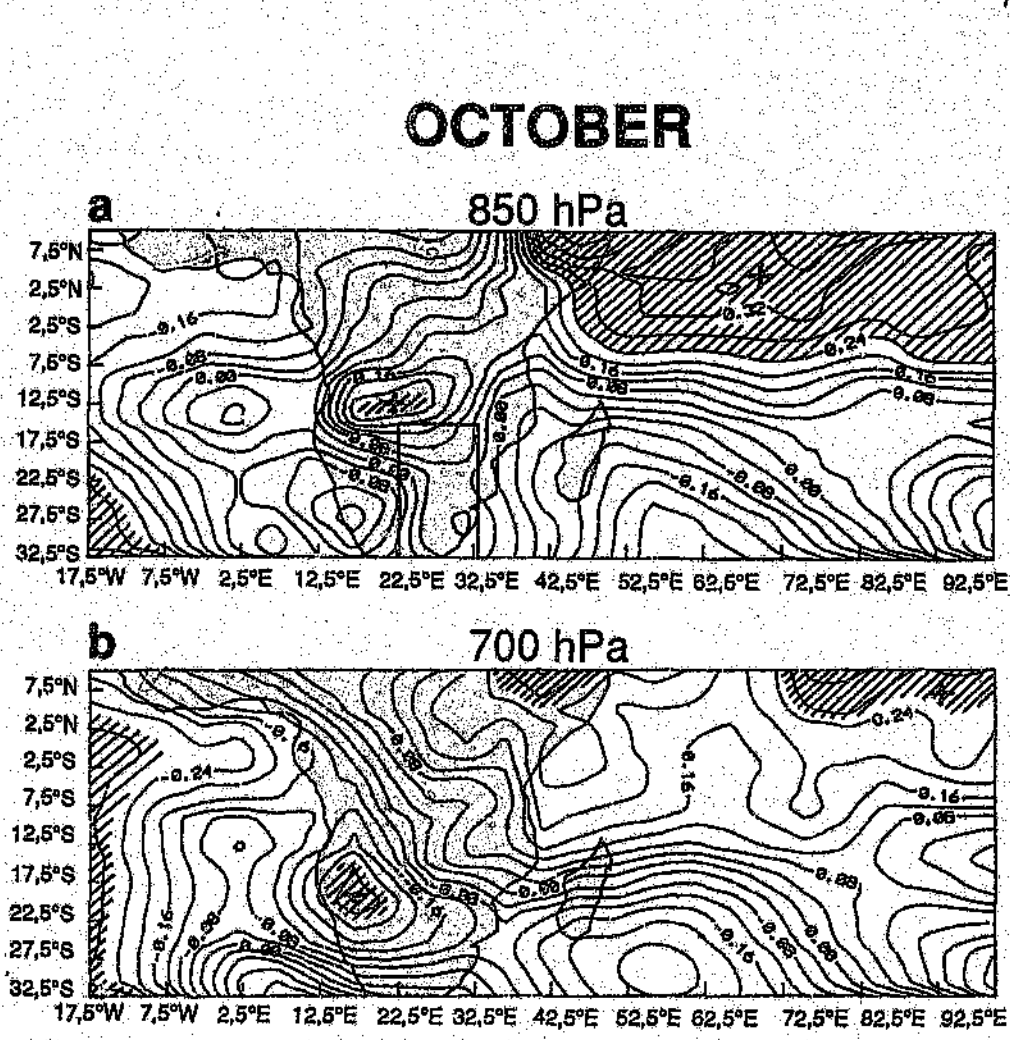

Figure 4.1: Mean October correlation fields between precipitable water over the study area (indicated by the rectangle in a) and geopotential height at: a) 850 Hpa; and b) 700 hPa. Plus signs denote local maxima of positive correlation; minus signs local minima of negative correlation. Hatched regions denote significance at the 99,9 per cent level.

occurring over subtropical Africa (Fig. 4.1a). This correlation of +0,24 (significant at the 99 per cent level, with field significance) implies a weak linear relationship between anticyclonic circulation over subtropical Africa and precipitable water over central southern Africa (Fig. 4.1a). The influence of the cyclonic circulation can be best seen in Figure 4.1b. At the 700 hPa level the negative correlations of 0.28 (significant at the 99,9 per cent level, with no field

significance) indicate a weak link between low pressure over the southwestern coastal regions and water vapour content over the summer rainfall region of South Africa (Fig. 4.1b).

The correlation fields for mid summer (December) differ marginally from those for early summer. The most important feature of the 850 and 700 hPa correlation fields is the negative correlations of 0.35 (significant at the 99,9 per cent level, with field significance at 700 hPa) over central southern Africa and the extreme eastern South Atlantic Ocean (Fig. 4.2a, 4.2b). This implies that a low pressure system situated over western southern Africa and the eastern Atlantic Ocean is important for the maintenance of water vapour over central southern Africa.

In late summer the pattern of correlation changes. At the 850 hPa level positive correlations of 0,48 (significant at the 99,9 per cent level, with field significance), indicate the importance of an anticyclonic circulation off the east coast of southern Africa for the maintenance of water vapour over central southern Africa (Fig. 4.3). This pattern is reflected at the 700 hPa level where correlations of +0,52 (significant at the 99,9 per cent level, with field significance) also indicate the importance of an anticyclone off the east coast. The -0,28 correlation (significant at the 99,9 per cent level) over the western interior of southern Africa (as opposed to -0.14 at 850 hPa) implies increased importance of cyclonic circulation over southern Africa at 700 hPa. This relationship between water vapour content over the central interior of southern Africa and spatial variations in the geopotential height field over southern Africa and adjacent oceans necessitates a closer inspection of the mean synoptic conditions prevailing in wet and dry early, mid and late summer months.

Mean Wet and Dry Synoptic Conditions

Mean wet early summers (October) are characterised by a trough over western South Africa and ridge of the South Indian Anticyclone over the

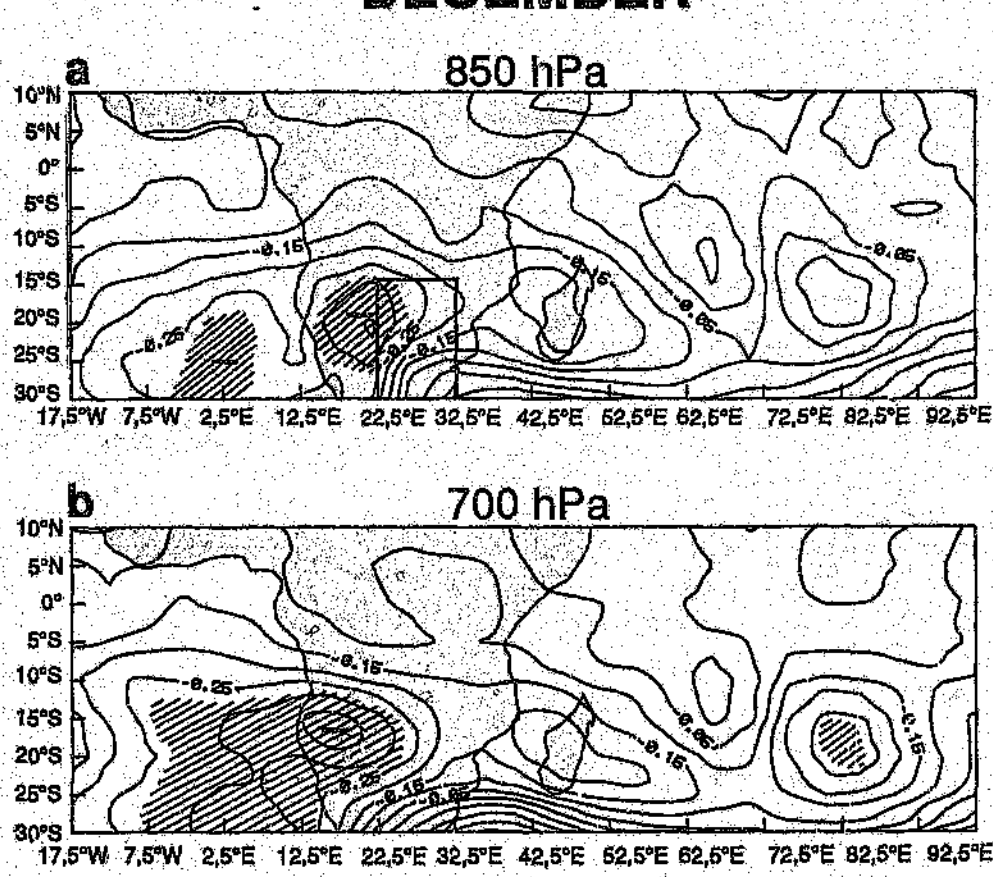

Figure 4.2: Mean December correlation fields between precipitable water over the study area (indicated by the rectangle) and geopotential height at: a) 850 Hpa; and b) 700 hPa. Plus signs denote local maxima of positive correlation; minus signs local minima of negative correlation. Hatched regions denote significance at the 99,9 per cent level.

Mozambique channel at 850 hPa (Fig. 4.4a). At 700 hPa, an anticyclone occurs over subtropical southern Africa with an extensive trough off the west coast of Africa (Fig. 4.4b). This conforms with the negative correlation fields shown earlier over the eastern Atlantic Ocean. The westerly wave at 700 hPa is reflected at 300 hPa (Fig. 4.4c). Mean dry early summers are also characterised by a trough over western South Africa and ridge of the South Indian Anticyclone over the Mozambique channel at the 850 hPa pressure level (Fig. 4.5a). At 700 hPa however, the trough over the western parts of southern Africa is less

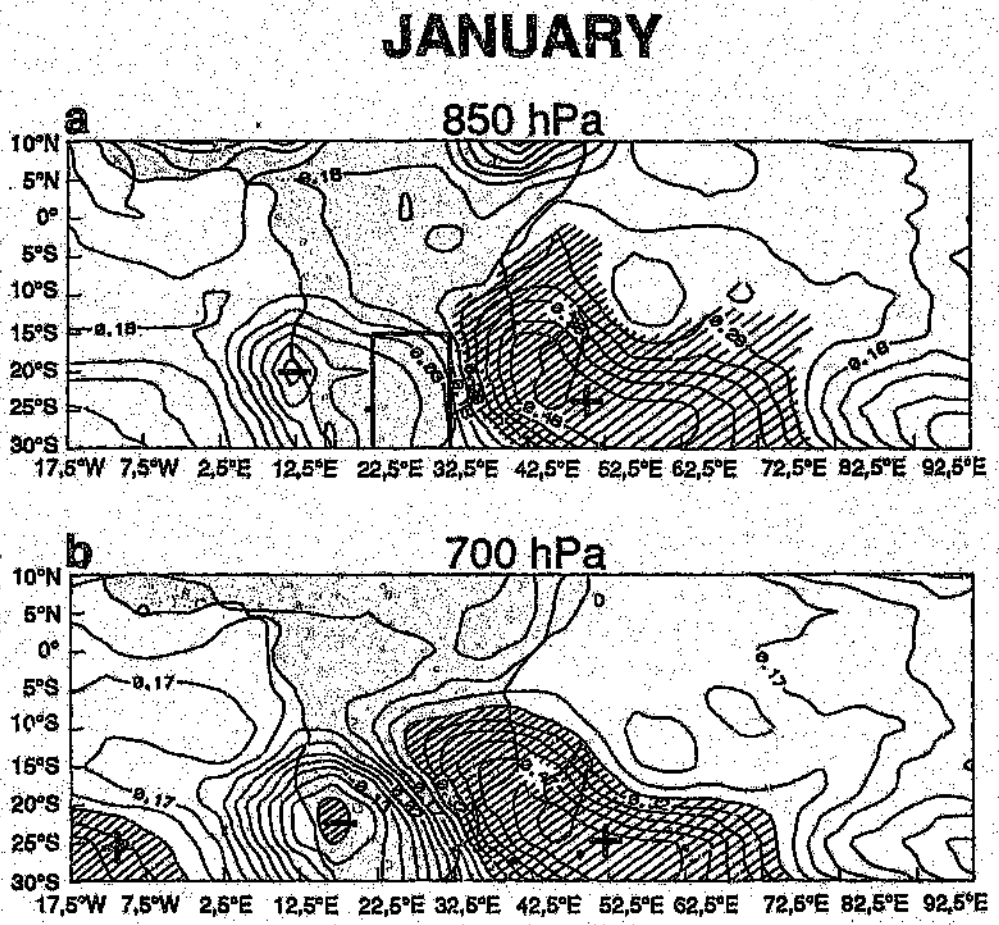

Figure 4.3: Mean January correlation fields between precipitable water over the study area (indicated by the rectangle) and geopotential height at: a) 850 Hpa; and b) 700 hPa. Plus signs denote local maxima of positive correlation; minus signs local minima of negative correlation. Hatched regions denote significance at the 99,9 per cent level.

well-developed than in mean wet Octobers, with a ridge extending across the subtropical eastern Atlantic Ocean (Fig. 4.5b). The 300 hPa level for mean dry Octobers to similar to that of mean wet Octobers, although the isolines are more zonally orientated during the mean dry years.

Pressure patterns at 850 hPa for wet and dry Decembers are similar, although a closed cell of low pressure exists over subtropical southern Africa, a feature absent during mean dry Decembers (Figs 4.6a, 4.7a). The 700 hPa level again

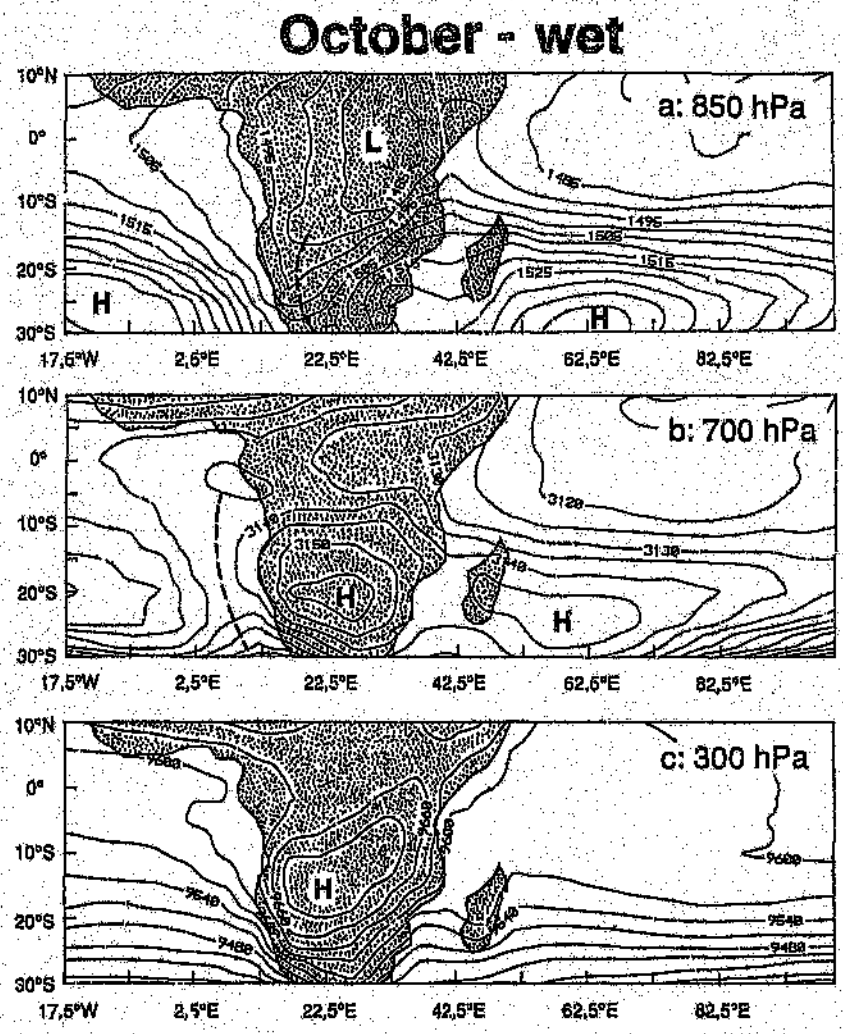

Figure 4.4: Mean wet October pressure fields at: a) 850 hPa; b) 700 hPa; and c) 300 hPa. Dashed lines indicate approximate positions of troughs.

shows marked differences between wet and dry years, with a trough linking the tropics and the mid-latitudes (i.e. a tropical-temperate trough) off the west coast of South Africa in mean wet Decembers (Fig. 4.6b), and a ridge in that position during mean dry Decembers (Fig. 4.7b). A further difference between wet and dry Decembers is the more zonally-orientated isobars over South Africa in mean dry years (Figs 4.6b, 4.7b). The above results reflect the correlations of precipitable water with the 700 hPa pressure level, where low pressures off the west coast are negatively correlated with high precipitable water over South Africa. Pressure

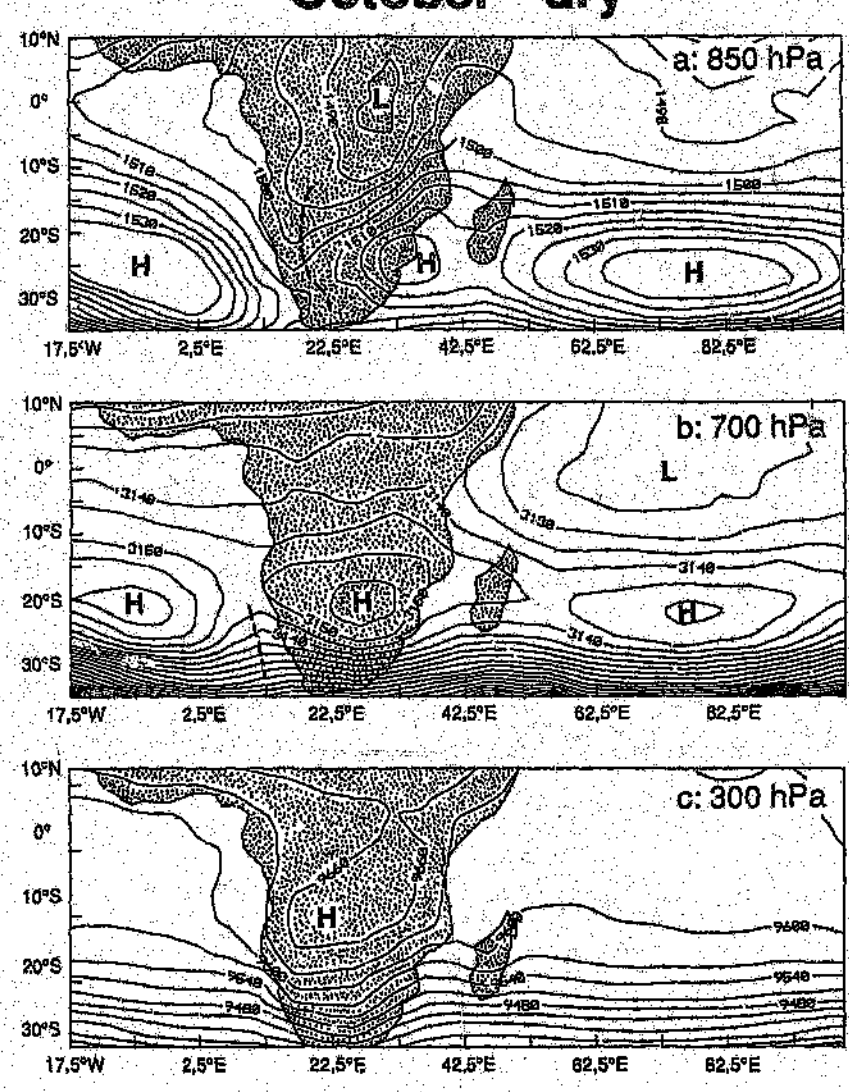

Figure 4.5: Mean dry October pressure fields at: a) 850 hPa; b) 700 hPa; and c) 300 hPa. Dashed lines indicate approximate positions of troughs.

patterns at 300 hPa are very similar between wet and dry Decembers (Figs 4.6c, 4.7c).

Comparisons of mean wet and dry Januaries reveal some differences at the 850 hPa pressure level. Mean wet Januaries are characterised by a well-developed trough extending from the tropics southward over Africa and a ridge of the South Indian Anticyclone over the Mozambique Channel (Fig. 4.8a). Mean dry Januaries, in contrast, are characterised by a less-developed trough over southern Africa at the 850 hPa level (heights of approximately 1495 gpm in the mean dry

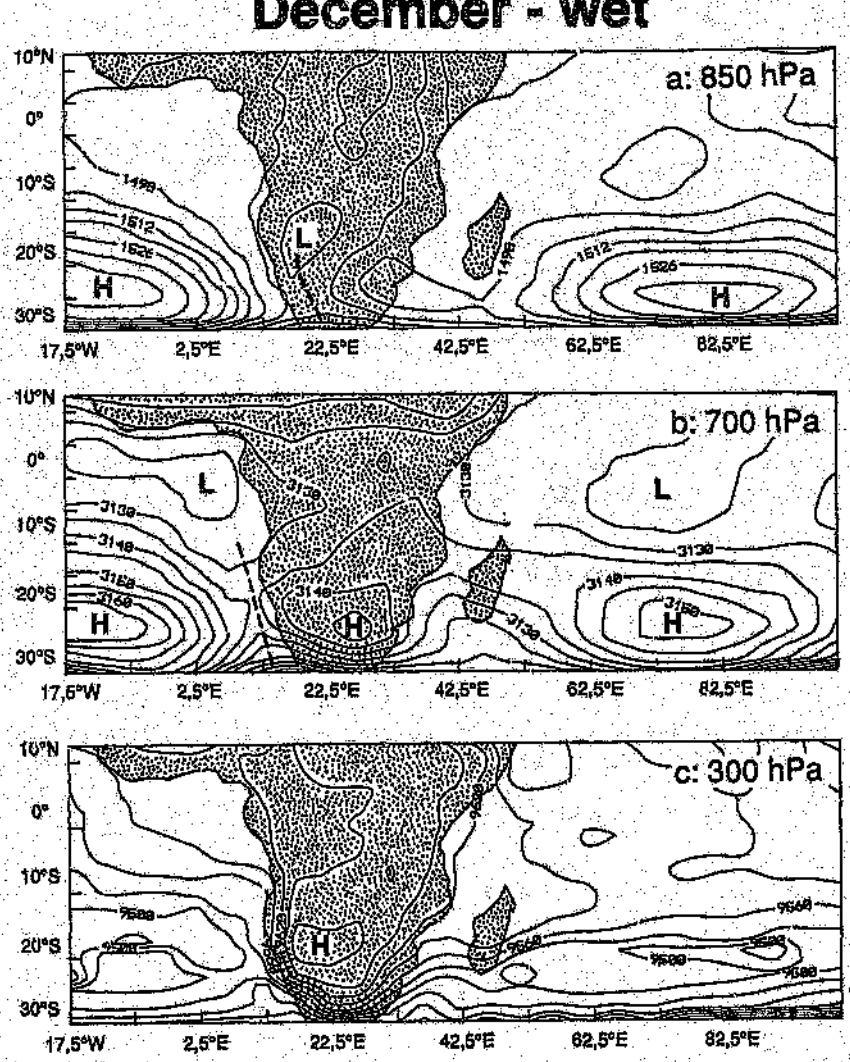

Figure 4.6: Mean wet December pressure fields at: a) 850 hPa; b) 700 hPa; and c) 300 hPa. Dashed lines indicate approximate positions of troughs.

as opposed to 1480 gpm in the mean wet Januaries) (Fig. 4.9a). Another feature of the mean dry January is the southeastward displacement of the South Indian Anticyclone such that the ridge over the Mozambique Channel is replaced by a trough in dry Januaries (Fig. 4.9a). The pressure pattern at 700 hPa show the greatest difference between wet and dry Januaries. A wet January has a tropical-temperate trough over the western regions of South Africa, while in the dry January the trough is replaced by an anticyclonic circulation (Figs 4.8b, 4.9b). The correlation fields for January for 850 and 700 hPa generally reflect this observation that low (high) pressure over the central interior of southern Africa

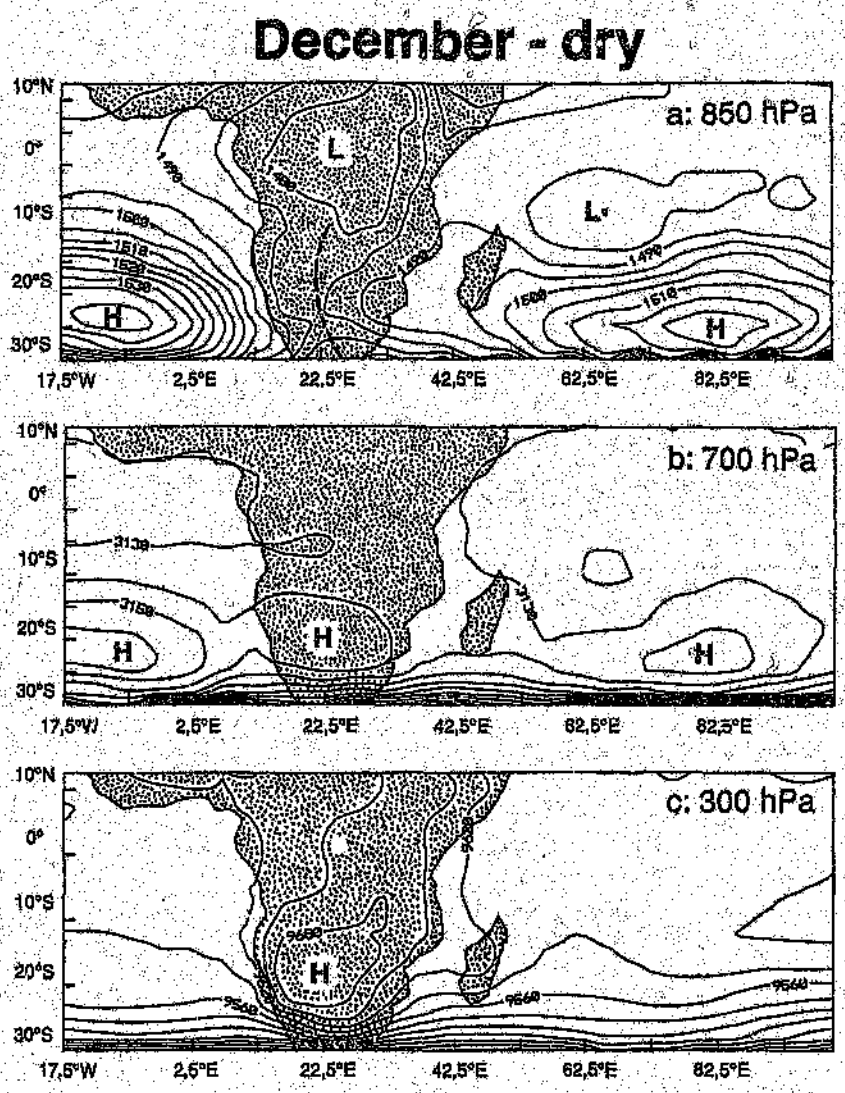

Figure 4.7: Mean dry December pressure fields at: a) 850 hPa; b) 700 hPa; and c) 300 hPa. Dashed lines indicate approximate positions of troughs.

and high (low) pressure over the Mozambique Channel results in high (low) precipitable water over the study area. The 300 hPa pressure patterns for a wet and a dry January are similar (Figs 4.8c, 4.9c).

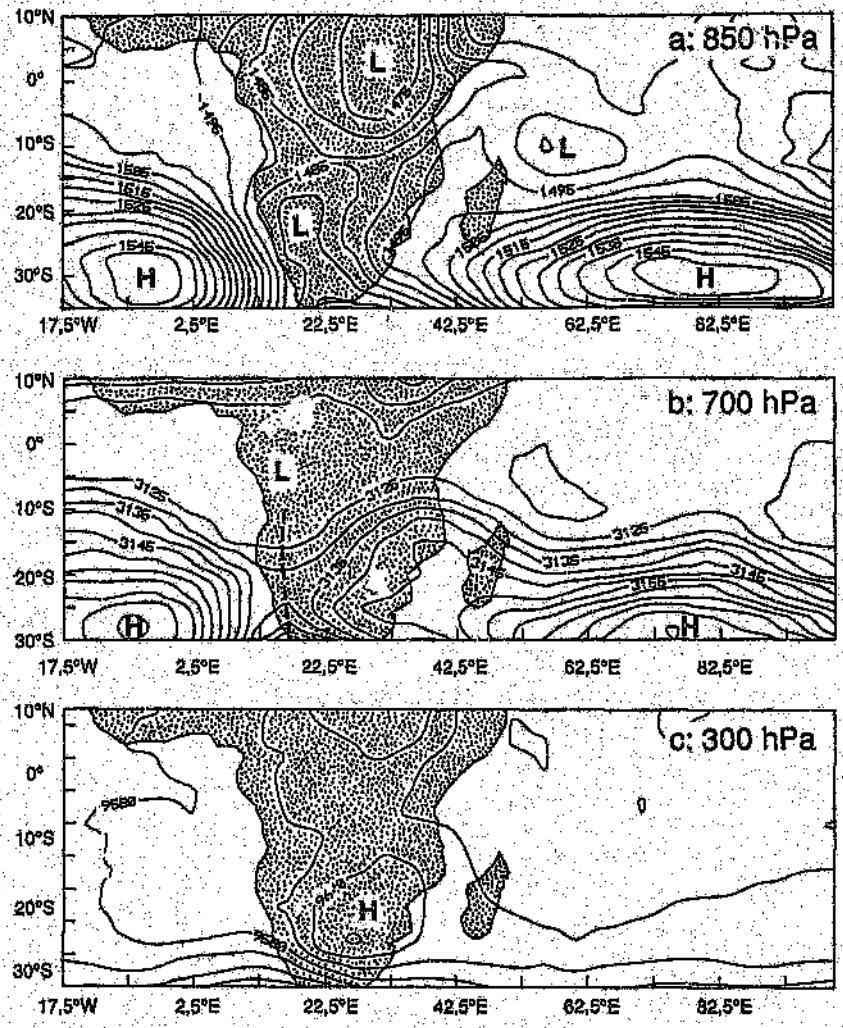

Figure 4.8: Mean wet January pressure fields at: a) 850 hPa; b) 700 hPa; and c) 300 hPa. Dashed lines indicate approximate positions of troughs.

The Synoptics of Tropical-temperate Troughs

The synoptic situations associated with both major and truncated cloud bands have been examined in detail by various researchers (Harrison and Harangozo, 1983; Harrison, 1984, 1986a; Harangozo, 1989). Despite the synoptic situation of tropical-temperate troughs over southern Africa having been well-documented, the conditions preceding cloud band formation and during cloud band dissipation in early to late summer have not been investigated.

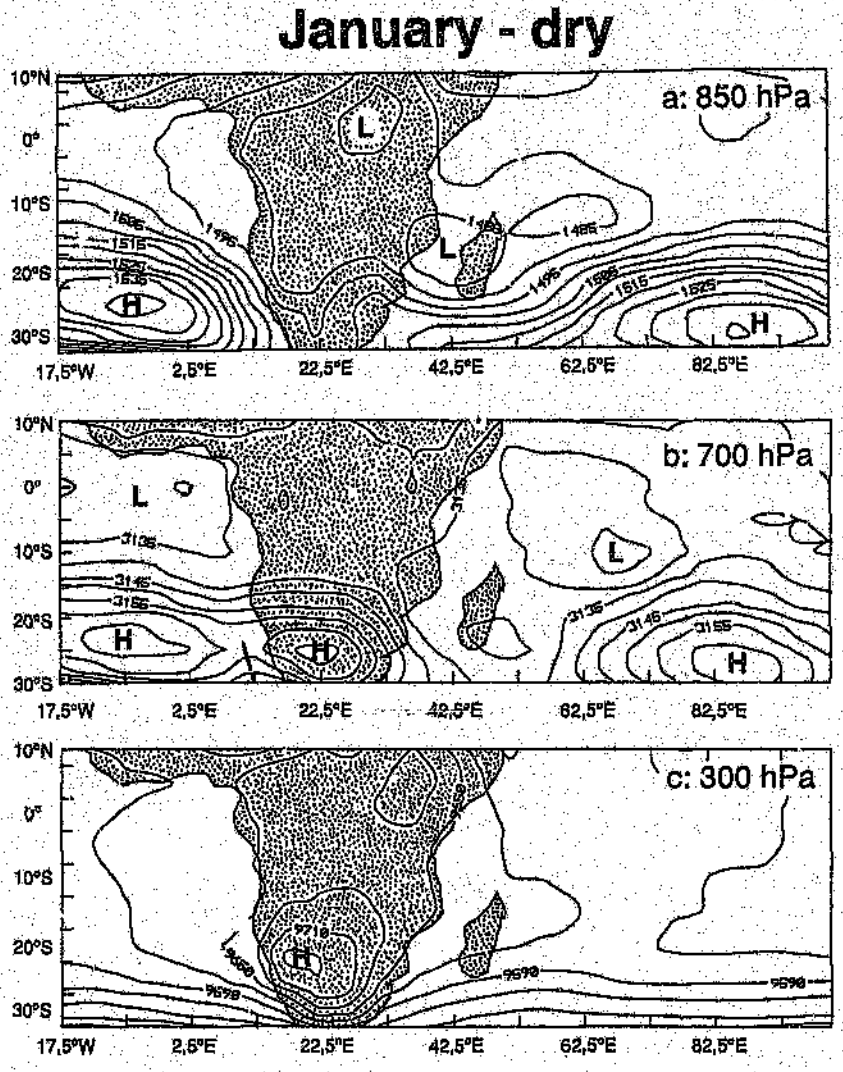

Figure 4.9: Mean dry January pressure fields at: a) 850 hPa; b) 700 hPa; and c) 300 hPa. Dashed lines indicate approximate positions of troughs.

Inspection of sequential satellite photographs has revealed preferential regions where the cloud bands dissipate or *disconnect*). During early summer (October), cloud bands linking the tropics to mid-latitudes have been found disconnect in the general vicinity of southern Africa at 25°S and, more commonly, over Madagascar (Fig. 4.10a). During mid summer (December), cloud band dissipation occurred predominantly over the Mozambique Channel between 15° and 25°S (Fig. 4.10b). By late summer, the highest frequency of disconnection occurred over the Southwest Indian Ocean at approximately 27°S (Fig. 4.10b). In general, the region of cloud band disconnection shifts southward

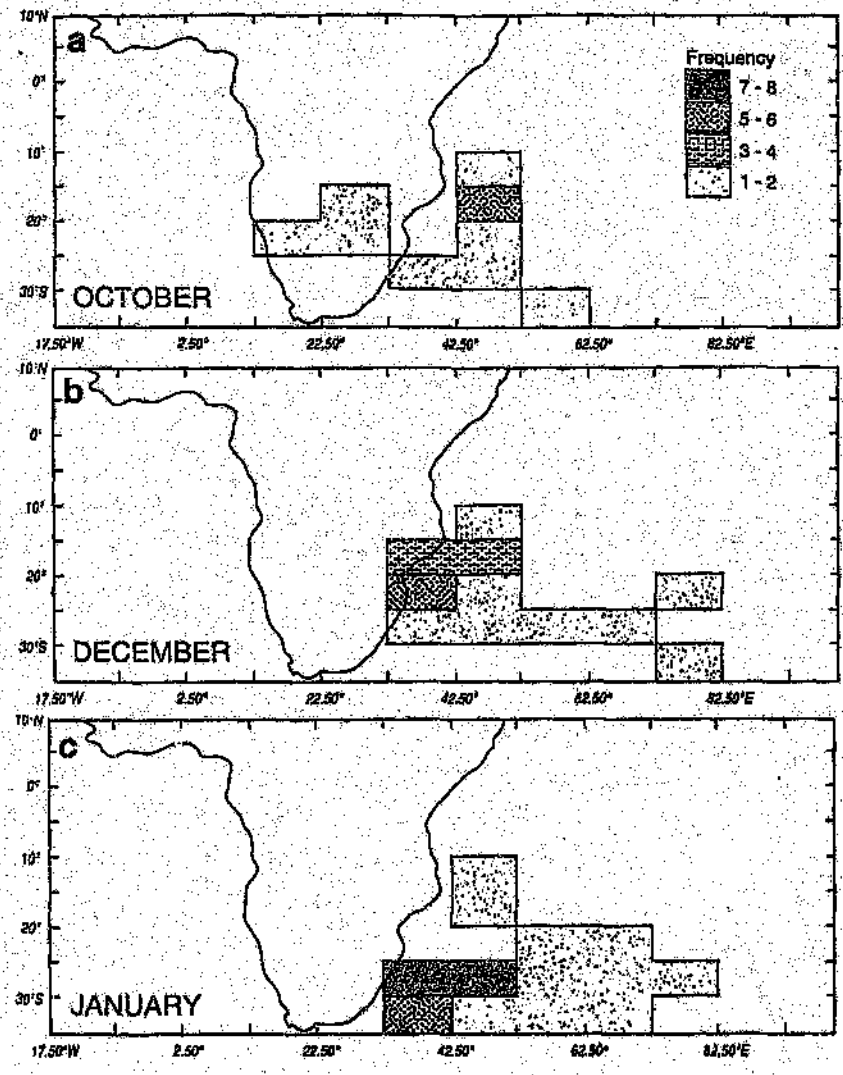

Figure 4.10: Frequency of dissipation of cloud bands within a 5° square grid over a 20 year period (1965-1984) for: a) October; b) December; and c) January.

from early to late summer with the southward displacement of the mid-latitudinal westerlies and associated synoptic systems in summer.

The circulation pattern for the pre-cloud band day of 15 October 1986 reveals a tropical-temperate trough over the western coast of southern Africa, linking a subtropical depression at 15°S, 10°E to a temperate trough at approximately 35°S, 20°E (Fig. 4.11a). The anticyclone over the eastern interior of southern Africa, coupled to the trough, has resulted in a southward transport of water vapour over southern Africa (cf. Fig. 4.4b). A major cloud band had developed by 16 October 1986. At 700 hPa the temperate trough had shifted eastward and the subtropical depression at 15°S, 7°E had weakened slightly (Fig. 4.11b),

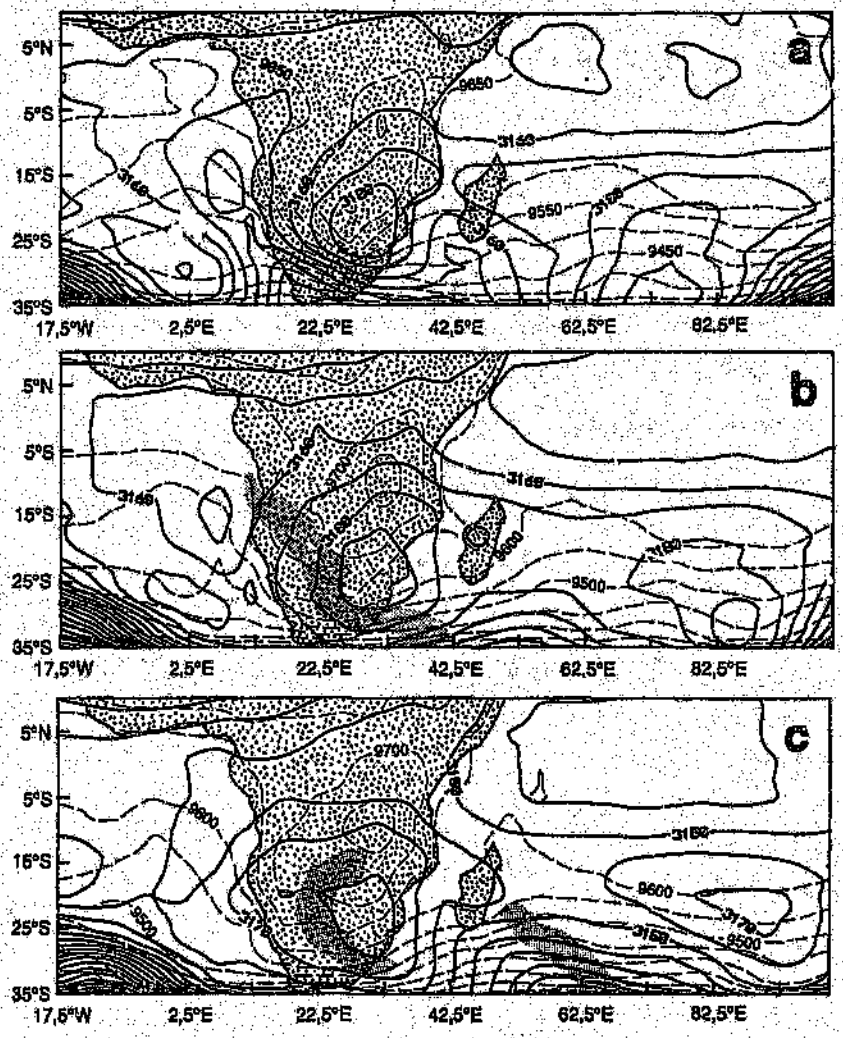

Figure 4.11: Pres...e fields at 700 hPa and 300 hPa for an early summer cloud band case study for: a) pre-cloud band-15 October 1986, b) cloud band-16 October 1986, c) post cloud band-17 October 1986. Dark solid lines represent 700 hPa pressure level and light dashed lines the 300 hPa pressure level. Shading indicates cloud.

although the anticyclone over eastern southern Africa had intensified, resulting in continued southward transport of water vapour over the region (Fig. 4.11b). The trough at 300 hPa over the eastern Atlantic off the coast of South Africa on 15 October, was still present on the following day (Fig. 4.11a,b). Partial dissipation of the cloud band occurred on 17 October 1986 coincides with a westward shift of the anticyclone at 700 hPa to extend over the entire southern African subcontinent (Fig. 4.11c).

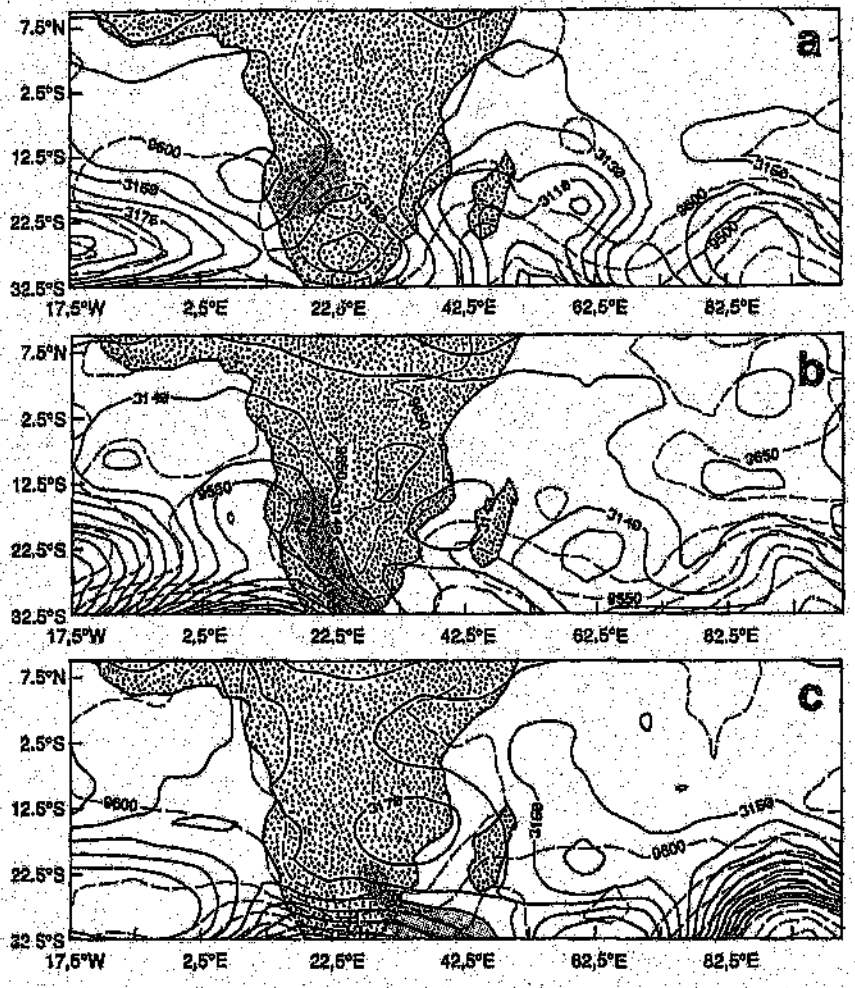

Figure 4.12: Pressure fields at 700 hPa and 300 hPa for a mid summer cloud band case study for: a) pre-cloud band-4 December 1982, b) cloud band-5 December 1982, c) post cloud band-7 December 1982 Dark solid lines represent 700 hPa pressure level and light dashed lines the 300 hPa pressure level. Shading indicates cloud.

A cloud band case study conducted during a dry December (1982) reveals a circulation pattern for 4 December (pre-cloud band) dominated by an anticyclone over the interior of South Africa at both the 700 and 300 hPa levels (Fig. 4.12a). A closed depression was evident off the west coast of subtropical Africa by 5 December (cloud band), with a well-defined trough linking the subtropical depression to a westerly wave. The trough was present off the western parts of South Africa at both the 700 and 300 hPa levels (Fig. 4.12b). By the following day (7 December), the circulation was characterised by a weakening of the

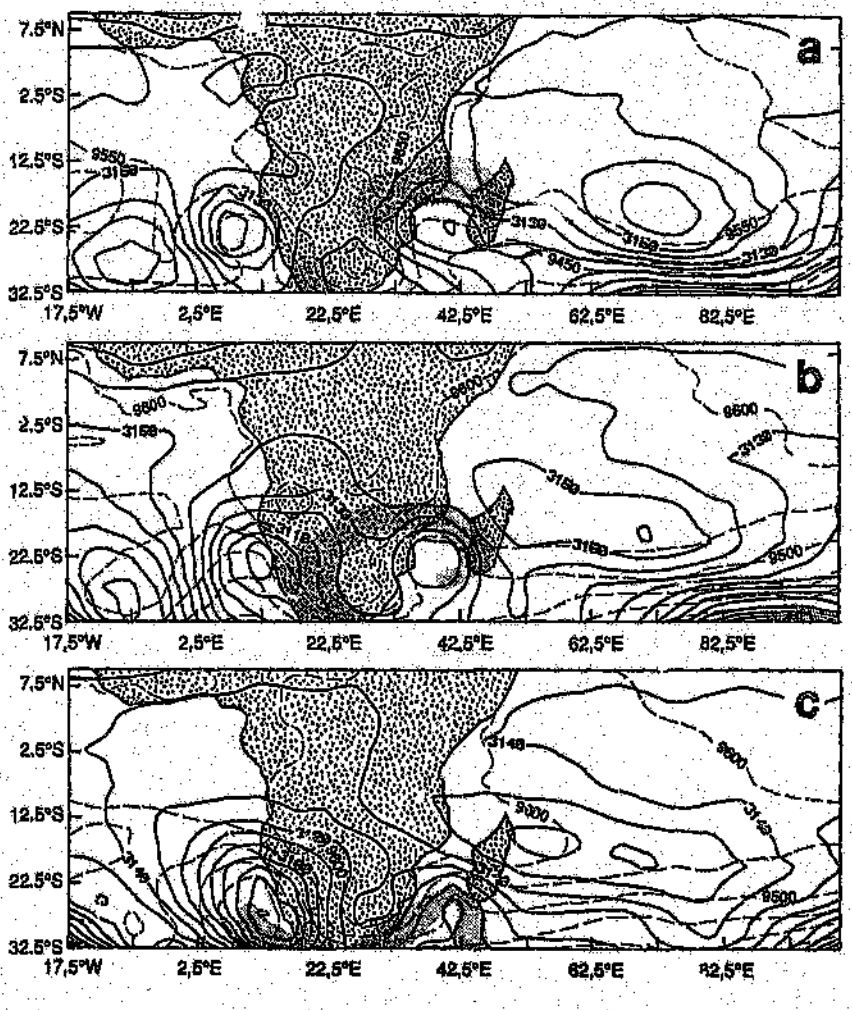

Figure 4.13: Pressure fields at 700 hPa and 300 hPa for a mid summer cloud band case study for: a) pre-cloud band-1 December 1985, b) cloud band-2 December 1985, c) post cloud band-3 December 1985 Dark solid lines represent 700 hPa pressure level and light dashed lines the 300 hPa pressure level. Shading indicates cloud.

temperate trough at 700 and 300 hPa such that the circulation over South Africa was largely zonal (Fig. 4.12c).

