MECHANISMS OF SHORT TERM RAINFALL VARIABILITY OVER SOUTHERN AFRICA

by

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Mechanisms of short term rainfall variability over southern Africa

A report to the Water Research Commission produced by the
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Executive summary

Motivation

The water balance over southern Africa is affected by convective weather systems which link the tropical heat and moisture sources with mid-latitude dynamical features. The rainfall is non-homogeneous in time and space, and is organised into multi-day events by atmospheric waves with cycles of 15-40 days. At present weather prediction models provide reasonable forecast guidance up to 5 days, and efforts have recently been made to understand year-to-year oscillations in climate. This leaves intermediate scale weather phenomena for improved understanding.

The purpose of this WRC-sponsored research project is to develop a foundation of knowledge on the antecedent conditions, causes and structure of wet and dry spells, through analysis of meteorological data. These include surface observations, numerical weather analyses and satellite data sets. It was postulated that common features would emerge through statistical analysis and enable 1 - 2 week lead-time weather forecasts with application to seasonal agricultural and water resource management strategies.

Objectives

To identify and understand mechanisms which govern in-season (15-40 day) variability of summer convection over the plateau of southern Africa and adjacent ocean areas through composite analysis of regional and local weather data.

Review of results

To identify 15-40 day cycles in summer convection over southern Africa, area-averaged pentad (5 day mean) rainfall indices were analysed. The most commonly observed convective cycle was around 25 days in almost 75% of cases. Analysis of convective indices at sub-monthly scale demonstrated a peculiar seasonal distribution. The major wet spells tend to occur around 17-21 November, 21-25 January, and 12-16 March; interrupted by a mid-summer dry spell at the end of December. A change from apparent water deficits before mid-January to water balance in the second half of summer is noted in data collected over the highveld and central plateau of South Africa.

Following identification of intra-seasonal oscillations (ISO) over South Africa, it was necessary to determine underlying causative factors. ECMWF weather data were obtained in the period 1986-1992 and ISO lifecycles were grouped into various phases, namely dry, onset, wet and decay. Cases chosen on the basis of various rainfall indices, whether for the western Transvaal, Zimbabwe or the Drakensberg, revealed consistent patterns of evolution and structure. Thus interpretations of intra-seasonal weather dynamics could be generalised for southern Africa.

Evidence presented in the research theses of Levey (MSc) and Makarau (PhD) demonstrates that intra-seasonal oscillations are influenced by slow, eastward- moving 'waves' in both the tropics and mid-latitudes. The contribution from either source is variable and results in a wide range of characteristics. About half of all summer wet spells develop internally and are quasi-stationary over southern Africa. They derive from tropical export of warm humid air. About one-third of identified cases shifted eastward during their lifespan in sympathy with the eastward progression of convective waves in the lower and higher latitudes either side. A smaller number of in-season wet spells shifted westward from the Indian Ocean, whilst even fewer appear to be a result of variations in Hadley overturning. These results apply to areas south of 25°S. Further north in Zimbabwe, shifts in the position and intensity of the inter-tropical convergence zone (ITCZ) often result in faster developing ISO which are influenced by westward moving waves. It is likely that global warming will cause a poleward shift of weather characteristics. Thus knowledge of historical conditions over Zimbabwe could benefit our future knowledge of weather over the northeastern third of South Africa.

Mechanisms underlying intra-seasonal oscillations were brought out in composite analyses of numerical weather data. Factors which contribute to the development of summer wet spells include:

- moisture is brought in from the tropical Indian Ocean some 5-15 days in advance, owing to a relaxation of the monsoon there,

- an upper trough shifts eastward in the mid-latitudes towards southern Africa in the onset phase, followed by a ridging anticyclone,

- uplift during the wet phase is widespread over southern Africa and compensated by sinking in the tropics and mid-latitudes,

- the local intra-seasonal oscillations are embedded within a half cycle of the tropical wave.

Intra-seasonal oscillations develop differently in early and late summer. In general water vapour transport over the Atlantic Ocean is seaward and uninfluential, except over Angola. In early summer there is little evidence for monsoon effects and convection from tropical troughs is absent. Conditions are relatively warm and dry leading to high evaporative water losses. Westerly flow in the upper levels is a prevailing feature, and anomalies therein determine the phase and character of in-season wet spells.

In late summer, upper westerly winds retreat polewards and the lower atmosphere is moist as a result of confluence of flow from the Congo basin and the Mozambique Channel. During wet spells, two troughs usually lie across southern Africa. The first is oriented zonally in the 15-20°S band and the second extends southward along 20-25°E. An 'anchor-point' is found over Angola.

