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A synoptic climatology of South African rainfall variations

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APPENDIX G

STANDING WAVES OF THE SOUTHERN HEMISPHERE

The properties of the standing waves of the Southern Hemisphere, the mechanisms forcing the waves and associations between waves and the cloud bands are discussed in the following. Orographic controls play major roles in the forcing of the standing waves of the Northern Hemisphere (Trenberth, 1983) but the comparatively small area of the Southern Hemisphere covered by land inhibits similar forcing of the southern waves. Modelling studies have, however, suggested that the middle and high latitude waves may be excited by the Antarctic continent (Mechoso, 1981). Standing waves in the Southern Hemisphere subtropics are instead forced primarily by heat release in the tropics (Paegle *et al.*, 1983; Kalnay and Paegle, 1983; Nobre, 1983). Three cardinal areas of tropical heat release are present (darkest areas in Figure 7-2 - see also Figure 8 of Barton, 1983) during the austral summer months. Standing waves in the Southern Hemisphere tend to be of uniform phase through the troposphere (van Loon and Jenne, 1972; van Loon *et al.*, 1973) and the accompanying meridional winds are thus of consistent direction at all levels. Poleward flow develops to the south of the regions of tropical heating when standing waves are excited (Paegle *et al.*, 1983). Mean winds at all levels throughout the summer months at Bloemfontein are poleward when a tropical-temperate trough with its associated cloud band overlies the station (Harangozo, 1986), a result that supports the inference that the cloud bands mark standing waves across southern Africa initiated through heat release over tropical Africa.

Spectral analysis of 500 mb data obtained during the International Geophysical Year reveals that the polewerd flux of angular momentum in the Southern Hemisphere is contributed by the shorter, moving waves rather than the longer, quasi-standing waves, and that the latter tend to carry momentum equatorward (Kao *et al.*, 1971). Transient fluxes at Bloemfontein are associated with poleward transport on tilted troughs with

rainfall on the leading edges (see Chapter 5). Toroidal fluxes are directed in opposing directions according to the presence or absence of a rain-bearing system over the western Orange Free State (Figs. 5-7 and 5-8). Fluxes on no rain days are equatorward suggesting, following Kao *et al.* (1971), that these fluxes may be associated with the Atlantic standing wave (see Chapter 6). During the period May 1972 to January 1978 there were semi-annual cycles in the locations of both standing waves 1 and 3 at 500 mb and 20°S such that the waves lay further west during the high seasons (Figures 2 and 4 of Tranberth, 1980b). The ridge of wave 1 lay over the Greenwich Meridian in April and in September to November, at 60°W in mid-winter and between 0° and 60°W in midsummer, movements which correspond with the displacements of the South Atlantic Anticyclone according to McGee and Hastenrath (1966) and of the semi-permanent cloud band through the year (Fig. 4-7). Similar vacillations of the Atlantic ridge of wave 3 to those of wave 1 were also present. It is plausible therefore that the Atlantic bands mark standing waves over the oceans.

The most frequent number of cloud bands in all locations across the Southern Hemisphere on any particular day is either three or four, with these numbers predominating in the summer and winter seasons respectively (Streten, 1973). The apparent association between the locations of the bands and of the major westerly troughs suggested to Streten (1973) a link to the wave 4 patterns at 700 and 500 mb deduced by Staver (1969) and Noar (1973) respectively. Spectral analysis of satellite brightness for three periods of 1969, in which the regions of highest brightness were collocated with the cloud bands of the hemisphere, established the importance of the long waves at subtropical latitudes north of 45°S (Yasunari, 1977). Waves 1, 2 and 4 were dominant in most seasons and latitudes (Fig. G-1), with maxima in the brightness on waves 2 and 4 corresponding closely with the locations of the bands across South Africa (Fig. G-2 - cf. Fig. 2-3). Wave 3 is related to the Atlantic rather than to the African band in Figure G-2 and has been associated with both the mid-oceanic troughs of the Southern Hemisphere and the regions of convection over the three tropical continents during the austral summer (Krishnamurti *et al.*, 1973). Thus the apparent dominance of band number 3 detected by Streten (1973) during the summer months is

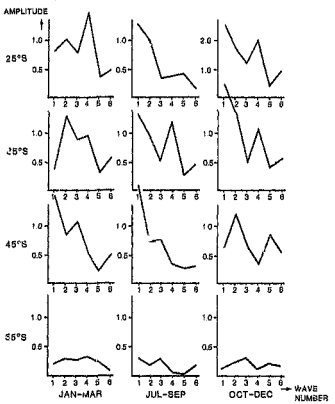


Figure G-1. Amplitudes (digital values of average brightness) of waves 1 to 6 of satellite brightness variations at four latitudes for three periods of 1969 after Yasunari (1977). Note change in ordinate scale for October to December at 25°S.

probably related both to wave 3 and to the distribution of the tropical continents and the associated heat sources. Equivalent results were obtained during an analysis of satellite brightness data for February 1971 (Krueger and Winston, 1974). Waves 1, 3 and 4 were dominant in the brightness spectra at 20°S but at the Equator waves 1, 2 and 4 rather than 3 predominated, a result attributed to the non-uniform distribution of the continents around the globe. Similarly the cloud bands are not distributed uniformly in longitude and spectral analyses of brightness fields may accordingly emphasise wave 4 as opposed to wave 3, a consideration that probably resolves the apparent discrepancies between the

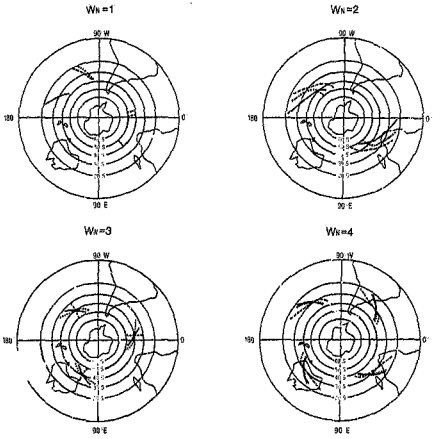


Figure C-2. Locations of regions of maximum satellite brightness associated with waves 1 to 4 for three periods of 1969 after Yasunari (1977). Locations marked by solid lines are for January to March, by dashed lines for July to September and by dotted lines for October to December.