The circulation pattern for 1 December 1985 (pre-cloud band) was largely anticyclonic over South Africa at both the 700 and 300 hPa levels, although a closed cell of low pressure had developed off the west coast of South Africa at 700 hPa (Fig. 4.13a). The depression had intensified and moved slightly eastward by 2 December (cloud band), as had a trough at 300 hPa such that the circulation

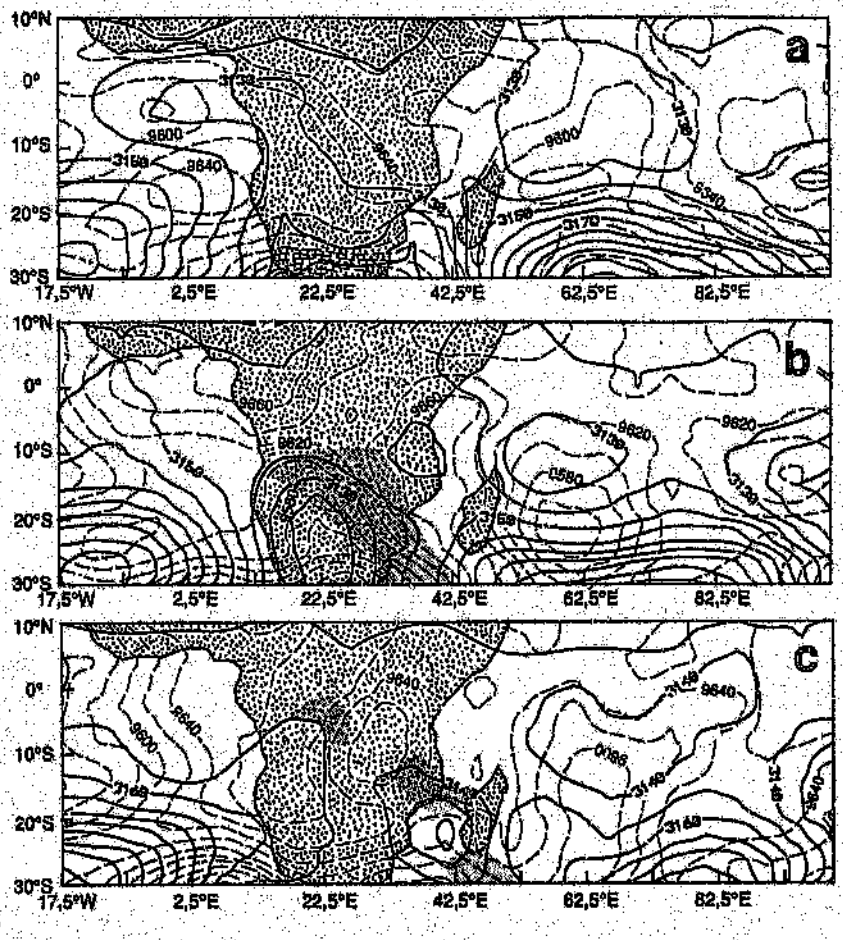

Figure 4.14: Pressure fields at 700 hPa and 300 hPa for a late summer cloud band case study for: a) pre-cloud band-6 January 1980, b) cloud band-7 January 1980, c) post cloud band-8 January 1980. Dark solid lines represent 700 hPa pressure level and light dashed lines the 300 hPa pressure level. Shading indicates cloud.

over South Africa was northerly (Fig. 4.13b). The depression moved southwestward the following day, displacing the northerly circulation and the cloud band slightly westward over eastern southern Africa (Fig. 4.13c).

The first case study for late summer involves a cloud band occurrence during the relatively dry January of 1980. The circulation pattern for the pre-cloud band conditions of 6 January reveals a trough extending across the eastern parts of South Africa northwestwards to the equatorial west coast of Africa (Fig. 4.14a). At the 300 hPa level the pattern was generally similar to the 700 hPa level, with a trough over South Africa (Fig. 4.14a). By the following day the cloud band had

formed. Northward displacement of the depression at 700 hPa and an intensification of the trough at 300 hPa (Fig. 4.14b), resulted in a northerly transport of water vapour. The cloud band had moved eastward over Madagascar by 8 January, and was reflected by an eastward displacement and weakening of the depression to be situated over the Mozambique Channel. A ridge of the South Atlantic Anticyclone occurred over South Africa (Fig. 4.14c). The trough at 300 hPa on the previous day had also been replaced by a ridge, inducing a southerly flow over South Africa at that level (Fig. 4.14c).

The second case study for late summer involved a cloud band during the wet summer of 1981. The pre-cloud band conditions on 22 January revealed a trough at 700 hPa over the western interior of South Africa, also reflected at the 300 hPa pressure level (Fig. 4.15a), while a ridge of the South Indian Anticyclone extended over the Mozambique Channel and the eastern regions of southern Africa. On 23 January (cloud band), the trough at 700 hPa over the western parts of southern Africa had intensified (Fig. 4.15b). The cloud band partially dissipated the following day but redeveloped on 26 January. On that day the 700 hPa level was dominated by a strong ridge of the South Indian Anticyclone over eastern southern Africa and a trough over the western coast of South Africa (Fig. 4.15c). The cloud band had partially dissipated by 27 January. The most noticeable feature of the 700 hPa circulation pattern was the westward ridging of the South Indian Anticyclone such that it extended over virtually the entire eastern and central parts of southern Africa (Fig. 4.15d). The trough at the 300 hPa level had weakened by 27 January. Pressure tendencies associated with early mid and late summer cloud bands are discussed in Appendix C.

Discussion

An important feature of the geopotential height differences between wet and dry early summer months is the existence of a trough at 700 hPa over the western parts of the southern African region/eastern Atlantic Ocean. This trough found at 700 hPa during mean wet years (cf. Figs 4.2, 4.4, 4.6, 4.8, 4.11, 4.13, 4.15) may be a manifestation of the trough in the long waves at 500 hPa (Taljaard, 1989; Triegaardt, 1989; Triegaardt *et al.*, 1991). The development of a quasi-stationary

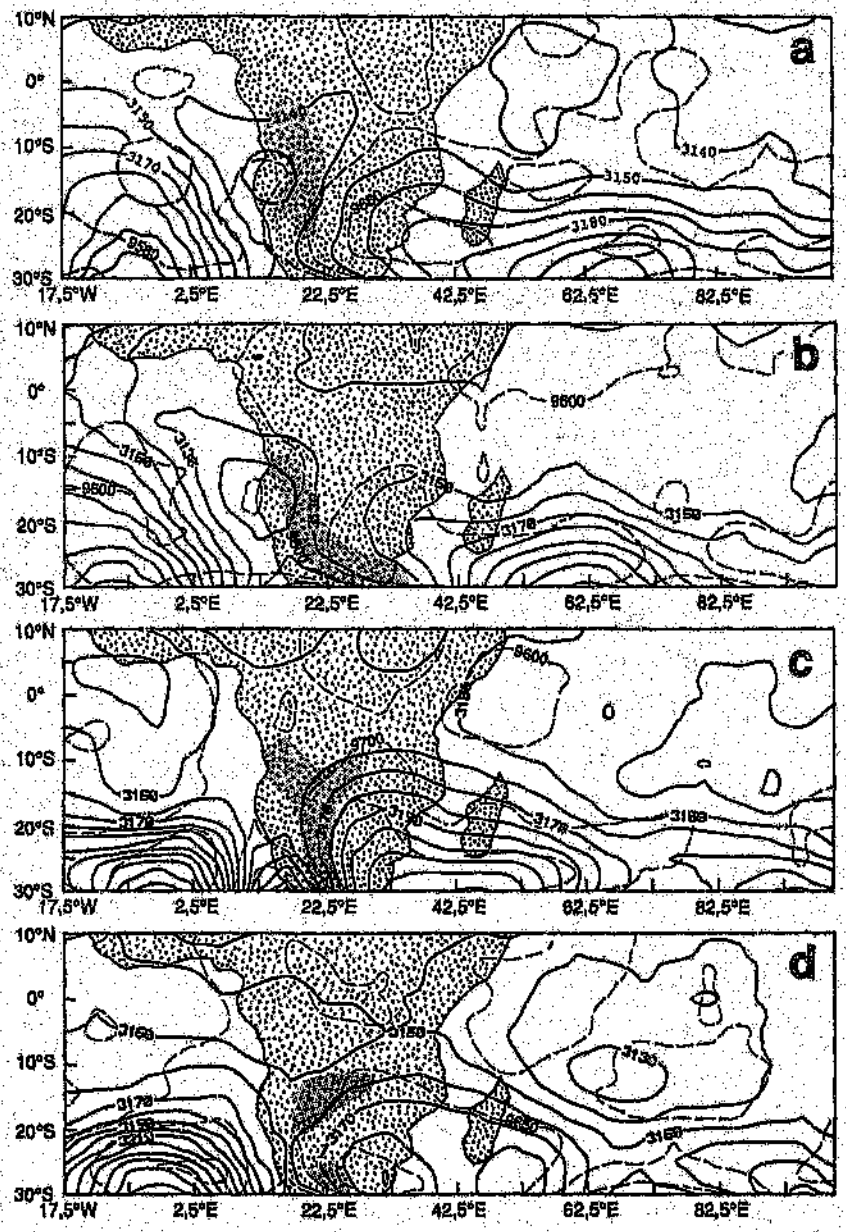

Figure 4.15: Pressure fields at 700 hPa and 300 hPa for a late summer cloud band case study for: a) pre-cloud band-22 January 1981, b,c) cloud band-23-26 January 1981, d) post cloud band-27 January 1981. Dark solid lines represent 700 hPa pressure level and light dashed lines the 300 hPa pressure level. Shading indicates cloud.

500 hPa trough in the westerlies over the west coast of southern Africa has been associated with wetter conditions over the summer rainfall region (Dyer, 1982; Tyson, 1986). These semi-stationary longwaves (thermally or orographically forced), control the formation of cloud bands (Palmen and Newton, 1969; Mechoso, 1981; Webster, 1983). Cloud bands are to be found along the leading edges of these westerly waves (Streten, 1973; Harangozo and Harrison, 1983). The cloud band case studies generally conform to this (Figs 4.11 - 4.15), although the importance of the 700 hPa pressure level in water vapour transport and hence cloud band formation is clearly seen. In early (late) summer, the energy flux is equatorward (poleward), and baroclinic or mid-latitude (tropical) forcing appears to play a greater role in modulating the rainfall over southern Africa (Harrison, 1986a, 1986b; Lindesay, 1988a). Forcing, however, does take place in both directions due to the interdependence of tropical and temperate circulation adjustments (Webster, 1983; Lindesay, 1988a). Fluctuations in the position of these long waves is such that upper-tropospheric meridional flow across southern Africa tends to be poleward (equatorward) in late (early) wet summers (Miron and Lindesay, 1983; Harrison, 1986a, 1986b, 1986c) although cloud bands in early as well as late summers are characterized by poleward flow (Figs 4.11-4.15) (Harrison, 1986a). The more zonal westerly circulation found to occur in the middle and upper troposphere during dry years has been indicated in earlier studies by Taljaard (1989), Triegaardt (1989), and Triegaardt *et al.* (1991).

The upper waves are reflected in the lower troposphere and the semi-annual wave in the upper troposphere may account for 75 per cent of the annual variance of sea-level pressure in the southern hemisphere (van Loon and Rogers, 1984; Tyson, 1986). A trough at 700 hPa extends from the temperate latitudes to a depression over tropical regions in mean wet years, a feature absent from the mean dry years when a ridge replaces the trough across the subtropics over the west coast of southern Africa (cf. Figs 4.4 - 4.7). Reduced 700 hPa geopotential height, mainly as a west coast trough, is important for water vapour content over South Africa, particularly during early summer (Fig. 4.1b - 4.2b). The trough thus serves as a conduit for southeastward vapour transport from the tropical Atlantic Ocean over South Africa in wet years. Water vapour, which diverges over the subtropical oceans (Peixoto and Oort, 1983, 1992), is transported southeastward due to the prevailing pressure fields over the South Atlantic Ocean

in wet early and mid summer months and cloud band cases (cf. Figs 4.4, 4.6, 4.11, 4.12). In dry years, a ridge over the subtropical western regions of southern Africa restricts the southeastward transport of water vapour from the tropical Atlantic Ocean over South Africa (Figs 4.5, 4.7). The decreased geopotential heights over the western parts of southern Africa in wet early summer conform with the findings that the wet (dry) conditions are coupled with lower (higher) geopotential heights over the same region (Lindesay, 1988a, 1988b; Harangozo, 1989). The trough over the region is a westerly wave trough, the most important synoptic type over southern Africa in October (Taljaard, 1982), again indicating the importance of the temperate circulation for early summer rainfall over South Africa. The extensive trough over the western parts on the pre-cloud band days in early and mid summer allows for the poleward advection of vapour over southern Africa (Fig. 4.11a). This coincides with the negative correlation between geopotential height and precipitable water found over the western parts of southern Africa. The fully developed cloud band in early summer is reflected by the poleward extension of the total latent heat for that day, indicating the position of the cloud band to the west of the continental anticyclone and to the east of the westerly wave southeast of Africa (cf. Figs 3.9b, 4.11b). Dissipation of the early and mid summer cloud bands occurred with an eastward or westward expansion of the anticyclone at 700 hPa, thereby disrupting the link between the tropical African convective region and the temperate latitudes (cf. Fig. 4.11c, Plate 3.1c). This is indicated by the disconnection of the latent heat maximum between the tropics and the temperate latitudes over southern Africa (cf. Figs 3.9c, 4.11c), and represents a discontinuation of the poleward transfer of energy and momentum by the tropical-temperate trough (Harrison, 1986a; Tyson, 1986).

The relationships between geopotential height, precipitable water and rainfall over southern Africa differ in late summer months. Highest positive correlations between geopotential height (at 850 and 700 hPa) and precipitable water over southern Africa occur over the southwest Indian Ocean and the Mozambique Channel at both levels (Fig. 4.3a, b). This is indicated by the geopotential height fields for the mean wet and dry Januaries where anticyclonic (cyclonic) circulation occurs over the Mozambique Channel during wet (dry) years at both the 850 and 700 hPa level (Figs 4.8, 4.9). The depression (anticyclone) over the Mozambique Channel is synonymous with dry (wet) conditions over southern

Africa and the concomitant eastward (westward) shift of the cloud bands to overlie Madagascar (southern Africa) during those periods (cf. Figs 1.7b, 3.8b) (Harrison, 1986b; Lyons, 1991; Lindesay and Jury, 1991; Mason, 1992; Matarira and Jury, 1992). The low (high) sea-level pressures over the Mozambique Channel during dry (wet) years (Triegaardt and Kits, 1963; Tyson, 1981) may be associated with the fluctuations in the position of the standing wave between wet and dry years, or the convective effects of anomalous sea surface temperatures over the region (Harrison, 1986a; Lindesay, 1988a; Mason, 1992). It has been suggested that tropical circulation anomalies force mid-latitudinal circulation in late summer when energy fluxes are poleward (Webster, 1972, 1983; Gill, 1980; Harrison, 1986a, 1986b; Lindesay, 1988a). The increased total latent heat and the poleward extension of relatively high latent heat in late summer (Figs 3.8, 3.11), coupled with increased static energy over subtropical southern Africa (Table 3.1) and poleward transport of geopotential energy at 300 hPa, point to the likelihood of thermal forcing in late summer. Non-verification of the Eliassen-Palm relationship over South Africa by Harrison (1986b, 1986c) further corroborates this theory (Fig. 3.12b). Surface (850hPa) geopotential heights are similar over southern Africa in both wet and dry Januaries (cf. Figs 4.8, 4.9), and confirm earlier observations that the interior surface troughs are thermally induced features which owe their existence to heating of the underlying surface in both wet and dry summers (Taljaard, 1953, 1981; Harangozo, 1989). Easterly waves which are common during wet late summers, in contrast, are barotropic or cool-cored closed lows that occur in the lower troposphere and are capped by a warm-cored ridge of high pressure (Figs 4.8a, c) (Taljaard, 1985; Tyson, 1986; Harangozo, 1989). Evidence from latent heat values indicates that intensification of an existing thermal depression may be partially controlled by latent heat release during condensation - a wave conditional instability of the second kind (CISK) mechanism (e.g. Lindzen, 1974; Stevens and Lindzen, 1978), or decreased static stability (Table 3.2) (Anderson and Stevens, 1987). This is suggested as a possible explanation for the trough at 850 hPa also (not) indicated at the 700 hPa geopotential level for mean wet (dry) Januaries (Fig. 4.8, 4.9). Enhanced surface convergence, convection, cloudiness and precipitation serves to cool the lower troposphere and warm the upper troposphere as a result of the latent heat release, reflecting the observed thermodynamics of easterly waves over southern Africa (Taljaard, 1985; Tyson, 1986).

The interior of southern Africa is dominated by an anticyclone during mean dry years (Figs 4.5, 4.7, 4.9), which is reflected in the strong anticyclonic vorticity present over Zimbabwe (Matarira and Jury, 1992). Earlier analyses of geopotential fields support these findings (Trieguardt and Kits, 1963; Taljaard, 1981; Tyson, 1981; Miron and Tyson, 1984; Lindesay, 1988a, 1988b). The influence of the ridge (trough) over the Mozambique Channel results in increased easterly (westerly) transport over subtropical southern Africa in wet (dry) late summer months (Figs 4.8, 4.9) (Harrison, 1986a; Lindesay, 1988a). The high precipitable water over South Africa during mean wet Januaries is mirrored by the high total latent heat values over the same region (Fig. 3.2c, 3.8a), with the tongue of relatively high latent heat extending southeastward coincidental to the leading edge of the westerly wave western part of the South Indian Anticyclone. During mean dry Januaries, in contrast, the anticyclone at 700 hPa results in divergence of water vapour from southern Africa such that the maximum in total latent occurs further north and is weaker than in wet Januaries (Fig. 3.8b). The poleward tongue of high latent heat occurs further east extending from the depression over Madagascar along the western edge of the South Indian anticyclone (cf. Figs 1.5b, 4.9b). This again conforms with the eastward shift of the cloud bands during dry summers (Harrison, 1986a; Tyson, 1986). The synoptic situation for cloud band occurrences reflects the mean wet conditions. Cloud bands over southern Africa are often associated with a wave in the upper westerlies, a trough/depression over western southern Africa and an anticyclone over the Mozambique Channel/Madagascar at 700 hPa (cf. Figs 1.5, 4.14, 4.15). (Harrison, 1983, 1986a; Harangozo and Harrison, 1983). Dissipation of the late summer cloud band occurs in conjunction with the replacement of the cyclone/trough over the continent by an an anticyclone from the west or east. Pressure tendencies examined in Appendix C generally reflect the observations made in this chapter for early, mid and late summer cloud band case studies.

In summary, water vapour content over South Africa is dependent on the presence of a trough off the west coast of southern Africa at the 700 and 300 hPa levels in early, mid and late summer months. During late summer months, the presence of an anticyclone over the Mozambique Channel is of importance to the vapour content of the atmosphere above southern Africa. Consequently, high water vapour content over southern Africa in late summer is facilitated by the

anticyclone, whereas early and mid summer vapour is largely the result of the temperate trough over the western parts of southern Africa. Cloud bands are generally found to form in association with a well-defined trough or depression over western southern Africa at 700 hPa (and 300 hPa), and dissipate with the replacement of the trough by a ridge at 700 hPa from the west or the east.

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The pressure fields at 700 hPa, and to a lesser extent at 300 hPa, constitute an important link between regional water vapour transport and water vapour content over southern Africa in early summer, late summer and for cloud band formation. Pressure fluctuations have been suggested as the reason for the inter-seasonal and inter-annual variability of water vapour content over southern Africa. These synoptic changes, coupled with the role of latent heat release in forcing a circulation over subtropical Africa in late summer, necessitates the examination of water vapour transport variability over the southern African region during early to late summer months and for cloud band case studies.

CHAPTER 5

WATER VAPOUR TRANSPORT

Introduction

Water vapour is an important driving mechanism of the tropical atmosphere (McIlveen, 1986). It is responsible for forcing through latent heat release a zonal Walker circulation (Bjerknes, 1969; Krishnamurti *et al.*, 1973; Heddinghaus and Krueger, 1981; Harrison, 1986a; Lindesay, 1988a, 1988b), and a meridional Hadley circulation (Gill, 1980; Lau and Lim, 1982; Harrison, 1983; Rind and Rossow, 1984; Lindesay, 1988a; Hack and Schubert, 1990). The quasi-stationary nature of convective systems over southern Africa, as discussed in Chapter 3, indicates that the water vapour (and energy source) is introduced to the subcontinent from source regions elsewhere.

Despite the importance of water vapour transport to rainfall over southern Africa, relatively few analyses of the availability of atmospheric moisture have been undertaken for any part of the region. On a hemispheric scale James and Anderson (1984) have shown that tropical-midlatitude transport of water vapour increases the growth rate and vigour of midlatitude baroclinic systems. Whereas regional studies of atmospheric moisture have been undertaken for North Africa (Flohn *et al.*, 1965), West Africa (Adedokun, 1978; Anyadike, 1979), South America (Rathor *et al.*, 1989), North America (Benton and Estoque, 1954; Hastenrath, 1966; Rasmusson, 1967) and Australasia (Hutchings, 1961), the content, intra- and inter-annual variability, and transport of atmospheric moisture over the southern African region as a whole have not been considered previously. The low levels of atmospheric moisture attributable to evaporation from the relatively arid continental surface indicate that water vapour is introduced to the subcontinent from source regions elsewhere. The sources of water vapour over the region during summer are the subject of debate. The

south-west Indian Ocean is seen as one possible source region for central southern Africa, water vapour being advected west- and southward over the interior around the semi-permanent anticyclone off the east coast (Tyson, 1986; Taljaard, 1986, 1987, 1990). Alternatively, the atmospheric moisture that contributes to rainfall over the summer rainfall region may originate in the tropics from sources over the Indian Ocean as well as the Atlantic Ocean (Mc Naughton and Wurzel, 1972), and move southward from disturbances along the Zaïre Air Boundary (ZAB) (Harrison, 1986a).

In this chapter the characteristics of water vapour transport over the southern African region will be examined for the months of October (early summer), December (hiatus) and January (late summer). Different atmospheric dynamics are dominant in the two halves of summer, rainfall-producing systems being more baroclinic in early summer and more barotropic in structure during the late summer months (Harrison, 1986a, 1986b), and intra-annual variations in vapour content and vapour fluxes may be expected. Finally, water vapour transport will be examined for cloud band case studies during a wet October and a wet and dry December and January.

Vertically Integrated Vapour Fluxes

Studies have shown that while circulation vapour transport is the most important transport mechanism over southern Africa (Matarira and Jury, 1992), the importance of meridional eddy water vapour transport along the east coast of South Africa cannot be ignored (McGee, 1970). The relative importance of the various components of meridional water vapour transport over the summer rainfall region of South Africa has been examined using a single interior station - Bloemfontein (see Fig. 2.1 for location), using radiosonde data for the 10-year period 1968-1977 (Table 5.1).

Meridional eddy fluxes are generally much lower than the corresponding circulation fluxes in all three months (Table 5.1). The eddy fluxes decrease in importance between early summer (October) and and late summer (January) (Table 5.1). The circulation transport, in contrast, increases in importance as the

Table 5.1. Mean vertically-integrated meridional circulation and eddy vapour transport for Bloemfontein South Africa, for the 10-year period 1968-1977. Abbreviations CF represent circulation and EF eddy vapour transport. Units are $g.cm^{-1}.s^{-1}$ and are rounded off to the nearest 10.

	Oct		Dec		Jan	
Year	CF	EF	CF	EF	CF	EF
1968	840	220	650	240	430	90
1969	910	200	590	50	400	120
1970	160	50	700	230	510	150
1971	820	230	250	80	530	60
1972	400	250	400	200	940	160
1973	500	190	900	150	420	170
1974	700	190	300	60	950	140
1975	700	300	640	330	650	270
1976	350	150	370	120	890	120
1977	650	100	660	-	740	250
Mean	600	190	550	160	650	150

summer season progresses. Comparisons between circulation and eddy vapour transport and rainfall show that there is little correspondence between eddy transport and rainfall in all three months (Tables 2.1 and 5.1). Increased meridional circulation transport, as has been ascertained previously, does correspond with increased rainfall over the central interior of South Africa in December and January (Tables 2.1 and 5.1). No such correspondence is revealed in October. The relative unimportance of eddy vapour transport is further evidence of the link between mean circulation systems and rainfall over the summer rainfall region in the interior of South Africa.

Analysis of vertically integrated circulation water vapour fluxes for mean October conditions (Fig. 5.1a) reveals maximum fluxes of 1400 g. $cm.^{-1}$ s^{-1} over the western Zaïre Basin in tropical Africa, and secondary maxima in excess of 1000 g. $cm.^{-1}$ s^{-1} over Madagascar to the east, and over central South Africa at about 30°S. Minimum moisture fluxes occur in the subtropics across Namibia, Botswana and southern Zimbabwe. Fluxes over Madagascar are northeasterly,

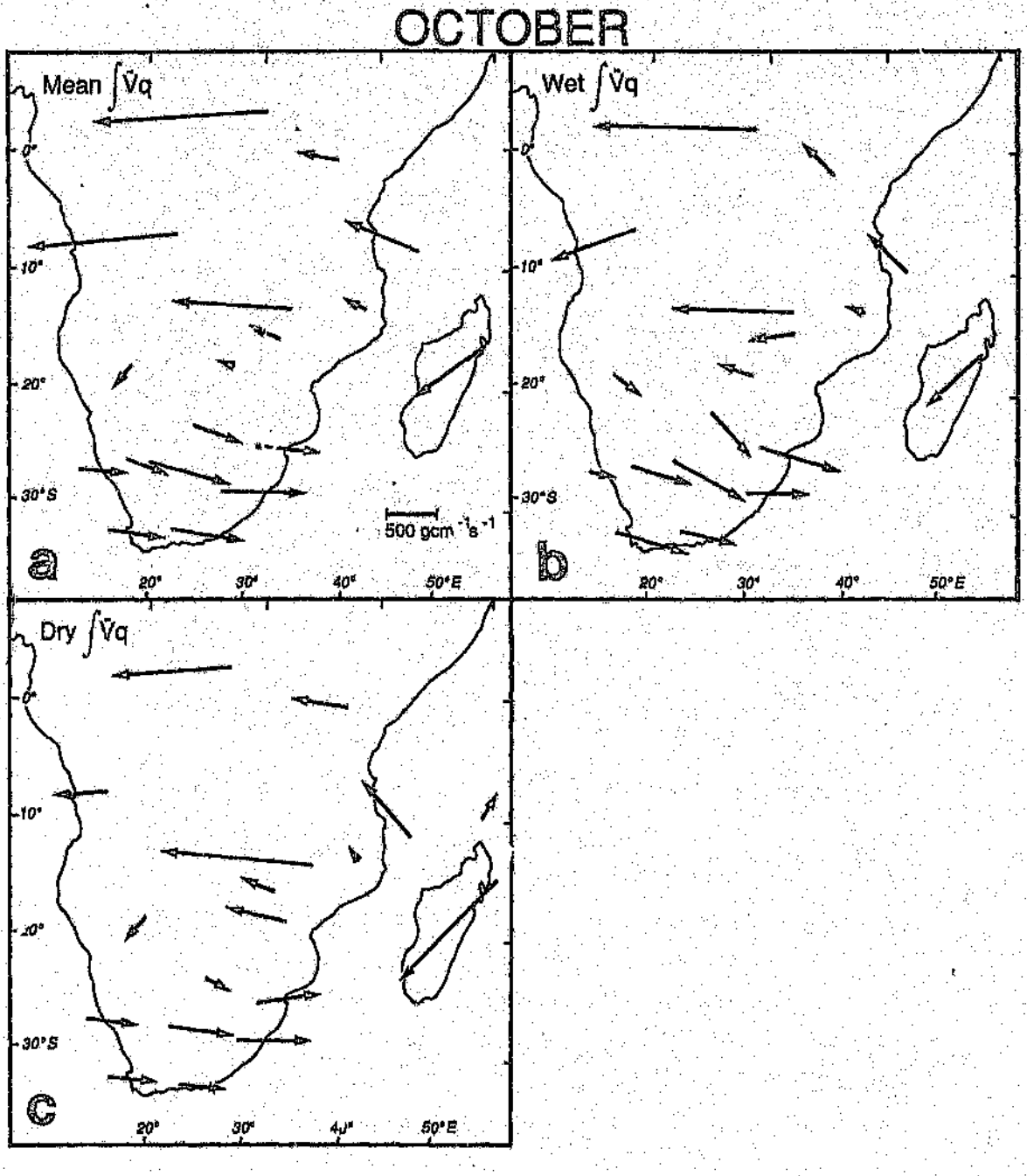

Figure 5.1: Vertically-integrated circulation fluxes of water vapour for: Mean Octobers; b) mean wet Octobers; c) mean dry Octobers. Arrows indicate direction of vector fluxes, and units are $g.cm^{-1}.s^{-1}$.

but further north over the Seychelles, where October atmospheric moisture levels are relatively low (Hastenrath and Lamb, 1979), southerly fluxes prevail. Across the east coast of the subcontinent north of about 20°S vapour fluxes are easterly to southeasterly, becoming northeasterly further to the west in the region of greatest moisture concentration in October. Northeasterly fluxes extend over northern Namibia, but south of 25°S all fluxes are westerly to northwesterly (Fig. 5.1a).

Anomalously wet months of October are characterized by an eastward shift of the zone of maximum circulation vapour flux over tropical southern Africa (Fig. 5.1b), while that over central South Africa expands. The vapour fluxes over South Africa during wet Octobers remain westerly to northwesterly, as in the mean, and southeasterly fluxes across the east coast in lower latitudes are also unchanged. In the subtropics, however, the fluxes change to northwesterly (from northeasterly) over northern Namibia, and to northeasterly (from mean southeasterlies) over northern Zimbabwe (Fig. 5.1a, 5.1b). During the driest months of October in the study period (Fig. 5.1c), an extensive region of weak vapour flux is apparent over the western subcontinent, extending over northern Mozambique to the east. By contrast, fluxes are strong over Madagascar where they exceed 1600 g. $cm.^{-1}$ s^{-1}. Vapour fluxes over South Africa remain westerly to northwesterly, but an extensive region of southeasterly flux occurs over eastern and central southern Africa (Fig. 5.1c). Over northern Namibia the vapour fluxes in dry Octobers are northeasterly as in the mean; in general, the pattern of fluxes during wet Octobers differs from mean conditions more than that for dry Octobers (Fig. 5.1a-c).

The most important features of the changes in vertically integrated circulation vapour fluxes between wet and dry Octobers are clearly illustrated by a comparison of fluxes on the zonal and meridional components of airflow for the stratified data (Fig. 5.2). Wet months are characterized by a northward expansion of westerly fluxes over the southern subcontinent, particularly the western and central parts (Fig. 5.2a), whereas in dry Octobers the region of westerly fluxes is reduced and the maximum lies over the southeast coast (Fig. 5.2b). The easterly vapour fluxes over tropical and subtropical southern Africa are weaker during wet than during dry Octobers (Fig. 5.2a, b); this is particularly

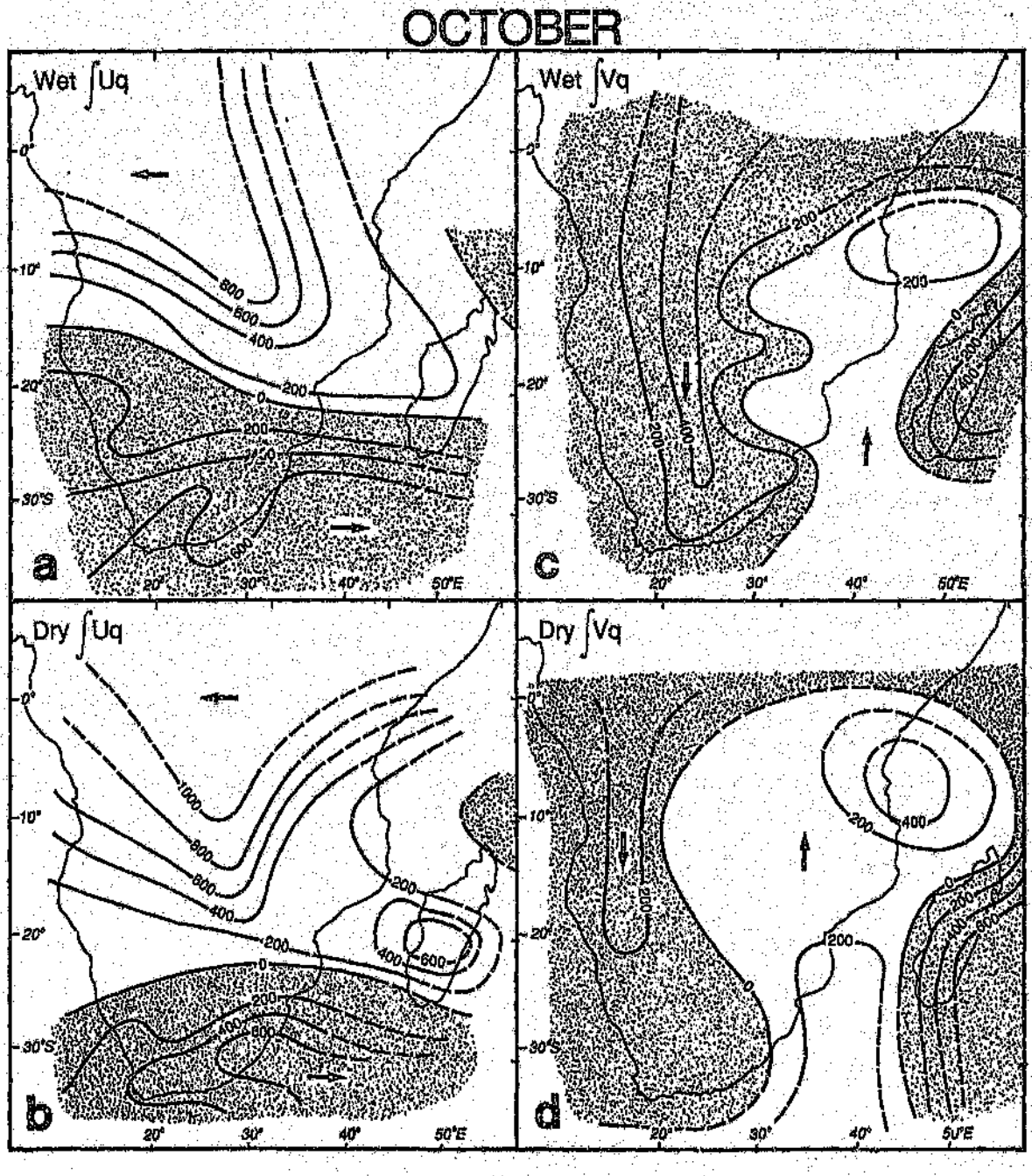

Figure 5.2: Vertically-integrated circulation fluxes of water vapour for zonal (U): a) mean wet Octobers; b) mean dry Octobers, and meridional (V): c) mean wet Octobers; d) mean dry Octobers. Northerly (poleward) meridional and westerly zonal fluxes are shaded; and units are $g.cm^{-1}.s^{-1}$

evident over Madagascar, and over central tropical Africa. Meridional vapour fluxes during wet Octobers (Fig. 5.2c) are predominantly northerly over all but the east coast of the subcontinent, reaching maximum values over the central regions. During dry Octobers (Fig. 5.2d), although northerly fluxes do occur over the western parts, these fluxes are displaced westward and are considerably weaker than the fluxes during wet Octobers. An exception occurs over the south-west Indian Ocean, where stronger northerly fluxes occur southeast of Madagascar in dry rather than in wet months. The area of southerly fluxes over the subcontinent expands during dry months, with a maximum over the east coast, in accord with the diminished role of northerly fluxes across the subcontinent in these months. Thus wet (dry) months of October are characterized by reduced (enhanced) tropical and subtropical easterly moisture fluxes, enhanced (reduced) westerly fluxes south of about 20°S, increased (diminished) northerly fluxes across the western parts, and diminished (increased) southerly fluxes over the eastern subcontinent.

Analysis of vertically integrated circulation water vapour fluxes for mean December conditions (Fig. 5.3a) reveals that as in mean Octobers maximum fluxes of 1400 $g.cm^{-1}.s^{-1}$ occur over tropical Africa north of the equator. Secondary maxima occur over Madagascar and eastern Africa north of 15°S, and over South Africa at about 30 to 35°S. Minimum moisture fluxes occur in the subtropics at 20°S at the transition zone between easterly and westerly fluxes. Fluxes north of 20°S are generally northeasterly to southeasterly, but south of 25°S all fluxes are southwesterly to northwesterly (Fig. 5.3a). The decrease in magnitude of the westerly fluxes over South Africa from mean Octobers to Decembers point to a decreasing importance of temperate weather systems as the summer progresses.

Anomalously wet months of December are characterized by northeasterly vapour transport over the entire subcontinent north of 25°S (Fig. 5.3b). Anomalously dry Decembers are similar to wet Decembers north of 10°S, but markedly different further south. Fluxes over subtropical southern Africa (10 - 20°S) veer to southeasterly, while further south the westerlies shift northward to north of 25°S and the magnitudes increase (Fig. 5.3c). The most important features of the changes in vertically integrated circulation vapour fluxes between

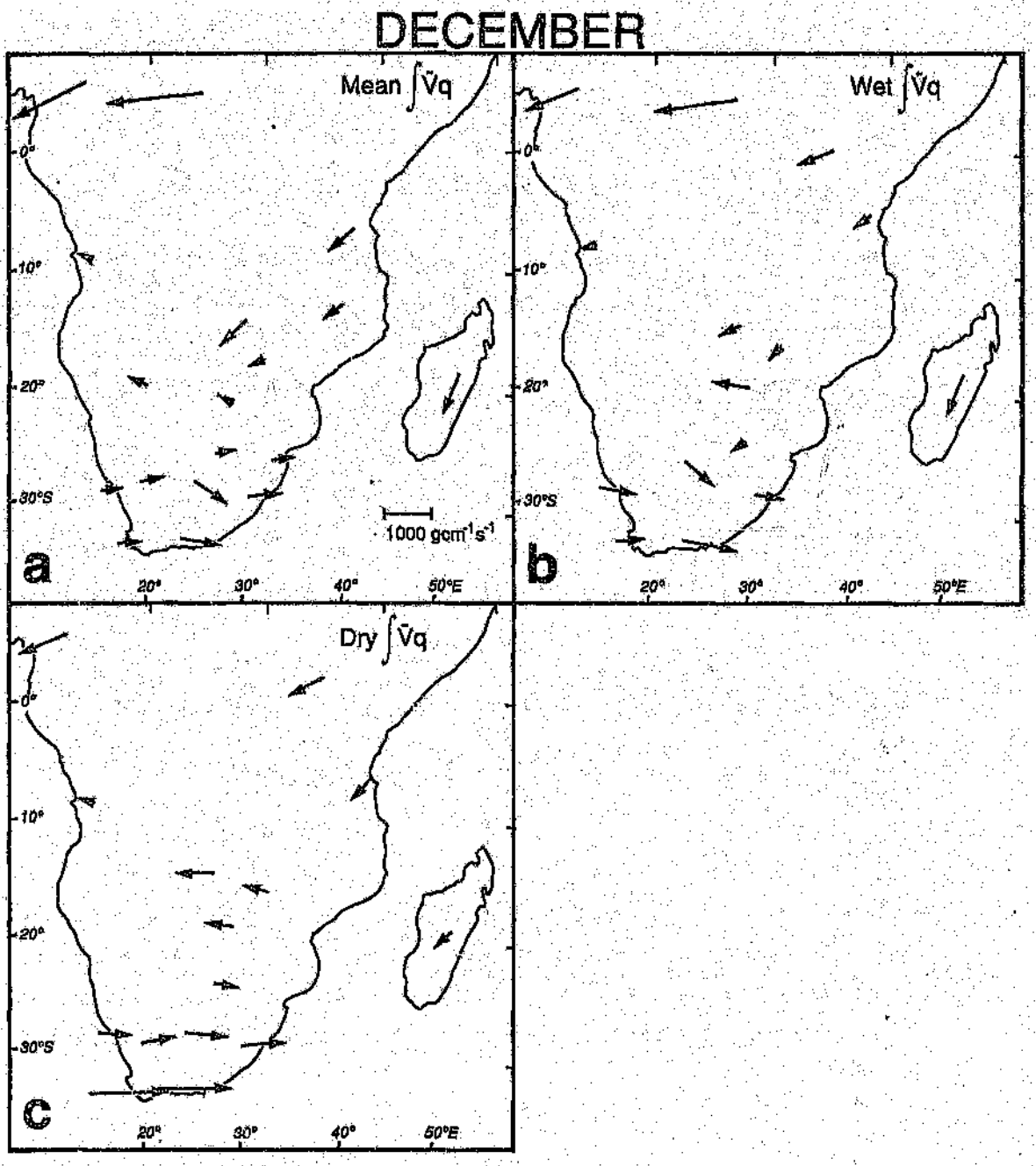

Figure 5.3: Vertically-integrated circulation fluxes of water vapour for: Mean Decembers; b) mean wet Decembers; c) mean dry Decembers. Arrows indicate the direction of vector fluxes, and units are $g.cm^{-1}.s^{-1}$.

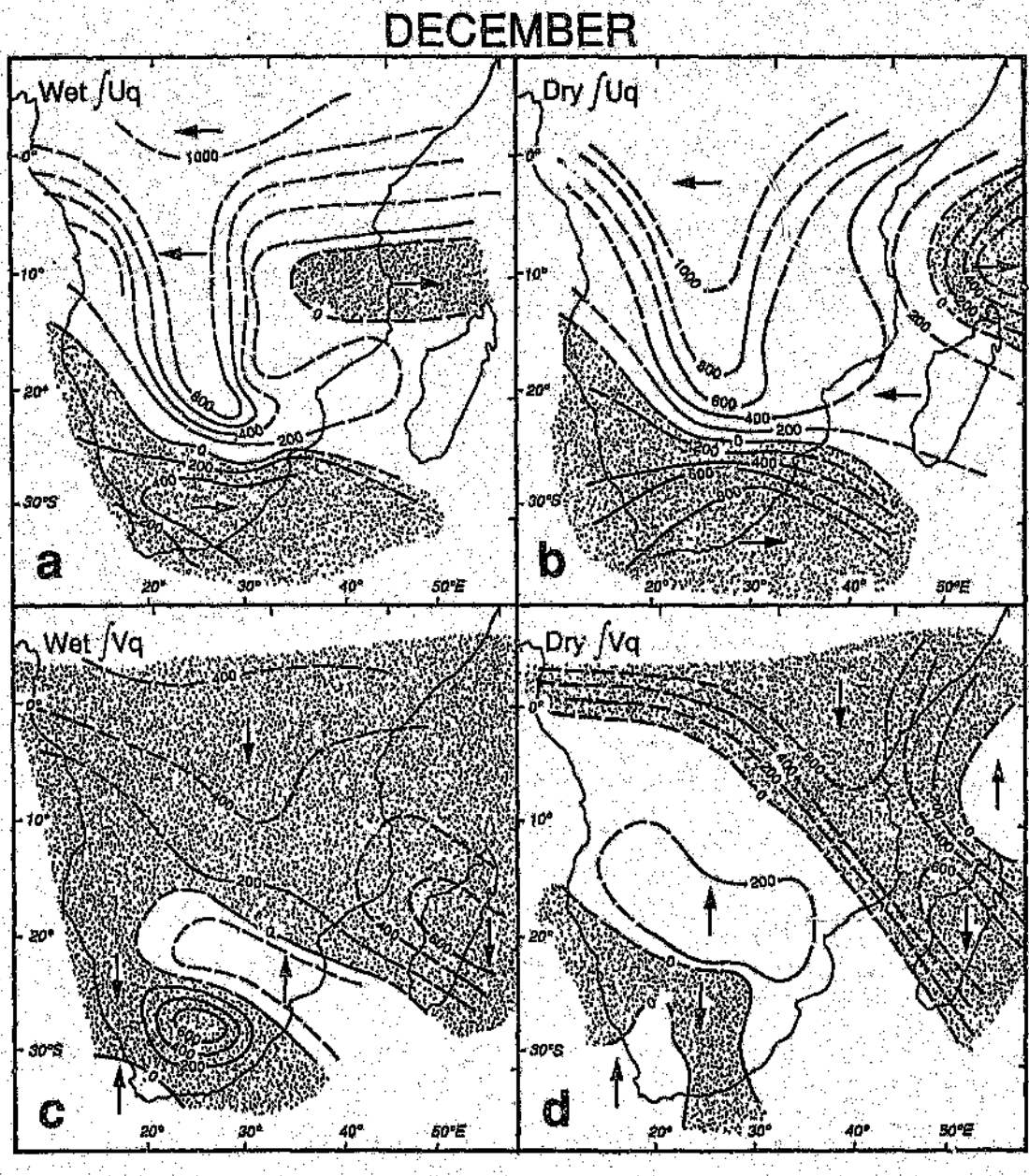

Figure 5.4: Vertically-integrated circulation fluxes of water vapour for zonal (U): a) mean wet Decembers; b) mean dry Decembers, and meridional (V): c) mean wet Decembers; d) mean dry Decembers. Northerly (poleward) meridional and westerly zonal fluxes are shaded; and units are $g.cm^{-1}.s^{-1}$.

wet and dry Decembers is the more zonal character of the transport in dry years and meridional in wet years (Fig. 5.3c).

The increased zonal water vapour transport in mean dry Decembers is clearly illustrated in Figure 5.4a and b. Westerly transport over South Africa shifts northward and intensifies. Water vapour transport over the tropics and subtropics are predominantly easterly, with relatively small areas of westerly transport over the equatorial Indian Ocean in dry months (Fig. 5.4a, b). Dry Decembers therefore represent and intensification and equatorward displacement of mid-latitude systems. Meridional vapour fluxes are predominantly northerly during mean wet Decembers (Fig. 5.4c). Dry Decembers in contrast, are characterized by reduced northerly and enhanced southerly transport across southern Africa (Fig. 5.4d). Significant northerly transport occurs further east, coinciding with the eastward shift of the cloud bands during dry months. In summary, wet (dry) Decembers unlike wet Octobers, are characterized by increased (decreased) northerly and decreased (increased) westerly vapour transport across South Africa. This indicates an increased tropical (mid-latitude) influence on rainfall over South Africa during wet (dry) Decembers.