During dry spells the Botswana high suppresses convection in association with anticyclonic spin (vorticity) and mid-level sinking motions. Anomalies of upper convergence and lower divergence (mass flux) are then present. Vertical sections indicate that mid-level heating and upper easterly flow are important features of late summer wet spells, whereas upper westerlies and decreased mid-level temperatures are common in dry spells.

Conclusions

The objectives of the research programme have been met. Intra-seasonal oscillations of summer convective rainfall and their underlying mechanisms have been identified. This discovery is of practical use in developing 10-30 day weather forecasts. Two high-quality research theses have been produced, from which a number of international journal articles will emanate. The research has elevated the intra-seasonal scale to its rightful position of fundamental importance in respect of rainfall-producing weather systems of southern Africa (Levey 1993, Makarau 1995). A number of data sets were obtained and 'readied' for analysis, which will facilitate on-going studies in WRC and related projects.

A major finding of the project is that in-season oscillations of rainfall are of a significant amplitude over southern Africa. In the tropical band to 20°S the major wet spells are pulsed by the monsoon and occur at preferred times during summer. By contrast over South Africa, the wet spells occur more randomly owing to forcing by chaotic mid-latitude weather patterns. A conspiracy of forcing factors combine to enhance wet spells, including Easterly waves in the sub-tropics, Rossby waves in the mid-latitudes, the tropical Madden Julian Oscillation, etc. These various contributors to the mechanisms of short-term rainfall variability over southern Africa are outlined in the research presented here.

Recommendations

National weather services in southern Africa should develop the capability to combine daily weather data into 5-day averages, expressed as departures from historical mean conditions for the period under consideration. Real-time diagnostic trends could then be tracked to establish the development, evolution and intensity of dry and wet spells. 10-30 day forecasts need to be communicated to farmers, etc to assist decisions regarding irrigation demand, planting, fertilising, etc. Most weather services currently predict short term rainfall variability on the basis of total meteorological values without the advantage of time filtering and removal of the background mean. This increases the risk of 'missing' important signals which lead wet and dry spells over southern Africa.

Development and utilisation of dynamical extended range numerical models should move ahead with the recognition of the importance of slowly evolving ISO cycles. Interaction between year-to-year and week-to-week scales of weather variability should be assessed in simulation exercises.

Continued dissemination of results should be pursued in international journal articles, related publications and conference presentations. Some revision of textbooks and curricula in tertiary atmospheric science courses may be needed to take account of these results. For example, the importance of ridging sub-tropical anticyclones in the production of southern African wet spells needs upgrading.

Further observational work on ISO phenomena should be pursued. Relationships between ISO over South Africa and events elsewhere in the region could be assessed. Distinctions between ISO operating during El Nino years, La Nina years, and in-between years could be made. This may offer useful insights to changes in the seasonal distribution of rainfall, to spatial focusing of drought and flood events and to impacts therefrom. Principal components analysis of pentad OLR data could provide additional insights to the various modes of intra-seasonal behaviour, and this work is on-going at UCT. ISO impacts could be investigated through the use of pentad soil moisture and satellite vegetation data.

Technical overview

Research findings are presented of the 1992-1995 WRC project on intra-seasonal oscillations of summer rainfall over southern Africa. Two journal articles (currently under review) which summarise the research theses of Levey (MSc) and Makarau (PhD) form the main part of the scientific presentation here.

A background to ISO methodologies employed and results of data reports and theses in terms of spectra, hovmoller plots, vertical sections and mean/ anomaly composites is outlined in Chapters 2 and 3. Various surface and localised pentad (5 day mean) indices of convection are analysed for spectral cycles and corresponding statistics, such as duration and intensity, particularly for frequencies of 20-35 days are outlined. Hovmöller and longitude/time plots at latitudes 10°, 25° and 40°S and longitudes 25° and 60° E have demonstrated that four ISO modes exist: eastward and westward moving, standing waves (especially at 25°S) and Hadley overturning. Vertical sections of various meteorological parameter anomalies offer useful explanations as to what is occurring in the entire troposphere.

The surface data sets used consist of area-averaged rainfall. The selection of cases should depend on the locations of stations used. However it was found, by comparing the pentad rainfall distributions for Zimbabwe, the western Transvaal and the eastern highlands of South Africa (Drakensberg), that the seasonal cycles are consistent and major wet spells are widespread and affect all three locations. The pentad rainfall correlation between the regions is statistically significant in more than half the years. The pentad rainfall correlation declines below the 95% confidence limit when isolated weather events such as tropical cyclones (1984) or concentrated floods (1988) impact a localised area.

Composite analyses of various parameters form the bulk of the work undertaken to better understand the ubiquitous ISO phenomena over southern Africa. Various methods employed to highlight the mechanisms operating during the development of wet spells are outlined. Emphasis is placed on the precursor stages of wet spells for predictive purposes, and major wet and dry spells for explanation of the various thermodynamic and kinematic forcings operating during these events. Differences in the forcing mechanisms and moisture sources during the seasonal progression of summer are demonstrated.