various analyses. It may be concluded that the evidence is consistent with the contention that the cloud bands mark standing waves forced by heat release over the tropical continents

APPENDIX H

THE RAINFALL HIATUS AND THE RAINFALL INTERCLUSION

THE RAINFALL HIATUS

Two important aspects of the annual rainfall cycle over the central interior of South Africa will be considered in the following. These are the rainfall hiatus in December and the reduced early season rainfall over the western areas. The hiatus results from a relative decline in the frequency of tropical-temperate troughs (Fig. 3-4) despite the southerly location of the Inter-Tropical Convergence Zone across Africa in December. Only the transient flux on rain days markedly reflects a possible circulation adjustment over the central interior of South Africa related to the hiatus. In most months this flux is poleward but in December (in addition to in August) the flux is weakly equatorward (Fig. 5-9). Concurrently there is an opposing maximum in the flux on no rain days. Although the contributions from most types of systems to the total rain flux decrease in December in comparison to in November the greatest reduction is that for the truncated troughs for which the flux becomes equatorward. Mean December zonal winds at 200 mb for the truncated troughs are rather stronger than for any other system while the corresponding meridional winds are equatorward as low as 600 mb - a much lower level than in any other month (Harangozo, 1986). Differences in the transient flux result from changes in the correlation between the zonal and meridional components caused by changes in the amplitudes and wavelengths of the westerly waves. It appears that these changes affect the truncated troughs to a greater extent than the remaining systems. A dip in the rain earth angular momentum flux caused primarily by a decrease in the contribution from the truncated troughs also occurs in December (Fig. 5-7).

Evidence for a major change in the Southern Hemisphere 200 mb circulation in December 1971 was obtained from the EOLE data. A rapid adjustment from the circulation of the winter to that of the summer occurred (Morel and Desbois, 1974; Webster and Curtin, 1974). Both longitudinal-mean zonal and meridional winds at 30°S reflected the adjustment in which zonal winds reached a minimum in December. Weak December minima in the 200 mb zonal components are present at the coastal stations of Cape Town and Port Elizabeth (Katsiambirtas, 1979) prior to the major minima in April suggesting that the adjustment in the zonal flow in December is a common occurrence. Any possible association between the circulation change in December and the rainfall hiatus remains to be examined. It is interesting to speculate that the hiatus may represent a period of change-over between the circulations of the vernal transitional and the summer seasons and may therefore be linked to circulation changes on the semi-annual cycle. In the later part of the rainfall season the circulations over tropical Africa and over the Indonesian region are directly linked through the Indian Ocean Walker Circulation (see Chapter 10). Convection in the winter monsoon region typically does not form until late December or early January and the onset of convection is associated with a distinct circulation change in the Australian region (McBride, 1983). It may be speculated that circulation variations causing the rainfall hiatus are related to those in the Indonesian region prior to the onset of the winter monsoon through the zonal circulation across the tropical Indian Ocean.

THE RAINFALL INTERCLUSION

At present the causes of the reduced early season rainfall over the western as compared to over the eastern regions are unknown. Rainfall systems are blocked from affecting the western regions (see Chapter 3) and so the phenomenon may be referred to as the rainfall interclusion. On present evidence the interclusion may not be related directly to either the tropical or temperate circulations as all systems are affected uniformly (see Chapter 3). During the latter part of the season the low-level at-

mospheric circulation changes in a manner consistent with the observed rainfall patterns. The trough and heat low over the central interior of the country, which are well established in the mean low-level circulation of the high summer months (Taljaard, 1981b), dissipate. As a result the flux of moist tropical air across the western interior of the country is strengthened (Taljaard, 1982b). The observation does not explain the phenomenon, however, as cloud-free conditions are a necessary prerequisite for rather than an antecedent of heat low formation. A possible explanation is that the standing wave across southern Africa lies anomalously eastward in the early part and westward in the later part of the rainfall season (see Appendix E). These longitudinal displacements of the wave, which are related to circulation changes on the semi-annual cycle, offer a possible basis for an explanation of the interclusion.

APPENDIX I

VERTICAL VELOCITIES AND FLUXES

Vertical motions may not be directly estimated from the Bloemfontein radiosonde data but it is proposed in the following that there may be semi-annual cycles in both the mean vertical motion and in the vertical transient momentum flux over the central interior of South Africa. In the barotropic and tropospheric jet-stream zones correlations of both temperatures and meridional components with rainfall on the semi-annual cycle are of similar phase (Figs. 8-1b and 8-3b), a relationship that holds in individual years (Fig. 8-4). Temperature changes are therefore caused by changes in advection resulting from differences in the meridional circulation. In the stratospheric jet-stream zone correlations with rainfall of the meridional component on the semi-annual cycle are of similar phase as in the barotropic zone but the phase for correlations with temperature reverses. Temperature changes are therefore not related to advection. Colder stratospheric temperatur accompany the stronger tropospheric ascent of the wetter periods both in the rainfall season on the annual cycle and in the summer on the semi-annual cycle, a result that suggests that the mechanism connecting temperatures on either side of the tropopause may be that proposed by Reed and Vlcek (1969). Thus the wetter transitional seasons the anomalous vertical motion in the troposphere may be downward in association with the colder stratospheric temperatures. Vertical motions may therefore be modulated on a semi-annual cycle with anomalous ascent in the high seasons. Accordingly the vertical flux of momentum by the mean circulation is also modulated on a semi-annual cycle.