Total vertically integrated vapour fluxes for mean January conditions (Fig. 5.5a) reveal an area of maximum flux over southern Angola/northern Namibia and east of Madagascar, and a minimum over Zimbabwe and eastern Botswana. Fluxes are generally northeasterly to easterly north of about 25°S, and westerly to southwesterly or northwesterly poleward of this latitude. Westerly fluxes also occur further north, across the Angolan coast to the west and across the east coast and northern Mozambique Channel at similar latitudes. Anomalously wet Januaries are characterized by large northeasterly vapour fluxes over Madagascar and subtropical southern Africa (exceeding 1200 g. cm.$^{-1}$ s^{-1}), between 15° and 20°S(Fig. 5.5b). Both equatorward and poleward of this zone of high moisture flux, values decrease to minima over western tropical Africa (northwesterly fluxes), southwestern South Africa (northwesterly to southwesterly fluxes), and the southeastern subcontinent (southeasterly flux across the coast) (Fig. 5.5b). The driest area is that over the tropical-subtropical west coast. Vapour fluxes are predominantly northerly during the wet Januaries, being northeasterly over the eastern subcontinent and Madagascar, and northwesterly further west. South

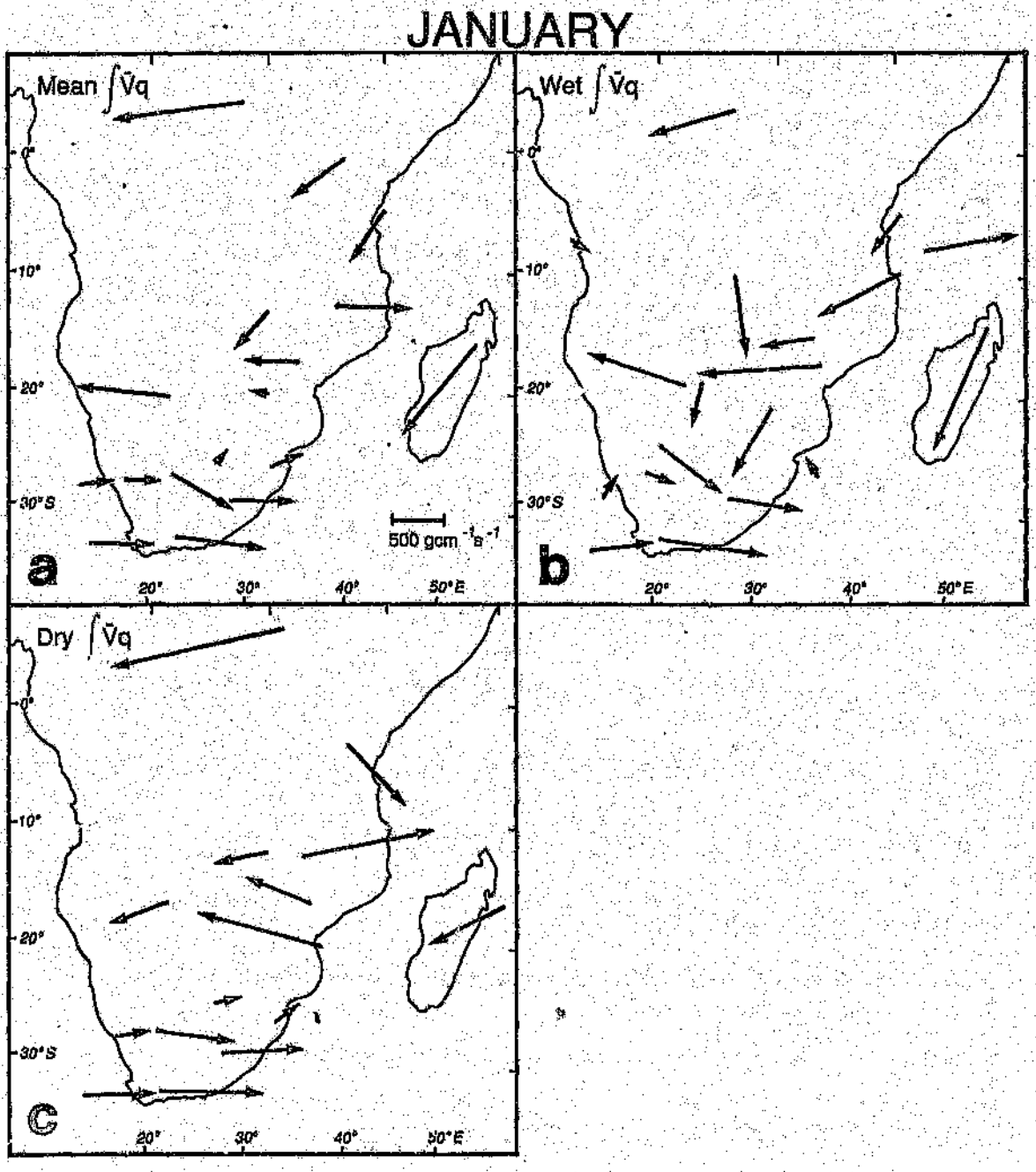

Figure 5.5: Vertically-integrated circulation fluxes of water vapour for: Mean Januaries; b) mean wet Januaries; c) mean dry Januaries. Arrows indicate direction of vector fluxes, and units are $g.cm^{-1}.s^{-1}$.

of approximately 30°S fluxes are generally westerly to southwesterly (Fig. 5.5b). In dry months of January, by contrast, strong vapour fluxes are concentrated over eastern subtropical southern Africa (Fig. 5.5c), rather than extending over the south-west Indian Ocean as in wet Januaries. Fluxes are easterly, southeasterly or southwesterly over the eastern and central subtropical regions, compared with the predominantly northerly fluxes in wet Januaries. Minimum vapour fluxes further north are largely unchanged from the wet-January pattern, with northwesterly fluxes in both cases (Fig. 5.5b, c), but over the southern subcontinent fluxes less than 600 g. $cm.^{-1}$ s^{-1} extend further equatorward in dry than in wet months, and are as low as 200 g. $cm.^{-1}$ s^{-1} across the west coast (Fig. 5.5c).

Vapour fluxes on the zonal component of airflow are weakly westerly in the tropical regions in wet months of January (Fig. 5.6a); easterly fluxes extend over the subtropics, with a maximum across the subcontinent at 20°S, and there are westerlies further south over South Africa. Westerly fluxes also occur between the equator and about 15°S in dry Januaries (Fig. 5.6b), but are stronger and more extensive than in the wet months. Fluxes over the subtropics are easterly, with a maximum concentrated over Zimbabwe at 20°S. Although maximum easterly fluxes over the subtropical regions are not as strong in wet as in dry Januaries, the area in which fluxes exceed 600 g. $cm.^{-1}$ s^{-1} is larger in the wet months, as is the overall area of easterly fluxes. Comparison of zonal vapour fluxes for anomalously wet and dry months of January thus indicates a northward displacement of the midlatitude westerly and subtropical easterly fluxes between wet and dry months (Fig. 5.4a, b), and a simultaneous northward movement and strengthening of the tropical westerly fluxes which extend across the subcontinent from the Atlantic to the Indian Ocean in dry Januaries (Fig. 5.6a). Meridional vapour fluxes (Fig. 5.6c, d) are predominantly northerly over much of the subcontinent in both wet and dry Januaries, as is true for wet and dry Octobers, but maximum northerly fluxes are considerably stronger in wet than in dry months of January (Fig. 5.6c, d) and the core of the poleward vapour flux lies further east in the wet months. Stronger southerly vapour fluxes occur over the southeastern parts in dry months of January and over the western regions in wet months, in accord with the south- and eastward displacement of the region of northerly fluxes between dry and wet months. To summarize, wet

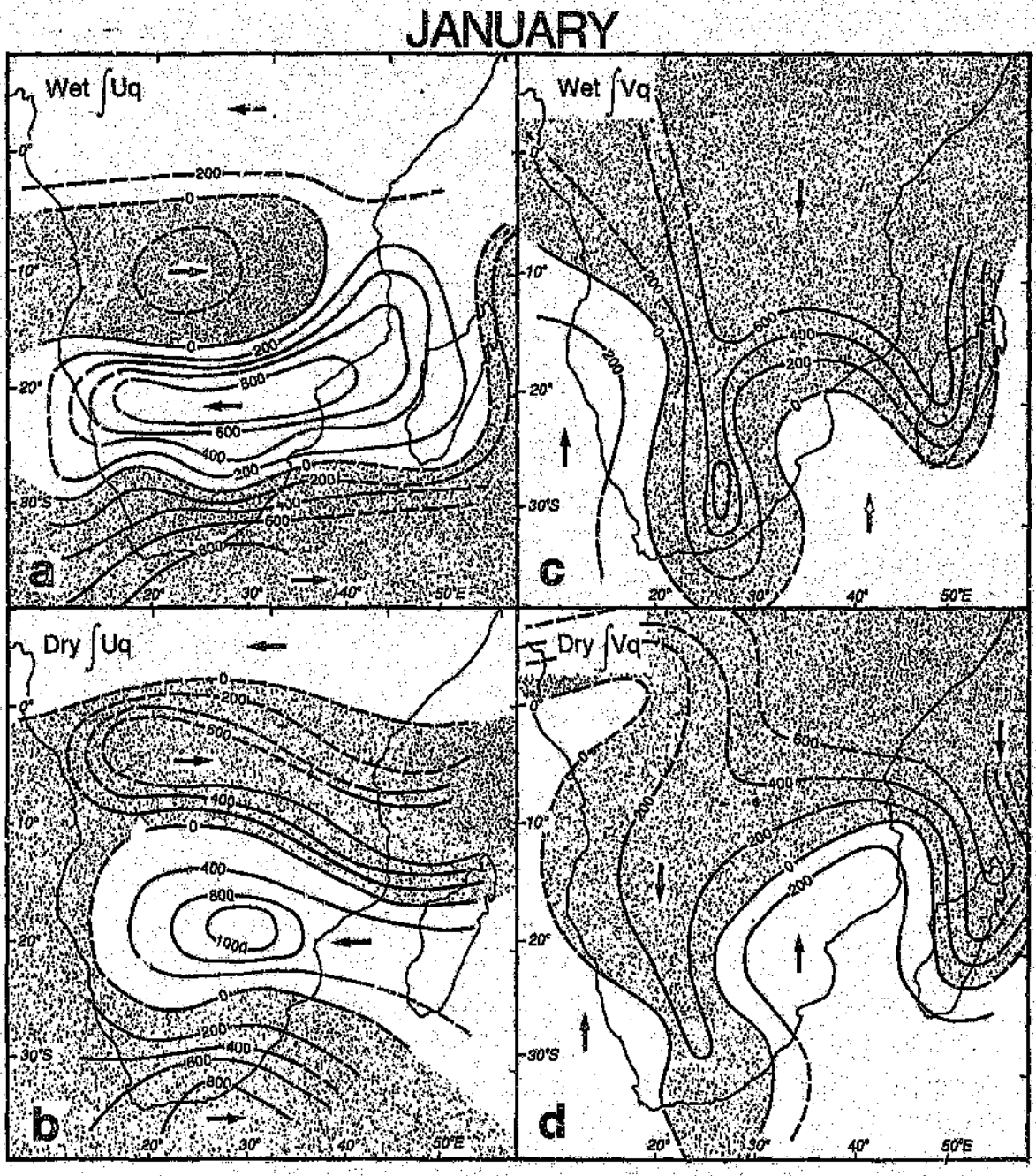

Figure 5.6: Vertically-integrated circulation fluxes of water vapour for zonal (U): a) mean wet Januaries; b) mean dry Januaries, and meridional (V): c) mean wet Januaries; d) mean dry Januaries. Northerly (poleward) meridional and westerly zonal fluxes are shaded; and units are $g.cm^{-1}.s^{-1}$.

(dry) months of January are marked by a weaker (stronger) band of tropical westerly vapour fluxes across the subcontinent, poleward (equatorward) displacement of the midlatitude westerly fluxes, and compression (expansion) of the subtropical easterly flow; and by stronger (weaker) northerly vapour fluxes which are displaced eastward (westward) over central southern Africa.

Vertical Structure of the Vapour Fluxes

Important inter-seasonal and inter-annual differences in vapour fluxes over southern Africa are evident in the analysis of vertically integrated fluxes, on the basis of both vector and component winds. It is to be expected, however, that there will be changes in the vapour fluxes with height in the troposphere, reflecting the changes in dominant circulations between seasons and between wet and dry months. An appropriate method of determining the vertical structure of the vapour fluxes is through the construction of latitudinal and longitudinal cross-sections (Hastenrath, 1966; Rasmusson, 1967; McGee, 1971). Latitudinal cross sections of vapour fluxes for wet and dry months of October at 10°S (Fig. 5.7 *upper left* and *lower left*) reveal the presence of deep easterly fluxes across the width of the subcontinent to approximately 50°E in both dry and wet months. The easterly flow extends to 300 hPa in the west and to 500 hPa everywhere across the continent, with a core at the surface near 28°E, and is slightly stronger and deeper in dry months than in wet months of October. Low-level tropical westerly fluxes occur east of 50°E, and are stronger and more extensive in dry than in wet Octobers (Fig. 5.7 *upper left* and *lower left*). Wet months are characterized by the addition of a shallow zone of westerly fluxes over the western parts of the subcontinent (Fig. 5.7 *upper left*), which results in a zone of vapour convergence around 15°E where the near-surface easterly and westerly fluxes converge. This feature is absent in dry Octobers. Another noteworthy feature is the stronger low-level vapour flux divergence over the northern Mozambique Channel, between the Seychelles and Nampula, in dry than in wet Octobers. Further south, along 30°S (Fig. 5.7 *upper right* and *lower right*), the differences in zonal vapour fluxes between wet and dry Octobers are small; noticeable changes include the westward displacement of the maximum westerly

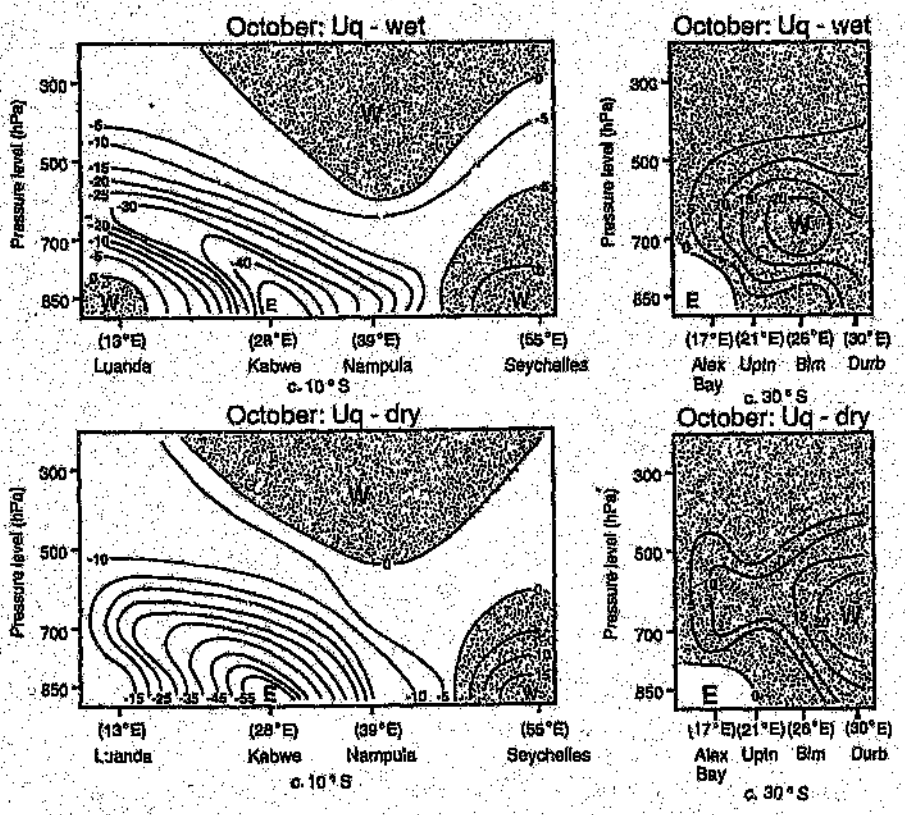

Figure 5.7: Vertical structure of vapour fluxes on the zonal component of airflow at approximately 10°S (left) and 30°S (right) during wet and dry months of October. Areas of westerly fluxes are shaded; W and E denotes westerly and easterly fluxes respectively; and units are g.hPa.cm^{-1}.s^{-1}.

vapour flux at 700 hPa from a position over the southeast coast in dry months to one over the subcontinental interior during wet Octobers.

Latitudinal sections of meridional vapour fluxes for wet and dry Octobers along 10°S reveal some differences. Along 10°S (Fig. 5.8 *upper left*), northerly fluxes occur between 850 and 500 hPa, east of about 39°E, with southerly fluxes occurring west of 39°E in wet Octobers. Above 500 hPa the circulations are reversed, implying a Hadley cell over the Indian Ocean and eastern Africa and a Ferrel cell over the western part of the subcontinent. In dry Octobers southerly fluxes expand westward to virtually dominate the entire subcontinent (Fig. 5.8 *lower left*). This implies a westward expansion of the Hadley cell during dry

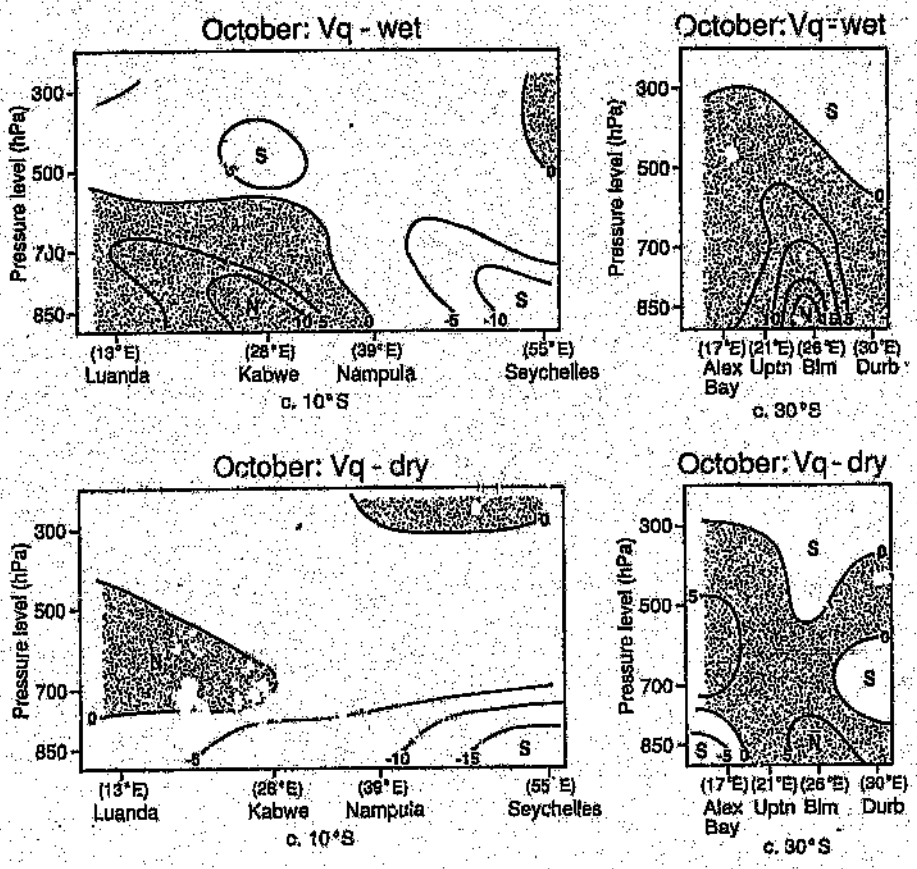

Figure 5.8: Vertical structure of vapour fluxes on the meridional component of airflow at approximately 10°S (left) and 30°S (right) during wet and dry months of October. Areas of northerly fluxes are shaded; N and S denotes northerly and southerly fluxes respectively; and units are $g.hPa.cm^{-1}.s^{-1}$.

Octobers, and is corroborated by the correlations with district rainfall over the summer rainfall region of South Africa. Harare, in Zimbabwe has a correlation coefficient of -0.55 and -0.5 with the two regions in South Africa, implying more (less) rain with northerly (southerly) vapour transport at 850 hPa. This decrease in northerly circulation vapour transport between wet and dry Octobers is reflected further south at 30°S when northerly transport decreases from 20 g. $cm^{-1}.s^{-1}.hPa^{-1}$ to 5 $g.cm^{-1}.s^{-1}.hPa^{-1}$ over central South Africa (Fig. 5.8 *upper right* and *lower right*).

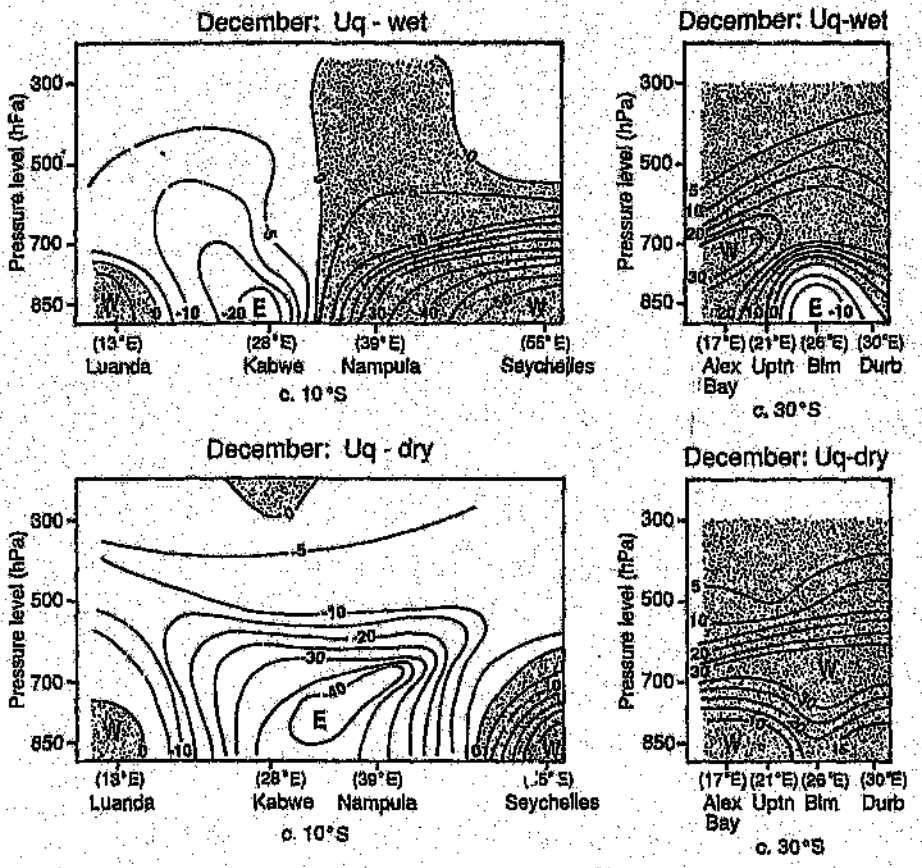

Figure 5.9: Vertical structure of vapour fluxes on the zonal component of airflow at approximately 10°S (left) and 30°S (right) during wet and dry months of December. Areas of westerly fluxes are shaded; W and E denotes westerly and easterly fluxes respectively; and units are $g.hPa.cm^{-1}.s^{-1}$.

Zonal vapour fluxes along latitudes 10° and 30°S for wet and dry Decembers are illustrated in Figure 5.9. Wet Decembers (Fig. 5.9 *upper left*) are characterized by convergence of the easterly and westerly circulation vapour flux at 10°S over western southern Africa at approximately 15°E and divergence over central Africa at approximately 30°E. Dry Decembers, by contrast, have divergence to the east of the subcontinent over the northern Mozambique Channel, and an area of vapour flux convergence at approximately 15°E over the western subcontinent. Easterly fluxes increase in magnitude from 20 $g.cm^{-1}.s^{-1}.hPa^{-1}$ to 40 $g.cm^{-1}.s^{-1}.hPa^{-1}$ between wet and dry Decembers, and the shallow westerlies over the western subcontinent decrease from wet to dry

Decembers (Fig. 5.9 *upper left* and *lower left*). Tropical easterly fluxes are therefore more strongly developed in the dry and months of December. Further south at 30°S (Fig. 5.9 *upper right* and *lower right*) the shallow zone of lower-tropospheric easterlies over the central parts in wet months disappears in dry Decembers, when westerly fluxes dominate.

Comparison of the latitudinal sections of meridional circulation vapour transport across southern Africa at 10°S for wet and dry Decembers (Fig. 5.10) shows northerly fluxes over the centre of the region in both wet and dry months. In dry Decembers (Fig. 5.10 *lower left*), and in contrast to Octobers, the northerly fluxes are stronger and are displaced slightly eastward from their position in wet months (Fig. 5.10 *upper left*). In addition, dry months are characterized by an eastward shift and expansion of southerly fluxes from the west. At 30°S strong northerly circulation vapour transport is much reduced during dry Decembers (Fig. 5.10 *upper right* and *lower right*).

Zonal vapour fluxes along latitudes 10° and 30°S for wet and dry Januaries are illustrated in Figure 5.11. At 10°S wet Januaries (Fig. 5.11 *upper left*) are characterized by divergence of the fluxes to the east of the subcontinent over the northern Mozambique Channel, and an area of vapour flux convergence at approximately 30°E over the central subcontinent. Dry Januaries, by contrast, are characterized by a deep westerly vapour flux extending east of 35°E at 10°S, and an easterly flux extending westward to approximately 20°E (Fig. 5.11 *lower left*). Convergence occurs over the western subtropical areas, at least 10° further west than in the wet months, while divergence is evident over the eastern parts. Thus tropical easterly fluxes are more strongly developed in the wet and westerly fluxes in the dry months of January. Further south at 30°S (Fig. 5.11 *upper right* and *lower right*) the shallow zone of lower-tropospheric easterlies over the western parts in wet months disappears in dry Januaries, when the maximum westerly flux at 700 hPa is stronger and extends further westward than in wet Januaries.

Comparison of the sections across southern Africa for meridional circulation vapour transport for wet and dry Januaries (Fig. 5.12) shows a strong northerly

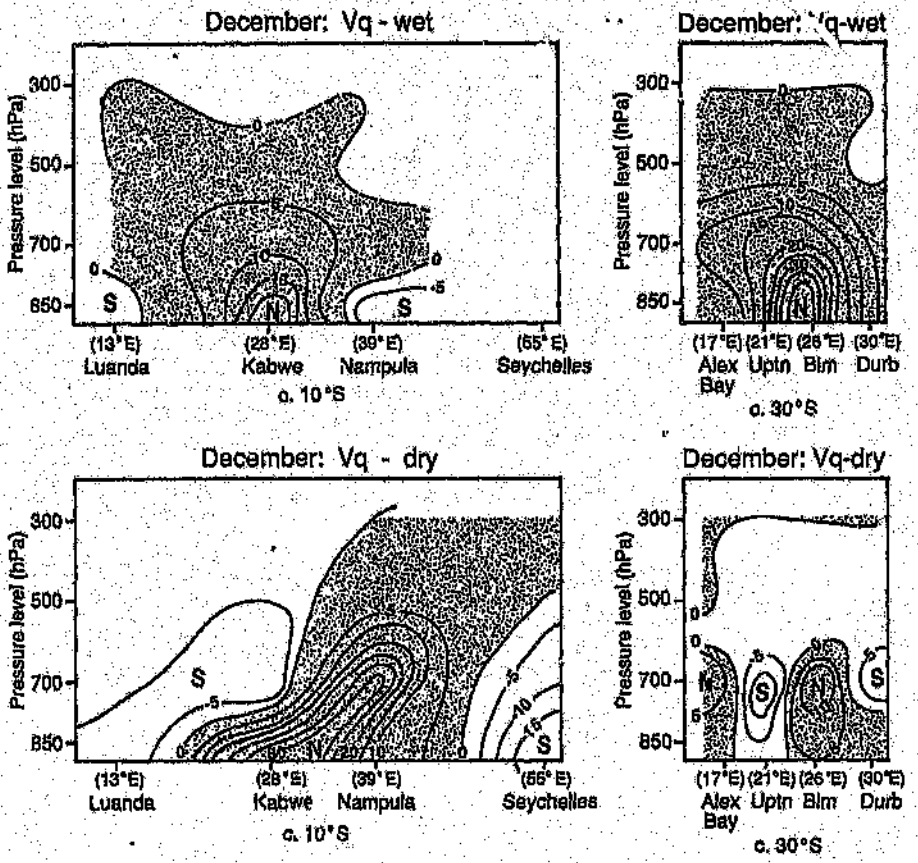

Figure 5.10: Vertical structure of vapour fluxes on the meridional component of airflow at approximately 10°S (left) and 30°S (right) during wet and dry months of December. Areas of northerly fluxes are shaded; N and S denotes northerly and southerly fluxes respectively; and units are $g.hPa.cm^{-1}.s^{-1}$.

flux over virtually the entire region in wet Januaries. In dry Januaries (Fig. 5.12 *lower left*), however, the northerly fluxes are weaker and of a smaller spatial extent, being replaced from the east by southerly transport in the lower troposphere and northerly in the upper troposphere. This suggests, as in Octobers, a westward expansion of the Hadley cell over the eastern part of the subcontinent at 10°S in dry Januaries (Fig. 5.12 *lower left*). At 30°S meridional fluxes decrease marginally from wet to dry Januaries. Southerly fluxes in the west of South Africa increase in magnitude and shift slightly eastward (Fig. 5.12 *upper right* and *lower right*).

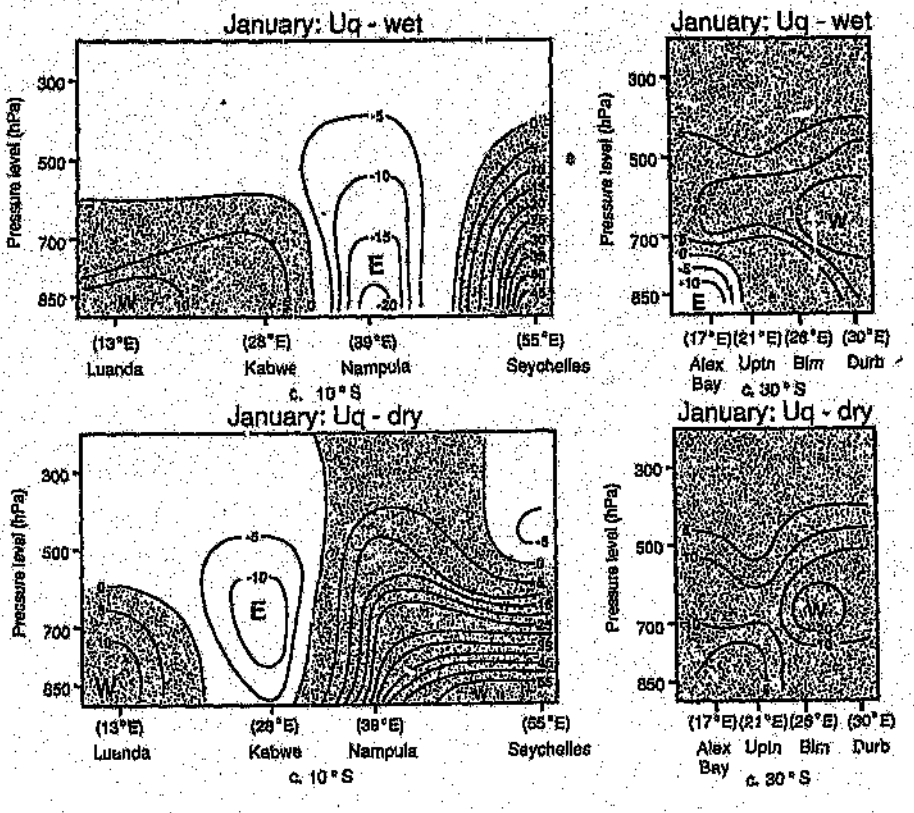

Figure 5.11: Vertical structure of vapour fluxes on the zonal component of airflow at approximately 10°S (left) and 30°S (right) during wet and dry months of January. Areas of westerly fluxes are shaded; W and E denotes westerly and easterly fluxes respectively; and units are g.hPa.cm^{-1}.s^{-1}.

Outgoing Longwave Radiation Anomalies

Vertical sections of zonal and meridional vapour fluxes across southern Africa have been used to identify area of vapour flux divergence and convergence in wet and dry months. These findings are corroborated by an analysis of outgoing longwave radiation (OLR) anomalies for wet and dry Octobers, Decembers and Januaries (Fig. 5.13). Wet months of October (Fig. 5.13a) are characterized by negative OLR anomalies (above-average convective activity and cloudiness) over

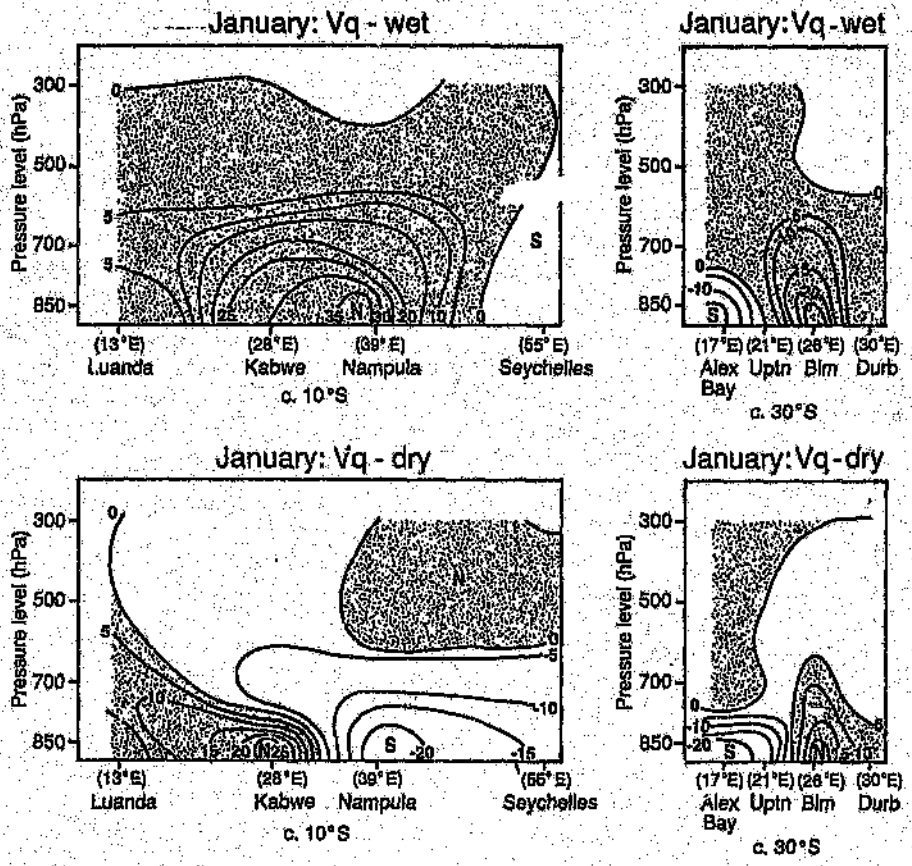

Figure 5.12: Vertical structure of vapour fluxes on the meridional component of airflow at approximately 10°S (left) and 30°S (right) during wet and dry months of January. Areas of northerly fluxes are shaded; N and S denotes northerly and southerly fluxes respectively; and ut are $g.hPa.cm^{-1}.s^{-1}$.

the entire subcontinent, with maximum conve n indicated across central southern Africa from the equator to 35°S. Dry Octobers (Fig. 5.13b), by contrast, have positive OLR anomalies and hence little convective activity in these areas. The negative OLR anomalies coincide closely with the areas of convergence identified from zonal vapour fluxes (Fig. 5.7). In wet months of December (Fig. 5.13c), OLR anomalies are negative over a large part of southern Africa, extending in a southeasterly direction from the general area of water vapour cc nvergence in the subtropics. Alternate bands of positive and negative OLR anomalies occur in a NW - SE direction across southern Africa and Madagascar. Dry Decembers show a shift of these bands of alternating positive

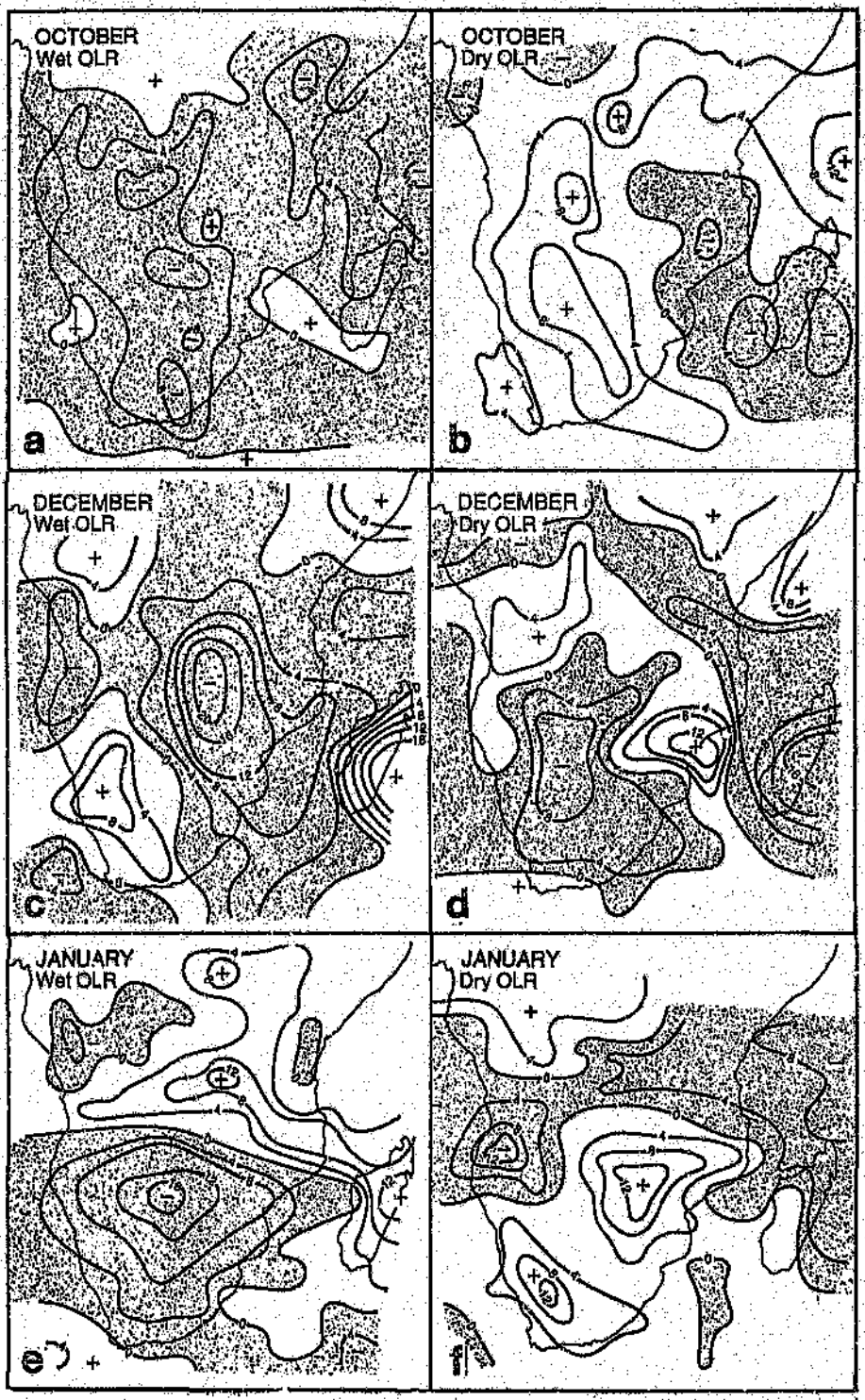

Figure 5.13: Outgoing longwave radiation (OLR) anomalies for mean a) Wet Octobers; b) dry Octobers; c) wet Decembers; d) dry Decembers; e) wet Januaries; and f) dry Januaries. Units are $W.m^{-2}$.

and negative OLR anomalies such that the negative OLR occurs over the extreme eastern parts of southern Africa with positive anomalies over South Africa and Madagascar (Fig. 5.13d). This eastward shift of negative OLR anomalies in dry Decembers conforms with the eastward shift of northerly vapour fluxes at 10°S in dry Decembers (Figs 5.10, 5.13).

OLR anomalies for wet Januaries (Fig. 5.13e) indicate strong convection over the central subcontinent at approximately 20°S. Cloud cover is greater than normal over the entire area south of 15°S, except for the northern Mozambique Channel where cloudiness is reduced in keeping with the divergence that occurs there in these months (Fig. 5.11). Vapour sources during wet months of January are thus over both the tropical Atlantic and Indian oceans. The OLR anomaly field for dry Januaries (Fig. 5.13f) is the inverse of that for wet Januaries, with reduced convection and cloudiness over the central and southern subcontinent and enhanced convection over western subtropical areas and northern Madagascar.

The OLR anomaly fields between wet Octobers, Decembers and Januaries reveal that wet early summers (Octobers) do not display spatially organized negative OLR fields while later summer (December and January) do. Negative OLR anomalies in late summer reveal strong convection in the tropics extending southward, a strong meridional spatial organization. This is a characteristic absent from October OLR fields. This may reflect a more tropical influence in later and more temperate influences in early summer.

Water Vapour Transport Variability

Time-longitude sections for vertically-integrated low-level (850-700 hPa) meridional vapour transport revealed an east to west movement across Africa at 10°S (Fig. 5.14a). Further south, at 25°S, the low-level northerly fluxes moved from west to east (Fig. 5.14b) The eastward displacement of northerly fluxes at 25°S and the westward displacement at 10°S reflect a temperate circulation regime at the former and a tropical circulation regime at the latter. The cloud band occurrence over the period 15 to 17 October was indicated by the relatively

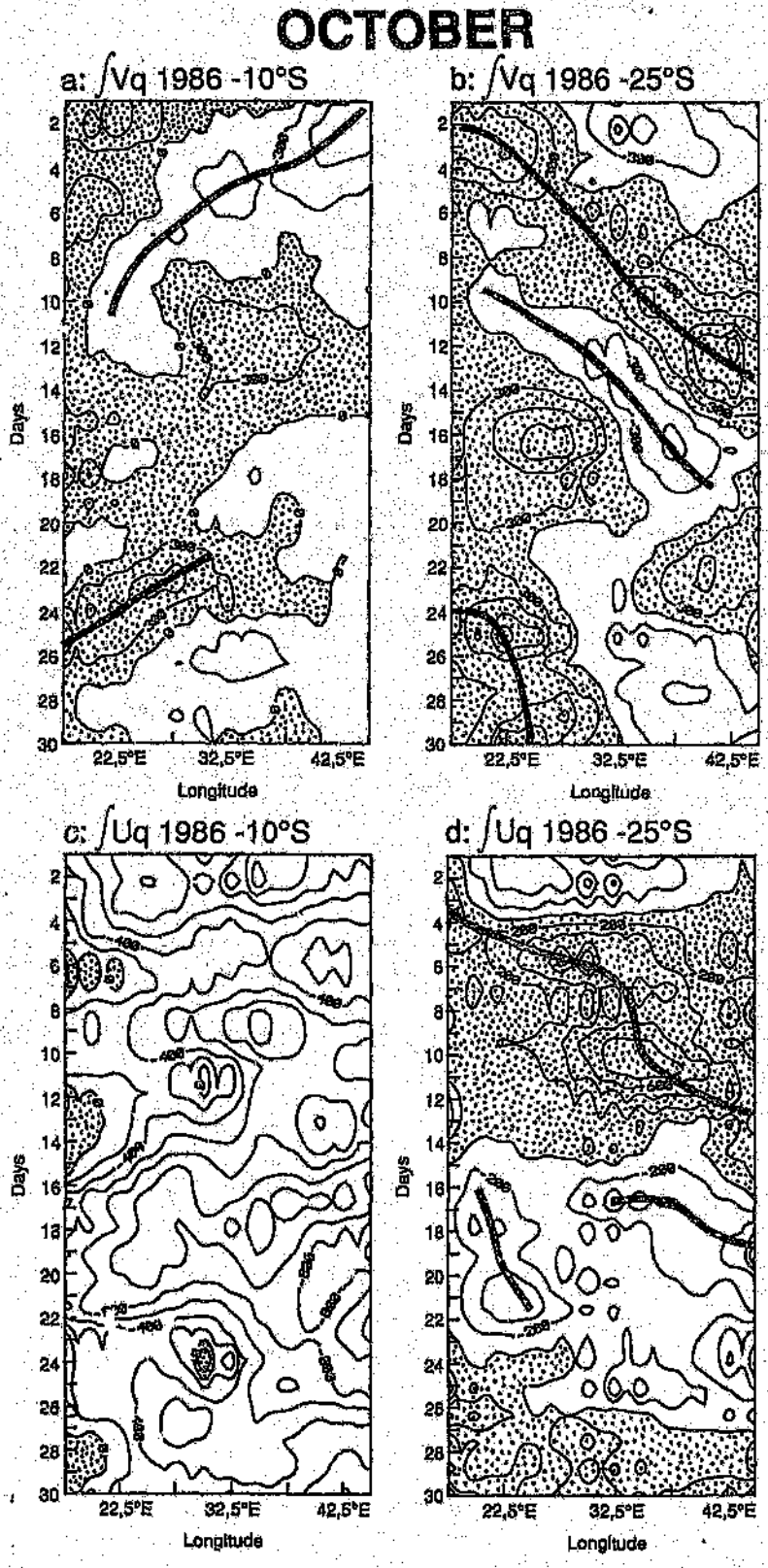

Figure 5.14: Time-longitude plots for low-level meridional vapour transport during October 1986 for: a) 10°S; b) 25°S; and zonal vapour transport for: c) 10°S; and d) 25°S. Shading indicates regions of northerly vapour transport and heavy lines indicate trains of meridional/zonal transport. Units are $g.cm^{-1}.s^{-1}$.

strong northerly flux at 25°E along the 25°S latitude band (Fig. 5.14b). Although easterly vapour transport prevailed over Africa at 10°S, the cloud band was reflected by the confluence of westerly and easterly vapour flux over tropical Africa at approximately 20°E (Fig. 5.14c). Comparing the meridional and zonal components for the cloud band, it is seen that the vapour transport at 25°S is northwesterly, becoming northeasterly with dissipation of the cloud band (Figs. 5.14b, d).

Hovmoller plots have also been examined for a wet and a dry mid-summer month at 10° and 25°S. The meridional transport at 10°S displayed a quasi-stationary nature. Although, generally stationary over Africa, areas of northerly transport travelling westward and eastward for relatively short distances during the dry December (Fig. 5.15a). The low-level meridional transport for the wet December is predominantly northerly, with maximum northerly transport moving across the latitude from the east as well as the west (Fig. 5.15c). At 25°S, marked differences occur in the low-level meridional vapour fluxes between wet and dry Decembers. During the dry year, areas of northerly transport displays a transient nature, with movement from the east (Fig. 5.15b), whereas in the wet year maximum northerly transport is mainly from the west (Fig. 5.15d). The cloud band case studies for mid summer generally coincide with strengthened northerly transport across 10° and 25° S (Fig. 5.15) and an eastward intrusion of westerly vapour transport such that convergence occurs over western subtropical southern Africa prior to and during the cloud band case studies (Fig. 5.17 top)

Time-longitude plots for low-level meridional transport at 10°S for the relatively dry January (1980) reveal a quasi-stationary nature, centred at approximately 37°E, with southerly fluxes prevailing further west, over the African continent (Fig. 5.16a). Further south, at 25°S, the low-level meridional transport was also quasi-stationary, with northerly transport over southern Africa (Fig. 5.16b). Increases in the northerly fluxes at 25°S corresponded with cloud band occurrences on 6 to 8 January (Plate 3.4), and with tropical cloud on 20 to 22 January. At 10°S, the region of northerly fluxes shift furthest west to approximately 23°E during the cloud band occurrence (Fig. 5.16a). During 8 and 20-22 January 1980 (not illustrated), cloud bands occurred over the Mozambique

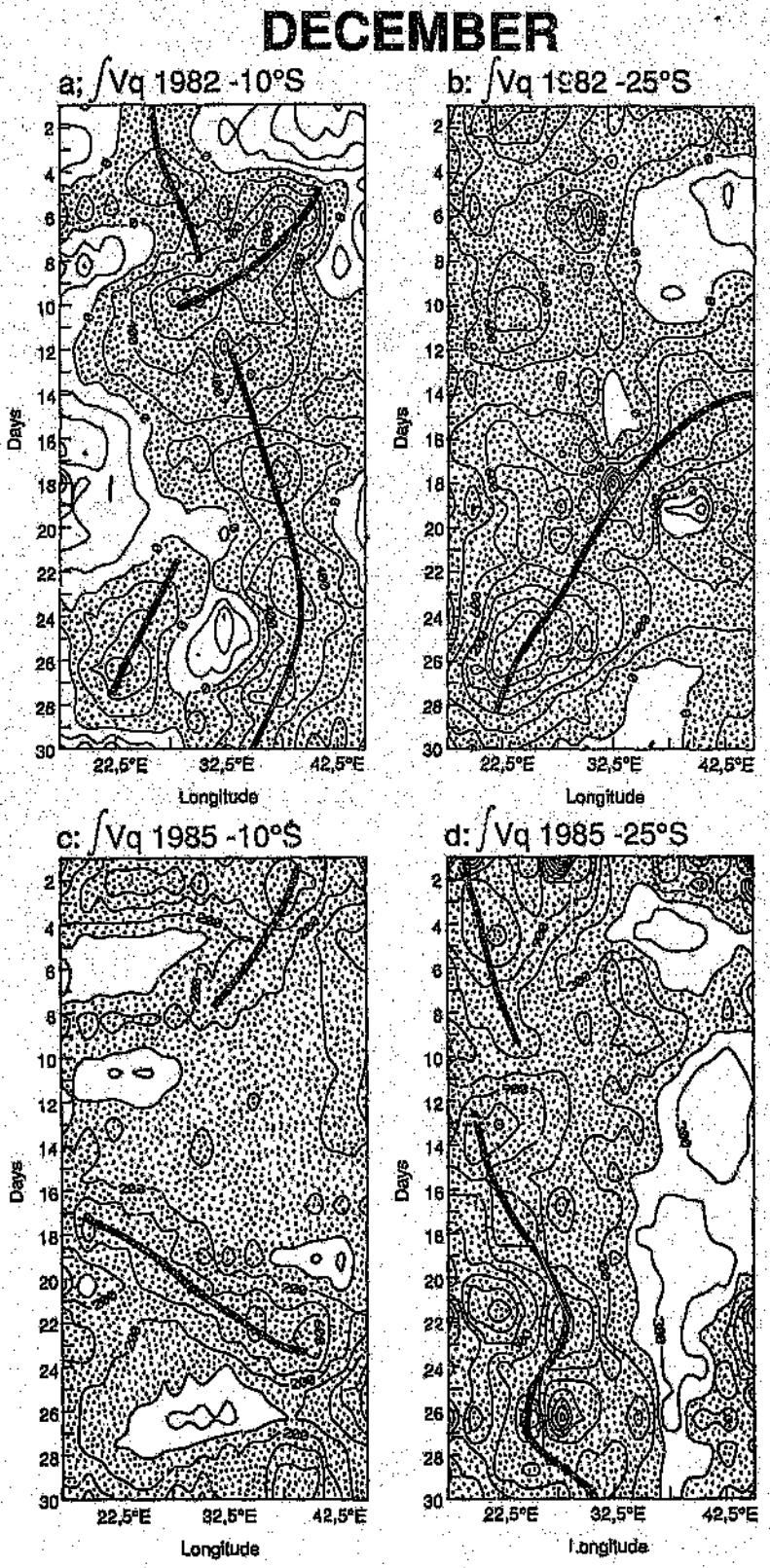

Figure 5.15: Time-longitude plot of meridional water vapour transport for a dry December (1982) for: a) 10°S; b) 25°S; and a wet December (1985) for: c) 10°S and b) 25°S. Shading indicates regions of northerly vapour transport and heavy lines indicate trains of meridional transport. Units are in $g.cm^{-1}.s^{-1}$.