The outcome of journal articles and research theses of Levey and Makarau together with contributions from Jury are consolidated in the report. The results offer statistical analogues for increased predictability of in-season wet and dry spells. All data analysed in support of this project are 'zipped' and archived on the computer network at UCT. These are available for futher research exploration.

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Chapter 1: Introduction

The availability of water resources and food plays an important role in the daily existence of millions of people in southern Africa. However the rain which occurs in the summer over the central plateau is highly variable (Nicholson et al 1988). Droughts and floods are common. Studies of rainfall variability over southern Africa have tended to focus on daily and inter annual time scales, whilst the intra-seasonal scale is relatively unexplored. It is of critical importance to understand and predict the intensity and duration of wet and dry spells, as maize yield in the region is directly influenced by the temporal distribution of summer rainfall. Links between weather regimes and climate teleconnections occur through these intra-seasonal oscillations of convection.

The climate of Africa south of 15°S (figure 1) has received increasing attention since the devasting drought of 1982-1984, when crop yields declined to 10% of historical values and numerous sources of water dried up. Because the region's economies are based on rain-fed agriculture and the availability of sufficient water resources, there is a need to understand and predict the temporal and spatial distribution of rainfall in the summer season. *Resource managers and farmers in southern Africa require more than a long-range forecast of total summer rainfall. What is desirable is a reliable prediction of the onset, duration and intensity of wet and dry spells within a season.* For this, the characteristics of weather systems operating at scales of 15-40 days should be recognised.

Year-to-year rainfall variability over South Africa has been examined in relation to regional circulation, synoptic weather type and climatic forcing by the El Nino - Southern Oscillation and southern hemisphere westerly wave patterns (Tyson and Dyer 1975, Gillooly and Dyer 1979, Dyer 1979, Tyson 1980, 1981, Miron and Lindesay 1983, Lindesay 1984, Miron and Tyson 1984, Tyson 1984, Taljaard 1986a, 1986b, Harrison 1986 and Lindesay 1988). A few studies detailing circulations associated with multi-day rainfall events (Taljaard 1985, Lindesay and Jury 1991, Barclay 1992, Jury and Lyons 1994) or multi-week wet spells (Taljaard 1981, Harrison 1986, Lindesay 1988, Matarira and Jury 1990, Lyons 1991) have been undertaken.

The intra-seasonal climate has been studied empirically through the use of composite wet and dry spells (Tyson 1981, Miron and Tyson 1984, Taljaard 1986, Matarira and Flocas 1989, Lyons 1991, Matariria and Jury 1992, and Levey 1993). These studies have determined common features of large amplitude events within the summer season. Harrison (1986), Van Heerden et al (1988) and Barclay (1992) found that most rain-producing systems in the early summer take the form of baroclinic westerly waves which move up from the mid-latitudes of the southern ocean. In contrast, late summer rains are tropically sourced and the associated weather systems are barotropically structured, that is to say vertically aligned and having a warm core. Makarau (1995) determined how the external forcing of widespread, multi-day wet spells over southern Africa varies from early to late summer. Sources of moisture and circulation patterns shift as the season progresses, thus ensuring a variety of characteristics and predictability for weather systems.

Recent studies have demonstrated the existence of Intra-Seasonal Oscillations (ISO) in meteorological conditions, particularly over the tropics. Madden and Julian (1971) detected 50 day cycle in tropical winds, the Madden-Julian Oscillation (MJO). Weickman et al (1989) and Lau and Chan (1986) have associated the properties of this oscillation with eastward-moving convective waves. More recently Hayashi and Golder (1993) have demonstrated two distinct spectral peaks centered at 25-30 and 40-50 days in tropical convection and upper circulation parameters.

Vincent et al (1990) concentrated on the southern tropics using ECMWF analyses. Upper level divergence and OLR were used to describe convective cycles of 33 and 50-65 days. These tropical ISOs propagated eastward around the globe and were most intense over the western Pacific. Rui and Wang (1990) explained the temporal evolution of ISO in the equatorial region. From composite OLR anomalies for 36 cases for the period 1975-1987 they found a four-stage development process: initiation over equatorial east Africa (related to a surging monsoon); intensification through the central Indian Ocean; evolution over Indonesia, re-development over the western Pacific; and dissipation near the date line. Wang and Rui (1990) used pentad mean anomaly maps in climatological studies. Of the 122 identified cases, 77 were found to be eastward moving and most frequent in the December-February season. Chen and Tzeng (1989) examined global-scale intra-seasonal and annual variations of divergent water-vapour transport. They found moisture surpluses and deep cloud regions were related to lower moisture convergence and upper divergence. Ghil and Mo (1990) studied 12 years of 500 hPa geopotential heights in the southern hemisphere and found a dominant cycle near 23 days, associated with a pattern of four westerly waves around the mid-latitudes. A secondary cycle was found at 40 days and related to wave-number three.