Increased surface easterly components are present in wetter months through the year (Table 8-6). On the assumption that the results for Bloemfontein may be extrapolated across the subcontinent then there is increased generation of westerly momentum through surface stresses in the wetter months. Additional lifting of momentum by the mean flow may

occur in the high but not in the transitional seasons on the semi-annual cycle. Thus the anomalous flux through the transients must be upward in the transitional seasons when that provided by the mean flow is downward. As a result of the anomalous upward flux by the mean flow in the wetter high seasons the requirement for increased vertical transport by the transients would then be reduced. Hence it may be speculated that there is a semi-annual cycle in the vertical transient term of Equation 6-1 anti-phase to that of the mean vertical term. Supporting evidence for this supposition is provided by the observations that the highest incidence of hail, an indicator of strong updraughts inside storms, in the southern Transvaal is in the vernal transitional season (Schulze, 1965; Carte and Held, 1978) whereas stratiform rain decks associated with general weak ascent of the air occur most frequently over the eastern Orange Free State in the summer months (Shaw, 1979).

APPENDIX J

RELATIONSHIPS BETWEEN RAINFALL AND CIRCULATION CHANGES ON RAIN AND NO RAIN DAYS

Analyses of frequency adjustments of major circulation types have often been used as the bases of investigations of climatic change over various regions of the World (e.g. Rex, 1950; Tsuchiya, 1963, 1964; Lamb, 1965, 1969; Dzerdzeevski, 1969; Murray and Benwell, 1970; Perry, 1970b) including southern Africa. Implicit assumptions in all previous studies of circulation adjustments following rainfall variations over southern Africa (e.g. Rubin, 1956; Triegaardt and Kits, 1963; Hofmeyr and Gouws, 1964; Tyson, 1984) have been that the mean structures of the atmosphere on rain and on no rain days remain constant independent of the total rainfall and that the observed patterns consequently result from frequency changes of the two types of days only. Confirmation that the frequency of rain days provides a useful first approximation to the total rainfall has been supplied by Harrison (1983b) but it was also demonstrated in this study that daily rainfall tends to increase with the annual and monthly totals. Thus the mean circulations on rain days may vary between years. Circulation modifications within particular classes of synoptic types do occur (Barry and Perry, 1969, 1970) and account for comparable proportions of the surface temperature variations to those associated with the frequency vacillations of the same classes *per se* both over the United Kingdom (Perry and Barry, 1973) and across the western United States (Barry *et al.*, 1981). Tests for the constancy of the kinematic structures and associated momentum fluxes in all months of the rain and no rain days over the western Orange Free State are presented below. Rather than seeking magnitudes of the contributions of intra-type changes to the integral variations these tests, as for the equivalent tests on the integral circulation in Chapters 8 and 10, investigate any systematic adjustments related to the rainfall variations that may be present. Mean values of the wind components have been calculated by month for the rain and the no rain days and the components of the momentum flux

*Table J-1. Values of Spearman rank correlation coefficients between rainfall and the vertically-integrated relative angular momentum of the atmosphere ($J\bar{u}$), the vertically-integrated flux of earth angular momentum ($J\bar{v}$) and the vertically-integrated circulation ($J\bar{v}\bar{u}$), transient ($J\overline{v'u'}$) and total ($J\overline{vu}$) relative angular momentum fluxes on rain days by month. Negative correlations, indicating decreased relative angular momentum or poleward fluxes in wetter months, are stippled. Asterisks indicate significance levels: * - better than 10 per cent; ** - better than 5 per cent; *** - better than 1 per cent.*

MONTHS	$J\bar{u}$	$J\bar{v}$	$J\bar{v}\bar{u}$	$J\overline{v'u'}$	$J\overline{vu}$
J	0.29	0.14	0.0[illegible]	0.29	[illegible]
A	0.54	0.43	0.43	0.[illegible]1	0.50
S	[illegible]	0.[illegible]3	0.[illegible]80	[illegible]	0.18
O	[illegible]	[illegible]	[illegible]	0.05	[illegible]2
N	[illegible]	0.01	0.03	0.07	0.08
D	0.09	0.12	[illegible]	[illegible]	0.08
J	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F	[illegible]	0.[illegible]5	0.56	0.38	0.[illegible]8
M	[illegible]	0.25	0.25	0.19	0.16
A	0.37	[illegible]	[illegible]	0.14	[illegible]
M	[illegible]	0.49	0.58	0.01	0.33
J	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

estimated from these means and the associated transients. Spearman correlations were subsequently calculated between both the wind and the momentum flux components with the monthly rainfall totals.

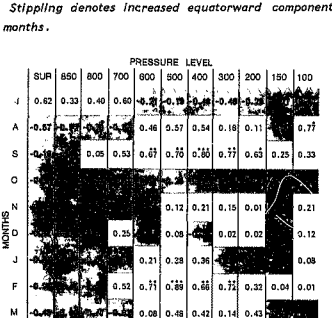
Zonal components on rain days are indirectly related to the rainfall at most levels in the atmosphere except in April and August and in the barotropic zone in December. Accordingly in all months apart from April,

Table J-2. As Table J-1 but on no rain days.

MONTHS	$\int \Omega$	$\int v$	$\int v\Omega$	$\int \overline{v}\,\overline{\Omega}$	$\int v\Omega$
J	0.53	-0.28	-0.33	-0.14	-0.10
A	0.22	0.12	0.23	-0.[illegible]	0.38
S	0.14	-0.[illegible]	-0.[illegible]	0.07	-0.19
O	-0.[illegible]	-0.16	-0.02	-0.[illegible]	0.04
N	0.03	-0.72	-0.[illegible]	0.30	-0.[illegible]
D	0.42	0.47	0.49	-0.[illegible]	0.42
J	-0.[illegible]	0.42	0.60	-0.[illegible]	0.22
F	-0.38	-0.[illegible]	0.43	0.31	0.43
M	-0.12	0.16	0.32	-0.[illegible]	0.07
A	0.18	0.08	0.10	-0.[illegible]	0.04
M	-0.38	-0.[illegible]	-0.[illegible]	-0.[illegible]	-0.[illegible]
J	0.21	-0.[illegible]	-0.[illegible]	-0.[illegible]	-0.[illegible]