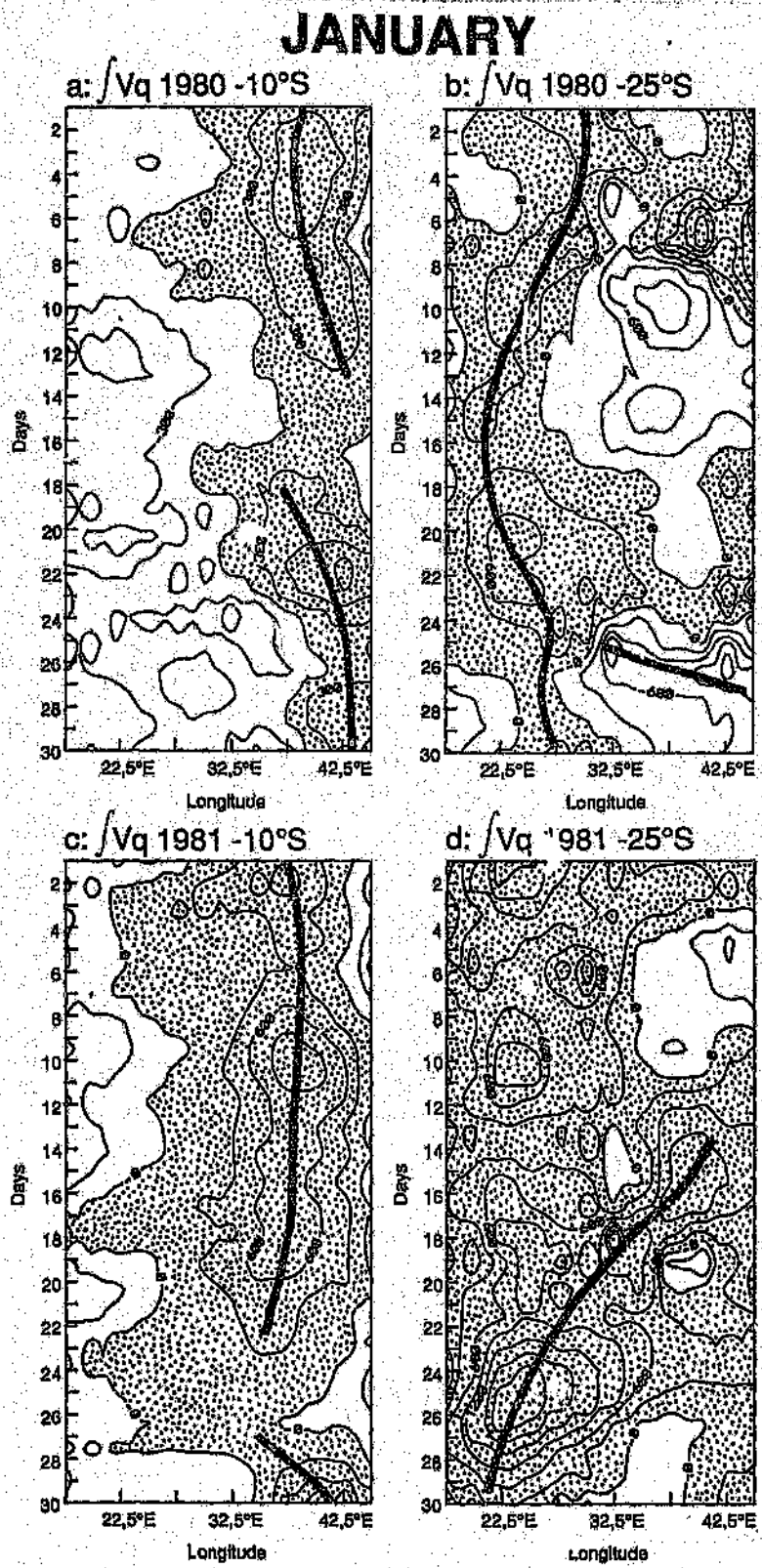

Figure 5.16: Time-longitude plot of meridional water vapour transport for a dry January (1980) for: a) 10°S; b) 25°S; and a wet January (1981) for: c) 10°S and b) 25°S. Shading indicates regions of northerly vapour transport and heavy lines indicate trains of meridional transport. Units are $g.cm^{-1}.s^{-1}$.

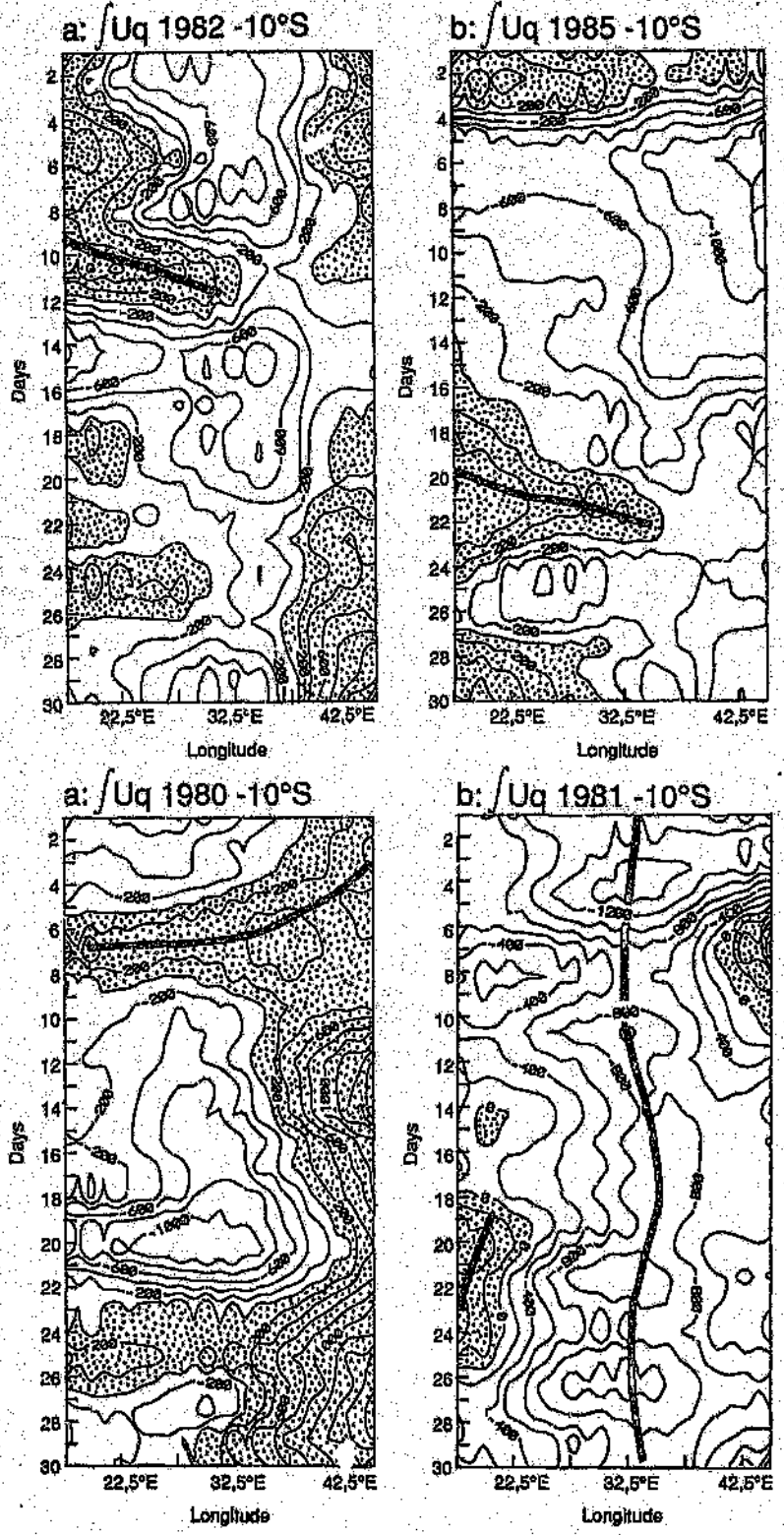

Figure 5.17: Time-longitude plot of zonal water vapour transport at 10° S for: top a) dry December (1982); b) wet December (1985); and bottom a) dry January (1980); and b) wet January (1981). Shading indicates regions of westerly vapour transport and heavy lines indicate trains of zonal transport. Units are $g.cm^{-1}.s^{-1}$.

Channel. These are reflected in the increased northerly transport at approximately 40°E at both 10°S and 25°S (Fig. 5.16a, b). Time-longitude plots of low-level vertically integrated zonal vapour transport at 10°S reveal a quasi-stationary nature. Easterly water vapour transport dominated the entire continental region, with occasional periods of westerly transport (Fig. 5.17 bottom a). The most noticeable coincidence of westerly transport occurred with the formation of the cloud band from 6 to 8 January 1980.

Time-longitude plots for low-level meridional vapour transport at 10°S during a relatively wet January (1981) show an increase in northerly fluxes (from January 1980) at approximately 37°E (Fig. 5.16b). Northerly transport also occurred further west (to approximately 23°E) (Fig. 5.16c). At 25°S, northerly vapour transport dominated the subcontinent, and displayed a more transient nature than during the dry January (Fig. 5.16d), with northerly fluxes moving in from the east. A cloud band formed over South Africa between 21 and 27 January when the northerly transport at 25°S had shifted westward and intensified (Fig. 5.16d). Similarly, the cloud band formed in conjunction with the eastward intrusion of tropical westerly air over the subcontinent so that convergence occurred over western subtropical Africa prior to and during the cloud band case (Fig. 5.17 bottom b).

Discussion

Important characteristics of mean vapour fluxes, and inter-seasonal and inter-annual changes in the fluxes, have been identified over southern Africa. The results indicate that both the spatial patterns and the vertical structure of the vapour fluxes change over the region between seasons and between wet and dry months in the summer rainfall area of South Africa. More particularly, it has been shown that a northward shift and intensification of the subtropical westerly fluxes occurs in wet months of October, i.e. zonal flow is enhanced (Fig. 5.2a), whereas southerly meridional vapour fluxes are more important over eastern southern Africa in dry Octobers (Fig. 5.2d). Mean dry Decembers are characterized by increased westerly and decreased northerly fluxes over South Africa (Fig. 5.4). The westward shift of the southerly transport over subtropical

southern Africa in mean dry Octobers and Decembers may represent a corresponding shift of an anticyclone such that it occurs over the central regions of the subcontinent (cf. Figs 4.5, 4.7, 5.4c, d). Wet Januaries are characterized by an increase in northerly meridional vapour fluxes across southern Africa (Fig. 5.6c), stronger and further east than in dry months (Fig. 5.6d). The tropical easterlies and subtropical westerlies are also displaced southward in wet relative to dry Januaries, as meridional fluxes are more dominant in the wet months. The importance of the westerly transport in early summer as opposed to the northerly transport in late summer has been tested using statistical tests of differences between wet and dry early and late-summer months (Table 5.2). The differences in zonal fluxes are significant over the western parts of the subcontinent as represented by Luanda in October and over the central subcontinent (e.g. Bulawayo and Bloemfontein) for meridional fluxes in January (Table 5.2).

Differences in the importance of the meridional vapour flux between wet and dry months, as well as between seasons, highlights the importance of changes in the vapour fluxes for rainfall over southern Africa. Predominantly zonal westerly fluxes across South Africa in wet early summer months, together with the enhanced vertical gradient in the zonal fluxes in these months (Fig. 5.8), accord well with the suggestion that October rainfall over the southern African interior is produced largely by midlatitude baroclinic systems. Similarly, the large contribution of northerly meridional and upper level easterly vapour fluxes over eastern southern Africa in wet months of January supports the idea that tropical systems and tropical-temperate interactions have an important influence on late-summer rainfall (cf. Table 5.2 and Figs 5.11) (Harrison, 1983, 1984, 1986a; Taljaard, 1986, 1987; Walker and Lindesay, 1989; Lindesay and Jury, 1991). In dry Octobers the zonal vapour fluxes are diminished, and in dry Decembers and Januaries the meridional fluxes are reduced, in keeping with the below-average rainfall in these months. Northerly meridional fluxes in wet months suggest the positioning of the leading arm of a westerly wave over southern Africa during these months, and southerly fluxes in dry months indicate that the trailing arm extends over the subcontinent at these times (Harrison, 1986a). In late summer, the southward displacement of the tropical easterly fluxes during wet Januaries indicates a concomitant intensification and southward movement of the semi-stationary easterly wave over southern Africa (cf. Figs 4.8, 5.5, 5.6) (Tyson,

Table 5.2: Results of the Mann-Whitney U test (2-tailed) for the significance of the differences in magnitude of vertically integrated zonal and meridional vapour fluxes between wet and dry months. * indicates significance at better than the 10% level, and ** at the 5% level.

	October		January	
Station	Uq	Vq	Uq	Vq
Dar es Salaam				*
Luanda	*			
Bulawayo		*		**
Alexander Bay				
Bloemfontein		*		**
Durban				
Cape Town				

1986), and the possible southward displacement of the Zaire Air Boundary (ZAB) and the disturbances associated with it (Taljaard, 1972, 1986). Confirmation, as in October, comes from correlations between meridional circulation vapour transport and South African summer rainfall districts where positive correlations of 0,5 to 0,65 (significant at 95 per cent level) at stations in tropical and subtropical Africa (Harare, Bulawayo, Kabwe, Pretoria, Bloemfontein) imply the stronger the flux from north, the higher the rainfall over the summer rainfall region of South Africa. The lack of a dominant water vapour transport component (zonal or meridional) corresponding to rainfall in December, reflects Harrison's (1986a) hypothesis that December is an hiatus month when the mainly baroclinic rainfall mechanisms of early summer give way to the barotropic mechanisms of late summer. The lack of cohesion between the northerly vapour transport over tropical and subtropical Africa in December also reflects the observed decrease in tropical-temperate interactions (i.e. major cloud bands in Fig. 1.4) (Harrison, 1986).

Schematic illustrations of the suggested pathways of vertically integrated water vapour for wet and dry months of October, December and January (Fig. 5.18) allow inter-seasonal and inter-annual changes in vapour fluxes to be distinguished. During wet Octobers (Fig. 5.18a) water vapour is advected over subtropical southern Africa from Madagascar and the northern Mozambique Channel, with a northward branch extending along the east coast of Africa. The

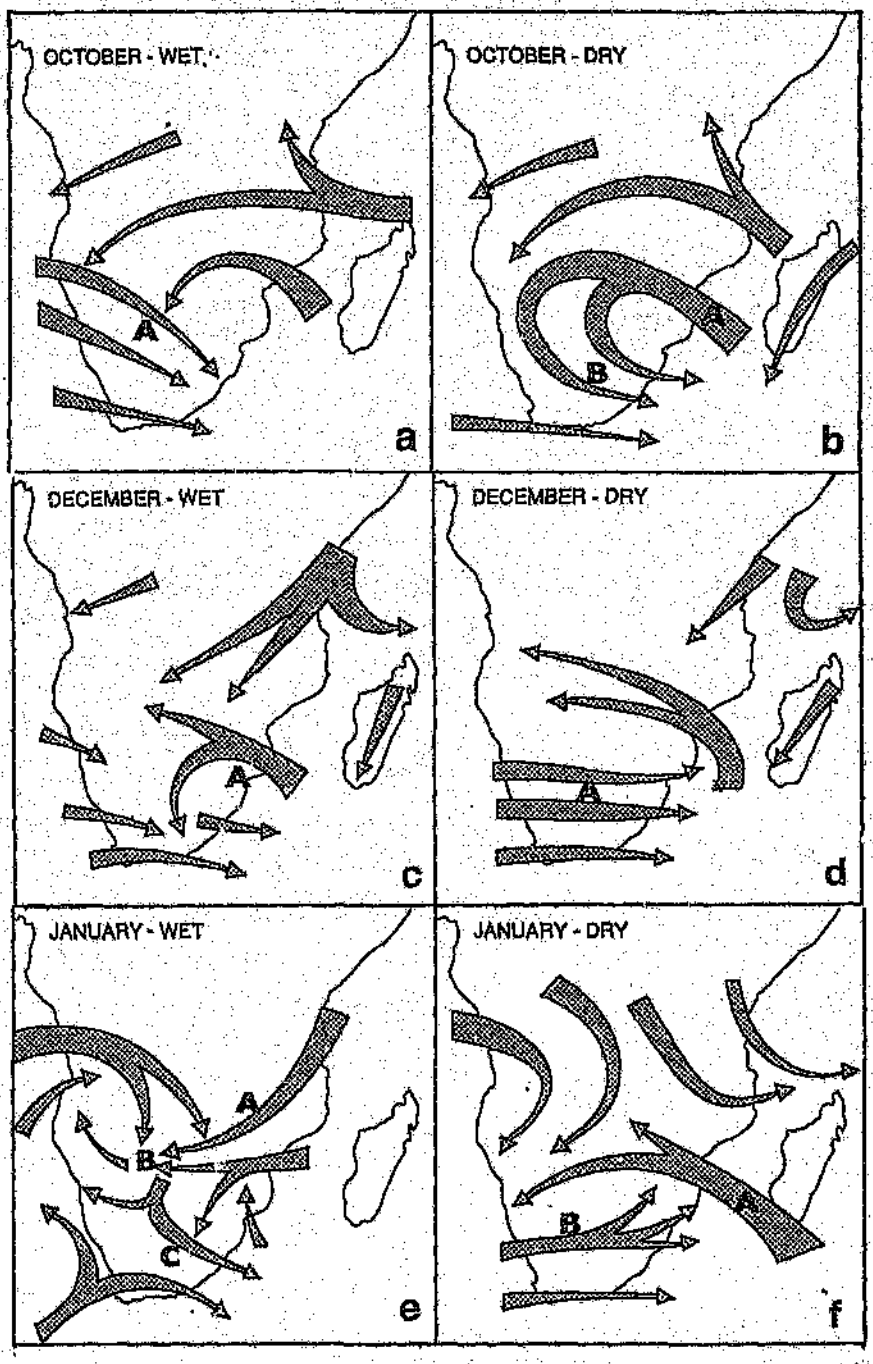

Figure 5.18: Schematic representation of the main vertically integrated circulation vapour transport over southern Africa in wet and dry months of October (a, b), January (c, d) and December (e, f).

flux is easterly to southeasterly, and converges over the western interior with a northwesterly flux from the tropical Atlantic Ocean (Fig. 5.18a). This pattern of airflow and convergence is typical of that which occurs along the ZAB in summer (Dhonneur *et al*, 1974; Lindesay, 1992). Vapour fluxes further south over South Africa are northwesterly to westerly from the Atlantic Ocean in association with the trough over western southern Africa (indicated A in Fig. 5.18a, 4.4b). Dry Octobers are characterized by a southeasterly vapour flux over the subcontinent from the Mozambique Channel (indicated A in Fig. 5.18b). The flux has two branches, one extending northeastward along the east African coast and into central Africa, and the second extending over subtropical southern Africa to recurve over the western interior (southeastern Angola). This southern portion of the tropical flux recurves southeastward over Namibia, southwestern Botswana and the northern parts of South Africa as a continentally modified airmass (indicated B in Fig. 5.18b) (Taljaard, 1958). The most obvious differences between wet and dry Octobers are the absence of the northwesterly vapour flux from the tropical Atlantic Ocean (see Fig. 4.5b), and of the strong easterly flux from the tropical Indian Ocean, in dry Octobers; and the occurrence of vapour flux convergence over the western-central interior in wet but not in dry months.

The schematic diagrams for vertically-integrated circulation vapour transport during mean wet Decembers reveal the increased importance of tropical and subtropical air masses to rainfall over South Africa. Moisture from the Indian Ocean is advected over southern Africa and constitutes an important source of water vapour during the wet December months (indicated by A in Fig. 5.18c). Mean dry Decembers, in contrast, are characterized by a northward shift of the westerlies (as in mean dry Januaries) (A in Fig. 5.18d), reflecting an equatorward shift of midlatitude weather systems (Harrison, 1986a).

The patterns of vapour fluxes in January are more complex than those in October (Fig. 5.18e, f). Wet Januaries have a strong northeasterly vapour flux from the northern tropical Indian Ocean extending across the subcontinent as far south and west as Namibia (A in Fig. 5.18e). This flux, which is probably associated with the Asian winter monsoon (e.g. Riehl, 1979; Hastenrath, 1985), becomes increasingly easterly as it passes across the subcontinent. Together with

a flux from over the Mozambique Channel, the easterly vapour flux converges with northerly to northwesterly fluxes from the tropical Atlantic Ocean over central southern Africa (Botswana and Zambia) in a disturbance along the ZAB (Fig. 4.8, B in Fig. 5.18e) (Taljaard, 1972, 1986). An important feature is the flux that extends southward across South Africa from that convergence zone (C in Fig. 5.18e); there is a further minor area of convergence over the northeastern part of South Africa. Westerly fluxes are found only over the extreme south of the subcontinent. During dry Januaries (Fig. 5.18f) the northeasterly flux from the tropical Indian Ocean is replaced by a northerly to northwesterly flux of continental air. Further west the northerly flux becomes northeasterly. Where there was an easterly flux from the central Mozambique Channel in wet Januaries, dry months are characterized by a strong southeasterly flux from the south-west Indian Ocean (A in Fig. 5.18f). The southeasterly flux, which is associated with the relatively stable southeast trade wind flow (Hastenrath, 1985), extends as far west as 20°E, suggesting an intensification and/or westward displacement of the anticyclone over southern Africa similar to that which occurs during dry summer seasons (Fig. 4.9b) (Miron and Tyson, 1984). This shallow, stable air mass serves to prevent the reduced northeasterly vapour flux from penetrating over the summer rainfall area of South Africa. Instead westerly fluxes expand northward between wet and dry Januaries, and affect the entire southern subcontinent in the dry months (B in Fig. 5.18f).

The important adjustments in areas of convergence and divergence of the vapour fluxes between wet and dry months, and the role of tropical convergence and convection in transporting moisture southward over the summer rainfall area, are illustrated schematically for January in Figure 5.19a. The tropical circulation cells are not well defined in October, probably because of the dominance of the subtropical westerly circulation over much of the subcontinent in early summer (Harrison, 1986), and further investigation of the circulation anomalies for this season awaits the analysis of more comprehensive data sets south of c. 30°S. Both the tropical zonal (Walker) and the meridional (Hadley/Ferrel) circulations undergo alterations between the wet and dry months, and these adjustments are represented here by the mean zonal and meridional components during wet and dry months of January. Vertical motion and areas

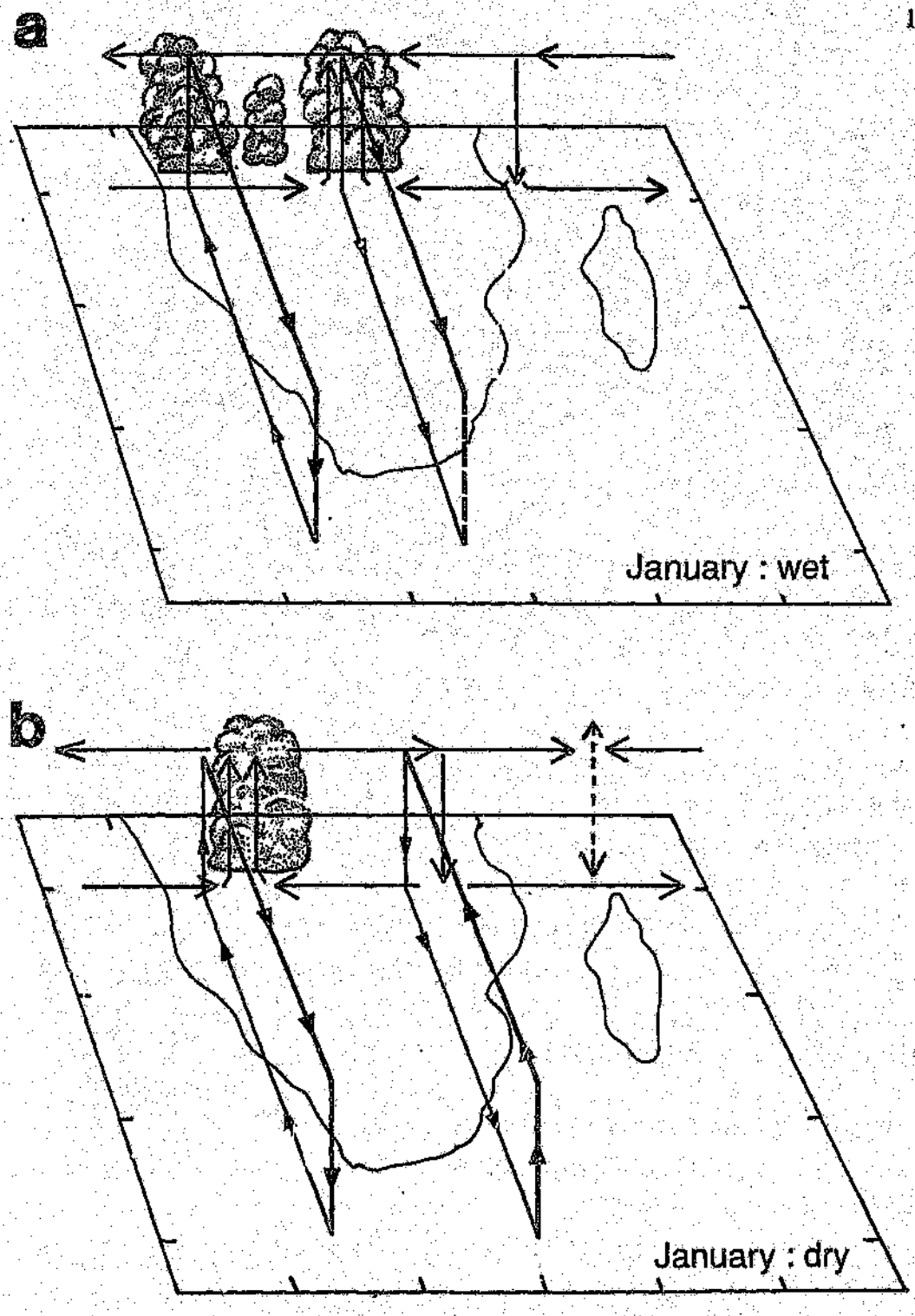

Figure 3.19: Schematic illustration of the zonal and meridional circulations associated with changes in vapour fluxes over southern Africa between wet and dry months of January and December.

of convergence and divergence are inferred from the vertical sections of vapour fluxes and from the analysis of OLR anomalies presented previously. The results show a more complex circulation over Africa than that presented by Bjerknes (1969), Krishnamurti (1979), Harrison (1984) and Lindesay (1988a). Wet Januaries are characterized by upper-level kinematic convergence and low-level divergence over the northern Mozambique Channel and an important area of convergence at about 30°E (Fig. 5.19a). This configuration has the appearance of a series of typical Walker circulation cells with a rising branch over central tropical southern Africa, and conforms with previously suggested associations between the typical Southern Oscillation high phase (cold eastern tropical Pacific Ocean) pattern and above-average summer rainfall in central southern Africa (Harrison, 1986a; Daniels and Vernekar, 1988; Lindesay, 1988a, 1988b). The area of wet-January convective activity is more extensive than has been suggested previously, with apparent low-level kinematic convergence across the African tropics from 30° to c. 10°E (see Figs 3.8a,b, 5.13e). Upper-tropospheric flow is anomalously easterly across the subcontinent, since the ITC is displaced southward during wet Januaries, and acceleration of the flow from 30° to 10°E could provide the necessary divergence to sustain the convection evidenced in the OLR anomaly field (Fig. 5.13e). The meridional circulation in wet Januaries has the characteristics of an extensive Hadley cell over the entire subcontinent west of c. 30°E, with ascent in tropical latitudes and descent in the subtropics connected by poleward flow through most of the troposphere over the eastern subcontinent. Earlier studies have also indicated a deep northerly flow across the eastern regions of South Africa during January (Fig. 5.20 middle left) (Harrison, 1986; Lindesay, 1988a). Lower (upper) tropospheric southerly (northerly) flow occurs further west (see Figs 5.12 and 5.20 middle right). The circulation pattern observed in Figure 5.12 corresponds with the circulation over southern Africa during the high (wet) phase of the Southern Oscillation (Lindesay, 1988a, 1988b). The enhanced Hadley circulation over southern Africa during wet late summer has been attributed to thermal forcing due to latent heat release over the tropics (Harrison, 1986b), as has been ascertained elsewhere (Heddinghaus and Krueger, 1981; Webster, 1983; Rind and Rossow, 1984). This thermal forcing of a standing wave over southern Africa in wet late summer months can be corroborated by the total latent heat for wet and dry late summers (cf. Figs 3.8, 3.11, 3.12). Latent heat release over southern Africa during the wet January (Fig.

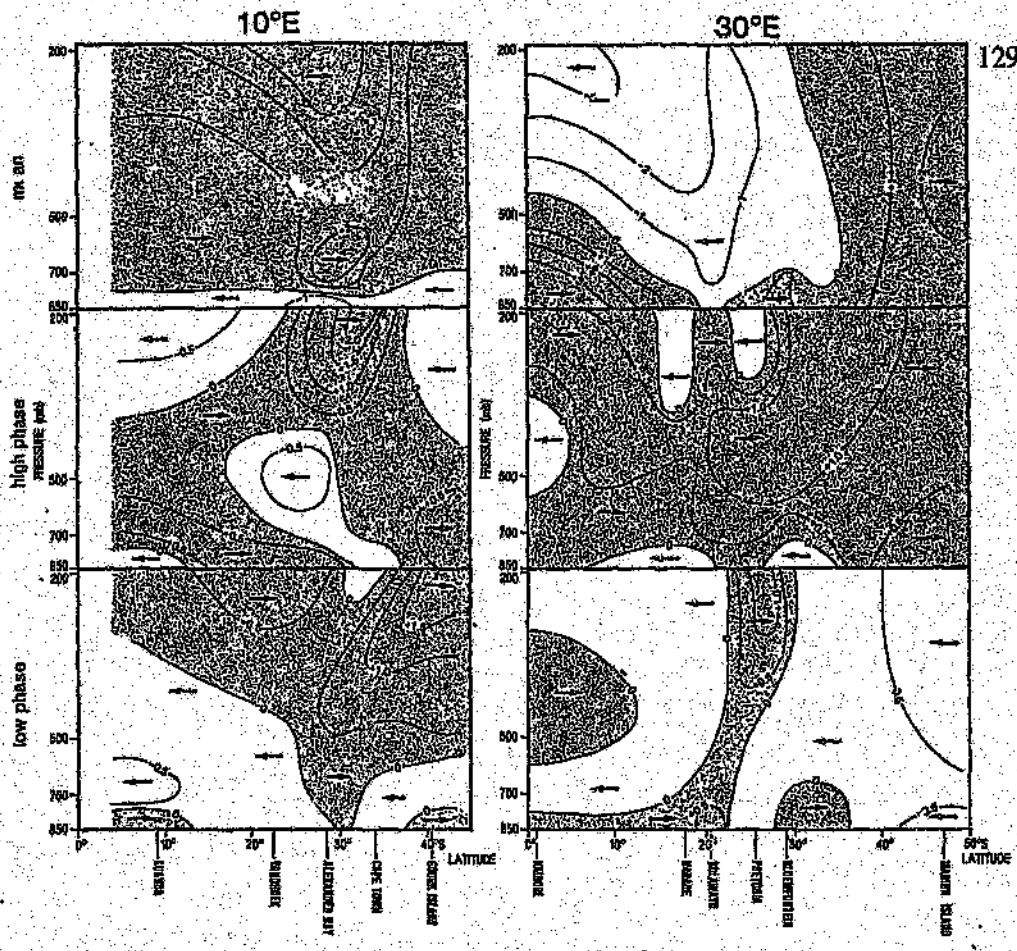

Figure 5.20: Sections along 10°E and 30°E for summer (January-March) mean meridional component ($m.s^{-1}$) and high- (wet) and low-phase (dry) deviations from the mean. Positive wind speeds or departures are poleward and shaded (after Lindesay, 1988a).

3.8a) forces a Walker cell (Harrison, 1986), and torques drive the Hadley circulation (Webster, 1972; Rind and Rossow, 1984). Moist tropical air, latent heat and momentum are thus transported southward from the convergence zone over the South African summer rainfall area (Figs 3.8a, 5.19a). This feature is reflected in the longitude-height section of velocity potential for a mean wet January (Appendix D).

By contrast, in dry Januaries there is a longitudinal shift of the zonal circulation cells (Fig. 5.19b), such that the main ascending limb occurs over the western parts of the subcontinent rather than over the central area, and there is descent over the eastern subcontinent. The positive OLR anomalies at c. 20°S, 30°E (Fig. 5.13f) and the westward shift of maximum total latent heat (cf. Fig. 3.8b) confirm the absence of convective activity there, while the decreased OLR

over the western subcontinent at similar latitudes indicates the location of the convection centre at c. 10°E. With the tropical easterly flow weaker and/or further north than usual in the dry months and the ITC poorly developed over southern Africa it is unlikely that widespread tropical convection would occur. This has been seen in the reduced total latent heat over southern Africa during mean dry Januaries (see Fig 3.8b). The upper-level meridional circulation is poleward over the western parts and there is a weak local Hadley-type circulation over the west coast (Figs 5.19b, 5.20 lower left), but over the central subcontinent the circulation has the characteristics of a thermally indirect cell with shallow poleward flow below and a deep layer of equatorward flow above. The local Ferrel cell over eastern southern Africa (Newell *et al.*, 1972; Lindesay, 1988a) accord well with this result (Figs 5.19b, 5.20 lower right) This feature may also indicate a stronger midlatitude influence on the circulation in dry than in wet Januaries, in keeping with the expansion of westerly moisture fluxes across the subcontinent in the dry months (Fig. 5.11). There is thus little southward transport of tropical air across central southern Africa in the meridional circulation, and therefore a reduced possibility of the vapour fluxes being sufficient to produce rainfall in the summer rainfall region. The direct relationship found between the Walker and Hadley cells over southern Africa (Lindesay, 1988a) is in contrast to the inverse relationship found to exist over the Pacific, Atlantic and Indian oceans (Bjerknes, 1969; Kanamitsu and Krishnamurti, 1978; Shukla and Wallace, 1983; Tyson, 1986). The reason for this anomaly is to be found in the preferential location of the cloud bands that originate in the area of diabatic heating over Africa and mark poleward transport of westerly angular momentum (Krishnamurti *et al.*, 1973; Harrison, 1986a; Tyson, 1986).

These circulation characteristics over southern Africa during wet and dry late summer months (Fig. 5.19), conform with Gill's (1980) theory of thermally-induced tropical circulation. The extensive diabatic heating over subtropical southern Africa (see Figs 3.8, 5.19) result in kelvin waves emanating from the heating region creating easterlies to the east and planetary waves creating westerlies to the west (Gill, 1980). Low-level poleward flow from the heating region occurs with return flow further to the west due to the planetary wave propagation (Fig. 5.19). Furthermore, upper level convergence on the

eastern side of the kelvin wave (east of the heating region) results in descending air and surface divergence in the levels below (Gill, 1980) (Fig. 5.19a,b).

Comparison between the time-longitude plots of low-level zonal and meridional water vapour and precipitable water for early summer reveal relatively close correspondence between peak precipitable water, northerly water vapour transport, and zonal vapour convergence (Figs 3.3, 5.14). This again confirms the importance of northerly water vapour transport to the total water vapour content over the southern African region. The quasi-stationary nature of the precipitable water is not reflected in the meridional vapour transport in the lower troposphere, that displays a more transient nature in both the tropics and the subtropics (Fig. 5.14a, b). In the tropics, the meridional wind displays a westward movement. Tropical disturbances over southern Africa have been found to conform to the model for travelling waves in the easterlies (Tyson 1986), but are more stationary than elsewhere (Taljaard, 1972). Recent studies have indicated that the convective waves between 10 and 20°S display a transient nature, although slow (Jury and Pathack, 1991). Further south, at 30°S the northerly vapour transport is also transient in nature, but movement is from west to east (Fig. 5.14b), conforming with the baroclinic nature of the atmosphere over South Africa during early summer (Harrison, 1986). In contrast, late summers have quasi-stationary northerly transport over tropical Africa (Fig. 5.16a, c), and transient westward moving transport over subtropical southern Africa during the wet year (Fig. 5.16d). This indicates a southward shift of the path of the easterly systems between early and late summer. Wet (dry) summers over southeastern Africa have been characterized by increased (decreased) frequency of westward moving convective systems over the southwestern Indian Ocean and subtropical southern Africa (Jury *et al.*, 1991), with increased (decreased) northerly vapour transport at 25°S.

Cloud bands generally coincide with convergence of the westerly and easterly circulation vapour transport along 10°S (Fig. 5.14, 5.17). This corresponds with the convergence of circulation vapour transport along 10°S during mean wet years (Fig 5.19a). Northerly water vapour transport in the lower troposphere transfers the converged water vapour poleward (Figs 5.14, 5.15, 5.16) in association with a trough over southern Africa or anticyclone over the

Mozambique Channel (Chapter 4). The northerly flux from the tropics thus marks the channel for the poleward export by the mean meridional circulation of momentum and energy as hypothesised by Harrison (1986a).

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The importance of the northerly circulation vapour transport for the summer rainfall over the interior of South Africa points to the dominance of the tropics as a moisture source, and circulation vapour transport for late-summer months indicate an anomalous Hadley cell over the region. Eddy vapour transport is more significant in early-summer, pointing to a more temperate control of the water vapour transport over southern Africa. Evidence suggests that regions of convergence and divergence over Africa and adjacent oceans, due to a complicated local Walker circulation, are of critical importance to the moisture supply over South Africa. This convergence and divergence of water vapour, along with transport in the lower troposphere, will therefore receive attention in Chapter 6 in order to better identify sources and sinks of water vapour.

CHAPTER 6

DIVERGENT AND NON-DIVERGENT VAPOUR TRANSPORT

Introduction

Identification of water vapour source and sink regions, and hence the link between water vapour transport and the atmospheric circulation, can be facilitated by the use of streamfunction and potential analysis (Rosen *et al.*, 1979; Salstein *et al.*, 1980; Chen, 1985). The adjustments of the mean circulation patterns between wet and dry early, mid, and late summer months have been addressed in Chapter 5. The significant differences in circulation transport observed earlier suggest sources of water vapour for the interior of South Africa different from those previously hypothesized (Taljaard, 1986, 1990; Tyson, 1986). An attempt will now be made to validate the manner which changes in divergence fields of water vapour affect the mean circulation of the atmosphere over southern Africa and adjacent oceans. The divergent and non-divergent components of the water vapour transport will be used for this purpose.

The large-scale water vapour transport in the atmosphere is largely described by the non-divergent component of the transport pattern, whereas the divergent component is useful in assessing intra- and inter-annual oscillations of sources and sinks of water vapour, and hence atmospheric energetics and cumulus convection (Krishnamurti, 1978; Salstein *et al.*, 1980; Rosen *et al.*, 1980; Peixoto *et al.*, 1981; Peixoto and Oort, 1983; Chen, 1985; Chen and Tzeng, 1990). Although most of the variance of the motion field is described by the non-divergent component (Krishnamurti, 1971), the divergent component is important to the hydrological cycle and the water balance (Peixoto and Oort, 1983, 1992). Convergence of water vapour is maintained by the planetary-scale divergent circulations (Chen, 1985; Chen *et al.*, 1989), and is related (through equation (2.18)), to diabatic heating resulting from latent heat release (Chen,

1985; Peixoto and Oort, 1992). This diabatic heating has been found to be important in forcing the meridional and zonal circulations in the tropics (Gill, 1980; Peixoto and Oort, 1983).

Divergent and non-divergent water vapour transport have been studied previously on a hemispheric or planetary scale (Rosen *et al.*, 1980; Salstein *et al.*, 1980; Peixoto, 1981; Peixoto and Oort, 1983, 1992; Chen, 1985; Chen and Tzeng, 1990). Inter-annual (Rosen *et al.*, 1980; Salstein, *et al.*, 1980) and inter-seasonal (Chen, 1985) variations in water vapour transport have been investigated. Global-scale propagation of divergent circulation has been found to be important in maintaining cumulus convection (Knutson and Weickmann, 1987; Chen *et al.*, 1988). The existence of a 30-50(60) day oscillation of divergent circulation at 200-250 hPa and associated precipitable water anomaly have been documented by a number of researchers (Krishnamurti *et al.*, 1985; Knutson and Weickmann, 1987; Chen *et al.*, 1988; Chen and Tzeng, 1990).

The question of divergent and non-divergent water vapour transport over southern and central Africa needs to be addressed on a regional scale to determine the characteristics of water vapour transport, divergence fields, diabatic heating through cumulus convection and associated mean circulation patterns. The vertically-integrated, low-level circulation and eddy water vapour transports have been separated into divergent and non-divergent components. Although circulation water vapour transport is representative of the total water vapour transport, eddy motions are effective in transporting water vapour poleward in mid-latitudes in the cyclone systems (Chen, 1985). It has therefore become necessary to examine both circulation and eddy water vapour transport over the African region in order to to the assess intra- and inter-annual variability of streamfunction and potential fields and hence convective regions. Physical interpretation of eddy non-divergent transport is not definitive, however, owing to the high noise level found (Chen, 1985). The variations of source/sinks and transport will be examined for cloud band conditions in early, mid and late summer case studies in an attempt to characterize areas of vapour convergence/divergence, the movements thereof, and vapour transport before, during and after cloud band conditions.

Divergent and Non-divergent Vapour Transport

Circulation transport

The divergent component of the vertically integrated low-level circulation vapour transport for mean wet Octobers show an area of mean water vapour convergence over Africa (highest over central tropical Africa) and divergence over the tropical Atlantic and Indian oceans (Fig. 6.1a). The divergent vapour transport from the areas of divergence to the area of convergence indicates an east-west circulation over the tropics. Results of planetary studies suggest that the high water vapour content over tropical areas is maintained by the Walker cells (Chen, 1985). The streamfunction (or non-divergent component) of the circulation vapour flux shows cyclonic cells off the west coast of subtropical Africa (weak) and over the tropical Indian Ocean (strong), with a weak anticyclonic cell over subtropical southern Africa (Fig. 6.1b). The divergent circulation maintains the water vapour over the continent and the non-divergent streamlines indicate southward transport over southern Africa from the vapour convergent region (Fig. 6.1b). The divergent component of the circulation vapour transport for mean dry Octobers is different to that in mean wet Octobers. During dry Octobers the convergent and divergent regions of water vapour intensify and shift westward to be situated at 5°S, 20°E and 10°S, 35°E respectively (Fig. 6.1c). The divergent circulation over the Atlantic Ocean weakens during dry Octobers and appears to have little influence on the water vapour content over southern Africa (Fig. 6.1a, c). The non-divergent circulation water vapour transport fields show the formation of a secondary cyclonic cell over tropical Africa, and an intensification of the anticyclonic cell over subtropical southern Africa (Fig. 6.1d). The absence of the cyclonic cell off the west coast of southern Africa during mean dry Octobers results in little or no moisture advection from the Atlantic Ocean over the interior of southern Africa (Fig. 6.1d).

Comparison of the divergent water vapour transport for wet and dry Decembers reveals significant differences. Mean wet Decembers are characterized

OCTOBER

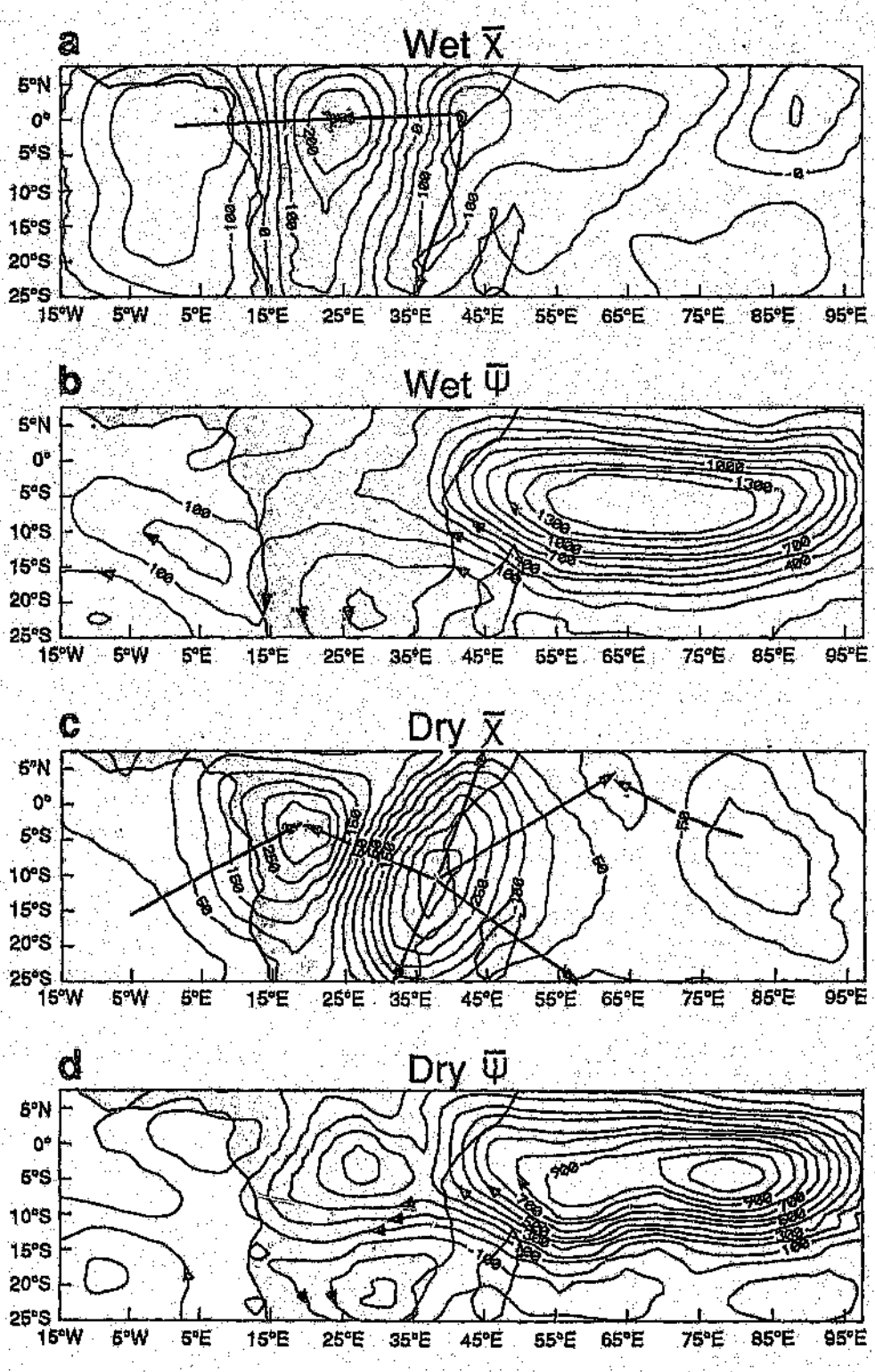

Figure 6.1: Distribution of divergent (χ) vertically-integrated circulation water vapour transport for: a) mean wet Octobers; c) mean dry Octobers; and non-divergent circulation (ψ) water vapour transport for: b) mean wet Octobers and d) mean dry Octobers. Integration is between 850 and 700 hPa; Arrows in the divergent mode represent direction of divergent transport; arrows in non-divergent mode represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

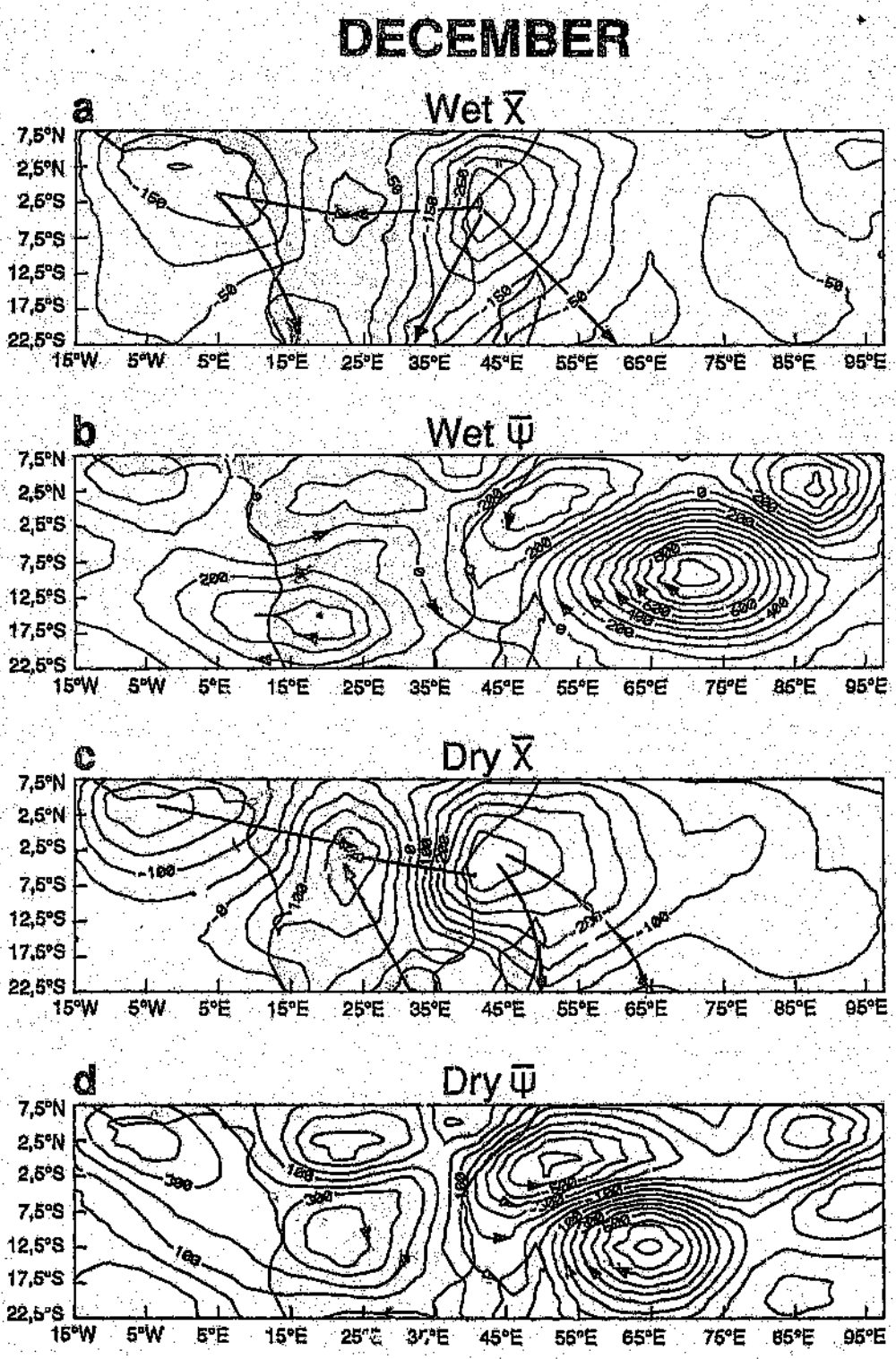

Figure 6.2: Distribution of divergent (χ) vertically-integrated circulation water vapour transport for: a) mean wet Decembers; c) mean dry Decembers; and non-divergent (ψ) circulation water vapour transport for: b) mean wet Decembers and d) mean dry Decembers. Integration is between 850 and 700 hPa; Arrows in the divergent mode represent direction of divergent transport; arrows in non-divergent mode represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

by divergence of water vapour from a source region in the lower levels of the atmosphere over the tropical Indian and Atlantic oceans, with convergence occurring over tropical Africa (2,5°S, 22°E) and subtropical western southern Africa (20°S, 20°E). Divergent flow indicates the presence of a Walker circulation along the equator with a descending branch over the Atlantic and Indian oceans and an ascending branch over tropical central Africa (Fig. 6.2a). The non-divergent circulation reveals an intensification and eastward shift of the cyclonic cell (over the Atlantic Ocean in October) to a location over the western regions of subtropical southern Africa (Fig. 6.2b). A weak anticyclonic cell over the extreme western tropical Indian Ocean (2,5°S, 45°E) displaces the cyclonic cell (dominant during October) eastward over the tropical Indian Ocean (Fig. 6.2b). The water vapour over tropical Africa is maintained by the Walker cell and is transported from the convergent region, southward over southern Africa through the divergent and non-divergent circulation (Fig. 6.2a,b). The divergent circulation water vapour transport for mean dry Decembers is characterized, as in mean wet Decembers, by divergence over the tropical Indian and Atlantic oceans and convergence over tropical Africa (Fig. 6.2c). A second region of divergence has been found to occur over the extreme southeastern parts of southern Africa, a feature absent during mean wet Decembers (Fig. 6.2c). This implies southerly divergent circulation water vapour transport in the lower layers over the southern African region, synonymous with an anticylonic circulation. The non-divergent component of circulation vapour transport during mean dry Decembers is similar to mean wet Decembers. An exception is the northward displacement of the cyclonic cell during dry Decembers (Fig. 6.2b, d). Circulation water vapour transport over southern Africa during mean dry Decembers is westward as opposed to the southwestward transport during mean wet Decembers, thereby inhibiting the intrusion of tropical air into the South African plateau regions (Fig. 6.2b, d).

During mean wet late summer months (January), the divergent component of the the low-level circulation vapour transport is such that strong divergence occurs over the tropical Indian Ocean with convergence over tropical Africa and southern Africa (Fig. 6.3a). This implies a Walker circulation maintaining water vapour over tropical Africa and an anomalous Hadley circulation supplying water vapour to southern Africa, as suggested by Harrison (1986a) and indicated

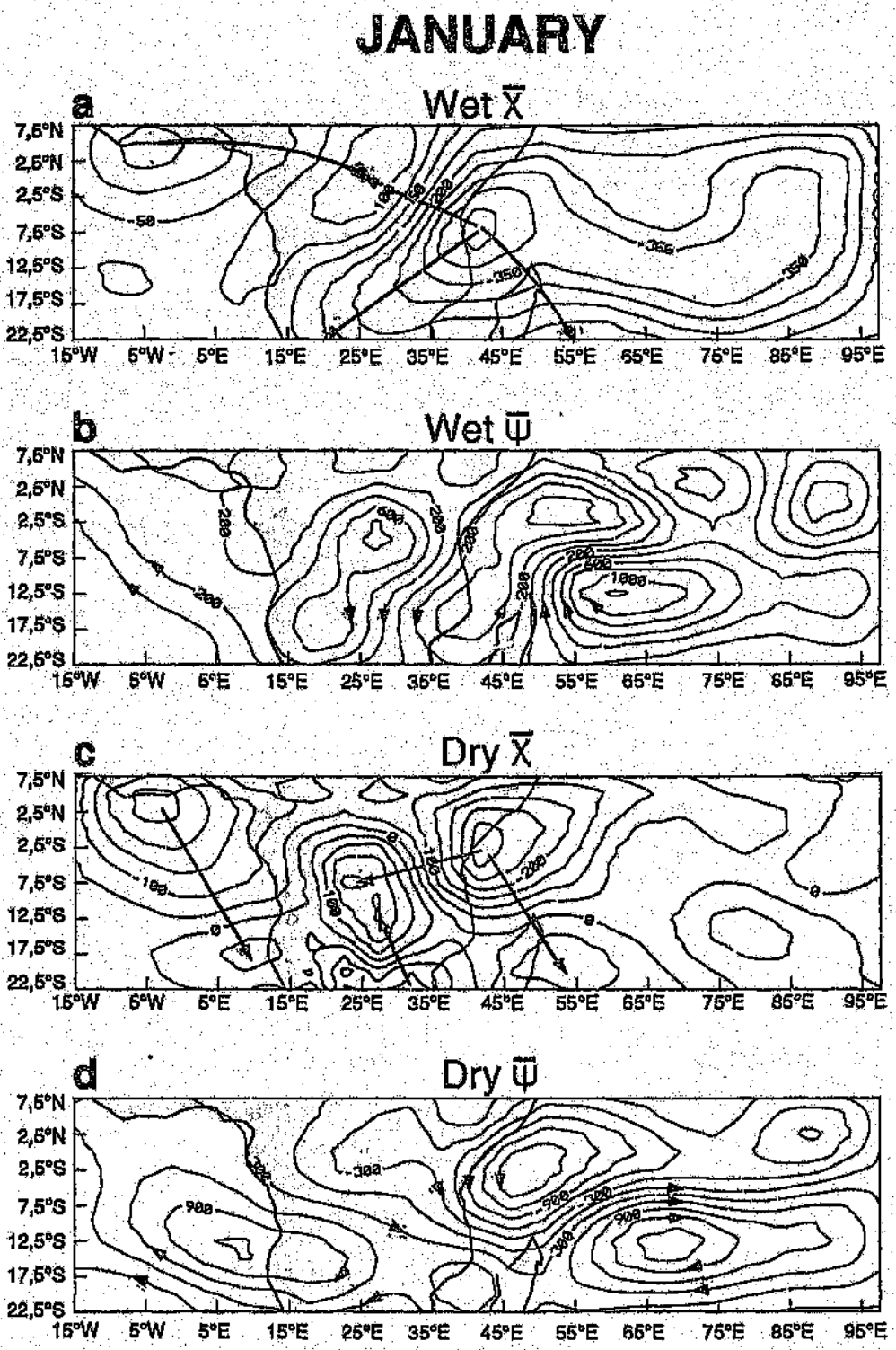

Figure 6.3: Distribution of divergent (χ) vertically-integrated circulation water vapour transport for: a) mean wet Januaries; c) mean dry Januaries; and non-divergent (ψ) circulation water vapour transport for: b) mean wet Januaries and d) mean dry Januaries. Integration is between 850 and 700 hPa; Arrows in the divergent mode represent direction of divergent transport; arrows in non-divergent mode represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

by the height-longitude section of velocity potential (Appendix D). The non-divergent component for mean wet Januaries reveals a southward shift of the Indian Ocean cyclonic cell to 12°S, 60°E (from 5°S, 75°E during wet Octobers), a more extensive anticyclonic cell over the western tropical Indian Ocean (extending southward into the Mozambique Channel), and a meridionally-aligned cyclonic cell over tropical and subtropical Africa (Fig. 6.3b). The streamlines show southward transport from the region of convergence over tropical Africa (Fig. 6.3b). Divergence occurs over the tropical western Indian Ocean and the tropical Atlantic Ocean, with convergence over tropical central Africa during dry Januaries (Fig. 6.3c). A region of divergence over eastern southern Africa indicates an anticyclonic circulation over southern Africa, with southerly divergent transport over the region (Fig. 6.3c). The non-divergent circulation vapour transport for mean dry Januaries differs from wet Januaries in that the cyclonic cell over the subtropical southern African interior is displaced westward and the anticyclone over the Mozambique Channel is replaced by a cyclonic cell. An anticyclonic cell occurs over the southern regions of subtropical southern Africa (Fig. 6.3d). Streamlines indicate a general southeasterly transport of water vapour over the summer rainfall region of South Africa (the southern-most regions of Africa in Fig. 6.3d). Transport from the vapour convergent region occurs further north and east, such that the major transport of vapour is across Madagascar.

Eddy transport

The divergent components of eddy vapour transport during mean wet early summer months are similar in spatial pattern to the circulation component (Fig. 6.1a). Divergence occurs over the western Indian Ocean and over the Atlantic Ocean, with convergence over tropical Africa and a second region of convergence over the western parts of southern Africa (Fig. 6.4a). The eddy divergent water vapour transport over southern Africa is from the northeast and from the northwest. Eddy non-divergent transport for mean wet Octobers, like the circulation transport, is characterized by an extensive cyclonic cell over the tropical Indian Ocean and an anticyclonic cell over eastern southern Africa (Fig. 6.4b). This results in a predominantly northerly eddy non-divergent transport of water vapour over southern Africa (Fig. 6.4b). The divergent eddy transport

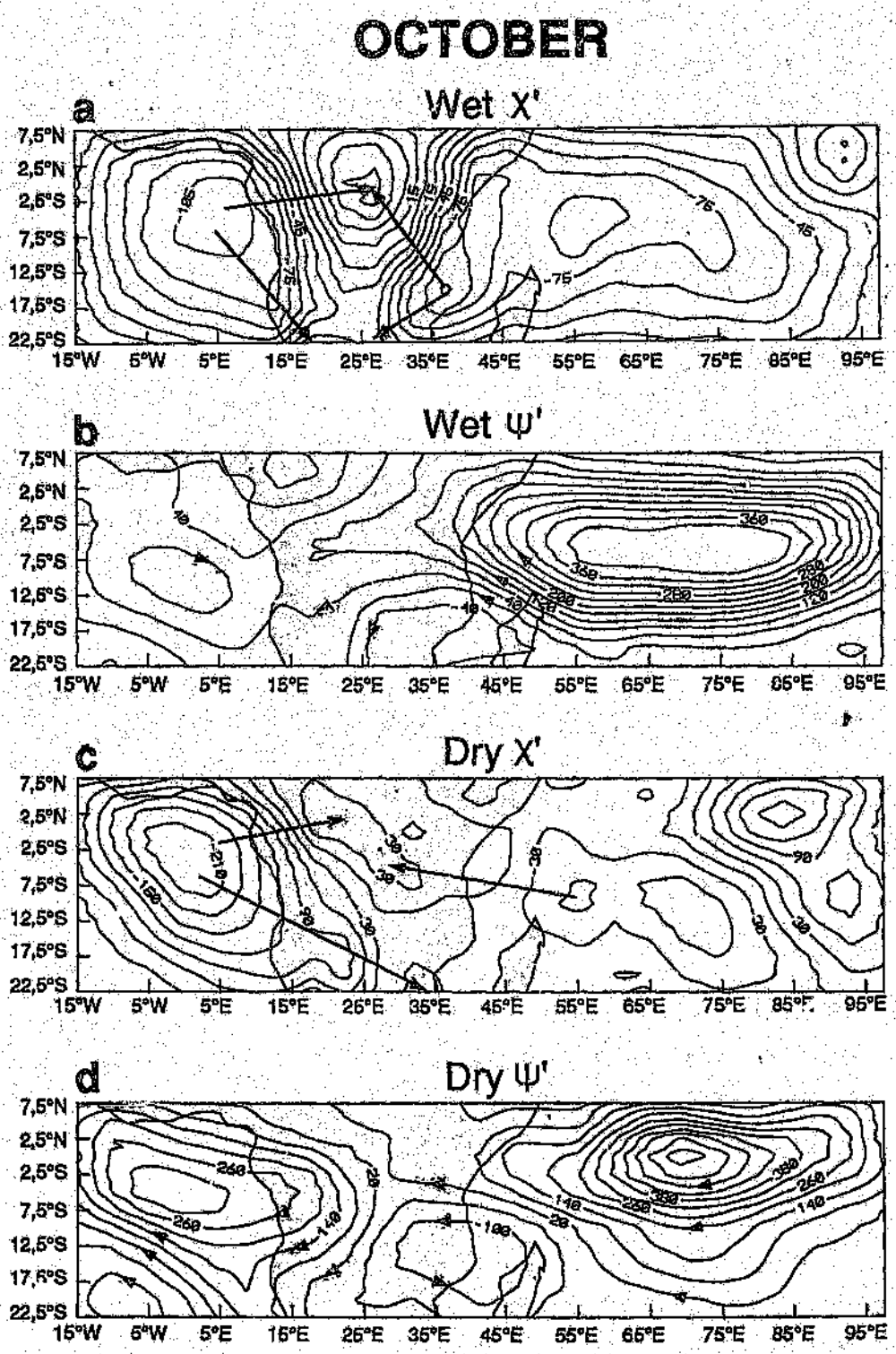

Figure 6.4: Distribution of divergent (χ) vertically-integrated eddy water vapour transport for: a) mean wet Octobers; c) mean dry Octobers; and non-divergent (ψ) eddy water vapour transport for: b) mean wet Octobers and d) mean dry Octobers. Integration is between 850 and 700 hPa; Arrows in the divergent mode represent direction of divergent transport; arrows in non-divergent mode represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

during mean dry Octobers is characterized by enhanced divergence over the Atlantic Ocean (Fig. 6.4c). The regions of convergence over tropical and subtropical Africa shift eastward so convergence of water vapour occurs over the extreme eastern parts of southern Africa (Fig. 6.4c). The non-divergent component during mean dry Octobers is similar to wet Octobers (Fig. 6.4d). The only difference being the much-enhanced cyclonic cell over the Atlantic Ocean and the northward shift of of the anticyclonic circulation over the southeastern parts of Africa. The streamlines for mean dry Octobers indicate a westward displacement of the northerly vapour transport.

The divergent eddy component for mean wet December is smaller in comparison to mean wet October (Figs 6.4a, 6.5a), indicating a reduction in the importance of transient systems for later summer rainfall. The tropical Atlantic Ocean (0°, 5°E) is the most important source region for eddy vapour transport, with a convergent region over the western parts of southern Africa (Fig. 6.5a). The non-divergent eddy component is similar to the circulation component in that cyclonic cells exist over the western parts of subtropical Africa and anticyclonic cells over the extreme western tropical Indian Ocean (Figs 6.5b, 6.2b). The streamlines of eddy non-divergent transport over southern Africa show transport from the northeast, as did the circulation field (Fig. 6.5b). The magnitude of the eddy non-divergent transport is less than the circulation transport, again indicating a reduced influence of transient systems. The divergent component of eddy vapour transport for mean dry Decembers is similar to mean wet Decembers (Fig. 6.5c). A difference is the enhanced divergence over the western tropical Indian Ocean (Fig. 6.5c). The non-divergent component for mean dry Decembers is is distinguished by the reduced and northward shift of the cyclonic circulation over the Atlantic Ocean in dry years and the enhanced anticyclonic circulation over the western Indian Ocean, such that northerly eddy vapour transport occurs to the east of southern Africa (Figs 6.5b).

The non-divergent eddy water vapour transport for mean wet Januaries reveals eddy divergence over the Atlantic and Indian oceans with convergence over virtually the entire Africa continent (Fig. 6.6a). The magnitudes of the divergent eddy components have been reduced from early summer, indicating small transient influences (cf. Figs 6.4a, 6.6a). The non-divergent eddy

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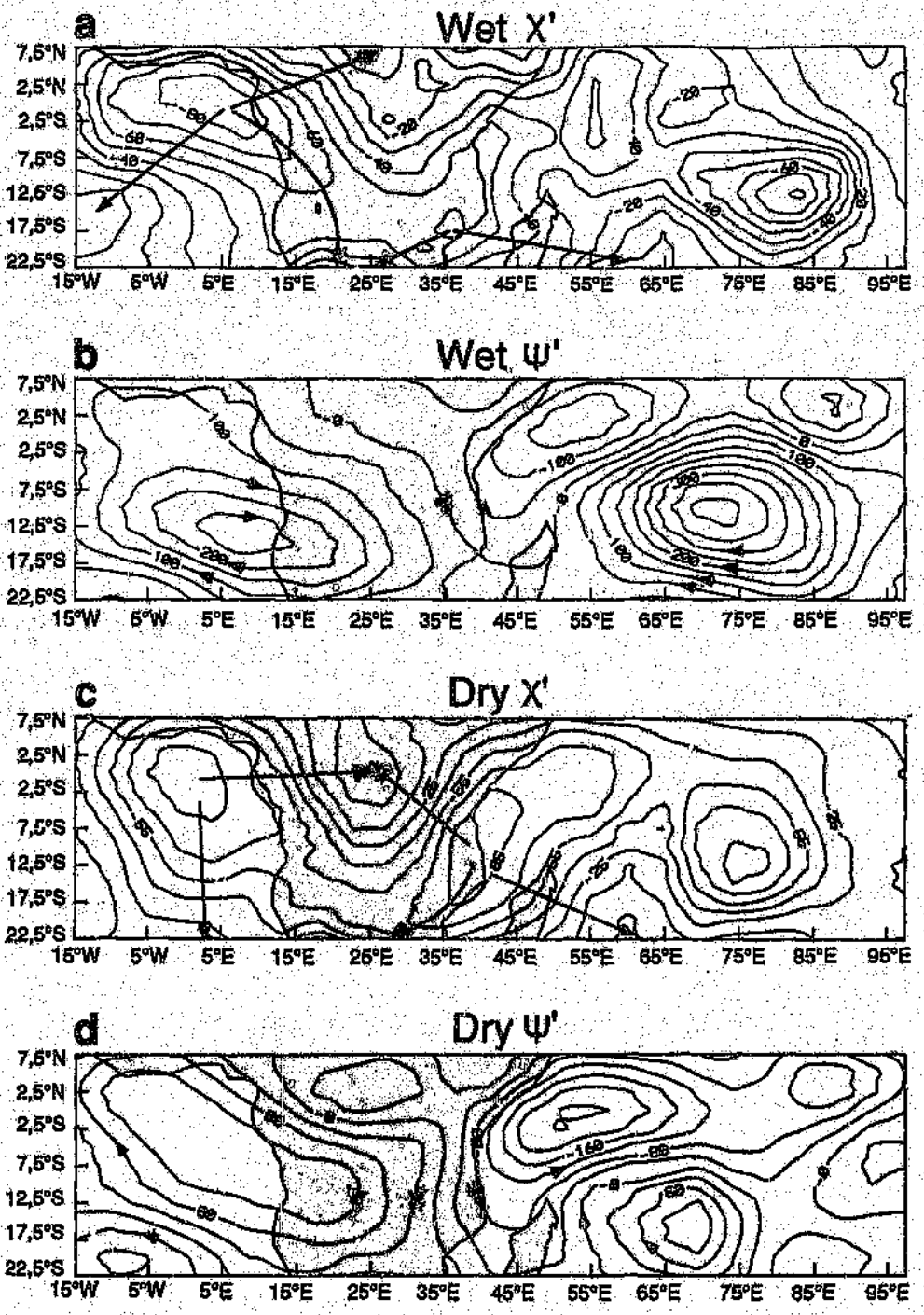

Figure 6.5: Distribution of divergent (χ) vertically-integrated eddy water vapour transport for: a) mean wet Decembers; c) mean dry Decembers and non-divergent (ψ) eddy water vapour transport for: b) mean wet Decembers and d) mean dry Decembers. Integration is between 850 and 700 hPa; Arrows in the divergent mode represent direction of divergent transport; arrows in non-divergent mode represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

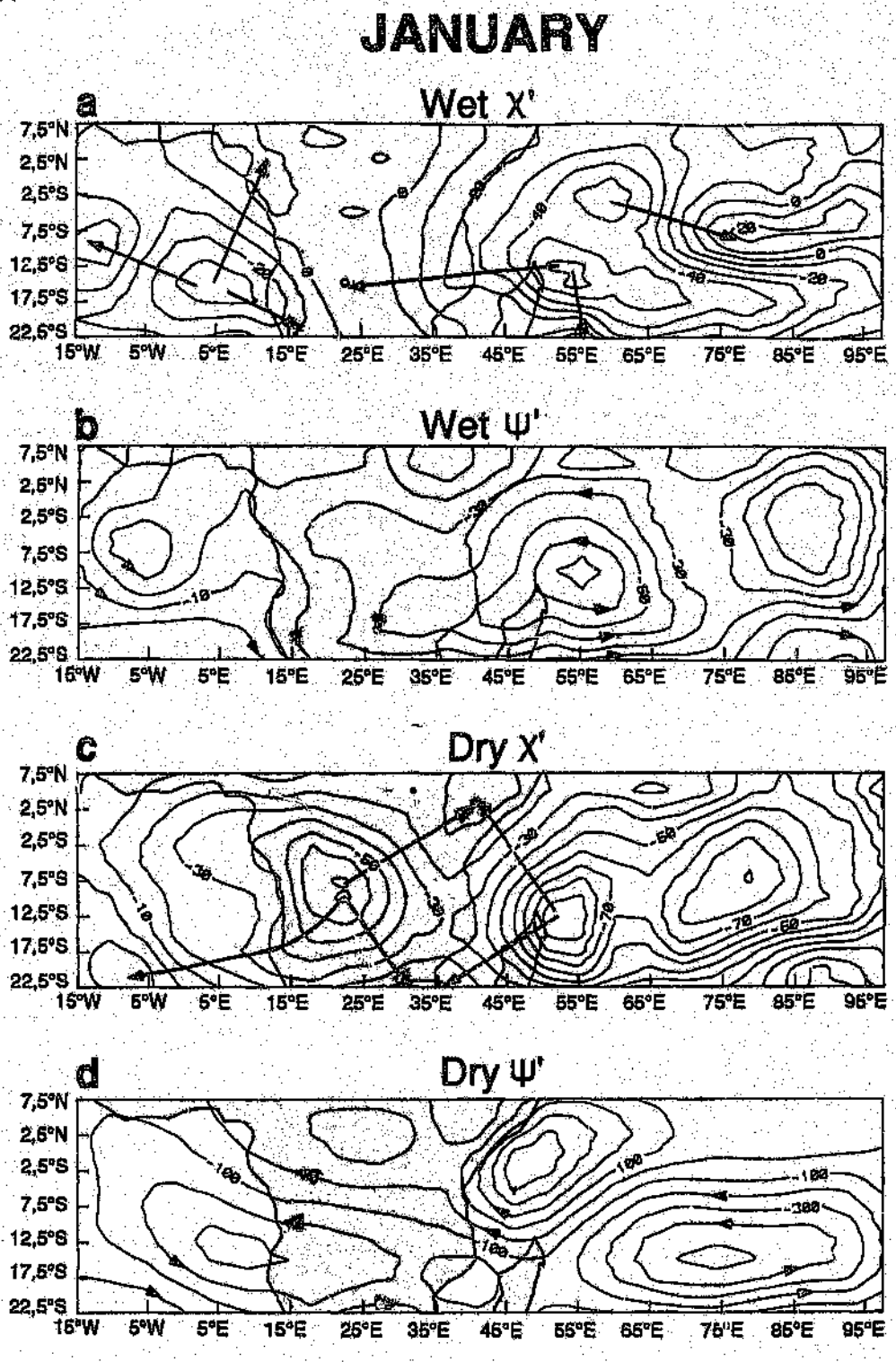

Figure 6.6: Distribution of divergent (χ) vertically-integrated eddy water vapour transport for: a) mean wet Januaries; c) mean dry Januaries; and non-divergent (ψ) eddy water vapour transport for: b) mean wet Januaries and d) mean dry Januaries. Integration is between 850 and 700 hPa; Arrows in the divergent mode represent direction of divergent transport; arrows in non-divergent mode represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

component for wet Januaries is characterized by relatively weak anticyclonic and cyclonic circulation over the Indian and Atlantic oceans respectively (Fig. 6.6b), resulting in a southeastward eddy transport of vapour over southern Africa from the source region over the Atlantic Ocean. The divergent component for mean dry Januaries are characterized by enhanced divergence of water vapour over subtropical and tropical Africa (in contrast to convergence during mean wet Januaries) and the Indian Ocean (Fig. 6.6c). Convergence is restricted to the extreme eastern parts of southern Africa. Anticyclonic cells extending across subtropical Africa and the Indian Ocean result in southeasterly non-divergent eddy vapour transport over subtropical Africa and southwesterly to westerly transport over southern Africa (Fig. 6.6d).

The chapter thus far has dealt exclusively with mean divergent and non-divergent eddy water vapour transport during wet and dry early, mid, and late summer months. The transport of water vapour before, during, and after cloud bands will now be investigated for the case studies.

Non-divergent and Divergent Flow and Tropical-temperate Troughs

Changes in the divergent and non-divergent components of vapour fluxes on the short time scale have been investigated to find changes in the components for pre-cloud band, cloud band, and post-cloud band conditions during early, mid and late summer months. The vertically integrated low-level divergent mode for the formative/pre-cloud band conditions (a truncated cloud band from southern Angola through central southern Africa) on 15 October 1986 indicates a strong vapour source over the eastern tropical Atlantic Ocean and a secondary source over East Africa (Fig. 6.7a). Moisture convergence occurred over tropical central Africa and southern Africa. Northerly non-divergent transport occurred around the cyclonic cell over western southern Africa and the anticyclonic cell over eastern southern Africa, transferring moisture from tropical and subtropical Africa (Fig. 6.8a). Figures 6.7b and 6.8b depict the divergent and non-divergent modes for 16 October 1986 when the cloud band was best defined (see Plate 3.1b). The divergent region off the west coast of Africa decreased in intensity and the convergent region over southern Africa shifted marginally northward (Fig.

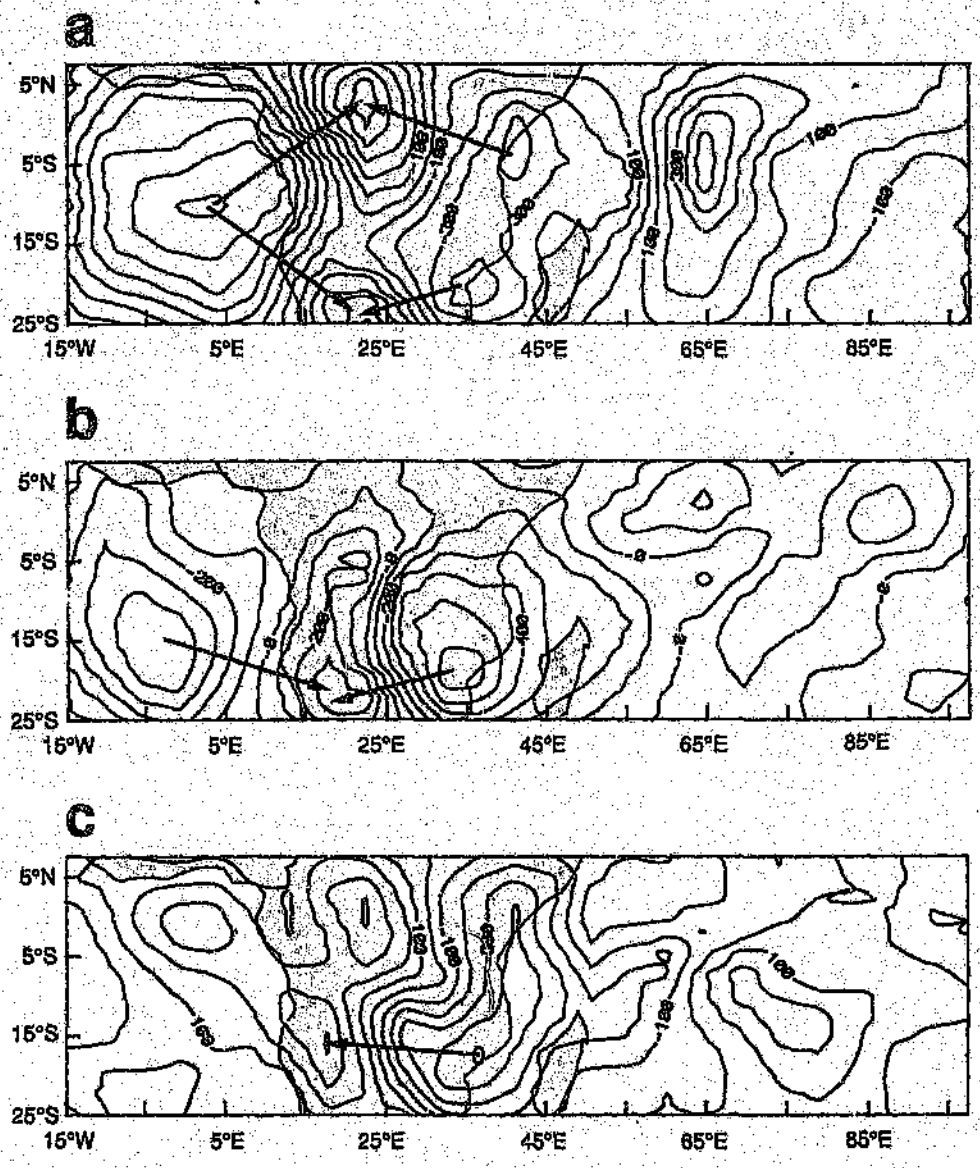

Figure 6.7: Distribution of divergent (χ) vertically-integrated water vapour transport for a) 15 October 1986 (pre-cloud band); b) 16 October 1986 (cloud band); c) 17 October 1986 (post-cloud band). Integration is between 850 and 700 hPa; arrows represent direction of divergent transport. Units are 10^6 kg.s^{-1}.

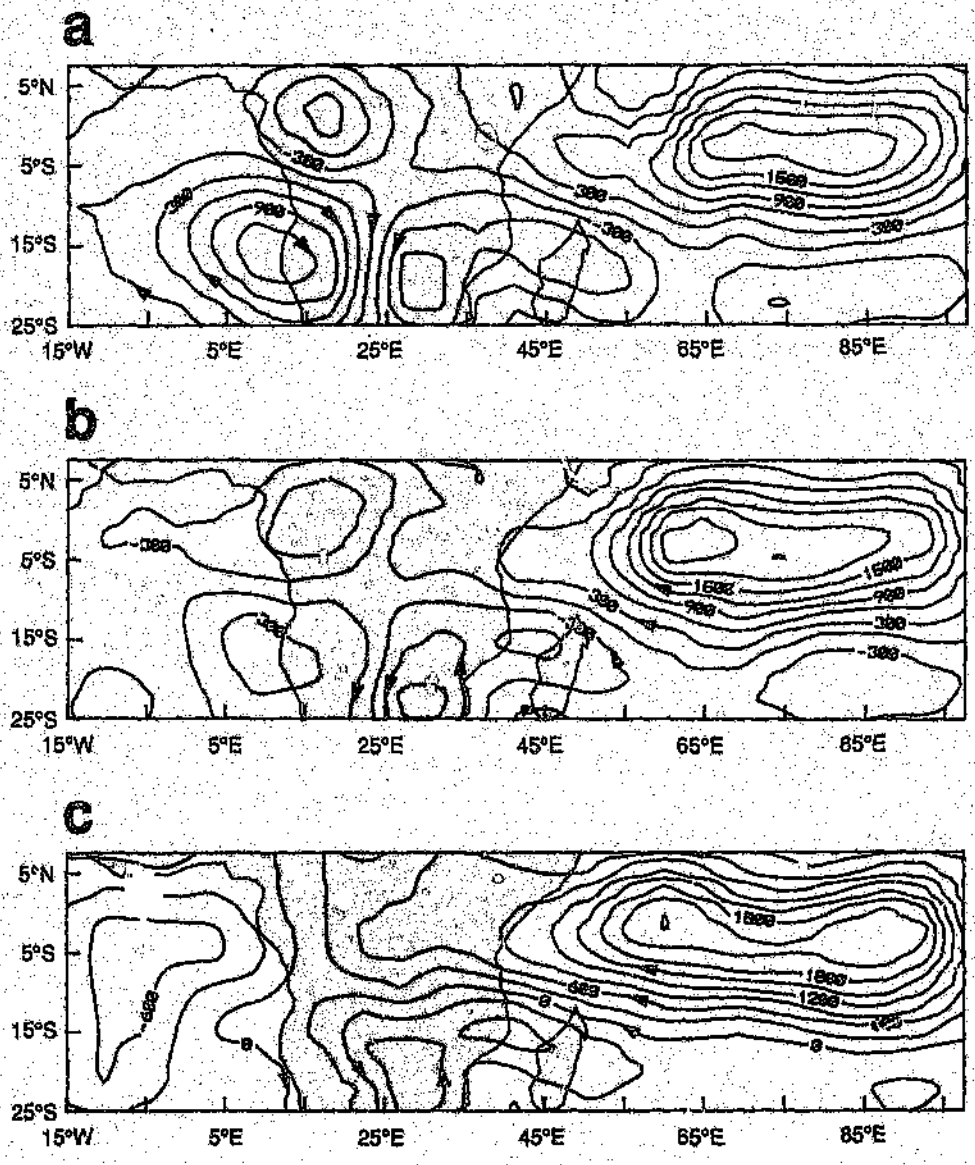

Figure 6.8: Distribution of non-divergent (ψ) vertically-integrated water vapour transport for for: a) 15 October 1986 (pre-cloud band); b) 16 October 1986 (cloud band); and c) 17 October 1986 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

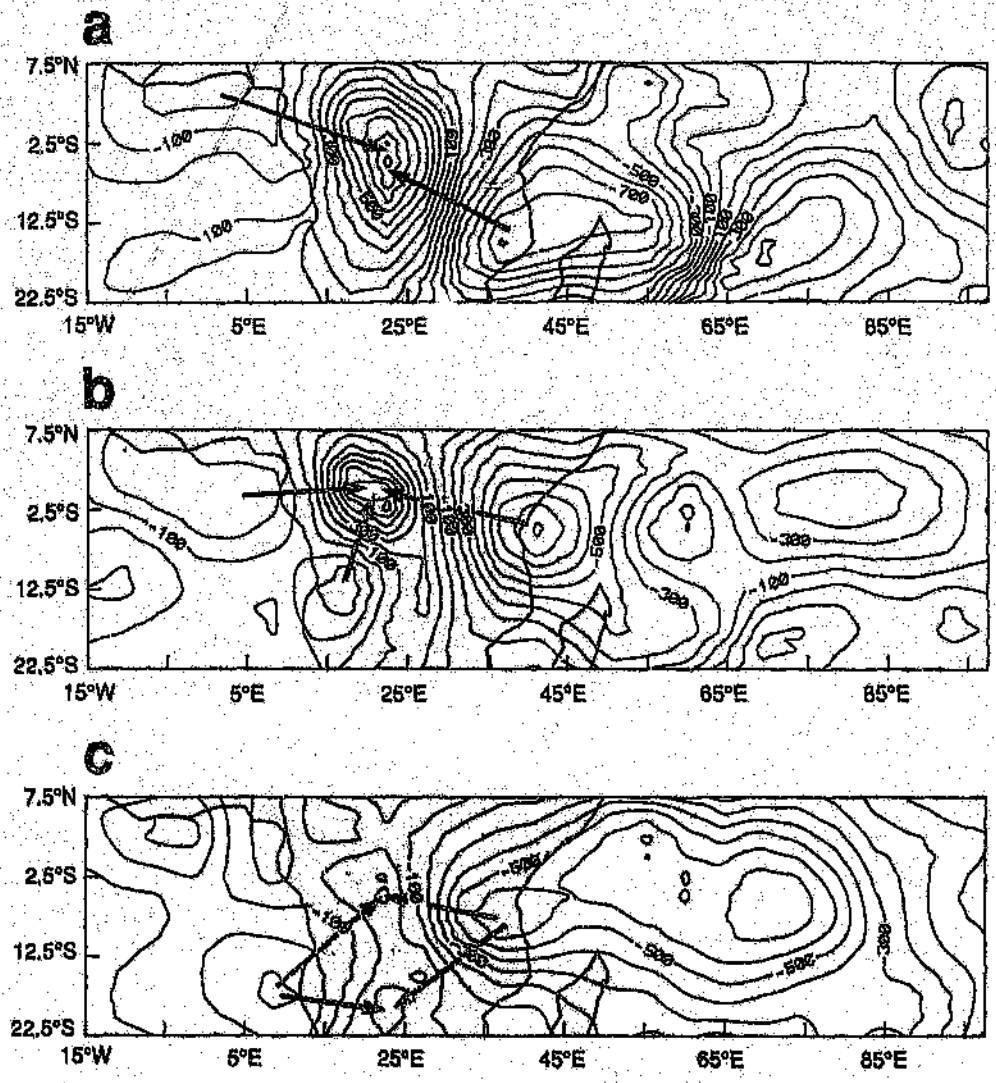

Figure 6.9: Distribution of divergent (χ) vertically-integrated water vapour transport for a) 4 December 1982 (pre-cloud band); b) 5 December 1982 (cloud band); c) 7 December 1982 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of divergent transport. Units are 10^6 kg.s^{-1}.

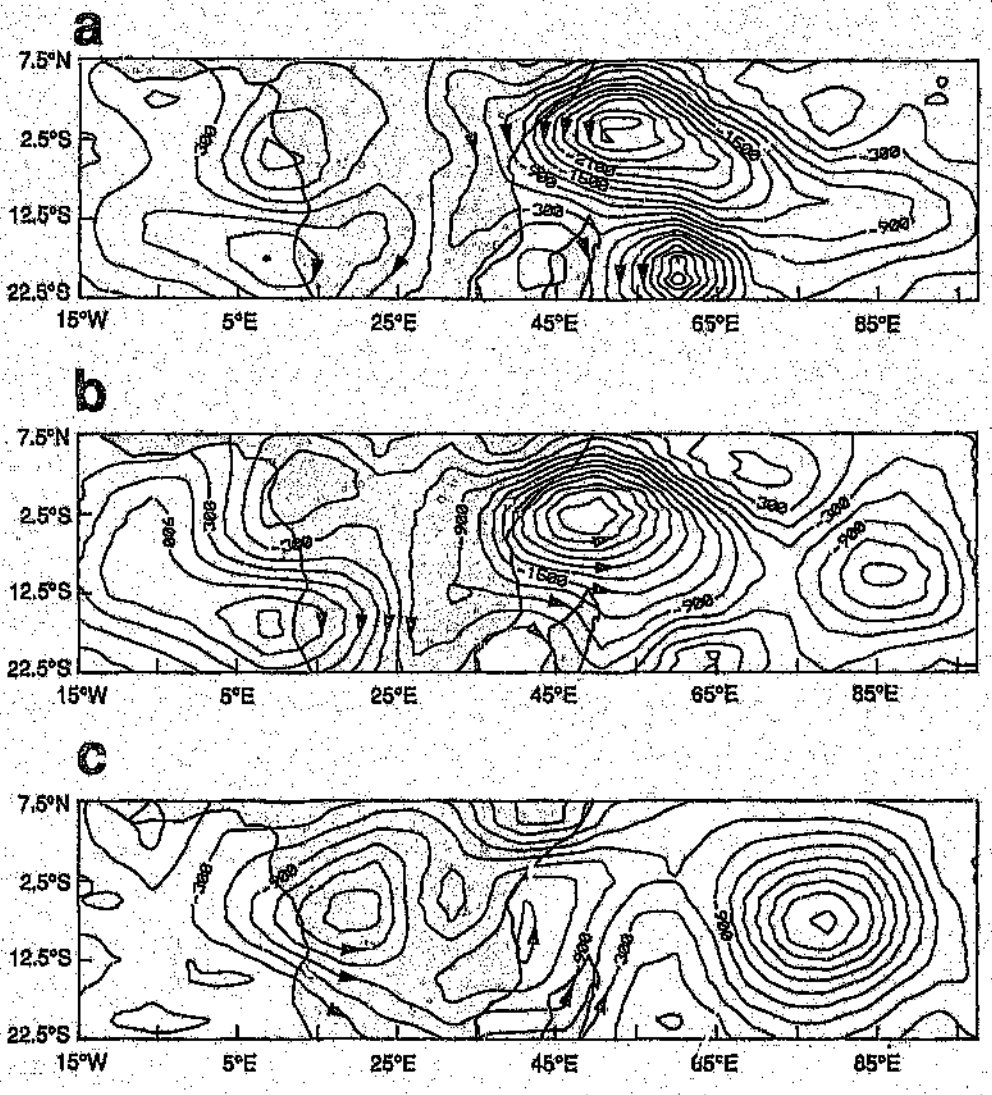

Figure 6.10: Distribution of non-divergent (ψ) vertically-integrated water vapour transport for a) 4 December 1982 (pre-cloud band); b) 5 December 1982 (cloud band); c) 7 December 1982 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of non-divergent transport. Units are 10^5 kg.s^{-1}.

6.7b). Although the cyclonic cell present over western tropical Africa weakened, the anticyclonic cell over eastern southern Africa maintained the southward transport of water vapour from the convergent region over subtropical Africa (Figs 6.7b, 6.8b). On 17 October 1986 the cloud band had dissipated to cloud clusters (cf. Plate 3.1c). The divergent component reveals much reduced divergence over the Atlantic Ocean and over eastern southern Africa, and a northwestward shift and weakening of the area of convergence (Fig. 6.7c). This indicates a general weakening of the systems supplying and maintaining water vapour to continental southern Africa and is reflected in the non-divergent component, where the anticyclonic cell over eastern southern Africa weakened and the cyclonic cell over the western regions disappeared (Fig. 6.8c). Although the southward vapour transport was maintained from the convective region over western subtropical Africa, it was reduced because of the reduced convergence of vapour over those regions. The vapour transport during cloud band conditions approximates the mean eddy transport seen in wet Octobers, suggesting that cloud bands during early summer are formed as a result of transient water vapour transport associated with the more temperate circulation systems.

Two case studies were conducted for mid summer (December) cloud band conditions. The first study occurs during the dry December of 1982. The divergent component 24 hours prior to major cloud band formation on 4 December 1982 reveals a strong source of water vapour over the northern Mozambique Channel, a weaker source over the tropical Atlantic and strong convergence over tropical Africa (Fig. 6.9a). The cyclonic cell over the extreme western regions of southern Africa advects moisture southward over South Africa from the region of convergence further north (Figs 6.9a, 6.10a). The divergent mode on 5 December (major cloud band) reveals a northward shift in both the Indian Ocean divergent and the African convergent regions (Fig. 6.9b). The non-divergent component shows an intensification of the cyclonic cell over the western Atlantic Ocean and a westward extension of the anticyclonic cell over the tropical western Indian Ocean (Fig. 6.10b). The streamlines of vapour transport indicate an increased northerly transport from the convergent regions over tropical Africa. The divergent component on 7 December 1982 (post-cloud band) is reflected in changes in the divergent component. A decrease in the divergence over the western Indian and eastern Atlantic oceans are coupled with a decrease

in convergence over subtropical and tropical Africa (Fig. 6.9c). The non-divergent component reveals a westward extension of the anticyclonic cell to over the entire tropical part of Africa and a dissipation of the cyclonic cell off the west coast of southern Africa (Fig. 6.10c). The streamlines imply a southeastward transport of water vapour across southern Africa (to the north of South Africa) during post-cloud band conditions as opposed to the southward transport from the tropical convergent region during cloud band conditions. The second case study has been conducted for the wet December of 1985. The divergent component for the pre-cloud band conditions of 1 December shows weak convergence over Africa with weak divergence over eastern southern Africa, the Atlantic Ocean and the tropical western Indian Ocean (Fig. 6.11a). The non-divergent component reveals weak anticylonic cells over the tropical Indian and Atlantic oceans and a weak cyclonic cell over western tropical and subtropical Africa (Fig. 6.12a). Strong divergence over tropical Africa and adjacent oceans with convergence over western South Africa (Fig. 6.11b) characterize the cloud band conditions on 2 December 1985. The non-divergent component showed intensification of the anticyclonic cell over the western tropical Indian Ocean and the cyclonic cell over the western regions of southern Africa (Fig. 6.12b). The streamlines indicate southward transport of vapour over southern Africa. The divergent component on 3 December (post-cloud band) is similar to that of the previous day, although the divergence over tropical Africa is reduced (Fig. 6.11c). The non-divergent component reveals a significant difference from 2 to 3 December. The anticyclonic ce.. intensified and extended over the entire African continent which, coupled to a dissipation and southward displacement of the cyclonic cell over western southern Africa, resulted in a northwesterly flux across subtropical southern Africa (Fig. 6.12c). The flux of vapour therefore occurred ..ely to the north and east of South Africa.

Cloud band case studies have also been conducted for late summer (January). The first study has been selected for a dry January 1980. The divergent component of the pre-cloud band conditions of 6 January reveal weak divergence over tropical and subtropical Africa with convergence over eastern southern Africa (Fig. 6.13a). The non-divergent component is characterized by an anticyclonic cell over the western tropical Indian Ocean and a weakly developed cyclonic cell over western subtropical Africa (Fig. 6.14a). On 7 January the

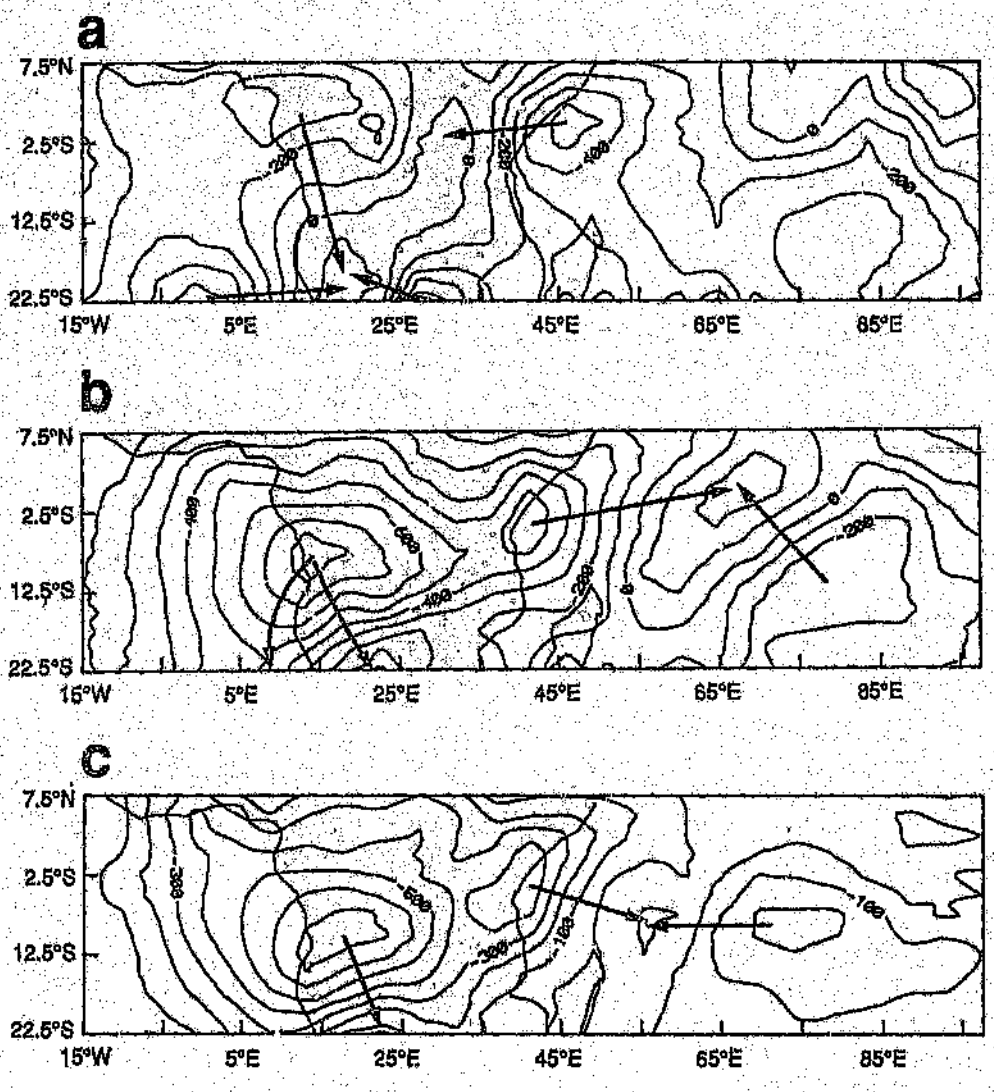

Figure 6.11: Distribution of divergent (χ) vertically-integrated water vapour transport for a) 1 December 1985 (pre-cloud band); b) 2 December 1985 (cloud band); c) 3 December 1985 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of divergent transport. Units are 10^6 kg.s^{-1}.