July, August and December the relative angular momentum of the atmosphere on rain days decreases as the rainfall increases (Table J-1). Negative correlations between rainfall and zonal components on no rain days occur in all months except June, October, November and December in the boundary zone and in all [illegible]nths except April, June, July, August, September, November and December in the barotropic zone. Signs and magnitudes of the relative angular momentum correlations on no rain days are comparable to those of the rain days in most months (Table J-2). Signs of both sets of correlations are similar to those with the integral circulation (Table 8-6). Only 20° (20 days) separates the phase angles of the three first harmonics and associated explained variances are similar for all distributions of the relative angular momentum correlations on rain, no rain and all days (Table 10-2). [illegible]similarity of the results for all three sets of correlations ir[illegible] parallel systematic adjustments of the zonal circulation with va[illegible]fall affect both the rain and the no rain days independently.

Table J-3. As Table J-1 but for meridional wind speeds on rain days. Stippling denotes increased equatorward components in wetter months.



Systematic adjustments to the meridional circulations of the rain and the no rain days as rainfall varies are not necessarily of the same sense in all months. The poleward component in the boundary zone declines in ten months on rain days as the rainfall increases (Table J-3). In several months, including April, June, July and October, positive correlations in the barotropic and jet-stream zones indicate that the Hadley Circulation weakens (or that the Ferrel Circulation intensifies) in the wetter months. Alternatively in February, March, May, August and September the Hadley Circulation strengthens in the wetter months. The sense of the adjustments in the three months November to January is not immediately apparent. In four months the earth angular momentum flux on rain days is indirectly related to the rainfall (Table J-1).

Table J-4. As Table J-1 but on no rain days.

MONTHS	PRESSURE LEVEL 850	800	700	600	500	400	300	200	150	100
J	-0.38	-0.33	-0.30	-0.58*	-0.45	0.03	-0.26	-0.10	-0.17	-0.12	-0.37
A	0.45	0.11	0.07	0.19	0.25	0.35	0.37	0.33	0.24	0.43	0.38
S	0.13	0.30	0.05	0.04	0.09	-0.15	-0.27	-0.27	-0.35	-0.22	0.58*
O	-0.30	-0.04	-0.21	-0.44	-0.21	-0.12	-0.18	0.00	0.30	-0.13	-0.20
N	-0.50	-0.35	-0.50	-0.65*	-0.60	-0.73**	-0.82***	-0.65*	-0.75**	-0.66*	-0.63*
D	0.19	0.20	0.07	0.02	0.10	-0.08	0.39	0.55*	0.75**	0.64*	-0.19
J	0.33	0.08	0.13	-0.17	-0.55*	0.22	0.57*	0.45	0.23	-0.05	-0.67*
F	-0.29	-0.62*	-0.67*	-0.29	-0.33	-0.17	0.02	-0.19	0.60*	0.33	0.12
M	-0.07	0.03	-0.04	0.01	-0.26	-0.09	0.27	0.14	0.36	0.25	0.67**
A	0.33	-0.16	-0.16		15	0.07	0.10	0.03	0.09	0.14	0.33
M	0.05	-0.36			0.59*	-0.70**	-0.57*	-0.84***	-0.75**	-0.66*	-0.71**
J	0.01	0.12	-0.09	-0.12	-0.15	-0.25	-0.38	-0.37	-0.21	-0.38	-0.20

Signs of the correlations with rainfall of the boundary zone meridional component on *no rain days varies through* the year (Table J-4). Above the boundary zone the Hadley Circulation intensifies in the wetter months of January, March, April, August and December. Direct associations between the earth angular momentum flux and rainfall on *no rain days* occurs in January, March, April, August and December (Table J-2). Similar distributions of the coefficients to those for the earth angular momentum flux correlations are also present for the circulation and total flux correlations for both the rain and the no rain days (Tables J-1 and J-2). In four months for the rain days and nine months for the no rain days, including January in both cases, the association between rainfall and the transient flux is indirect (Tables J-1 and J-2).

Parameters of the second harmonic of the earth angular momentum flux correlations with rainfall are similar both the rain and no rain sets, in either case with a phase angle close to that *for the integral earth*

angular momentum flux correlations (Table 10-2). Only a negligible proportion of the variance is captured by the first harmonic of the rain day correlations but 24 per cent by that of the no rain correlations. Neither the first or second harmonic contributes in excess of eight per cent of the variance to the distribution of the transient flux correlations with rainfall (Table 10-2). Nor does the second harmonic make a major contribution to the variance of the correlations for the no rain days. Twenty-three per cent of the variance is captured by the first harmonic of the no rain correlations with a phase roughly inverse to that of the first harmonic of the rain correlations. Systematic variations affect the circulations of both the rain and the no rain days as the rainfall varies. Adjustments to the meridional circulation are essentially similar for rain and no rain days only for changes to the semi-annual cycle of the circulation. No complete model of the causes of the rainfall vacillations may be developed based simply on frequency changes of rain days.