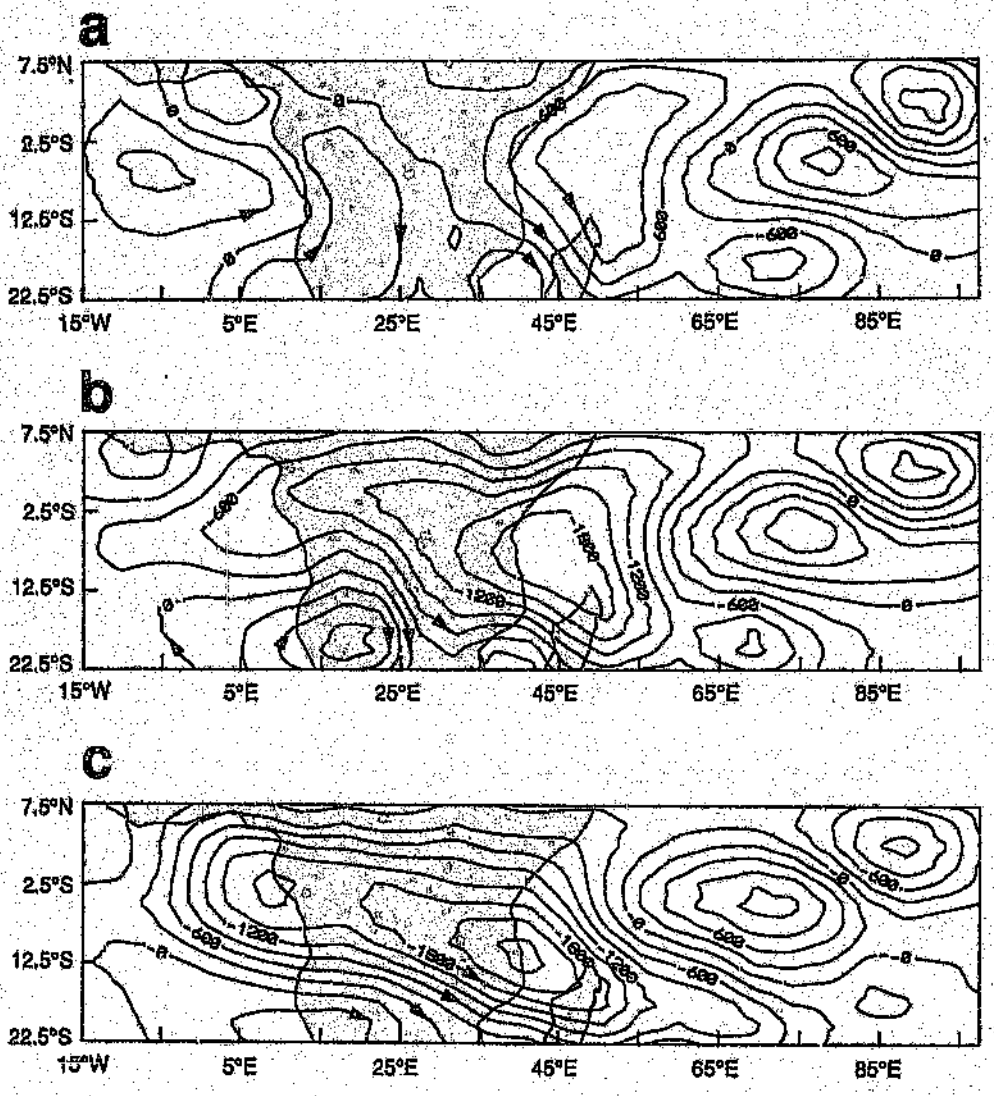

Figure 6.12: Distribution of non-divergent (ψ) vertically-integrated water vapour transport for a) 1 December 1985 (pre-cloud band); b) 2 December 1985 (cloud band); c) 3 December 1985 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

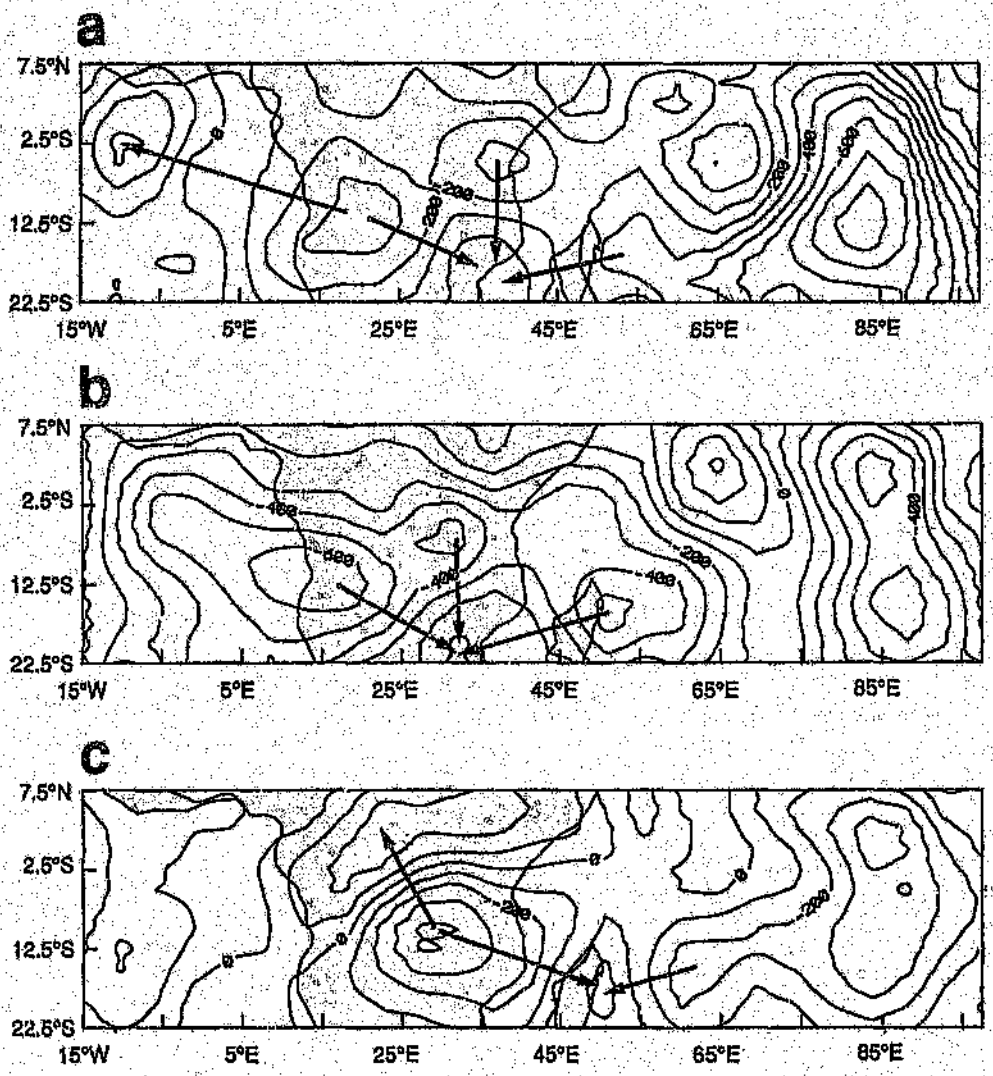

Figure 6.13: Distribution of divergent (χ) vertically-integrated water vapour transport for a) 6 January 1980 (pre-cloud band); b) 7 January 1980 (cloud band); c) 8 January 1980 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of divergent transport. Units are 10^6 kg.s^{-1}.

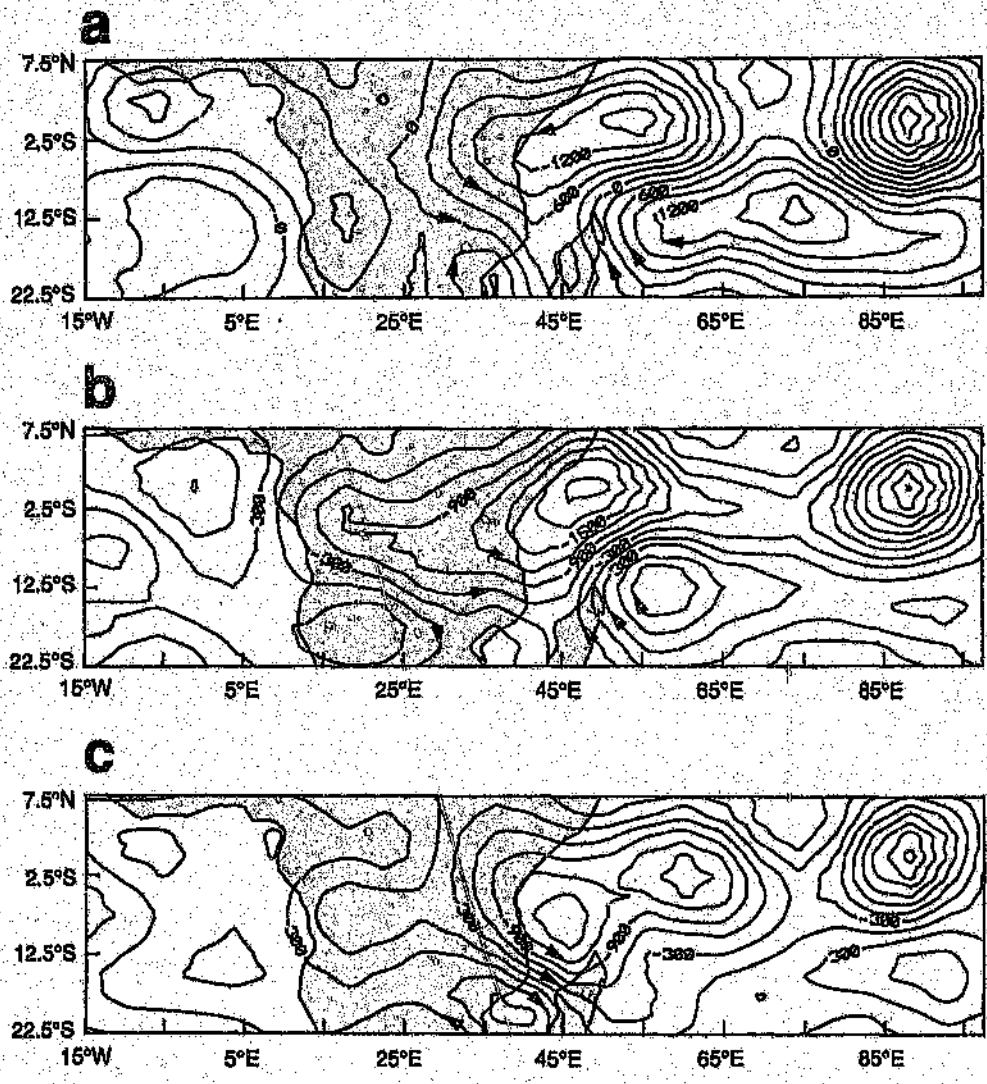

Figure 6.14: Distribution of non-divergent (ψ) vertically-integrated water vapour transport for for: a) 6 January 1980 (pre-cloud band) b) 7 January 1980 (cloud band); and c) 8 January 1980 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

divergence over subtropical Africa had intensified (Fig. 6.13b). The cyclonic cell over subtropical western Africa and the Mozambique Channel, as well as the anticyclonic cell over the tropical Indian Ocean, had intensified, resulting in southward vapour transport over southern Africa and the Mozambique Channel (Fig. 6.14b, Plate 3.4b). The divergent component for the post-cloud band conditions on 8 January reveals an eastward shift of the divergent and convergent regions such that the former were situated over eastern subtropical Africa and the latter over Madagascar (Fig. 6.13c). The non-divergent component reflects the pattern of the divergent field. A general eastward shift of the anticyclonic and cyclonic cells resulted in southeastward water vapour transport occurring over Madagascar (Fig. 6.14c, Plate 3.4c).

The divergent component for the pre-cloud band conditions of 22 January 1981 reveals sources of moisture over the subtropical Indian and tropical Atlantic oceans, and sinks over tropical Africa and the west coast of southern Africa (Fig. 6.15a). The east-west circulation over the tropics implies the presence of a Walker cell, while a second east-west circulation extends across southern Africa from the northern Mozambique Channel to the west coast of southern Africa. The non-divergent water vapour flux for the pre-cloud band day is characterized by cyclonic cells over tropical Africa, the Atlantic and Indian oceans, and an anticyclonic cell over the Mozambique Channel (Fig. 6.16a). Water vapour transport is southwestward over southern Africa. The patterns of the divergent mode show changes for the cloud band day of 23 January 1981. The divergent (source) region over the Atlantic Ocean weakened whereas that over the Indian Ocean intensified and occurred adjacent to the coast of East Africa (Fig. 6.15b). Water vapour convergence occurred off the west and east coasts of southern Africa and over tropical Central Africa. The non-divergent vapour transport during the cloud band conditions also shows some differences to that of the previous day. The anticyclonic cell over the southern Mozambique Channel intensified, as did the anticyclone over the tropical Indian Ocean (Fig. 6.16b). The juxtaposition of the cyclonic cells over tropical and subtropical Africa with the anticyclone over the Mozambique Channel resulted in continued northerly transport of water vapour over southern Africa (Fig. 6.16b). Cloud band conditions continued virtually uninterrupted, inclusive of 26th January 1981. Conditions on that day remained similar to the previous days. The divergent

mode reveals a southward shift of the source region over the northern Mozambique Channel with a sink over tropical Africa and the South Atlantic Ocean. Southward divergent transport occurred across subtropical Africa (Fig. 6.15c). The non-divergent mode reveals the continued presence of an anticyclonic cell over the southern Mozambique Channel and a cyclonic cell over western southern Africa and tropical Africa, resulting in continued, although weaker, vapour transport from the source region southward over southern Africa (Fig. 6.16c). Partial dissipation of the cloud band occurred with a further weakening of the major vapour source on 27 January 1981 (Fig. 6.15d).

The most important feature of the divergent mode is the changes to the spatial field and intensities during the dissipative stage. The divergent region in the tropical Indian Ocean weakened and shifted westward from the coast of Africa to lie over the eastern subcontinent, hence the reduced vapour source (Fig. 6.15d). A secondary divergent region of water vapour formed over the tropical East Atlantic Ocean. The non-divergent mode shows a disappearance of the cyclonic cell over subtropical southern Africa and a southwestward rather than southward transport over subtropical southern Africa from the reduced vapour source (Fig. 6.16d). The fact that cyclonic cells form (dissipate) in regions of water vapour convergence (divergence) point to the importance of water vapour for the maintenance of pressure systems over Africa during January. The divergent water vapour transport for the wet late summer case study, generally maintaining the rain-inducing conditions of northerly to northeasterly divergent vapour transport over southern Africa, conforms with the mean circulation transport for mean wet Januaries. This points to the importance of the mean circulation (anomalous Hadley circulation) during wet late summer cloud band occurrences.

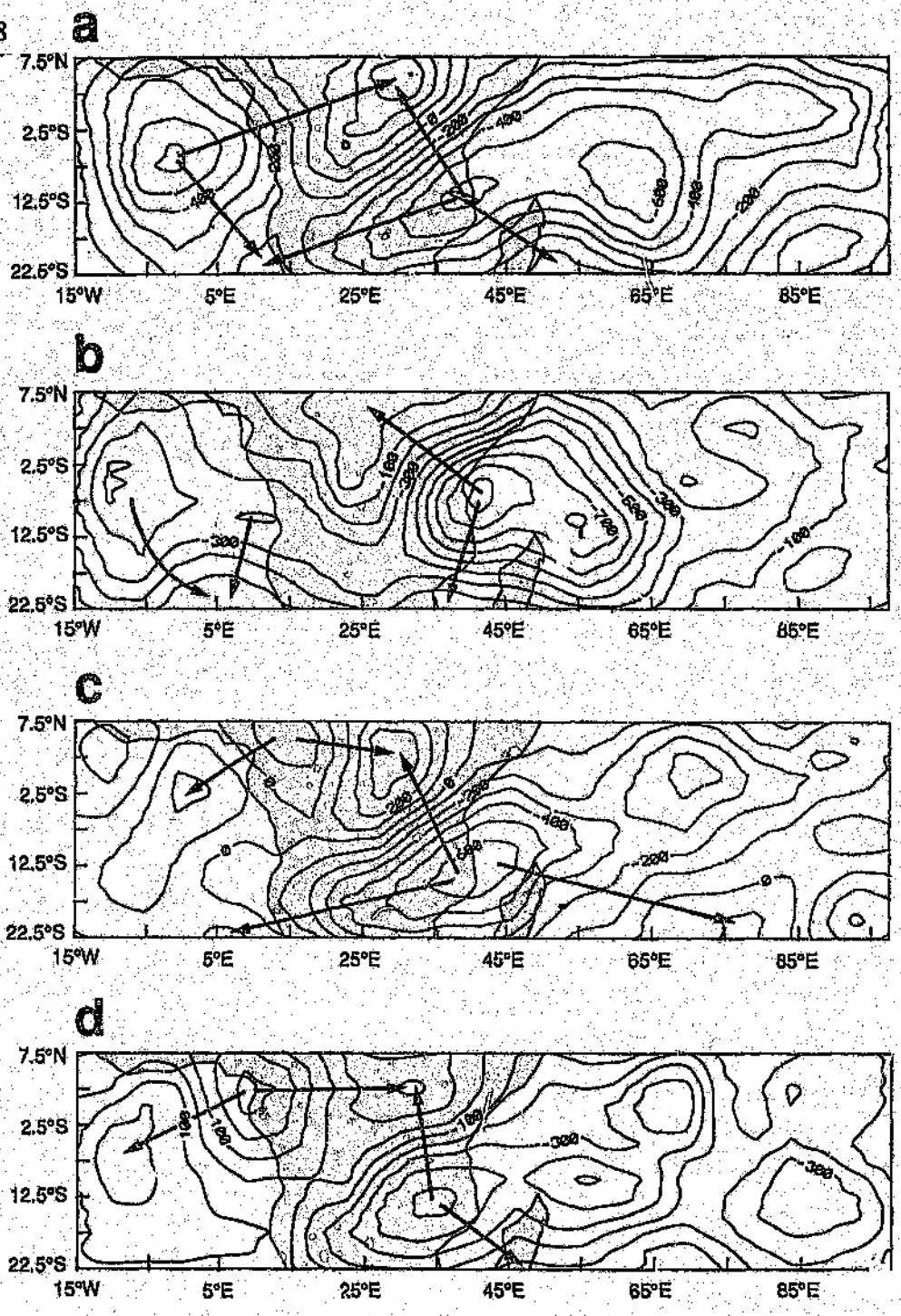

Figure 6.15: Distribution of divergent (χ) vertically-integrated water vapour transport for a) 22 January 1981 (pre-cloud band); b) 23 January 1981 (cloud band); c) 26 January 1981 (cloud band); d) 27 January 1981 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of divergent transport. Units are 10^6 kg.s^{-1}.

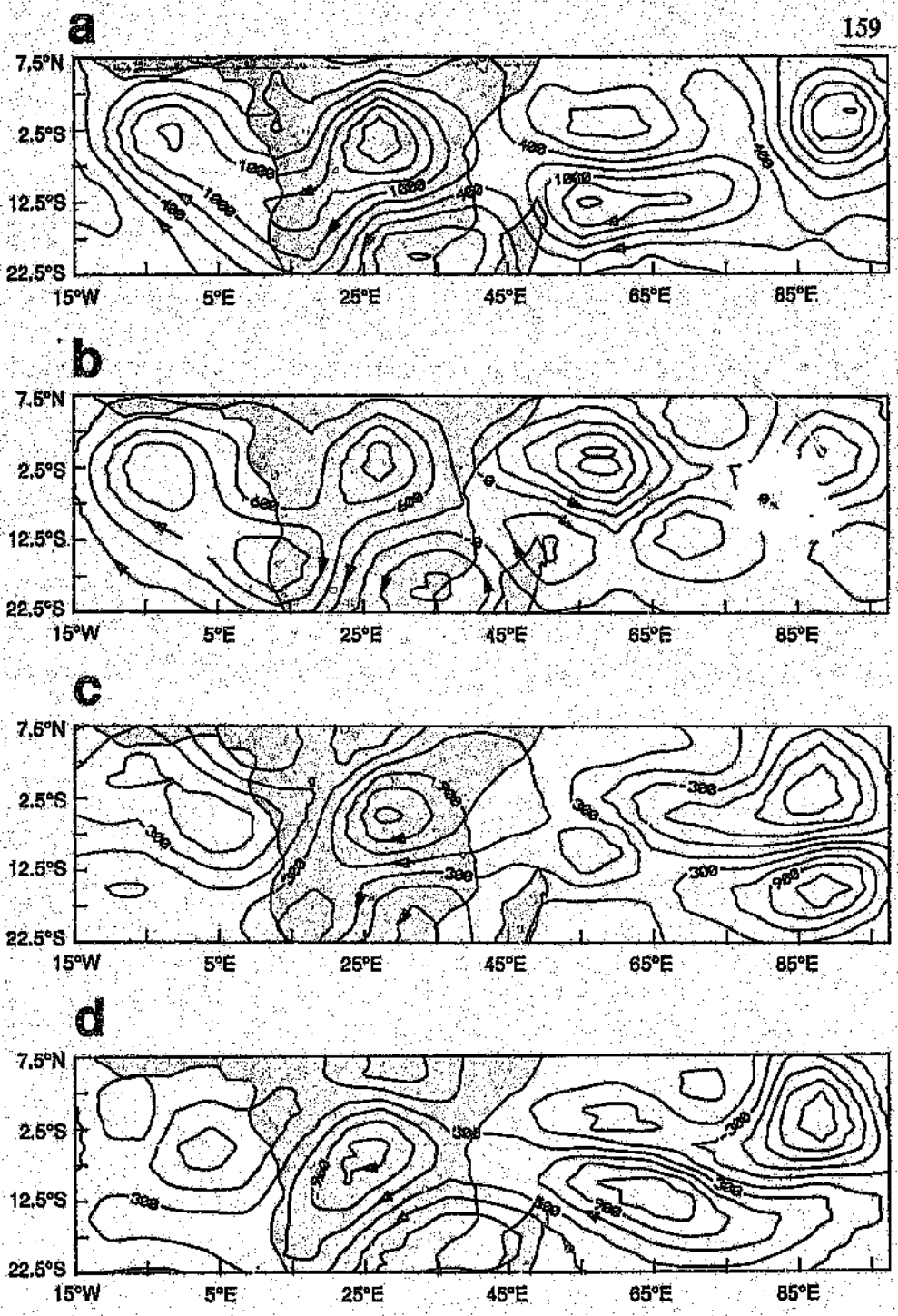

Figure 6.16: Distribution of non-divergent (ψ) vertically-integrated water vapour transport for a) 22 January 1981 (pre-cloud band); b) 23 January 1981 (cloud band); c) 26 January 1981 (cloud band); d) 27 January 1981 (post-cloud band). Integration is between 850 and 700 hPa; Arrows represent direction of non-divergent transport. Units are 10^6 kg.s^{-1}.

Discussion

Divergent and non-divergent circulation and eddy water vapour transports over southern Africa and adjacent oceans provide confirmation of the links between divergence fields, water vapour transport and rainfall over South Africa. The divergent and non-divergent modes of water vapour transport display marked inter-seasonal as well as inter-annual variation, and are the result of influences by the temperate upper-tropospheric flow and the tropical circulations. These tropical circulations are mainly the result of zonal temperature contrasts such as sea surface temperature (SST) differences. In the tropics, horizontal gradients are small and a heat source, such as continental regions or warm sea surfaces, causes strong upward motion, due to the turbulent mixing between sea surface and the overlying air (Bjerknes, 1969; Philander, 1990). Consequently, intense convection has been found over regions of maximum sea surface temperature (Horel and Wallace, 1981; Neelin and Held, 1987). While the effects of the tropical Pacific surface temperature on the Southern Oscillation have been well documented (Bjerknes, 1969; Hastenrath and Wu, 1983; Philander, 1983; Lindesay, 1988a), other oceans also have an effect on the Southern Oscillation (Hirst, 1986; Philander, 1990; Peixoto and Oort, 1992) and on circulation and rainfall elsewhere. The influence of sea surface temperatures on the summer rainfall region of South Africa has been extensively studied in recent years (Walker, 1989; Mason, 1992). Significant correlations between sea surface temperatures and South African summer rainfall have been found to move from the tropical Atlantic in early summer, where negative correlations of 0,59 exist, to the tropical Indian Ocean in late summer (-0,42) (Fig. 6.17a) (Walker, 1989; Mason, 1992). This importance of the western Indian Ocean to southern African summer rainfall is reflected by it having the most stable association with South African rainfall (Mason, 1992). A possible link between western Indian Ocean temperatures and the Southern Oscillation is found in the strong positive correlation (0,8) between Darwin sea level pressures and Indian Ocean SSTs (Fig. 6.18), reflecting a relationship between high surface pressure at Darwin (during El Nino) and high SST over the western Indian Ocean. It is impossible however, to imply cause and effect.

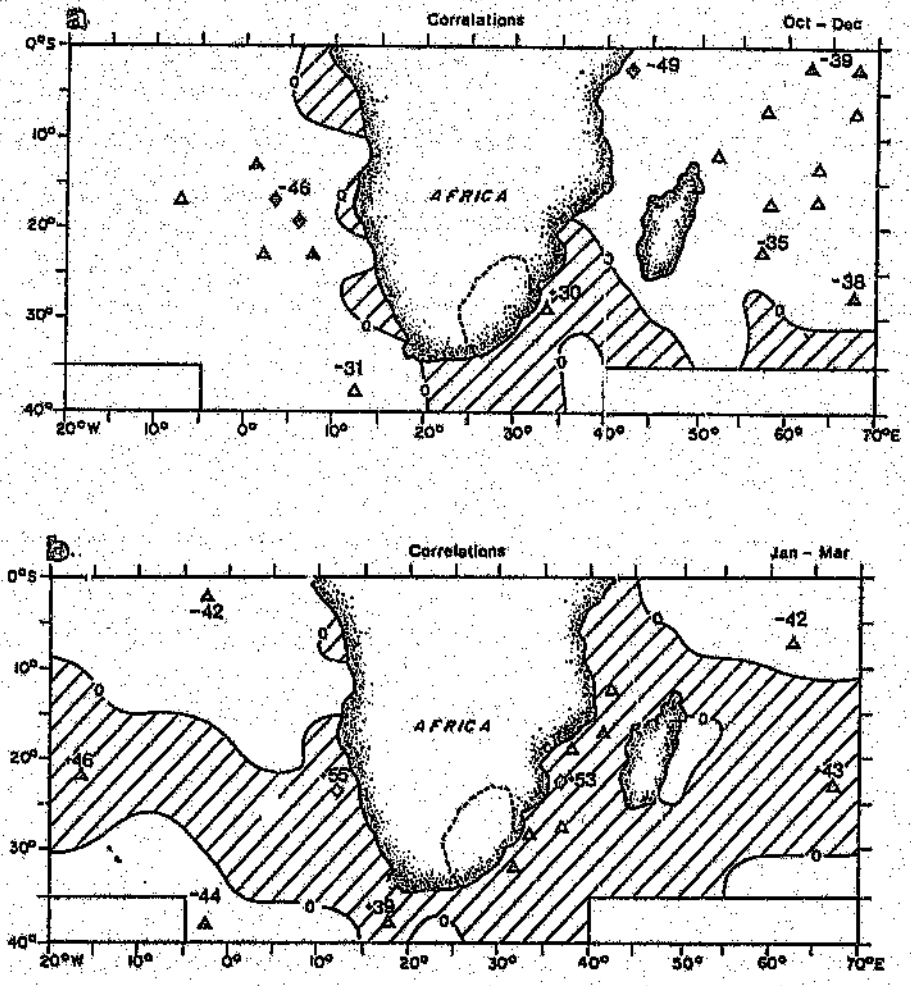

Figure 6.17: Linear correlations (x 100) between area-averaged rainfall and grid-square sea surface temperature departures for a) early summer and b) late summer (after Walker 1989). Shaded diamond represents significance at better than the 99 per cent level; shaded triangle at better than the 95 per cent level; open triangle at better than the 90 per cent level. Hatching depicts areas of positive correlation.

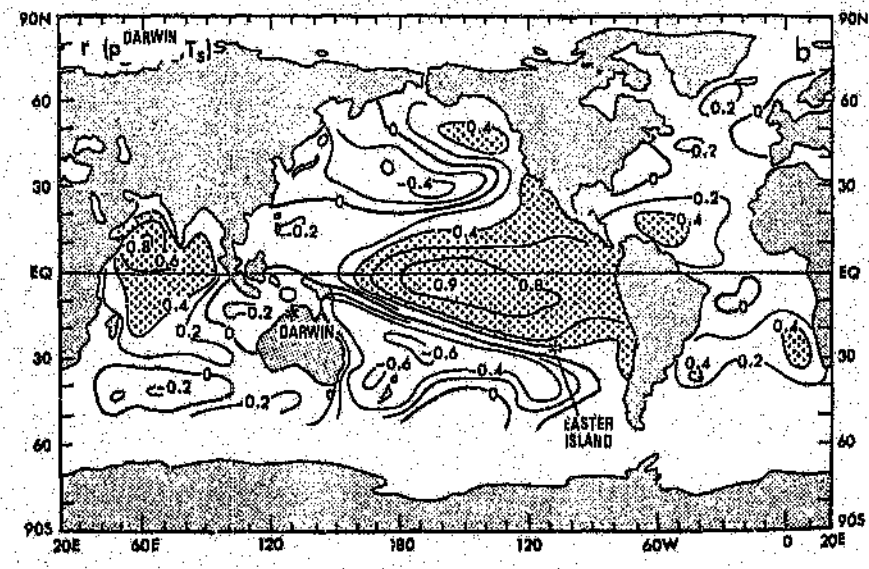

Figure 6.18: Horizontal distribution of the correlation coefficient between annual-mean sea surface temperature anomalies and Darwin sea level pressures for a 30-year period. Areas with anomalies greater than 0,4 are stippled (after Peixoto and Oort, 1992).

In the high phase of the Southern Oscillation (wet), conditions over the Indian and Atlantic Oceans and Africa are such that the weak Zaire cell is in place with ascending air over Africa and descending air over the western Indian Ocean and eastern Atlantic Ocean (see Fig. 1.7a) (Bjerknes, 1969; Newell, 1979; Harrison, 1984; Lindesay, 1988a). The relatively cold equatorial Indian Ocean temperatures possibly reflect this local modification of the Walker circulation in a way described by Bjerknes (1969) and Hastenrath and Wu (1983): Low sea surface temperature cools the atmospheric column above it, resulting in a decrease in the upper tropospheric topography over the cool SST region and a subsequent increase in surface pressure (Hastenrath and Wu, 1983). This results in the strong divergence in the lower troposphere over the western Indian Ocean during mean wet Januaries and over the eastern tropical Atlantic Ocean during mean wet Octobers (Figs 6.1, 6.3). The descending and diverging air over the anomalously cool western tropical Indian Ocean (cf. Fig. 6.17b) during mean wet

Januaries serves to modulate the Southern Oscillation in the region and also to supply water vapour for the convection (and the ascending limb of the Southern Oscillation) over tropical and subtropical Africa (see Fig. 5.13e). This is evident from the increased easterly winds over the tropical western Indian Ocean and Africa (see Figs 5.11, 5.19a) (Harrison, 1986a; Lindesay, 1988a, 1988b). The trough over the subcontinent (see Figs 1.7, 4.8a, b), as observed by Harrison (1986a) and Mason (1992) and seen in the non-divergent mode for mean wet Januaries (Figs 6.3b), plays a role in the convection over Africa. The effects of water vapour convergence over southern Africa are best seen by the maxima in total latent heat over the region during mean wet Januaries (see Fig. 3.8a). This latent heat maximum may play a critical role in forcing a meridional circulation over southern Africa (Gill, 1980; Harrison, 1986a; Hack and Schubert, 1990). The circulation divergent vapour transport from the north dominates the vapour transport over southern Africa during mean wet Januaries (Figs 6.3), indicating the existence of an intensified Hadley cell in mean wet years (Harrison, 1986a; Lindesay, 1988a). Vertically integrated low level water vapour transport from the tropical Indian Ocean, southward in the trough over southern Africa (Figs 4.8, 5.18e), also conforms with the upper level transport hypothesized by Harrison (1986a). This suggests a deep northerly flow from the tropical Indian Ocean southward over southern Africa, modulated by the standing thermal wave in the upper troposphere (Figs 1.8a, 5.19a, 6.19c) (Harrison, 1986a, 1986b).

Dry conditions over southern Africa are characterized by the low phase of the Southern Oscillation (Lindesay, 1988a). In this phase, descending air occurs over Indonesia and Africa with ascending air over the western Indian Ocean (cf. Fig 1.7b). The ascending limb of the Walker cell over the Indian Ocean may be partially controlled by the warm sea underlying it. Anomalously high sea surface temperatures warm the column of air overlying the warm ocean, resulting in an increase in the upper tropospheric topography and upper level divergence (Hastenrath and Wu, 1983). Surface pressures fall, convergence occurs at the surface, with subsequent convection (or suppressed descending air) and a possible conditional instability of the second kind (CISK) feedback mechanism enhancing convergence (Lindzen and Nigam, 1987; Philander, 1990). Reduction in the large scale divergence associated with the Southern Oscillation occurs over the region, and is seen by the decreased surface circulation divergence over the tropical

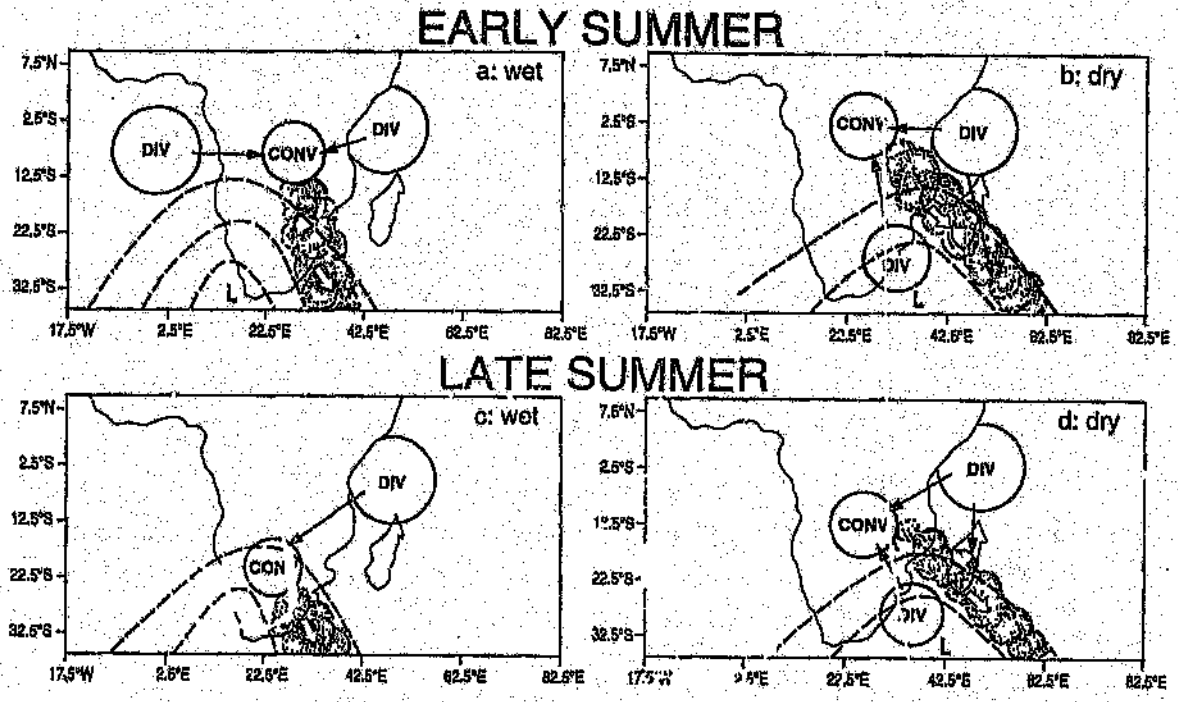

Figure 6.19: Schematic illustration of the relationship between low-level divergent circulations (from Figs 6.1-6.3) and upper-level flow during wet (a) and dry (b) early summer and wet (c) and dry (d) late summer. Abbreviations CONV is surface convergence and DIV is surface divergence. Dashed lines are upper level flow and thin arrows represent surface flow and thick unshaded arrows upper level flow.

western Indian Ocean during mean dry Januaries (Fig. 6.3). This decreased divergence is corroborated by the reduced subsidence over the western Indian Ocean as seen in the height-longitude sections of velocity potential (Appendix D). Reduction in the amount of water vapour supplied for tropical convection over Africa is reflected in the substantial decrease in total latent heat over Africa (see Fig. 3.8b). Southeastern Africa and the southwestern Indian Ocean become important sources of water vapour, resulting from an intensification of the South Indian Anticyclone and continental anticyclone over the region (Figs 4.9b, 6.3c). This conforms with Tyson's (1981) observations that pressures over the Indian

Ocean and southern Africa are higher during dry summers. Further north, convergence over the Mozambique Channel and Madagascar during mean dry Januaries (see Figs 5.13f, 6.3c) is partially modulated by the warmer SST over the western tropical Indian Ocean, and partially by the eastward displacement of the Atlantic wave (see Fig. 1.7b). and the surface easterly wave (Fig. 4.9a, b) (Harrison, 1986b; Mason, 1992), such that convection occurs preferentially over those regions. The Hadley cell intensifies with the increased sea surface temperatures and poleward angular momentum transfer occurs over Madagascar, marked by cloud bands (e.g. Julian and Chervin, 1978). Suppressed convection occurs over southern Africa beneath the trailing edge of the upper westerly wave (Fig. 6.19d) (Harrison, 1986a). The features characteristic of wet and dry late summer months are reflected in the height-longitude sections of the velocity potential (Appendix D).

Important areas of divergence present in the October and December studies coincide with strongly *negatively* correlated sea surface temperatures over a similar area, namely the subtropical east Atlantic Ocean (Fig. 6.17a) (Walker, 1989). This indicates the possible effects of SSTs on low level divergence of water vapour in similar fashion to that during January. Early summer (October to December) conditions are such that when SSTs are anomalously low over the tropical Atlantic Ocean, divergence from the region is high, and rainfall over South Africa is high (Figs 6.1, 6.2, 6.17a). Water vapour transport (circulation and eddy) in October therefore occurs from the divergent region over the Atlantic Ocean southeastward in the trough (Fig. 4.4b). The position of the upper westerly (Atlantic) wave during the mean wet early summer is such that the leading arm of the wave overlies southern Africa and a cloud band forms over the region (Fig. 6.19a) (Harrison, 1986a). The wave also serves to steer the transient systems over the subcontinent (Fig. 6.4) as described by Trenberth (1981). By December the convergent region (circulation and eddy) occurs further south over southern Africa (Figs. 6.2, 6.5), reflecting the increase of easterly low pressure systems over southern Africa from 0 per cent in October to 40 per cent in December (cf. Figs 4.4a, 4.6a) (Taljaard, 1982). The decrease in the importance of eddy transport from October to December reflects the transition from a baroclinic circulation in early summer to a more barotropic circulation in late summer (see Table 5.1) (Harrison, 1986a, 1986b). In dry early summers the

divergence from the tropical Atlantic Ocean decreases in response to SST warming, and the major source of water vapour shifts to the tropical and the southwestern Indian Ocean (Fig. 6.19b). The upper westerly wave undergoes an eastward shift such that the leading edge of the wave overlies Madagascar and serves as a conduit for water vapour, energy and momentum transport poleward (Harrison, 1986a) (Fig. 6.19b). The wave shift also results in the significant transient vapour transport occurring further to the east than in mean wet Octobers (cf. Fig. 6.4a, c). A tentative conclusion is that the water vapour in the lower troposphere originates over the tropical Atlantic Ocean and is transported eastward by the more significant transient systems of the westerlies in October, decreasing in importance by December and January when the circulation over South Africa becomes more barotropic and the major source of water vapour becomes the tropical Indian Ocean (cf. Table 5.1, Fig. 6.19) (Harrison, 1986a, 1986b). Further corroboration of the thermally forced wave in late summer and the orographically forced wave in early summer comes from the fact that the total latent heat differs significantly between wet and dry late summer months, while wet and dry early summer months do not differ as greatly (cf. Figs 3.6, 3.8). The weakened Walker cell across Africa in wet Decembers (Figs 6.5a, 6.7a), coupled with increased eddy non-divergent transport which is superficially larger than the eddy divergent transport, indicates a possible breakdown of the east-west Walker circulation across Africa. This conforms with Harrison's (1986) hypothesis that December is an hiatus month between the baroclinic systems of early and the barotropic systems of late summer. In this month the eddy and circulation non-divergent mode dominates the water vapour transport across southern Africa.

Conditions for cloud band formation are dependent on divergence fields of water vapour over the tropical oceans and the continental regions of Africa, coupled with a southward transport of vapour over southern Africa (Figs 6.1, 6.3). Cloud bands form in early summer when the converged water vapour over tropical and subtropical Africa is transferred southward ahead of the westerly wave, by the non-divergent transport (Figs 4.11, 6.7, 6.8). The most important source of water vapour during early summer, over the Atlantic Ocean, disappears with the dissipation of the cloud band over South Africa (Fig. 6.7c). The cyclonic cell over the eastern Atlantic Ocean, which transported the moisture southward,

also disappeared in conjunction with the dissipation of the cloud band. The importance of the Atlantic Ocean as a source of water vapour and in the non-divergent flow further indicating the importance of the westerly (baroclinic) circulation on early summer rainfall over southern Africa (Taljaard, 1982; Harrison, 1986a, 1986b).

Strong divergence over the western tropical Indian Ocean with convergence further south results in northeasterly to northwesterly non-divergent and divergent transport along the eastern edge of a trough/western edge of the South Indian Anticyclone over southern Africa during late summer cloud band conditions (Figs 4.14, 4.15, 6.13-6.16). The importance of the northerly divergent transport during January indicates the existence of the anomalous Hadley cell (as proposed by Harrison, 1986a, 1986c) over southern Africa during cloud band conditions. The dissipative stages in January occur with a westward shift of the source region (and anticyclone) over continental Africa, thereby reducing the amount of water vapour available for southward transport (Figs 4.14, 4.15d) The eastward shift of the convergent region during the cloud band case study in January 1980 conforms with the eastward displacement of the depression and cloud band over Madagascar in dry Januaries (Figs 4.14, 6.6, 6.13, 6.19d) (Harrison, 1986). Cyclonic (anticyclonic) cells correspond with regions of water vapour convergence (divergence) and point to the possibility of a CISK mechanism maintaining and possibly intensifying the depressions over southern Africa in late summer (e.g. Chen and Yen, 1985).

December cloud band conditions differ from those during October and January. The cloud band case study during a mean dry December (1982) points to a transport mechanism similar to that of October: convergence over subtropical Africa in the divergent mode (e.g. Walker or Hadley), with southward non-divergent transport from the convergent region (Figs 6.9, 6.10). The case study for the mean wet December (1985) corresponds more closely to that of late summer: convergence of water vapour occurs further south over southern Africa, and is attributed to the divergent (Hadley) circulation (e.g. Chen, 1985). As in the cloud band case for late summer, dissipation occurs with a shift of the source region to over Africa, hence reducing the supply of water vapour (Figs 6.11, 6.12). The cloud band case studies for December reflect the transitional nature

of that month in that the one case study (1982) coincides with early early summer flow, the other case study (1985) corresponds with late summer flow. This apparent inconsistency of water vapour transport again indicates that December may represent the transition between early and late summer circulation regimes.

Results of numerous researchers (Krishnamurti *et al.*, 1985; Knutson and Weickmann, 1987; Chen *et al.*, 1988; Chen and Tzeng, 1990) indicate the presence of a 30-50(60) day oscillation of eastward-moving convection anomalies. The surface convergence fields have been used as proxies for the 200 hPa divergence fields in order to identify the oscillation over Africa. Although the case studies in this thesis only cover 3-4 days, no general eastward propagation of the convergent and divergent centres has been found to occur. Only two case studies indicate eastward propagation: in the dry summer months of December 1982 and January 1980 (Figs 6.9, 6.10, 6.13, 6.14). The remainder of the case studies reveal a slight meridional oscillation or a small westward shift. No real significance can be attached to these findings, however, owing to the short time-period of observation and also to the fact that fluctuations of cumulus convection associated with the 30-50(60) day oscillation are generally small over tropical Africa (Chen and Tzeng, 1990).

In summary, the major water vapour source for southern Africa shifts from the Atlantic Ocean in early summer to the tropical Atlantic Ocean in late summer. Inter-annual variations have also been found to occur in water vapour sources. Dry early summer water vapour sources are mainly found over the tropical Indian Ocean whereas dry late summer sources are the southwest Indian Ocean, southern Africa and a reduced tropical Indian Ocean source. These inter-seasonal and inter-annual variations are related to sea surface temperature and/or Southern Oscillation fluctuations. In late summer, the sea surface temperature variations have an atmospheric response, predominantly in terms of modulating the Walker and Hadley cell over the African region. In contrast, the effects of sea surface temperatures on the atmosphere in early years is not as clearly seen. Tropical-temperate troughs generally reflect the mean seasonal transport. Water vapour transport is poleward for all cloud band case studies around cyclonic (anticyclonic) cells over western (eastern) southern Africa, confirming the importance of the tropical regions for southern African rainfall.

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Divergent and non-divergent components of circulation and eddy transport have been described in this chapter for wet and dry early-, mid-, and late-summer months as well as for cloudband occurrences. Results obtained point to the importance of different water vapour source regions between early and late summer. Convergence over Africa (maintained by the large-scale atmospheric circulation) and the non-divergent transport poleward show important inter-seasonal, intra-seasonal and daily variations. The link between water vapour convergence and diabatic heating over southern Africa and adjacent oceans will be investigated in Chapter 7 to assess the importance of water vapour on the energy exchanges over southern Africa during wet and dry early and late summer months and during cloud bands.

CHAPTER 7

ENERGY PROCESSES

Introduction

The importance of tropical water vapour for cloud band formation and precipitation over southern Africa has been identified in previous chapters. Although the immediate role of water vapour, that is supplying moisture for cloud formation and precipitation, is clear, the effect of diabatic heating of the atmosphere due to latent heat release has also been found to play an important role on the atmosphere over subtropical southern Africa (see Chapter 3). This diabatic heating has been suggested as being important in forcing a standing wave in the southern hemisphere subtropics (Vonder Haar, 1968; Kalnay and Peagle, 1983; Peagle *et al.*, 1983). The role of latent heat in forcing a standing wave over southern Africa in late summer has also been proposed by Harrison (1986a) as being an important factor in explaining the rainfall-producing mechanisms over the region.