APPENDIX K

GLOBAL CIRCULATION VACILLATIONS ASSOCIATED WITH THE SOUTHERN OSCILLATION

The Southern Oscillation was originally viewed as an exchange of atmospheric mass between two centres of action, one in the Indonesian region and frequently represented by data from Djakarta and one in the central subtropical Pacific Ocean and frequently represented by data from either Tahiti or Easter Island (Walker, 1923, 1924, 1928, 1937; Walker and Bliss, 1930, 1932; Berlage, 1957, 1966). Subsequent observations of an opposition of zonal wind anomalies over the equatorial Pacific and eastern Indian Oceans both at 200 mb (Troup, 1961) and in the stratosphere (Reed and Rogers, 1962) prompted Troup (1967) to suggest that the opposition was related, particularly during the austral summer months, to the Southern Oscillation. Troup (1965) also proposed that the centres of action may be linked by a direct zonal circulation cell, an inference confirmed by Bjerknes (1969) and named by him the Walker Cell in honour of Gilbert Walker's pioneering work. The Walker Cell over the Pacific Ocean, according to Bjerknes (1969), has its ascending limb in the region of the intense convection of the low pressure system in the vicinity of Indonesia and its descending limb over the cold equatorial waters west of Peru. Similar zonal circulation cells to that over the Pacific Ocean are present around the globe (Krishnamurti, 1971b; Krishnamurti *et al.*, 1973; Newell *et al.*, 1974; Kidson, 1975; Flohn and Fleer, 1975; Newell, 1979) and provide both the basis for an explanation of the opposition of the zonal wind anomalies noted above and one mechanism by which climate anomalies may be transmitted globally from the Pacific Ocean. The cell over the Indian Ocean (Fig. K-1) is of the opposite sense to that over the Pacific Ocean and is associated with the easterlies across Africa required for rainfall over southern tropical Africa and the formation of tropical-temperate troughs over South Africa. Ascending branches of all cells are collocated with the three main areas of tropical

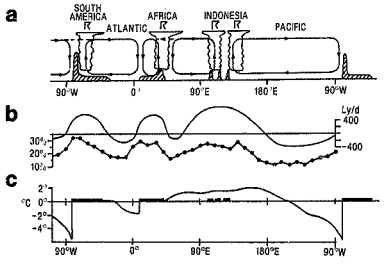


Figure K-1. a) Schematic representation of the zonal circulation cells around the Equator. b) Upper curve: vertically-integrated heat budget of the atmosphere in Langleys (cal cm^{-2}) day^{-1} (right-hand scale). Lower curve: satellite-derived planetary albedo (left-hand scale). c) Equatorial sea surface temperature anomalies. Adapted from Flohn and Fleer (1975).

convection (cf. Fig. 7-2), i.e. with either warm sea surface temperatures or heated continents, whereas descending branches occur in regions of relatively cool sea surface temperatures. Gradients of the net radiative flux at the top of the atmosphere are of comparable magnitude in both the zonal and meridional directions (Stephens and Webster, 1979) and thus the intensities of the zonal circulation cells are comparable with those of the meridional cells, as previously deduced from direct observations by Krishnamurti (1971b) for the austral winter and Krishnamurti *et al.* (1973) for the austral summer.

The phase of the Southern Oscillation for which the associated zonal circulation cells are schematically depicted in Figure K-1 is normally referred to as the high phase in which pressure is typically below normal in the Indonesian region and above normal in the central south Pacific. During the low phase these latter pressure anomalies reverse in conjunction with marked changes to the distribution of sea surface temper-

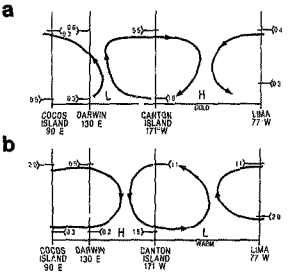


Figure K-2. Walker circulations over the eastern Indian and Pacific Oceans during the a) high and b) low phases of the Southern Oscillation according to Julian and Chervin (1978). Wind anomalies are depicted in ms^{-1} at 850 and 200 mb.

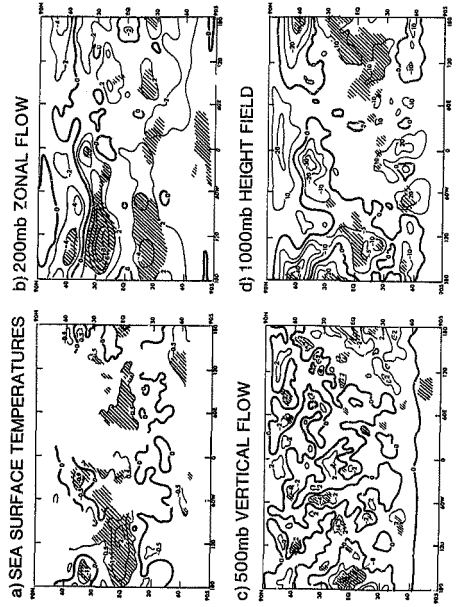
atures across the tropical Pacific Ocean. In particular temperatures off the Peruvian coast rise in association with the phenomenon referred to as El Nino (Bjerknes, 1961, 1966b; Quinn *et al.*, 1978; Ramage and Hori, 1981; Cane, 1983; Cane and Sarachik, 1983) concurrently with major atmospheric circulation anomalies both across the Pacific Ocean and globally (Bjerknes, 1966a, 1969, 1972; Krueger and Gray, 1969; Krueger and Winston, 1974, 1975). In the Indonesian region the directions of the Walker Cells reverse (Julian and Chervin, 1978) in association with decscent and drought across the Archipelago (Fig. K-2). The anomaly over the eastern Indian Ocean at 200 mb becomes westerly. The phenomenon derives, in part, from an imprecisely understood atmosphere-ocean interaction across the equatorial Pacific Ocean. In the high phase surface currents are driven westward towards the Indonesian heat source through surface stresses with the trade winds. Upwelling occurs off the Peruvian coast through Ekman pumping forced by the flow around the South Pacific anticyclone and results in the formation of a cold tongue of water along the Equator and, hence, of atmospheric descent over the eastern ocean.

During the low phase the stresses decline in association with a weakening, and sometimes with a reversal, of the trades. Upwelling also decreases and may disappear and with eastward advection of warm water from the western ocean warming of the waters off Peru occurs. The major heat source over Indonesia then migrates towards the warm surface waters, typically becoming established in the vicinity of the date line (Fig. K-2b). Descent then occurs in the Indonesian region and the Walker Cells reverse. Reviews of the history of the development of knowledge of the Southern Oscillation and the El Nino and of the present theories of the causes of the switches between the high and low phases have been provided by Barnett (1977), Julian and Chervin (1978), Horel and Wallace (1981), Rasmusson and Carpenter (1982), Rasmusson and Wallace (1983), Philander (1983) and Kousky *et al.* (1984). Present theories tend to stress the tropical and subtropical nature of the circulation reversals although it has also been proposed that the phenomenon may be forced from the higher latitude and Antarctic circulations (Walker, 1923; Budd, 1975; Wyrtki, 1975; Fletcher *et al.*, 1982; Chiu, 1983; Pittock, 1984).

Whatever the causes of the large-scale circulation vacillations referred to as the Southern Oscillation there is little doubt that they are related to world-wide climatic anomalies and in fact represent the major known internal source of non-seasonal climate variability (Newell and Chiu, 1981). Following the earlier treatment of the Oscillation as an east-west exchange of atmospheric mass it has been deduced that surface pressure, temperature and rainfall on the global-scale are significantly correlated with indices of the Oscillation (Walker, 1923, 1924, 1928, 1937; Walker and Bliss, 1930, 1932; Berlage, 1957, 1966; Wright, 1977). Subsequent analyses have confirmed the statistical significance of the associations with global temperatures (Angell and Korshover, 1983; Pan and Oort, 1983; Parker, 1985) and sea-level pressure (Harnack and Harnack, 1985; Mo and White, 1985), particularly in the austral summer months. Pressure, temperature and rainfall over the interior of South Africa are in phase with that in the Indonesian region such that highest rainfall occurs in the high phase of the Oscillation (Lindesay, 1986). Inverse phase relationships occur between the western Cape of South Africa and the Indonesian region.

Sea surface temperature anomalies in the tropics and subtropics are well correlated both with indices of the Southern Oscillation and with sea level pressures across all oceans, although anomalies may lag or lead those in the central Pacific Ocean by several months (Covey and Hastenrath, 1978; Hastenrath and Kaczmarczyk, 1981; Chiu and Newell, 1983; Pan and Oort, 1983). According to Pan and Oort (1983) sea surface temperatures in the Indian Ocean as far south as 30°S increase in the low phase of the Oscillation (Fig. K-3a) whereas 1000 mb heights over the ocean and across southern Africa are concurrently raised (Fig. K-3d). Tropical convection tends to be collocated with the highest sea surface temperatures so that there are marked changes in the regions of maximum cloudiness over the Pacific Ocean between the opposing phases of the Oscillation. In the high phase the region of maximum convection is located in the Indonesian region whereas, together with the Pacific cloud band, it is displaced eastward in the low phase (Streten, 1975; Trenberth, 1976; Webster, 1981; Pazan and Meyers, 1982; Liebmann and Hartmann, 1982; Lau and Chan, 1983a). Resultant changes in outgoing long-wave radiation over the Pacific Ocean are linked with equivalent changes over other regions of the globe in patterns related to the phases of the Southern Oscillation (Heddinghaus and Krueger, 1981; Liebmann and Hartmann, 1982; Barton, 1983; Lau and Chan, 1983a, 1983b). Changes in the outgoing long-wave radiation in the southern African region between the phases of the Oscillation are not as defined as over some other regions of the globe. A switch in the pattern of the distribution of high clouds between the low and high phase months of January 1973 and January 1974 respectively suggestive of changes in the longitudinal location of cloud bands over Africa and Madagascar in phase with that of the Pacific cloud band is, however, evident in the results of Barton (1983) (Fig. K-4). Movements of the bands over the Indian and Pacific Oceans also appear to be reflected in the field of the first eigenvector of tropical rainfall (Fig. 8-6) according to Kidson (1975) - an interpretation supported by Heddinghaus and Krueger (1981) - the time series of which is significantly correlated with an index of the Southern Oscillation. In the African region movements of the cloud band are also denoted by adjustments in the vertical motion field in patterns which resemble the two preferred locations of the band (Fig. K-3c - cf. Fig. 2-6). Over the Indian Ocean the flow at 200 mb is anomalously westerly during the low phase of the Oscillation (Fig.

K-3b), an anomaly which, as suggested in Chapter 5, may be related to the eastward displaced location of the band.



Thus it appears that longitudinal displacements of the tropical-temperate troughs and associated cloud bands in the African region are modulated with the Southern Oscillation in similar manner to the band in the Pacific Ocean, modulations which in turn are linked to the distribution of sea surface temperatures across the latter ocean through the zonal Walker Circulation (Julian and Chervin, 1978; Horel and Wallace, 1981; Lau and Chan, 1983a). Bands in the African region are displaced in the low phase towards the anomalous high tropical and subtropical sea surface temperatures of that phase (Fig. K-3a). Equivalently in the high phase the bands are located across southern Africa in association with the relatively warm sea surface temperatures along the east coast of the subcontinent according to both Figure K-3a and Walker-van Heerden (1935). Although the earlier theories of the mechanisms of the Southern Oscillation incorporated only the circulation across the Pacific Ocean flow changes over the Indian Ocean are, according to Barnett (1984b), as intimately related to the vacillations of the Southern Oscillation as are those over the Pacific Ocean, described earlier by Barnett (1981), Pazan and Meyers (1982), Rasmusson and Carpenter (1982) and Newell *et al.* (1982). Both zonal and meridional low-level flows over the Indian and Pacific Oceans are related such that observed changes in the tropical zonal wind field across the Eastern Hemisphere are consistent with the theoretical studies of adjustments in the forcing of the Walker Circulation caused by vacillations in the location and extent of the latent heat release in the Pacific heat source (Barnett, 1983, 1984a, 1984b).

Figure K-3 (opposite). Circulation changes between periods when the equatorial sea surface temperature at 130°E was relatively warm and relatively cold in the December to February period adapted from Pan and Oort (1983). Hatched areas indicate differences significant at better than the 5 per cent level. a) Sea surface temperatures - positive values indicate warmer temperatures during a warm anomaly at 130°E; b) zonal winds at 200 mb - positive values indicate a westerly anomaly during a warm anomaly; c) vertical motions at 500 mb - positive values indicate anomalous descent during a warm anomaly; d) 1000 mb heights - positive values indicate increased heights during a warm anomaly.