The impact of diabatic heating has also been approached from an energetics point of view, where the generation of available potential energy has been assessed by Danard (1966), Kidson *et al.* (1969); Gall (1976), Vincent *et al.* (1977), Lin and Smith (1979), and Robertson and Smith (1983). Since the partitioning of potential and kinetic energy into zonal and eddy forms (Lorenz and Nigam, 1955), studies of the atmospheric energy cycle have mainly been focused on the planetary and hemispheric scales (Saltzmann and Fleisher, 1960; Oort, 1964; Lorenz, 1967; Peixoto and Oort, 1974; Arpe *et al.*, 1986). Smith (1969) developed energy integrals for available potential energy and kinetic energy in isobaric coordinates for a limited area. This led to investigations of energy budgets for synoptic-scale systems over limited areas. Norquist *et al.*

(1977) applied the equations of Meunch (1965) to African wave disturbances, while Edmon and Vincent (1979) calculated the total energy budget of the synoptic-scale flow of a hurricane. Brennan and Vincent (1980) expanded on this by partitioning the synoptic-scale energy budget into zonal and eddy forms. Limited area energetics have also been investigated for monsoon depressions (Krishnamurti, 1985; Rajamani and Sikdar, 1988) as well as mid-latitude depressions (Johnson, 1970; Robertson and Smith, 1983; Michaelides, 1987).

The study of energetics over southern Africa has been restricted to investigations of static energy and its annual cycle (Theron, 1990), or its influence on atmospheric stability (Harrison, 1986a, 1988; Steyn, 1987). Although the effects of atmospheric moisture on static stability over South Africa have been investigated (Harrison, 1988; Theron, 1990), energy studies in terms of available potential energy and kinetic energy and the transformations between them have not been undertaken. This chapter will therefore constitute a first study of the energy processes over the tropical and subtropical regions of Africa and their possible relationship to water vapour. Consequently, a number of assumptions will have to be made as the generation of potential energy and the conversions between the potential and kinetic energies have not been calculated previously. No attempt has been made to calculate fluxes of energy across the boundaries of the limited areas or to determine the generation of available potential energy. Consequently the energy balance cannot be considered (e.g. Kidson *et al.*, 1969). Unreliability of data has also limited the study of energetics over subtropical southern Africa to potential energy and its conversion to kinetic energy. The results outlined in the following sections have therefore been restricted to the direct conversions between available potential energies and kinetic energies.

Inter-annual Variability of Energetics

Energetics for the various regions (Fig. 7.1) have been calculated in approximate form for mean wet and dry early, mid, and late summer months. These results only depict the *contributions* within each area to the global energy budget, and are presented schematically.

Tropical Atlantic Ocean

The mean wet October (Fig. 7.2a), shows that zonal kinetic energy (usually referred to as KZ) for the tropical Atlantic region (Area 1) is the most abundant form of energy. Eddy available potential energy (usually referred to as AE) is six times the size of zonal available potential energy (usually referred to AZ), and zonal kinetic energy is four times larger than the eddy kinetic energy (usually referred to as KE) (Fig. 7.2a). The high zonal kinetic energy over the region is the result of the constancy of the tropical easterlies. The energy conversions indicate that the zonal and eddy potential energies are increased at the expense of the kinetic energies (Fig. 7.2a), as a result of an anticyclonic system (Kung and Baker, 1975). The negative conversion of zonal kinetic to zonal potential energy (referred to as CZ) is also indicative of a Ferrel cell over the tropical Atlantic Ocean (Van Miegham, 1973). The occurrence of a Ferrel cell over the Atlantic Ocean confirms earlier findings (Lindesay, 1988a). Mean dry Octobers are similar to wet Octobers, with the exception of the increased Ferrel cell (indicated by a doubling in intensity of the the conversion from zonal kinetic energy to zonal available potential energy) (Fig. 7.2a).

As in early summer, AE is the most abundant form of energy during both wet and dry Decembers (Fig. 7.2b). The KZ in dry months is approximately double that of wet Decembers, whereas the KE in wet Decembers is marginally higher than in dry Decembers (Fig. 7.2b). The most notable difference between Decembers and Octobers is the conversion between zonal kinetic energy and zonal available potential energy. Wet Decembers are characterized by an increase

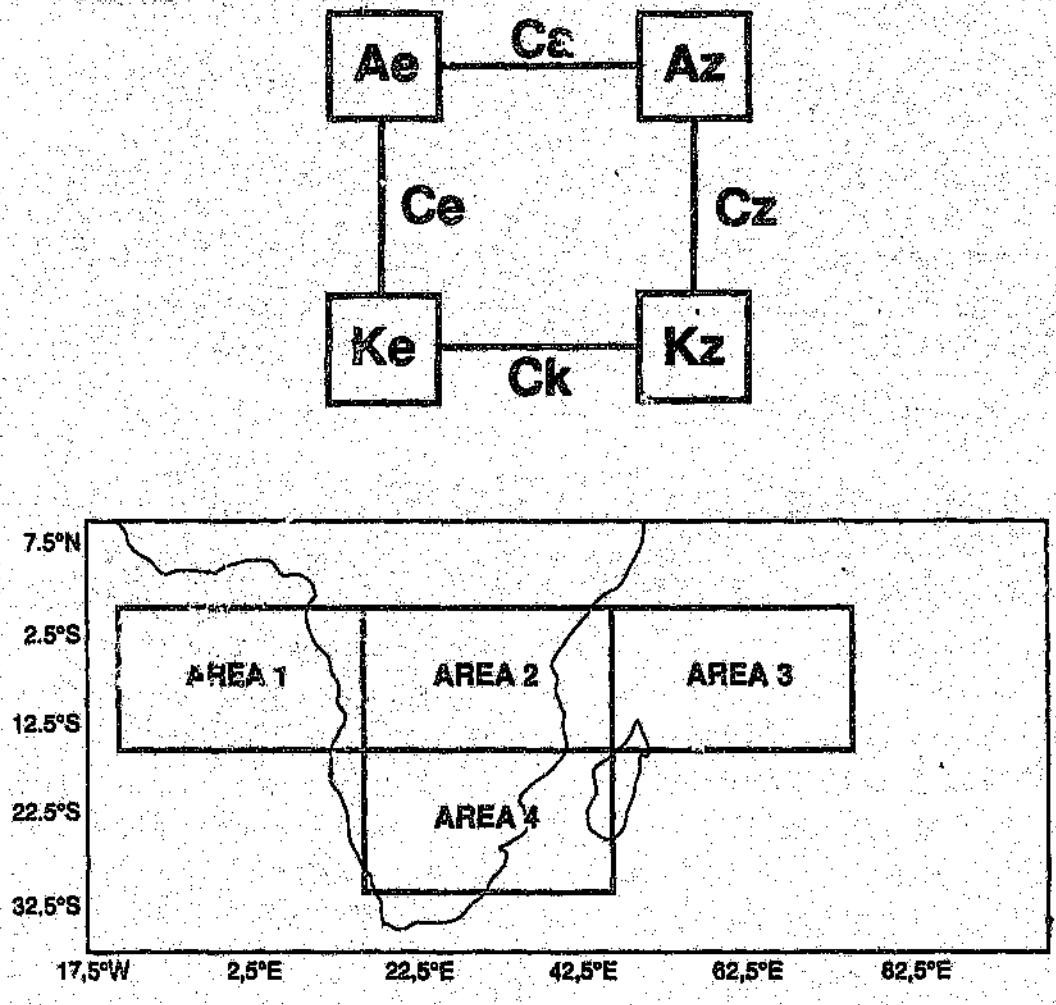

Figure 7.1: Top: Energy diagram for partitioned energies. See text for explanation of abbreviations. Bottom: Limited areas for the energy and energy conversion processes.

in CZ over that of dry Decembers. The eddy conversion, as in early and late summers, is stronger in dry than in wet months (Fig. 7.2b).

In wet late summer months, zonal kinetic and available potential energies exceed the eddy kinetic and available potential energies (Fig. 7.2c). In contrast,

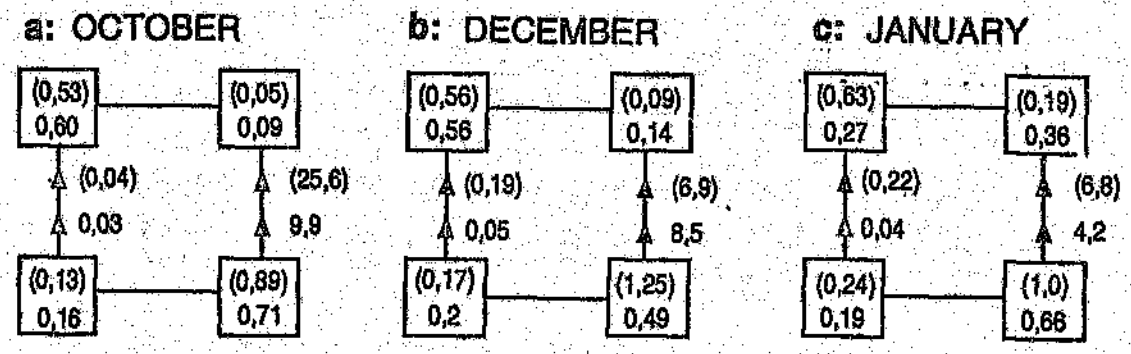

Figure 7.2: Contributions to the global energy budget of the tropical Atlantic Ocean (Area 1) for: a) Wet and dry Octobers; b) Wet and dry Decembers; and c) Wet and dry Januaries. Values in parenthesis are for mean dry years; Units of energy are x 10^5 $J.m^{-2}$ and conversions are $W.m^{-2}$.

during dry years an increase in eddy available potential energy and a decrease in zonal available potential energy occurs, such that the former exceeds the latter (Fig. 7.2b). This increase in eddy kinetic and potential energies corresponds with increased eddy water vapour transport over the region in wet Januaries (see Fig. 5.3). In both wet and dry late summer months kinetic energy is converted to potential energy. At the same time the magnitude of CZ increases from wet to dry Januaries (Fig. 7.2c). The conversion from eddy kinetic to eddy available potential energy (referred to as CE) increases eddy available potential energy by thermally forced circulations within latitude bands in both wet and dry late summer months. The Ferrel cell present over the region in all months is in agreement with earlier work (Lindesay, 1988). The negative CZ and CE terms may be associated with dynamically forced cold-cored subtropical depressions (Tyson, 1986), where KZ is increased by lateral advection of KZ and then converted to AZ by the ascent of cool air in the lower and subsidence of warm air in the higher levels. The high values of kZ and AE confirm the hypothesis of a cold-cored depression over the tropical Atlantic Ocean.

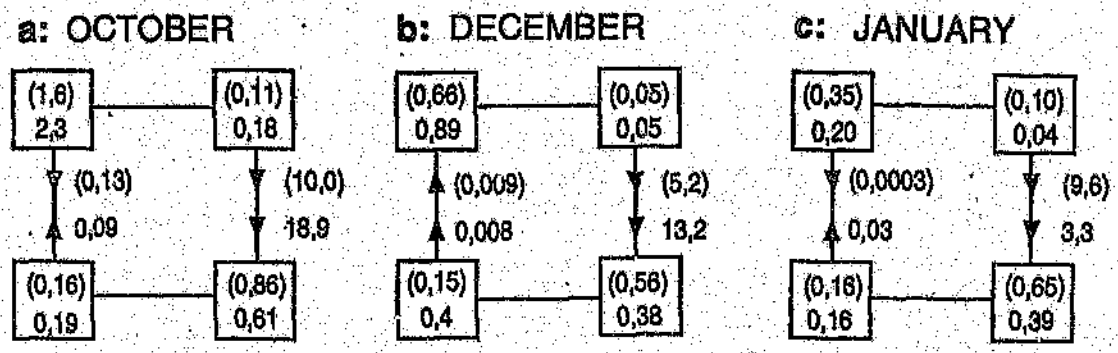

Figure 7.3: Contributions to the global energy budget of tropical Central Africa (Area 2) for: a) Wet and dry Octobers; b) Wet and dry Decembers; and c) Wet and dry Januaries. Values in parenthesis are for mean dry years; Units of energy are x 10^5 $J.m^{-2}$ and the conversions are $W.m^{-2}$.

Tropical Africa

Energetics for wet and dry Octobers over tropical Central Africa (Area 2, Fig. 7.3) are different from those over the tropical Atlantic Ocean (Area 1), particularly in respect of the energy conversion terms (Fig. 7.3a). The conversion between zonal available potential energy and zonal kinetic energy is positive in both wet and dry Octobers, indicating a thermally driven meridional Hadley circulation. The conversion is larger in wet than in dry Octobers (Fig. 7.3a). Eddy available potential energy (AE) is increased by thermally forced circulations in wet Octobers, and dissipated in dry Octobers (Fig. 7.3a). The increased AE corresponds with the increased eddy divergent and non-divergent transport over the region in mean October (see Fig. 6.4).

Energetics for wet and dry Decembers are generally similar to those of early summer months. Eddy available potential energy during wet Decembers decreases from wet Octobers, but still exceeds the AE of wet Januaries (Fig. 7.3b). Another similarity to early summer is the higher zonal kinetic energy in dry

than in wet Decembers (Fig. 7.3b), and the decrease from early to late summer. This conforms with the importance of zonal flow in dry early, mid and late summer months (see Figs 5.2, 5.6, 5.7). The positive conversion from zonal available potential energy to zonal kinetic energy indicates, as in October, the existence of a thermally driven mean meridional circulation (Hadley Cell) (Fig. 7.3b).

The most significant feature of the energetics during late summer (January) is the higher eddy available potential energy in dry years as opposed to wet years (Fig. 7.3c), and may be related to the increased water vapour convergence over the region in dry Januaries (see Fig. 6.3). This is opposite to the conditions found in wet and dry Octobers. As in October, dry conditions are characterized by higher zonal kinetic energies (Fig. 7.3c). The positive CZ term indicates a thermally direct circulation in both wet and dry Januaries, although larger conversion values in dry Januaries imply an intensified Hadley cell over tropical Africa. In general the kinetic and available potential energies are less in mean wet than in dry Januaries (Fig. 7.3c).

Tropical Indian Ocean

Zonal kinetic energy (KZ) is the most abundant form of energy over the western tropical Indian Ocean region (Area 3). All the other energy forms are relatively small (Fig. 7.4a). The zonal kinetic energy during wet Octobers is marginally larger than during dry Octobers. This high zonal kinetic energy over the tropical Indian Ocean may reflect the high zonal kinetic energy found over a similar region during the Indian monsoon season which ends in September/October (Krishnamurti *et al.*, 1981; Peixoto and Oort, 1992). Further confirmation of the decreased importance of zonal kinetic energy comes from a comparison of the non-divergent water vapour transport. Easterly transport around the cyclonic cell over the Indian Ocean decreases significantly between wet and dry Octobers (cf. Fig 6.1b, d). The positive conversion of zonal available potential energy (CZ) (depletion of AZ) is indicative of a thermally driven mean meridional Hadley circulation during wet Octobers, while negative CZ indicates

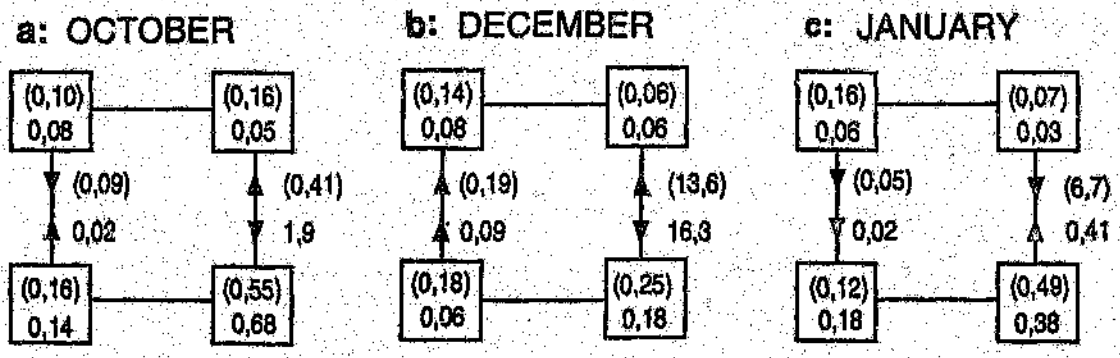

Figure 7.4: Contributions to the global energy budget of the tropical Indian Ocean (Area 3) for: a) Wet and dry Octobers; b) Wet and dry Decembers; and c) Wet and dry Januaries. Values in parenthesis are for mean dry years; Units of energy are x 10^5 $J.m^{-2}$ and the conversions are $W.m^{-2}$.

a Ferrel cell in dry Octobers (Fig. 7.4a). Eddy conversions are generally small and of opposite sign in wet and dry Octobers.

The energetics for wet and dry Decembers are similar to those of October. Positive conversions from zonal available potential to zonal kinetic energy occur in wet Decembers while negative conversions occur in dry Decembers (Fig. 7.4b). Zonal kinetic energy, although reduced in magnitude from October, is still the most abundant form of energy. Zonal kinetic, eddy kinetic and eddy available potential energy are larger in dry than in wet Decembers (Fig. 7.4b).

Wet late summer months are characterized by a reversal of the conversion term CZ from the positive in October to negative (Fig. 7.4c). During dry Januaries, in contrast, the positive CZ term is indicative of the symmetrical overturning found in the Hadley cell (Fig. 7.4c). The zonal kinetic energy is, as in Octobers, the most abundant energy form in wet and dry Januaries (Fig. 7.4c). Wet January zonal KZ is marginally smaller than in dry Januaries. Wet January eddy kinetic energy in contrast, is larger than dry January eddy kinetic energy (Fig. 7.4c). The increased eddy available potential energy in mean dry months

reflects the cyclonic circulation found over the northern Mozambique Channel in dry late summer months (see Figs 4.3, 4.9). Conversion from eddy available potential energy to eddy kinetic energy is similar in magnitude and direction in wet and dry Januaries (Fig. 7.4c).

Subtropical southern Africa

Data limitations have restricted the study of energetics over subtropical southern Africa (Area 4) to available potential energy and the conversions to kinetic energy. In wet Octobers, eddy available potential energy is greater than zonal available potential energy (Fig. 7.5a). The greatest conversion is from zonal kinetic to zonal available potential energy (Fig. 7.5a), indicating a thermally indirect circulation in the atmosphere (i.e. a Ferrel cell). During dry Octobers eddy available potential energy (AE) decreases and zonal available potential energy (AZ) increases although the former is still 1,8 times the latter (Fig. 7.5a). The decreased CZ term during dry Octobers indicates a weakening of the Ferrel cell (Fig. 7.5a). Corresponding to the decrease in eddy available potential energy (AE) is the decrease in eddy convergence of water vapour over southern Africa (see Fig. 6.4). Wet Octobers are characterized by a positive conversion from eddy available potential energy to eddy kinetic energy, while dry Octobers show a negative conversion (increase in AE at the expense of KE) (Fig. 7.5a).

Analysis of December energetics for wet months reveals a increase in both zonal available potential energy and eddy available potential energy from the October values (Fig. 7.5a, b), although AZ is more abundant in wet than in dry Decembers (Fig. 7.5b). Conversely, eddy available potential energy is less abundant in wet than in dry Decembers (Fig. 7.5b). Zonal conversions are positive in both wet and dry Decembers, although the magnitude of the conversion in wet Decembers exceeds that of dry Decembers (Fig. 7.5b). The generation of KZ from AZ indicates the increased importance of the thermally driven meridional Hadley circulation in dry Decembers. Negative values of CE increase eddy available potential energy by thermally forced circulations in wet and dry Decembers, although in wet years the conversion is 16 per cent of that of dry Decembers (Fig. 7.5b).

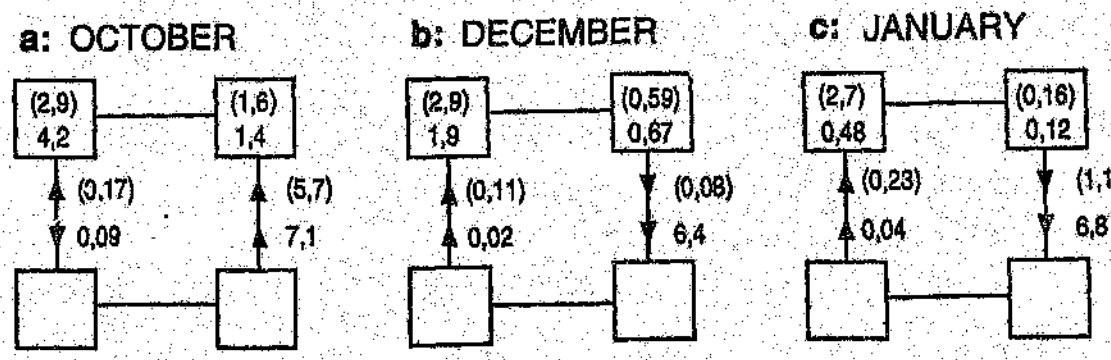

Figure 7.5: Contributions to the global energy budget of subtropical southern Africa (Area 4) for: a) Wet and dry Octobers; b) Wet and dry Decembers; and c) Wet and dry Januaries. Values in parenthesis are for mean dry years; Units of energy are x 10^6 $J.m^{-2}$ and the conversions are $W.m^{-2}$.

Available potential energies (eddy and zonal) decrease in values for both wet and dry Januaries. Dry January eddy and zonal available potential energies exceed those of wet Januaries (Fig. 7.5c). This again corresponds to the increase in eddy water vapour convergence over southern Africa during dry Januaries (see Fig. 6.6). The conversion term CZ, in contrast to October, is positive in wet Januaries (Fig. 7.5c). The conversion is also positive in dry Januaries, although 6 times smaller than in wet Januaries (Fig. 7.5c). This indicates an intensified Hadley cell over subtropical southern Africa during wet Januaries (Fig. 7.5c).

The Energetics of Tropical-temperate Troughs

Available potential energies and their conversions have been examined for cloud band case studies over subtropical southern Africa (Area 4) in early, mid and late summer. The pre-cloud band conditions for the early summer case study show relatively low magnitudes of area-integrated zonal available potential energy, and positive zonal conversion (CZ), indicative of a Hadley circulation

Table 7.1. Vertically-integrated, AZ and AE budgets for early, mid and late summer case studies over subtropical southern Africa (Area 4). Shading indicates cloud band days. Units are $W.m^{-2}$ except AE and AZ which are 10^5 $J.m^{-2}$.

Date	AE	$\frac{\partial AE}{\partial t}$	CE	AZ	$\frac{\partial AZ}{\partial t}$	CZ
15/10/86	6.30		0.5	2.20		6.6
		-4.17			0.23	
16/10/86	2.70		1.2	2.40		32.6
		0.00			-0.11	
17/10/86	2.70		-0.1	2.30		22.1
4/12/82	2.98		-0.5	0.97		-13.6
		-0.90			-0.60	
5/12/82	2.30		0.2	0.45		11.0
		0.81			0.01	
6/12/82	2.90		-1.0	0.46		2.4
1/12/85	3.50		0.1	0.49		5.1
		-0.23			-0.13	
2/12/85	3.30		0.0	0.49		19.4
		0.00			0.22	
3/12/85	3.30		1.6	0.57		13.0
20/1/80	1.30		0.5	1.45		23.9
		1.27			0.52	
21/1/80	2.40		-0.6	1.90		25.9
		-0.35			-0.46	
8/1/80	2.10		-0.4	1.50		-3.9
22/1/81	0.77		-0.0	0.30		1.9
		0.16			-0.09	
23/1/81	0.91		0.2	0.22		5.7
		0.57			0.08	
24/1/81	1.40		0.1	0.29		18.8
		1.27			-0.08	
25/1/81	2.50			0.22		
		-1.50			0.00	
26/1/81	1.00		0.1	0.22		10.5
		-0.42			0.22	
27/1/81	0.84		0.0	0.41		6.7

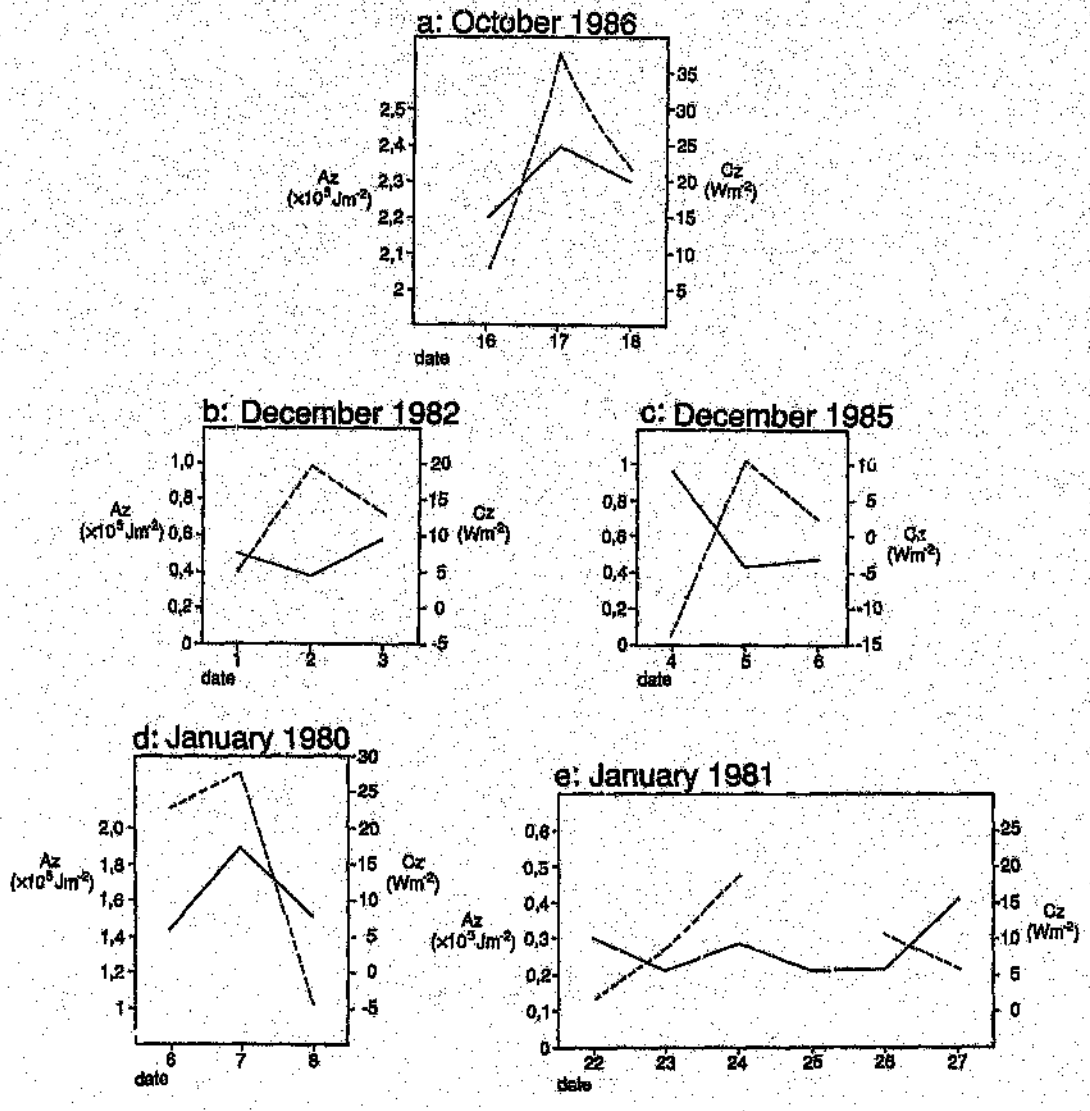

Figure 7.6: Contributions to the global energy budget of zonal potential energy (solid line) and its conversions (dashed line) in Area 4 (subtropical southern Africa) for: a) Early summer cloud band case study (October 1986); b,c) mid summer case studies (December 1982 and 1985); and d,e) late summer case studies (January 1980 and 1981). Units of energy are x 10^5 J.m^{-2} and conversions are W.m^{-2}.

(Fig. 7.6a, Table 7.1). Eddy available potential energy on the pre-cloud band day is approximately 3 times the zonal available potential energy (Table 7.1). The following day (cloud band) was characterized by an increase in the positive CZ with a corresponding increase in zonal available potential energy (Fig. 7.6a) (intensification of the Hadley cell). In contrast, eddy available potential energy for the same day was much reduced (-4.17 $J.m^{-2}$) from the previous day (Table 7.1). The zonal conversion had decreased by the following day (dissipative stage), indicating a slight weakening of the Hadley Cell (Fig. 7.6a, Table 7.1). The eddy APE and zonal APE have shown little change from the previous day (Table 7.1).

Energetics for cloud band case studies during mid summer months have revealed different characteristics from the early summer cloud band. Zonal available potential energy for December 1982 (Fig. 7.6b) and December 1985 (Fig. 7.6c) both show decreases in magnitude from pre-cloud band to cloud band days, followed by increases in zonal available potential energy on post-cloud band days (Table 7.1). The eddy available potential energy decreases (as in October) from the pre-cloud band to cloud band days in both December 1982 and December 1985 (Table 7.1). The zonal conversion term (CZ) is a mirror image of the zonal available potential energy (Fig. 7.6b), with highest (positive) values of CZ indicating a thermally driven mean meridional circulation (Hadley cell), reaching maximum intensity during the cloud band days (5 December 1982 and 2 December 1985) (Fig 7.6b,c). The negative CZ on the pre-cloud band day of 4 December 1985 (Fig. 7.6c) indicates the existence of a Ferrel circulation over subtropical southern Africa, before the establishment of a circulation in the sense of a Hadley cell during the cloud band day (5 December 1982).

The cloud band case studies during a mean dry (1980) and a mean wet (1981) late summer display similar characteristics in CZ to the early and mid summer case studies. Positive values of CZ increase from pre-cloud band days to cloud band days, and then decrease during the post cloud band days (Fig. 7.6c). This indicates a depletion of zonal available potential energy through the thermally forced Hadley circulations with maximum intensity during the cloud band days. The changes in zonal APE for the case study during the wet January (1981) are similar to those in early and mid summer, that is a decrease in zonal available potential energy from pre- to cloud band days, followed by an increase during the

post-cloud band day (Fig. 7.6d, Table 7.1). The eddy APE is generally similar to early and mid summer case studies, with a decrease in eddy available potential energy from pre- to cloud band days (Table 7.1). An exception has been found for the cloud band case study conducted during the generally dry January (1980) when an increase in both zonal available potential energy and eddy available potential energy occur between the pre-cloud band and the cloud band day (Table 7.1).

Discussion

Early studies have indicated that available potential energy is generated from zonal potential energy, cascaded to eddy form, and converted to eddy kinetic energy (Oort, 1964; Lorenz, 1967). This has been confirmed for wave disturbances over the eastern North Atlantic Ocean and northwest Africa, where the energy of systems is mainly derived from dry baroclinic (CA) and barotropic conversion (CK) processes (Norquist *et al.*, 1977), and conforms with the finding that waves originate through the barotropic instability of the mid-tropospheric west African jet stream (Burpee, 1972). Studies of the energetics over southern Africa during mean wet and dry early, mid and late summer months do not conform to Lorenz's global energy cascade. This is due to the studies having been conducted for limited areas, and as such the energetics and conversions between them are only *contributions* to the global energy budget. Similar results are characteristic of other studies conducted for limited regions (Kidson *et al.*, 1969; Norquist *et al.*, 1977; Brennan and Vincent 1980).

Assessment of the area energy processes over the three tropical regions around southern Africa (Area 1 to 3) indicate that Areas 1 and 2, over the tropical Atlantic Ocean and tropical Africa (see Fig. 7.1) show significant differences between wet and dry early, mid, and late summer months over South Africa (Figs 7.2, 7.3). In general, eddy available potential energy decreases from early summer to a late summer minimum over both areas. This decrease in AE is also seen in the decrease of eddy divergent water vapour transport over the tropical Atlantic Ocean and tropical Africa from early to late summer months (see Figs 6.4, 6,5, 6.6). The conversion from eddy kinetic energy to eddy available

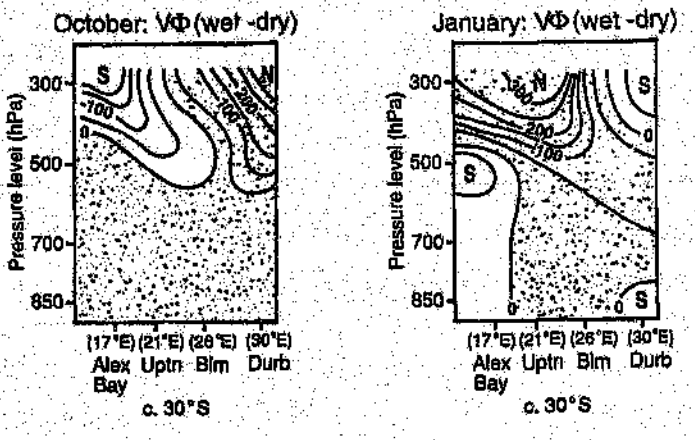

Figure 7.7: Meridional geopotential transport across southern Africa at approximately 30°S for wet minus dry: a) Octobers; and b) Januaries. Shading indicates increased northerly flow in mean wet years, and units are x 10^2 gpm.m.s^{-1}. Abbreviations Alex Bay, Uptn, Blm and Durb represent Alexander Bay, Upington, Bloemfontein and Durban (see Figure 2.1 for location).

potential energy over the tropical Atlantic Ocean represents an increase in thermally forced circulations within latitude bands, resulting in east-west temperature variance and thereby increasing eddy available potential energy (see Michaelides, 1987; Peixoto and Oort, 1992). This is seen by the increased eddy non-divergent transport over the tropical Atlantic Ocean during mean dry mid, and late summer months (see Figs 6.4, 6.6). Ferrel circulations dominate the area at all times, whereas over Area 2 (continental tropical Africa), the Hadley cell dominates. The increase in zonal kinetic energy between wet and dry early, mid and late summer months (Fig. 7.3) reflects the circulation changes over tropical Africa between wet and dry years. In Chapter 5, it was seen that the tropical easterlies increase in magnitude and spatial extent, reflecting greater amounts of zonal kinetic energy than in wet years when the circulation is predominantly meridional (see Fig. 5.19). The eddy available potential and eddy kinetic energies over the tropical Indian Ocean (Area 3) are higher in mean dry summers than in

mean wet summers (Fig. 7.4), coinciding with the increased sea surface temperatures over the western Indian Ocean during mean dry years (cf. Fig. 6.17). The increased convection over the region, especially in dry late summer thus results in a local Hadley cell in association with the convergence (Fig. 7.4c). This local, anomalous Hadley cell over the western Indian Ocean in dry late summer months corresponds with earlier findings that cloud bands and rainfall shifts eastward to extend across Madagascar when southern Africa is dry (see chapters 3, 5, 6). The decrease in zonal kinetic energy from October to December may represent the dissipation of the Indian Monsoon (Krishnamurti and Ramanathan, 1982), increasing by late summer in association with the East African Monsoon (Figs 5.18, 7.4).

Calculations have shown the importance of strong thermal overturning (positive CZ) in an anomalous Hadley cell over the southern African region during wet late summer months (Fig. 7.5). These observations confirm earlier findings that wet (dry) years are characterized by an increased (decreased) local Hadley circulation over southern Africa (Harrison, 1986a, 1986b, 1986c; Lindesay, 1988a). Further confirmation comes from the fact that the meridional circulation across southern Africa in wet (dry) late summer months and seasons is anomalously poleward (equatorward) (see Figs 5.12, 5.19, 6.3, 7.7) (Lindesay, 1988a, 1988b). The increased total latent heat (in space and magnitude) over the region and extending poleward in late summer months indicates the importance of diabatic heating over the summer atmosphere of southern Africa (see Fig. 3.8a). The thermally forced wave over southern Africa in late summer is further corroborated by the failure of the Eliassen-Palm relationship (Fig. 3.12b) and the increased northerly potential energy transport over the subtropical upper troposphere (Fig. 7.7) (Harrison, 1986b). The water vapour convergence over southern Africa (see Figs 5.11, 5.18, 5.19, 6.3) maintains the water vapour content over th subcontinent, therefore playing an im portant role in modulating the energy processes, circulation and rainfall over South Africa. The reduced positive CZ term in mean dry Januaries (Fig. 7.5), coupled with the reduced latent heat over southern Africa (Fig. 3.8b), indicates reduced thermal forcing and a reduced Hadley circulation. This is confirmed by the reduced northerly water vapour (Figs 5.12, 5.19b, 6.3) and geopotential transport (Fig. 7.7) across southern Africa during dry late summer months. The much-reduced vapour

convergence over southern Africa (Area 4) during dry late summers (see Figs 5.18, 5.19, 6.3) results in the reduced diabatic heating and hence reduced local Hadley cell and rainfall over South Africa.

The energy processes over southern Africa for mid summer are similar to those of late summer. An intensification of the anomalous Hadley cell occurs in wet years, conforming with the circulation water vapour transport over southern Africa in wet Decembers (cf. Figs 6.2a, 7.5b). The reduced Hadley cell during dry Decembers is indicated by the decreased CZ term (Fig. 7.5b) and reduced total latent heat over subtropical and tropical southern Africa (see Fig. 3.5). During October, the Ferrel cell over southern Africa (Harrison, 1986a, 1986b, 1986c) is indicated by the upper (lower) level equatorward (poleward) transport (Fig. 5.8), and the negative CZ terms in both wet and dry Octobers (Fig. 7.5a). This thermally indirect cell over southern Africa is also indicated by the equatorward geopotential energy flux in early summer months (Fig. 7.7). In general, both the eddy and the zonal available potential energy decrease as the summer progresses, while the conversion term CZ becomes positive and increases from early to late summer. This is indicative of an enhancement of tropical controls on the circulation over southern Africa between early and late summer months.

Investigations have revealed the link between diabatic heating and the generation of available potential energy (Robertson and Smith, 1983). It is hypothesized that the energy of the subtropical atmosphere over southern Africa is supplied by latent heat release. Evidence of this has been reviewed in previous chapters, and will now be further examined using the cloud band case studies. All the case studies show a significant increase in the CZ term to be strongly positive during the peak cloud band development (Fig. 7.6 and Table 7.1). This is indicative of a thermally direct circulation over the region, confirming the contention that tropical-temperate troughs are manifestations of anomalous Hadley circulations (Harrison, 1986a). In four of the case-studies, October 1986, December 1982, December 1985 and January 1981, cloud bands were generally preceded by high eddy available potential energies over the region (Table 7.1). This is associated with a convergence of water vapour in the region and an increase in total latent heat (cf. Figs 3.9, 3.10, 3.11, 6.7, 6.13, 6.15), and *may* indicate generation of eddy available potential energy by diabatic heating

(Holpainen, 1983). The eddy available potential energy decreases rapidly by the cloud band days, but this is not reflected by the baroclinic conversion term (CE) which is not consistent (Table 7.1).

Lack of proper calculations has resulted in the necessity for assumptions regarding energy conversion. One of these is that the large eddy available potential energy is converted to zonal available potential energy through the ascent of cool air and the descent of warm air (Norquist *et al.*, 1977). The assumption of this countergradient transport of heat to increase zonal available potential energy at the expense of eddy available potential energy is justified by the observed characteristics of easterly low pressure systems over southern Africa, that is cool (warm) at lower (upper) levels (Taljaard, 1985; Tyson, 1986; Harangozo, 1989). Furthermore, these results accord well with earlier studies which show that the tropical and subtropical regions are characterized by a loss of eddy available potential energy to zonal available potential energy (Krishnamurti, 1978). Two case studies do not accord well with the above results. These are the cloud band occurrences on 7 January 1980 and 23 January 1981. In both cases eddy available potential energy increased from the pre-cloud band to the cloud band day. This increase may be due to the intense generation of eddy available potential energy by the baroclinic cut-off low pressure systems predominating on those days (Estie, 1981; Taljaard, 1982). Studies have indicated the existence of cut-off lows with clouds band on several occasions (Harangozo, 1989).

To summarize, the energetics over southern Africa and adjacent tropical oceans display marked seasonal as well as inter-annual differences. The atmosphere over the tropical Atlantic Ocean is characterized by a thermally indirect circulation throughout the summer with a decrease (increase) in eddy available potential (energy zonal available potential energy) as the summer progresses. Over tropical Africa the conversion between zonal available potential energy and zonal kinetic energy is thermally-direct, indicating a weakening Hadley cell over the region throughout summer. Southern Africa is characterized by a thermally indirect circulation (Ferrel) in early summer, becoming a thermally direct Hadley cell as the summer progresses. A strengthened Hadley cell in mid and late summer coincides with anomalously wet months. Increased eddy

available potential energy and CE in dry mid and late summers indicates possible equatorward displacement of the mid-latitude baroclinic systems. Cloud band conditions are generally characterized by increased eddy available potential energy, through diabatic heating and conversion to zonal available potential energy through the countergradient transport of heat in the easterly wave low. The most important characteristic of tropical-temperate troughs and their associated cloud bands is, however, the large conversion of zonal potential energy to zonal kinetic energy, representing an intensification of the Hadley cell.

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Limited area energetics over the southern African region and adjacent oceans have been examined for wet and dry early, mid, and late summer months. Adjustments in the magnitude of the different energy components and conversions thereof have been found to occur between mean wet and dry years, as well as during the progression of the summer season. The energetics during tropical-temperate trough conditions point to an intensified Hadley circulation during the peak of the cloud band, maintaining the consistency of cloud band formation. Adjustments in the energy processes over southern Africa provides further evidence that early summer circulation is of temperate origin and late summer circulation of tropical origin, primarily due to diabatic heating.

CHAPTER 8

SUMMARY

Previous attempts at understanding rainfall variations over southern Africa have been limited to statistical, regional and planetary-scale dynamics of the atmosphere. The importance of water vapour, the transport thereof its effects on the energetics of the atmosphere over southern Africa have been largely ignored. Likewise, no quantitative study has been conducted to ascertain the source regions of water vapour found over southern Africa. It is therefore necessary to consider regional fluctuations in water vapour content and transport in seeking to understand the thermodynamic and energy processes pertaining to the summer circulation over southern Africa. The aim in this thesis has been to provide such an analysis.

A fundamental hypothesis on which this study rests is that water vapour is transported into southern Africa from the adjacent tropical oceans by the mean atmospheric circulation. Apart from the obvious role of water vapour in cloud formation and precipitation, it has been postulated that water vapour plays a major role in forcing planetary- and regional-scale circulations in the tropics and subtropics in late summer months. In addition, it has been suggested that poleward vapour and energy transport occurs primarily within the tropical-temperate troughs and associated cloud bands. In testing these ideas, a number of insights have been gained in respect of the summer circulation and the dynamics and energy processes of the important rainfall-producing system, the tropical-temperate trough, over the summer rainfall region of South Africa. These insights are summarized as follows:

1) Water vapour content over southern Africa displays a clear annual cycle, which is partially modulated by temperature so that precipitable water reaches a maximum during the summer months. Furthermore, moisture levels over South Africa are also determined by the nature of the moisture advection. Precipitable water and the associated latent heat release show inter-annual as well as intra-annual variability. Wet late summer months are characterized by high values of both precipitable water and latent heat over southern Africa. A southward protrusion of high latent heat indicates poleward transport. In contrast, dry late summer latent heat occurs further to the north and east so that poleward transport occurs over Madagascar. Latent heat values are generally lower over southern Africa during early summer months. This, coupled with the verification (non-verification) of the Eliassen-Palm relationship in early (late) summer, indicates an orographic (thermal) forcing of the upper-tropospheric waves over southern Africa in early (late) summer months. Poleward transfer of latent heat occurs over southern Africa within the tropical-temperate trough system in early, mid and late summer months.

2) Relationships between lower tropospheric circulation patterns over southern Africa and adjacent oceans and moisture content over the interior of South Africa are different between early and late summer months. A trough (ridge) over the western parts of southern Africa at the 700 and 300 hPa pressure levels results in mean wet (dry) early summers. In late summer, however, the development of an anticyclonic (cyclonic) circulation over the Mozambique Channel is of added importance for enhanced (reduced) advection of moisture over southern Africa in wet (dry) months.

3) Tropical-temperate troughs and associated cloud bands generally form in association with a trough linking a subtropical/tropical

depression and/or a westerly trough over the western parts of southern Africa. Cloud bands may also form in conjunction with a subtropical/tropical depression and a baroclinic cut-off low pressure system to the south. Dissipation of cloud bands occur with the eastward or westward displacement of the tropical-temperate trough and/or a ridge of high pressure at 700 hPa such that the link between the tropics and the temperate latitudes no longer occurs, and as such no further energy and momentum exchange can take place.

4) The quasi-stationary nature of precipitable water maxima over the interior of southern Africa indicates that water vapour is primarily introduced to the subcontinent by the mean atmospheric circulation, especially in mid and late summer months. Westerly zonal transport is important in wet early summers, while northerly meridional transport becomes most important during wet late summer months. This indicates the importance of the tropics as a primary moisture source for the interior of South Africa in late summer.

Inter-annual variations in the position and intensity of the poleward water vapour transport across South Africa determines much of the variability of rainfall over the summer rainfall region. The poleward transport from a water vapour convergence region associated with a Walker circulation over the tropics is an important tropical control of late summer South African rainfall. Fluctuations of the position of the ascending limb of the Walker cell associated with the low phase of the Southern Oscillation result in reduced convection and subsequently reduced poleward transport of energy and moisture across southern Africa during dry late summer months. Cloud band conditions in mid and late summer generally conform to a model wherein converged water vapour over tropical and subtropical regions is transported poleward across South Africa by enhanced northerly flow.

5) The importance of the Atlantic Ocean as a water vapour source in early summer, coupled to the relatively high northwesterly eddy transport over southern Africa, is further evidence of a temperate control on the rainfall over the summer rainfall region. Wet late summers, in contrast, are characterized by an important component of circulation transport from a water vapour source over the tropical Indian Ocean. The predominantly easterly transport is indicative of a more tropical control on late summer vapour transport. Sea surface temperature variations and associated variations of the Walker and Hadley circulations must be considered an important control on water vapour divergence and convergence. Anomalously low (high) sea surface temperatures result in increased (reduced) divergence of water vapour from the oceans to the African subcontinent. In late summer the low (high) surface temperatures of the western tropical Indian Ocean may serve to modulate the Walker cell so that wet (dry) months are characterized by descending (ascending) air over the ocean, thereby further enhancing (reducing) the horizontal divergence of water vapour from the oceans.

6) The divergent component of the water vapour transport maintains water vapour over Africa (Hadley and Walker cells) while the non-divergent component generally transports water vapour from the convergent region southward via cloud bands over southern Africa in wet months.

7) Water vapour convergence over subtropical and tropical Africa is not only essential for cloud formation and precipitation, but also decreases atmospheric stability over the region. This in turn enhances convection. The latent heat released by the convective process serves to increase eddy available potential energy which is converted to zonal available potential energy through the thermally indirect circulation found in easterly waves and lows

over southern Africa. The zonal potential energy is then converted to zonal kinetic energy by a thermally forced Hadley circulation. Atmospheric circulation over southern Africa during cloud band occurrences and wet mid and late summer months are associated with the positive energy conversion resulting from thermally direct overturning in the Hadley cell. The poleward transport of energy and relative angular momentum by the Hadley circulation is reflected by the increased westerly flow south of Africa during wet late summer months. Dry mid and late summers, in contrast, are characterized by a reduction in and a northward displacement of the maximum latent heat such that a reduction (increase) occurs in the thermal forcing over southern Africa (Madagascar). Tropical convection may also be initiated or enhanced by the intrusion of upper westerly waves into the tropics.

8) The month of December displays characteristics consistent with the hypothesis that December represents an hiatus when the temperate circulation control of early summer phases into the tropical circulation control of late summer. In general the water vapour transport is characterized by decreased circulation and eddy transport. The relative importance of the non-divergent modes of transport over the divergent modes suggests a breakdown (or weakening) of the Walker and East-West circulations. In addition, December is characterized by a change from thermally indirect energy conversion (i.e. Ferrel cell) to a thermally direct energy conversion (i.e. Hadley cell).

In tying together the above points, a number of general conclusions can be made regarding the circulation over southern Africa. Variations in the position of the early season orographically forced upper tropospheric standing wave off the west coast of southern Africa have far-reaching consequences for early summer rainfall over South African. Above- (below-) average rainfall occurs with the positioning of the leading (trailing) edge of the wave over southern Africa such that ascending (descending) air occurs over the region. Furthermore, water

vapour from the Atlantic Ocean is transported southeastward across southern Africa in conjunction with a surface trough or westerly wave over the eastern Atlantic Ocean. It has been found however, that this temperate control of the water vapour transport does not continue throughout summer. By late summer variations in the tropical Walker circulation play an important role in the modulation of rainfall over the interior of South Africa. Fluctuations in the position of the ascending limb of the Walker circulation, in response to tropical sea surface anomalies, are reflected by movements in the convective regions over tropical Africa and adjacent oceans. Wet (dry) Januaries are characterized by cool (warm) tropical Indian Ocean temperatures and hence descending (ascending) air over the ocean. This results in enhanced (reduced) horizontal water vapour divergence from the Indian Ocean, increasing (decreasing) the water vapour available for convection over tropical Africa. The increase in latent heat release over Africa in wet late summer months forces a stationary thermal wave over southern Africa through the direct conversion from available potential energy to kinetic energy, thereby allowing for the poleward transfer of energy and momentum in cloud bands. Latent heat release reduces atmospheric stability and enhances the convective process. A synthesis of the proposed coupling mechanisms, ocean-atmosphere feedbacks and energy conversions pertinent to tropical-temperate interactions over southern Africa in late summer is presented schematically in Figure 8.1.