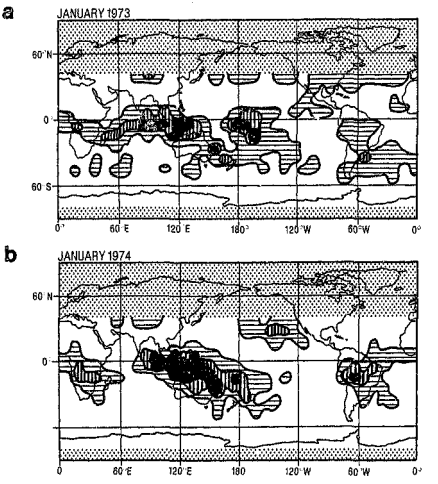


Figure K-4. Distribution of high clouds as determined by satellite reflectance levels in a) January 1973 (low phase of the Southern Oscillation) and b) January 1974 (high phase) according to Barton (1983).

Variations in the intensities of the Hadley Circulations also accompany the changes in the locations and magnitudes of the tropical heat release and may form one mechanism by which the influence of the Southern Oscillation is transmitted to higher latitudes, effects having been observed in both hemispheres (Angell, 1981; Navato *et al.*, 1981; van Loon and Madden, 1981; van Loon and Rogers, 1981; Angell and Korshover,

1982, 1983, 1984; Rogers and van Loon, 1982; Harnack *et al.*, 1982; Reiter, 1983; van Loon, 1984; Mo and White, 1985). Subtropical jet streams tend to be stronger in both hemispheres in the low phase of the Oscillation as a result, according to Bjerknes (1966a, 1969), of the intensification of the poleward absolute angular momentum transport. Direct inspection of the correlation between the northward momentum flux over the Pacific Ocean and an index of the Southern Oscillation does not, however, support Bjerknes' (1966a) contention (Chiu and Lo, 1979; Chiu *et al.*, 1981). Modelling studies have verified the existence of an enhanced poleward flux in the Northern Hemisphere associated with the transient and standing components of the transport in the low phase (Hanna *et al.*, 1984). A mechanism, consistent with Bjerknes' (1966a) hypothesis, whereby mid-latitude circulation changes result from adjustments in Rossby wave trains propagating from the Pacific source has been proposed by Horel and Wallace (1981) following the results of the wave-tracing model of Hoskins and Karoly (1981). Recent observations tend to corroborate this latter hypothesis (e.g. Reiter, 1983; Quiroz, 1983) although its validity in the Southern Hemisphere remains to be demonstrated. Adjustments in the zonal winds at low and middle latitudes accompanying phase changes of the Oscillation as indicated in the corresponding changes of atmospheric relative angular momentum itself (Stefanick, 1982; Chao, 1984; Carter *et al.*, 1984; Rosen *et al.*, 1984) are indicative of modifications to the meridional momentum flux between the phases of the Oscillation. Atmospheric angular momentum is higher in the Oscillation's low phase. Zonal displacements of the heat sources together with the resultant modifications to the flow at both low and middle latitudes are inevitably reflected in the long-wave structure of the atmosphere, reflections which are present in amplitude vacillations of wave 1 at 500 mb and 35°S (Trenberth, 1980a).

Relatively little is known of the flow adjustments contemporaneous with the phase reversals of the Southern Oscillation over the southern African subcontinent itself although 200 mb wind anomalies (Arkin, 1982; Pan and Oort, 1983) are consistent with the concepts of longitudinal displacements of the cloud bands and varying rainfall over South Africa in concert with the displacements of the Pacific heat source (Fig. 6-7). Models have, so far, produced conflicting directions of the flow anomalies over southern

Africa resu[illegible] from adjustments to the sea surface temperature gradient across the [illegible]uatorial Pacific Ocean - compare the results of Julian and *Chervin* (1978), *Cubasch* (1983), Keshavamurty (1983) and Voice and Hunt (1984) - and thus further support for the concepts must presently be sought in observations alone. In the most *detailed study based on* observations to date Lindesay (1986) has demonstrated that in the high phase of the Oscillation for the January to March season the zonal flow is anomalously easterly and *poleward over Africa* south of 20°S in association with an enhanced Hadley Circulation across the central interior of South Africa. Anomalies reverse in the low phase of the Oscillation.

APPENDIX L

CONTROLS ON TROPICAL CONVECTION

Two basic theories of the controls on the rainfall along the Inter-Tropical Convergence Zone have been forwarded. Evidence has been provided that annual rainfall variations over the Sahel are both dependent (Osman and Hastenrath, 1969; Ilesanmi, 1971; Bryson, 1973; Winstanley, 1973; Lamb, 1978; Motha *et al.*, 1980) and either partially or fully non-dependent (Tanaka *et al.*, 1975; Schupelius, 1976; Nicholson, 1980, 1981; Nicholson and Chervin, 1983) on latitudinal displacements of the Inter-Tropical Convergence Zone between years. In the first of these theories the extent of the latitudinal excursion of the Inter-Tropical Convergence Zone into the summer hemisphere has been linked to either changes in the meridional temperature gradient in the summer hemisphere itself with consequent latitudinal displacements of the subtropical anticyclones (Bryson, 1974; Greenhut, 1977), or to equivalent gradient changes in the *winter* hemisphere such as to appropriately adjust the amount of heat generated along the Inter-Tropical Convergence Zone and available for transport into the winter hemisphere (Kraus, 1977a, 1977b). The alternative hypothesis to that implying that subtropical rainfall anomalies are caused by latitudinal displacements of the Inter-Tropical Convergence Zone is that the Zone remains stably meridionally located between years but that the intensity of the convective overturning along the Zone, and hence the rainfall and energy release, changes following large-scale dynamic adjustments in the general circulation.

No unequivocal evidence has been provided to confirm either theory and observational results suggest that both may apply, perhaps at the same time. Satellite images have provided direct evidence that in the Southern Hemisphere latitudinal shifts of the Inter-Tropical Convergence Zone are related to tropical rainfall deviations both over South America (McQuate and Hayden, 1984), as had been indicated in earlier studies using surface data (Hastenrath and Heller, 1977; Kousky and Chu, 1978; Hastenrath,

1978; Moura & Shukla, 1981) and in the Australian region (Davidson, 1984). Statistical evidence has also been obtained, following Kraus' (1977a, 1977b) model, that the latitudinal excursion of the Inter-Tropical Convergence Zone over southern Africa is related to Northern Hemisphere winter temperature gradients (Meehl and van Loon, 1979) although zonal gradients between Europe and Greenland rather than meridional gradients were used in the analysis. Both temperature gradient models have been tested in terms of the latitudinal location of the Sahelian Inter-Tropical Convergence Zone (Greenhut, 1981). No direct support for either model was obtained. Statistically-significant correlations for the summer hemisphere gradient model of Bryson (1974) were obtained only when a constant vertical lapse rate was employed to calculate the gradients and for the winter hemisphere model of Kraus (1977a, 1977b) only with the gradient lagged by one year. Statistically-significant correlations have, however, been detected between pressure in December to February in a pattern suggestive of increased meridional temperature gradient variations over the North Atlantic Ocean in the wetter periods over southern Africa (Harnack and Harnack, 1985). The role of meridional temperature gradients in either hemisphere in the control of the location of the Inter-Tropical Convergence Zone over Africa remains to be resolved.

Direct investigation of rainfall distributions has indicated that variations at about 20°S over southern Africa are related to latitudinal displacements of the Inter-Tropical Convergence Zone only in years when rainfall anomalies of similar signs are also present in the equatorial zone (Nicholson and Chervin, 1983). No inter-Tropical Convergence Zone displacements appear to occur in years in which tropical and subtropical southern African rainfall anomalies are of inverse signs, as is normally the situation (Nicholson and Entekhabi, 1985a). Rainfall anomalies over the subcontinent south of 20°S tend to be of the same sign (Nicholson, 1986) such that the area covered by the rainfall expands or contracts southward but with a quasi-stably located northern limit. The strength of the upper-level easterly current in the region of the Inter-Tropical Convergence Zone is one of the determinant factors controlling the the intensity of the overturning along the Inter-Tropical Convergence Zone over northern Africa (Kanamitsu and Krishnamurti, 1978; Nicholson and Chervin, 1983) and stronger 200 mb easterly currents at Harare are also

associated with higher rainfall totals over the Orange Free State in January (Harrison, 1983a). Inter-annual differences in overturning along the Inter-Tropical Convergence Zone rather than latitudinal displacements of the Zone therefore appear to be the main cause of rainfall and energy release variations over the southern African tropics.

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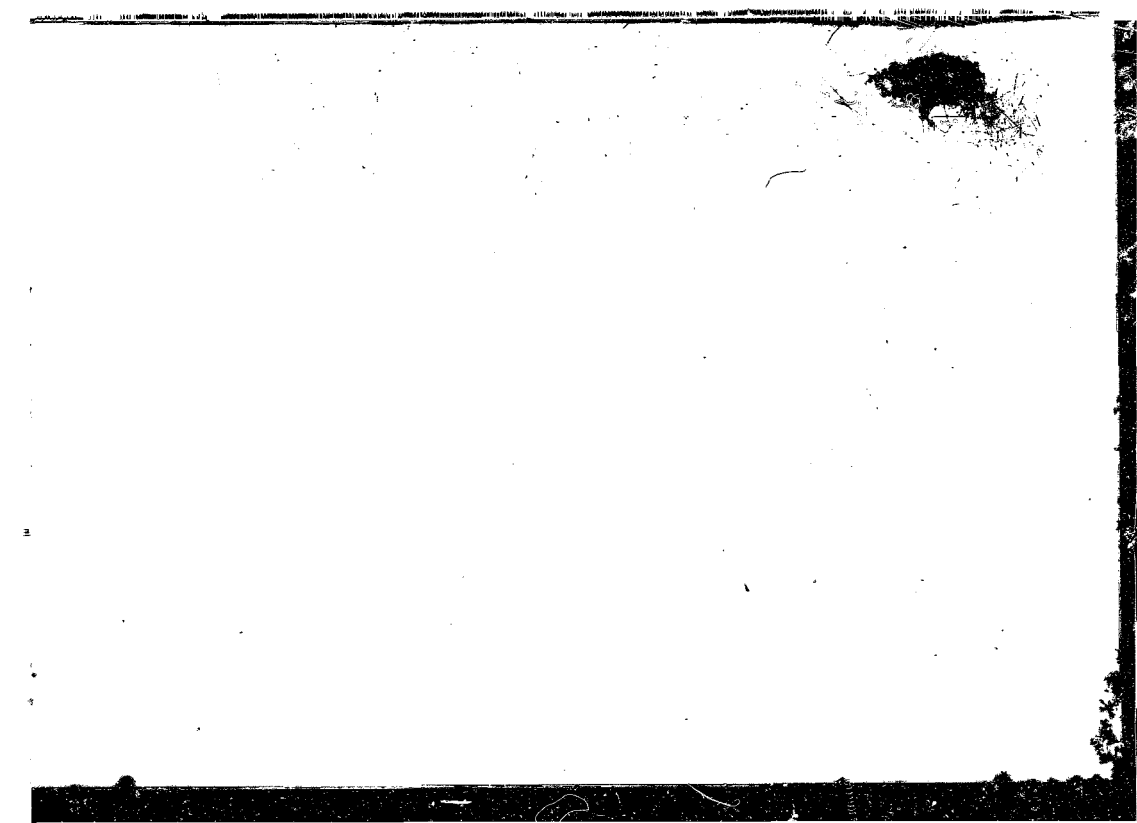
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