Circulation changes throughout the course of the summer illustrate the importance of water vapour transport, convergence and associated thermodynamic processes to the circulation and rainfall of southern Africa. It is now clear that early summer circulation is of temperate origin, whereas the late summer circulation is mainly of tropical origin and initiated by tropical water vapour convergence and the associated diabatic heating. Furthermore, a clear relationship has been found to occur between tropical sea surface temperatures and the hydrodynamics over southern Africa, resulting in a clearer understanding of the role of sea surface temperatures (water vapour source regions) in influencing rainfall over southern Africa. This serves to facilitate a clearer understanding of the dynamics associated with long-range weather predictions based on sea surface temperature anomalies.

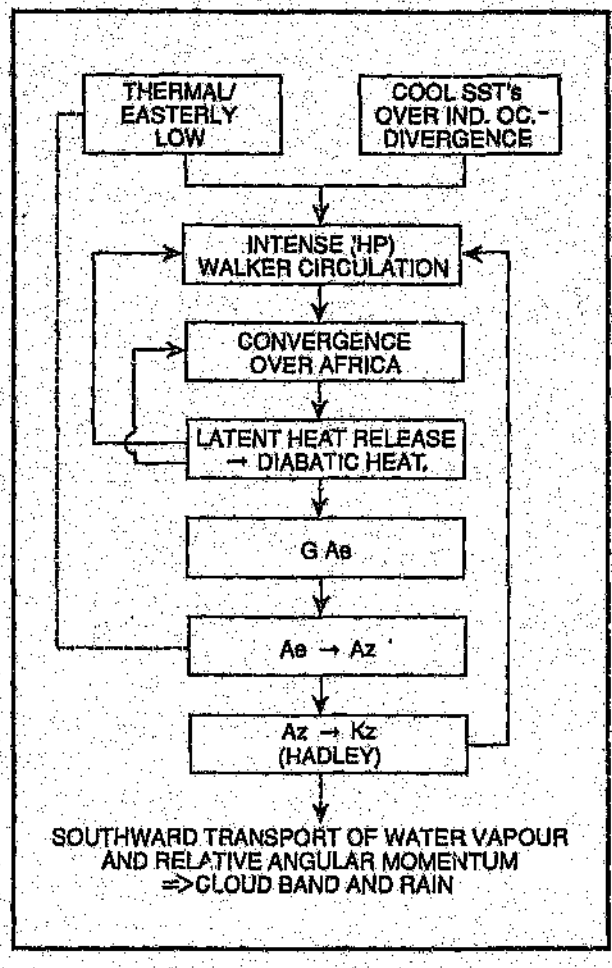

Figure 8.1: Flow chart of tropical-temperate coupling and feed back mechanisms pertinent to late summer rainfall over southern Africa. Abbreviations: SST = sea surface temperature; IND. OC. = Indian Ocean; G Ae = generation of eddy available potential energy; Az = zonal available potential energy; and Kz = zonal kinetic energy.

Since a major proportion of the rainfall over the interior of South Africa falls during late summer, it is imperative to include the effects of water vapour transport, convergence and diabatic heating into future models of the dynamics of the late summer atmospheric circulation over subtropical southern Africa. In this way a better understanding of the circulation and rainfall dynamics over southern Africa can be achieved. This thesis has laid the foundation for an improved understanding of the hydrodynamic and thermodynamic mechanisms driving the southern African summer circulation.

APPENDICES

APPENDIX A

Comparison of specific humidity calculated from dewpoint and from relative humidity

Calculation of specific humidity with dewpoint values has been discussed by McGee (1971). The equation for calculating saturation mixing ratio is:

$$E_s = 6.11 \times 10^{(7.57T/237.3 + T)} \qquad (A.1)$$

Now E = Es(Td), that is mixing ratio equals saturation mixing ratio at dewpoint (Godske *et al.*, 1957; Hess, 1959; McIlveen, 1986), making it possible to calculate mixing ratio by substituting dewpoint (Td) for temperature (T) in equation (A.1). This gives equation (2.1). The use of this method can lead to an underestimation of E of up to 10 per cent increasing to 20 per cent at lower temperatures (Gaffen *et al.*, 1991). Comparisons of specific humidity calculated from dewpoint (equation A.1) and from relative humidity for selected radiosonde stations over South Africa for the 850 to 300 hPa levels reveal less extreme differences. Figure A.1 shows a plot of specific humidity obtained from dewpoint (ordinate) against that obtained from relative humidity (abscissa). The relationship between the two is very strong, with values along the abscissa corresponding closely with values along the ordinate. Differences between the results of the two methods of calculations average at 6 per cent.

The results of the random study over South Africa, coupled with the fact that the study area is mainly in the tropics and subtropics, has resulted in the method being considered suitable for use.

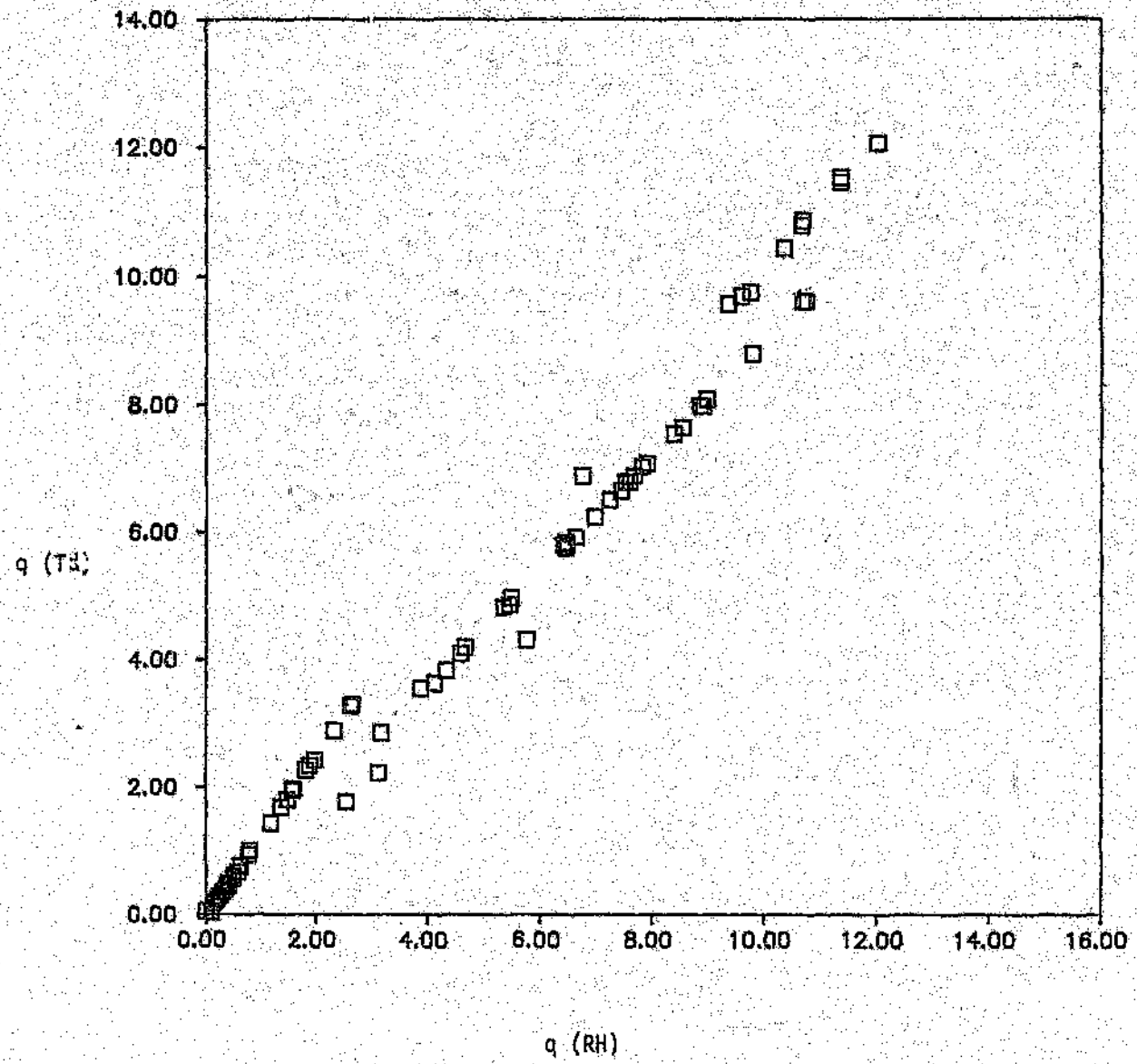

Figure A.1: Comparison of specific humidities calculated from relative humidity and from dewpoint (using Teten's relationship).

APPENDIX B

Theory of divergent and non-divergent derivation and calculation

Calculation of potential and streamfunction were performed on a modified version of the programme developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne, Australia (Allan, pers comm., 1992). A brief derivation, method of calculation as well as the boundary correction will be discussed.

Any vector V may be written in the form:

$$V = Ve + Vr$$

where Ve is the divergent and Vr the non-divergent vector. In cartesian co-ordinates:

$$V = \nabla\chi + k\times\nabla\psi \qquad (B.1)$$

where χ is velocity potential, ψ is streamfuction, k is the unit vector and ∇ the del operator. Therefore:

$$V_\chi = \nabla\chi \qquad (B.2)$$

$$V_\psi = k\times\nabla\psi \qquad (B.3)$$

But

$$\nabla = i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y}$$

Therefore,

$$V_\psi = k\times(i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y})$$

But for cartesian unit vectors i,j,k:

$$k \times i = j \quad k \times j = -i$$

Therefore

$$V_\psi = k\times(i\frac{\partial\psi}{\partial y}+j\frac{\partial\psi}{\partial x})$$

Now V = iu + jv (associative law). Therefore:

$$Ur=(-\frac{\partial\psi}{\partial y})$$

$$Vr=(\frac{\partial\psi}{\partial x})$$

Similarly for the irrotational component:

$$Uir=(-\frac{\partial_\chi}{\partial x})$$

$$Vir=(\frac{\partial\chi}{\partial y})$$

It therefore follows that:

$$\nabla^2\chi=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=\nabla\cdot V \qquad (B.4)$$

$$\nabla^2\psi=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}=k\nabla\times V \qquad (B.5)$$

Where the left hand side of equations (4) and (5) are horizontal divergence and vorticity respectively. (Godske *et al.*, 1957; Hess, 1959; Gordon, 1962; Holton, 1972; Allan, pers comm., 1992). Calculation of χ and ψ are performed using the relaxation method as described in Hess (1959) (Allan, pers comm. 1992).

Inaccuracies resulting from the constraints that the χ and ψ fields are equal to zero along the boundaries are corrected using a method described by Allan (pers comm., 1992). This method entails the relaxation of the finite approximation for the Laplacian of χ, obtain values for the domain, and use it to obtain the ψ boundary values (by step-wise integration), using the equations $Vn=\frac{-\partial\psi}{\partial s}+\frac{\partial\chi}{\partial n}$ and $Vs=\frac{\partial\psi}{\partial n}+\frac{\partial\chi}{\partial s}$. Vn and Vs are the velocity components normal and along the boundary respectively. The problem of evaluating the 4 corner points was overcome by initially leaving them equal to zero, and

evaluating the equations along the boundaries. Adjacent boundary values were then used to calculate the corner points, thereby preventing an arbitrary corner point from being used as an initial starting point.

APPENDIX C

Pressure tendency and cloud bands

In Chapter 4, the geopotential heights have been examined at 700 and 300 hPa, for pre-, to post-cloud band conditions over southern Africa. Evidence suggests that the 700 hPa pressure level plays an important role for precipitation and cloud band modulation over southern Africa. It has therefore become necessary to examine the pressure tendency over the region in order to further characterize the movement and strengthening/weakening of pressure systems and their effects on cloud band formation, movement and dissipation. The pressure tendencies over 24 hours for the period from pre- to post-cloud band conditions have been examined for the early, mid and late summer cloud band case-studies using the following derivative:

$$\frac{d\Phi}{dt} \qquad (C.1)$$

where Φ is geopotential height (gpm) and t is time (24 hours).

The pressure tendency for the 24 hours preceding cloud band formation in the early summer case study reveals increasing pressures at 700 hPa over the southern Mozambique Channel and decreasing pressures over the South Atlantic Ocean (Fig. C.1a). This indicates a strengthening and weakening of the South Indian and South Atlantic anticyclones respectively. The isallobars for the 24 hour period leading to cloud band formation is characterized by continued increasing pressure over the southern Mozambique Channel and decreasing pressure over central southern Africa (Fig. C.1b). This probably reflects the intensification of the anticyclone over eastern southern Africa and an eastward displacement of the trough over the west coast (cf. Figs 4.11a, b). Further evidence of this is the positive isallobars south of southern Africa. The 24 hour period leading to the dissipation of the cloud band is characterized by decreasing pressures over the Mozambique Channel and the Indian Ocean and increasing pressures over continental southern Africa (Fig. C.1c). This represents the

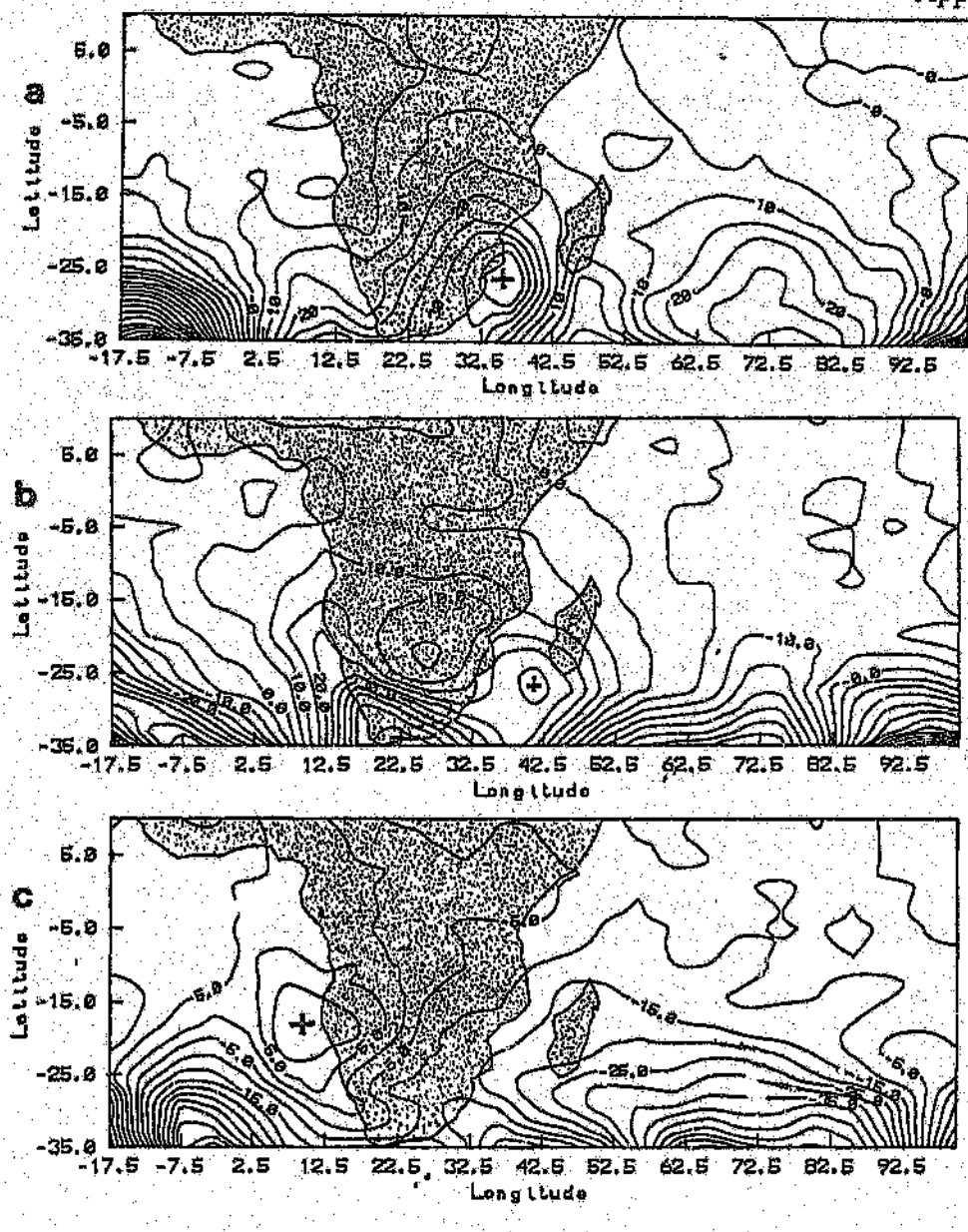

Figure C.1: Isallobars at 700 hPa for a) pre-cloud band (14-15 October 1986), b) cloud band (15-16 October 1986) and c) Post-cloud band (16-17 October 1986) case study for early summer.

westward displacement of the ridge of the South Atlantic Anticyclone over southern Africa (cf. Fig. 4.11c).

Pressure tendencies during mid summer (December) case studies are similar. The isallobars for the 24 hour period leading to pre-cloud band conditions are

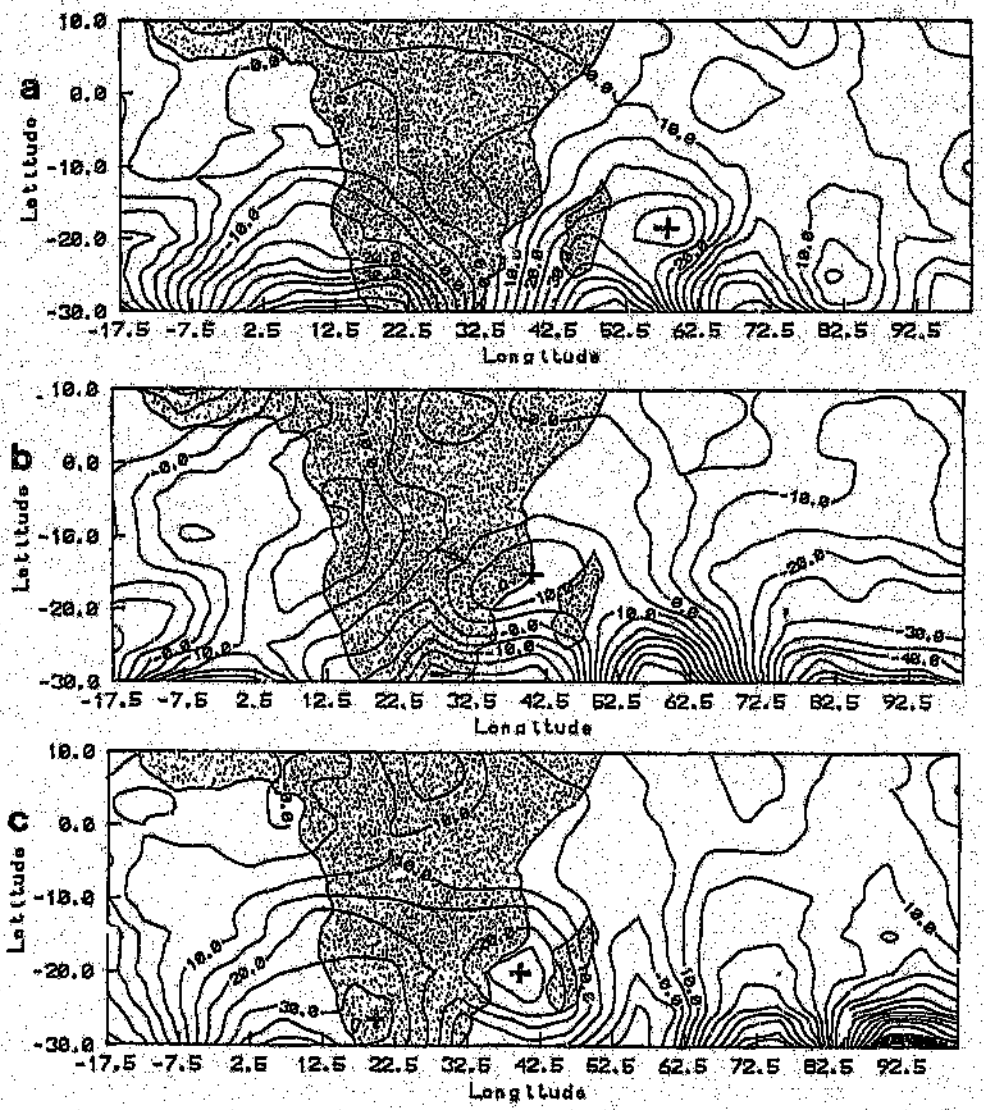

Figure C.2: Isallobars at 700 hPa for a) pre-cloud band (4-5 December 1982), b) cloud band (5-6 December 1982) and c) post-cloud band (6-7 December 1982) case study for mid summer.

characterized in both cases by decreasing pressures over the western parts of southern Africa/eastern Atlantic Ocean (Figs. C.2a, C.3a). This implies a trough/depression over those regions in the period leading to cloud band formation (cf. Figs. 4.12a, 4.13a). The 24 hour period leading to cloud band formation is characterized by continued decreasing pressures over the southern

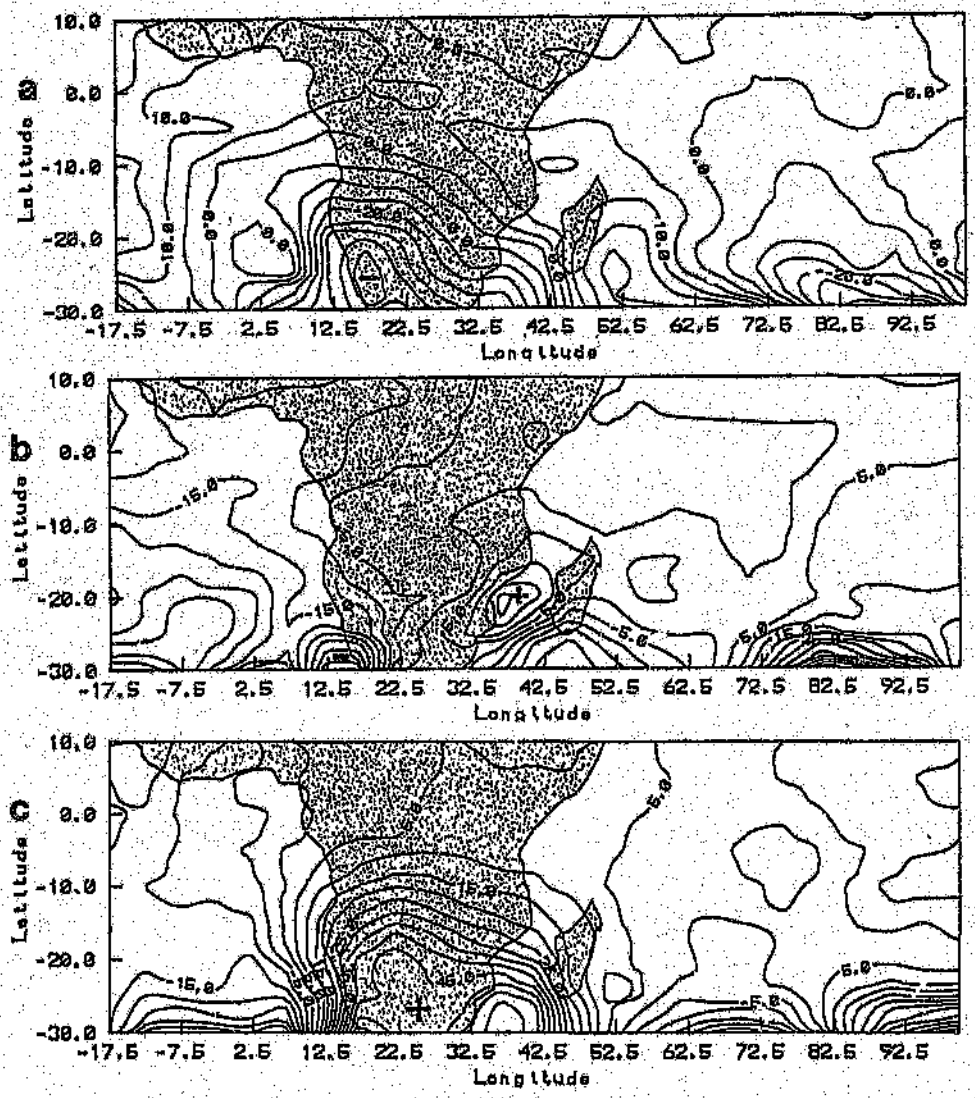

Figure C.3: Isallobars at 700 hPa for a) pre-cloud band (1-2 December 1985), b) cloud band (2-3 December 1985) and c) post-cloud band (4-5 December 1985) case study for mid summer.

Africa, with a secondary region of increased pressures over the Mozambique Channel (Figs C.2b, C.3b). This is reflected in the synoptic pattern for cloud band case studies, where a trough/depression occurs over the western parts of southern Africa and a ridge over the Mozambique Channel (cf. Figs. 4.12b, 4.13b). The isallobars for the dissipative stages of the cloud bands reveal, as in

late summer, increased pressures over southern Africa (Figs C.2c, C.3c). These isallobars indicate a westward ridging of the South Indian Anticyclone over southern Africa (cf. Figs 4.12a-c, 4.13a-c) resulting in the dissipation of the cloud bands.

The most notable aspect of the pressure tendencies for the 24 hour period leading to pre-cloud band formation in the late summer case studies is the decrease in the 700 hPa pressure level over the western parts of southern Africa for both case studies (January 1980 and 1981) (Figs C.4a, C.5a). This confirms the earlier findings (Chapter 4) that a trough/depression occurs over the western parts of southern Africa before cloud band formation. The isallobars for the 24 hour period leading to cloud band formation are similar. Decreasing pressures over southern Africa continue and pressures over the southwest Indian Ocean/Mozambique Channel increase (Figs C.4b, C.5b). This conforms with the findings that 700 hPa pressures over the Mozambique Channel are significantly positively correlated with precipitable water over southern Africa (Fig. 4.3). The isallobars for the 24 hours leading to the dissipation of the cloud band are again similar for both case studies. Pressure tendencies over southern Africa are positive, indicating increased 700 hPa pressures over the region (Figs C.4c, C.5d). The increased pressures are the result of the eastward ridging of the South Atlantic Anticyclone (January 1980) (Fig. 4.14c) or the westward ridging of the South Indian Anticyclone (January 1981) (Fig. 4.15d). Evidence therefore suggests that the dissipation of cloud bands occurs when the South Indian or Atlantic Anticyclones ridge across southern Africa, thereby resulting in a discontinuation of the tropical northerly airflow across southern Africa.

In summary, pressure tendencies generally show a decrease in pressure at 700 hPa over southern Africa and the eastern Atlantic Ocean before and during cloud band formation. This results in a poleward transfer of tropical air across southern Africa, a situation favourable for cloud band formation. In contrast, dissipation is characterized by increasing pressure over southern Africa, indicating westward expansion of the South Indian Anticyclone or eastward expansion of the South Atlantic Anticyclone (or displacement of the trough), thereby resulting in a discontinuation of the tropical airflow over the region.

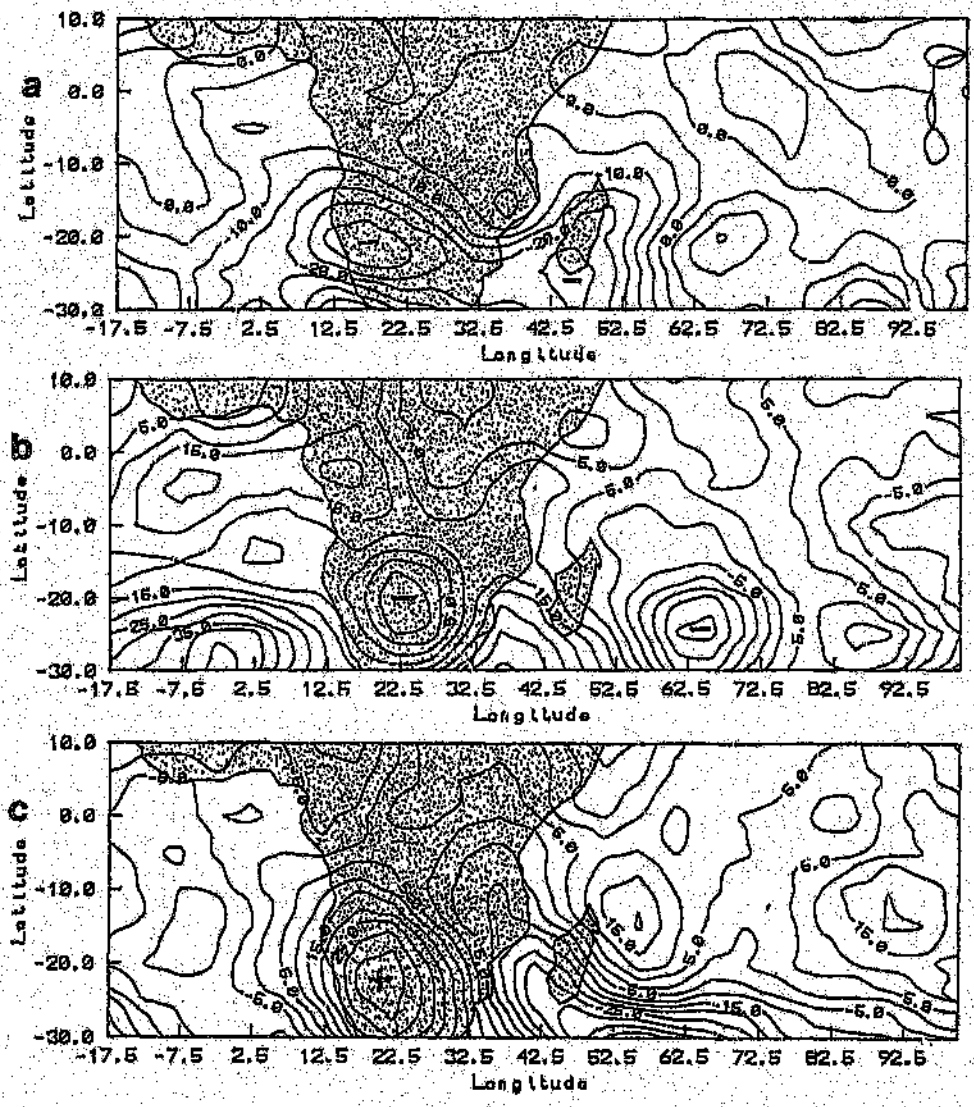

Figure C.4: Isallobars at 700 hPa for a) pre-cloud band (5-6 January 1980), b) cloud band (6-7 January 1980) and c) post-cloud band (7-8 January 1980) case study for late summer.

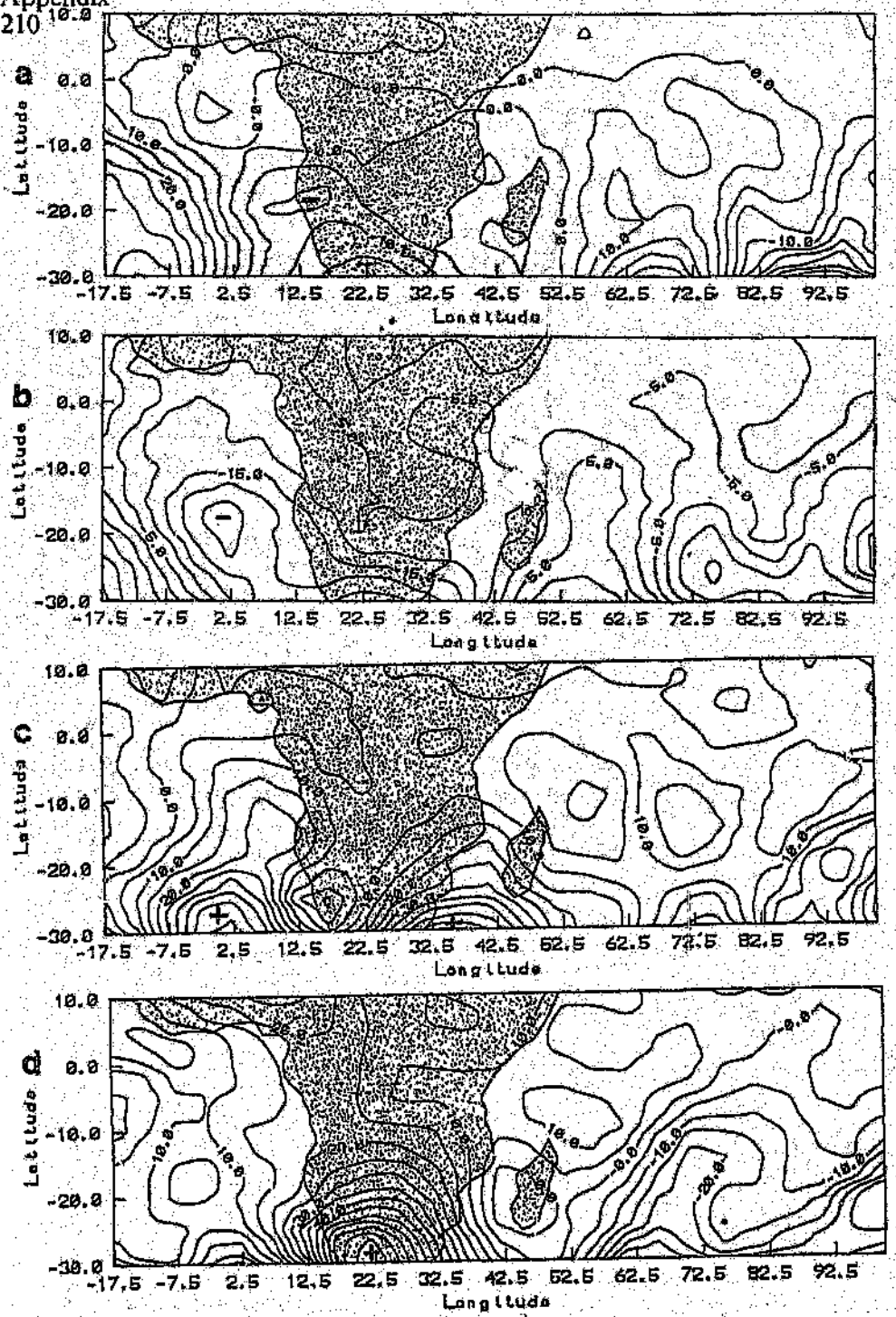

Figure C.5: Isallobars at 700 hPa for a) pre-cloud band (21-22 January 1981), b) cloud band (22-23 January 1981), c) cloud band (25-26 January 1981) and d) post-cloud band (26-27 January 1981) case study for late summer.

APPENDIX D

Vertical distribution of the divergent circulation

A section of velocity potential at 10°S has been conducted across southern Africa for a wet and a dry early and late summer month according to the method described by Chen *et al.* (1989). A wet (1988) and a dry early summer (1980) has been examined (Fig. D.1). The wet October is characterized by an increased and westward shift of the divergence at 700 hPa to the eastern Atlantic Ocean (as opposed to Africa) (Fig. D.1b). The dry early summer, in contrast, is characterized by reduced divergence over Africa at 700 hPa and a region of convergence over the Indian Ocean (55°E) at 700 hPa (Fig. D.1a). Apart from this marginal shift of the 700 hPa divergence, little significant difference is apparent between the two years, suggesting little tropical influence on the early summer rainfall over South Africa. The wet and dry late summers (January) display significant differences. Figure D.2a depicts a section taken during a mean wet January and indicates convergence (divergence) over Africa at 850 hPa (500 hPa) and divergence (convergence) over the tropical Atlantic and Indian Oceans. Evidence suggests the existence of a Walker Circulation with an ascending limb over Africa and descending limbs over the tropical Indian and Atlantic Oceans, with easterly flow across the east coast of Africa and a weaker westerly flow across the west coast of Africa into the convective region associated with the ascending arm of the Walker Cell (Fig. D.2a). Convection extends to approximately 500 hPa over Africa. The divergence at 500 hPa indicates transport at that level in a sense out of the page. That is southward (poleward) transport across Africa (Fig. D.2). The pattern of the Walker Cell over Africa and adjacent oceans generally conform with earlier findings. Increased easterly flow into tropical Africa during mean wet summers (Harrison, 1986a; Lindesay, 1988a) are reflected by the low-level easterly flow of the Walker Cell over Africa. The present study does however, indicate that the structure of the Walker Cell over Africa is different to that originally hypothesized (Harrison, 1986a; Lindesay, 1988a; Peixoto and Oort, 1992) (cf. Fig. 1.6). According to Harrison (1986a), the distance between the descending limb (Atlantic), the ascending limb (Africa), and the descending limb (Indian) are 30° and 15° respectively. In the

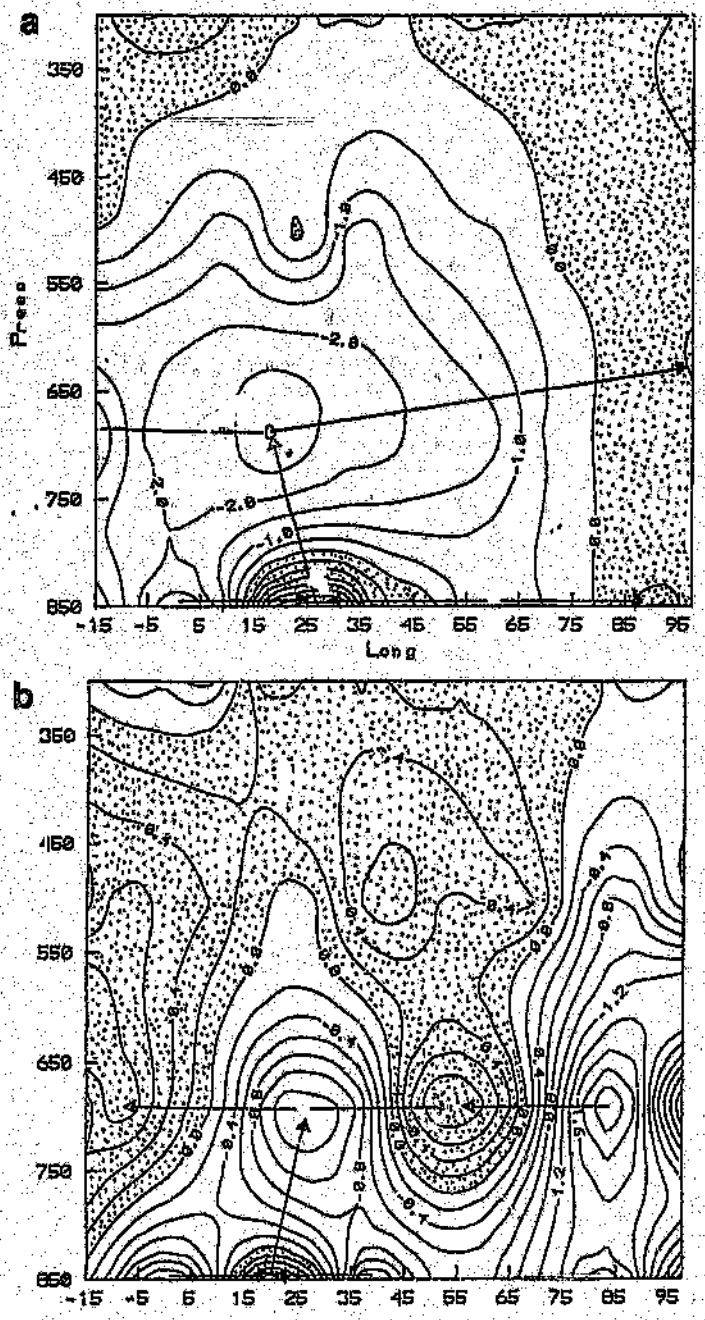

Figure D.1: Vertical cross section of divergent circulation along 10°S for: a) a mean wet, and b) a mean dry October. Units in 10^6 $m^2.s^{-2}$. Arrows depict idealized motion and stippling indicates convergence.

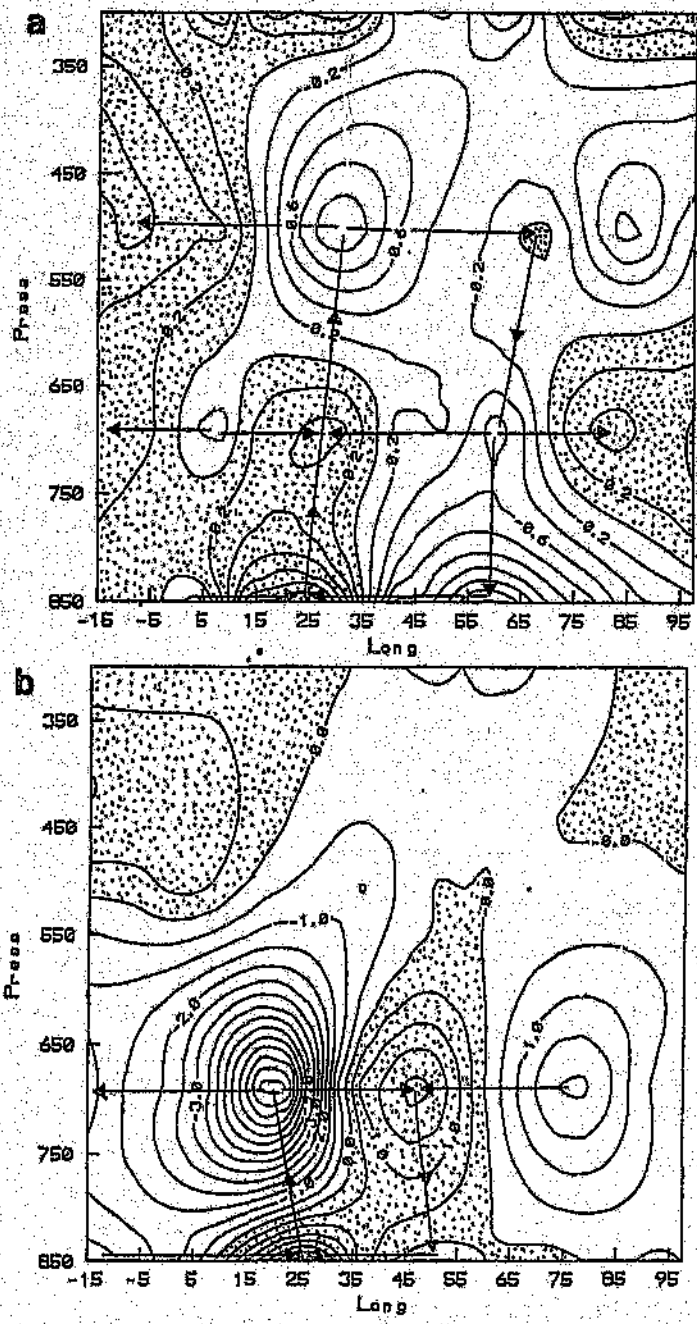

Figure D.2: Vertical cross section of divergent circulation along 10°S for: a) a mean wet, and b) a mean dry January. Units in 10^6 $m^2.s^{-2}$. Arrows depict idealized motion and stippling indicates convergence.

present study distances of 25° and 35° respectively (Fig. D.2a) indicates more equally-sized cells than originally hypothesized.

The mean dry January (1983) displays a number of differences from the wet January. Although the convergent and divergent centres are in similar position to those during the mean wet January (Fig. D.2b), the low-level divergence over the western Indian Ocean is however, considerably reduced (Fig. D.2b). The region of divergence above the surface convergence over Africa occurs at a lower level (700 hPa as opposed to 500 hPa) and occurs 10° further west than in the mean wet January (cf. Figs D.2a, b, 4.9b, 5.13e, f). Subsequently, convection over Africa only occurs in a shallow layer between 850 and 700 hPa, with subsiding air above 700 hPa. The divergence at 700 hPa conforms with the anticyclone predominating across southern Africa at that level during mean dry Januaries (Figs 4.9b, 6.3c, d).

The upper level divergence fields (300 to 500 hPa level) for the wet and dry January suggest that an eastward shift of the Atlantic wave (see Harrison, 1986a) occurs during the dry January such that the trailing arm of the wave overlies much of southern Africa and the leading arm overlies Madagascar/western Indian Ocean (Fig. D.2b). The wet January in contrast, is characterized by the leading arm of the Atlantic wave (divergence) overlying southern Africa (Fig. D.2a). This eastward shift of the Atlantic wave during the dry January conforms with previous findings that the Atlantic wave shifts eastward during dry years such that the leading arm (and cloud band) overlies Madagascar (Harrison, 1986a; Tyson, 1986) (Fig. D.3). Little differences are apparent between a wet and a dry early and mid summer month. This suggests that the tropical Walker cell is of lesser importance during that part of the summer season.

In summary, a wet January is characterized by a Walker circulation over Africa with the ascending limb of the cell over tropical Africa and descending air over the western tropical Indian Ocean. Convection over Africa is deep, extending up to 500 hPa. Although the Walker cell is present in the dry January, the ascending limb over Africa is relatively shallow (700 hPa). This results in less convection and diabatic heating to drive the circulation over southern Africa. The relatively small inter-annual variability displayed at 10°S in October corroborates

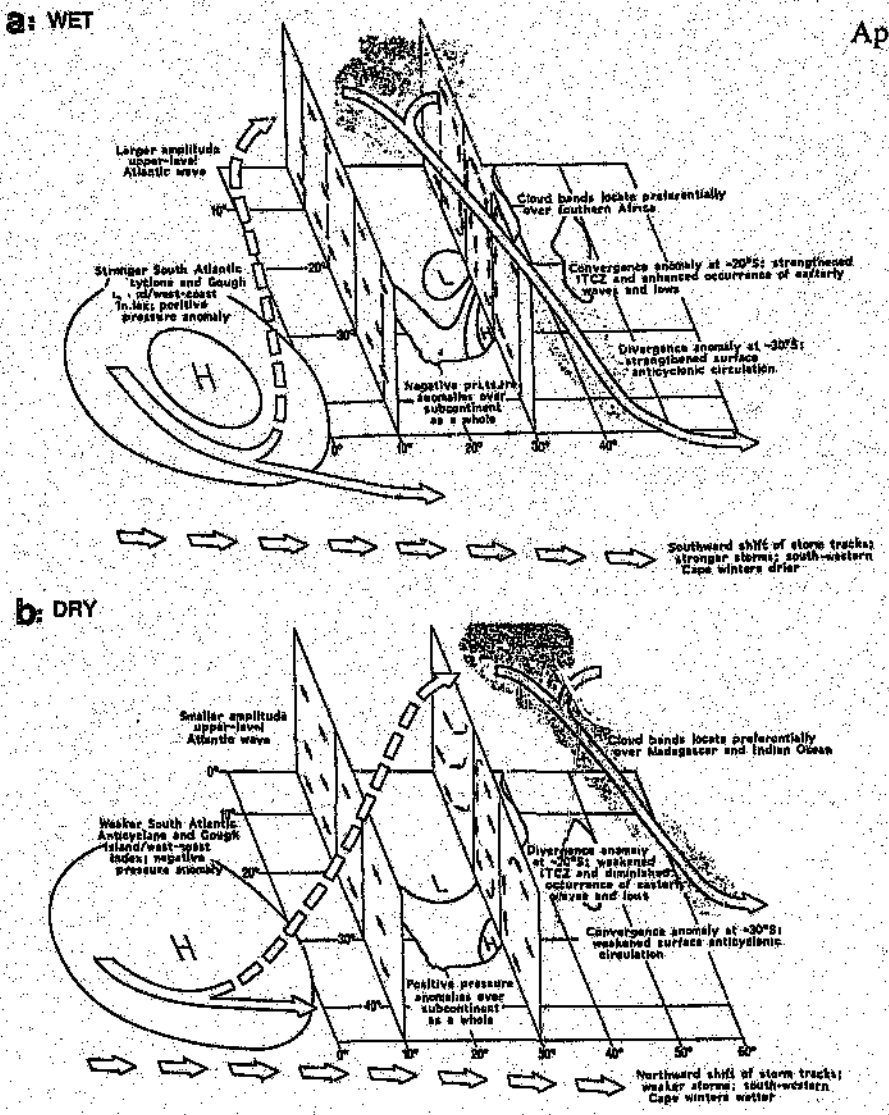

Figure D.. A schematic of the position of the upper tropospheric Atlantic wave and cloud bands for a) wet years and b) dry years (after Tyson, 1986).

earlier findings that early summer rainfall is due to mid-latitudinal, and not tropical forcing.

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