Research on subtropical ISO are less numerous. The major convective regions of the globe are naturally situated within the tropics, but many areas of the subtropics, such as southern Africa, derive their summer rainfall from links with tropical convective sources. It is unclear whether extratropical processes influence subtropical rainfall cycles to the same extent as the tropical waves.

Here we demonstrate that the intra-seasonal scale is a dominant temporal mode, that convective ISO are ubiquitous over southern Africa, and that local ISO are linked to the tropical and extra-tropical waves. We hypothesise that the temporal scale of intra-seasonal convective fluctuations will be shorter than that of the MJO as a result of higher frequency influences from mid-latitudes. What is evident from the studies dealing with wet and dry spells over southern Africa is a lack of in-depth diagnostic analysis. The project results fill this gap between event and seasonal scale rainfall variability.

The historical distribution of summer rainfall over southern Africa is typically composed of three to five major wet spells occurring at approximately monthly intervals from late November to late March. The first wet spell is important for crop planting, whilst the mid-summer wet spell in January often breaks a two to three week dry spell and comes at a critical time in the growth of maize, the staple food in the region. It is useful to describe the distinctive features and regional circulation patterns associated with composite wet spells. In this paper these convective phases are analysed and contrasts between early and late summer are highlighted. We accomplish this task through analyses of meteorological variables and by subtracting late summer composite data from early summer. In this way the influence of the seasonal cycle on convective events is demonstrated.

Chapter 2: Intra-seasonal oscillations of convection

2.1 Background and Methods

In this chapter, common features of major wet spells over central South Africa are studied using composite analysis. ECMWF (European Centre for Medium Range Weather Forecasts) meteorological data for the summers of 1986 -1992 are the primary source of gridded weather data used here. The data window encompasses an area stretching from 20° N to 60° S and 30° W to 100° E (Figure 1). The data are at a resolution of 2.5° x 2.5° at 12 UT each day from October to March of each year. As an independent check on surface and model data, outgoing longwave radiation (OLR) is used. OLR has been found to be a useful proxy for the depth of cumulus convection (Wang and Rui 1990, Chen and Tzeng 1989). The OLR data were extracted for a 5° diameter area centred on 25°S and 25°E which encompasses central South Africa and south eastern Botswana (Figure 1 circular shaded area). The OLR data-set extends from 1975-1987, with a short gap in 1978.

Daily rainfall data were collected for stations within a 5° diameter of 25° S, 25° E, coincident with OLR data. This area is an agriculturally productive district prone to El Niño-induced drought. Maize yields in the area vary from < 1 T/ha to > 4 T/ha depending on the seasonal distribution of rainfall. Rainfall and class A pan evaporation data were obtained from 1970 to 1991 for sixteen stations with complete records. The shortcomings of class A pan levels to estimate potential evaporation are recognised (Sutton 1953, Geiger 1965, Wiesner 1970). Factors such as sensible heating of the pan result in over-reading. An area-averaged precipitation minus evaporation (P-E) index is calculated.

Since a temporal resolution which captures the cyclic nature of the ISO but excludes high frequency 'noise' is desired, daily data for surface and field variables were combined into pentads (discrete 5-day means). Statistical and spectral analyses were performed on the unsmoothed time-series of the P-E index. Case studies for the period of overlapping ECMWF data: 1986-1992 were selected based on the summer time-series of pentad P-E. A strict objective selection criterion was used to identify large amplitude ISO, excluding flood events. A total of 16 cases were identified where the peak of the wet spell P-E was in the range +1.0 to +2.0 times the standard deviation. Temporally the cases fell between early November and mid-March. A time frame extending 15 days before the wet spell to 10 days after (six pentads) was adopted. The P-E criterion for P-2 (10-15 days before) was deviations <-0.5 and for P-1 (5-10 days before) deviations <-0.25, namely the 'dry' and 'onset' phases. The peak wet spell P-0 deviations were in the range +1.0 to +2.0, whilst the 'decay' phases, P+1 (0-5 days after) deviations were <-0.25, and P+2 (5-10 days after) <-0.5. Although most cases evolved within this 30 day time span, not every ISO developed within the prescribed ranges. Thus some onset and decay phases of ISO meeting the P-0 criteria were omitted prior to ensemble averaging. A mixture of short-term climate modes and forcing factors arises in these ensemble averages, with the advantage of common features and patterns in the meteorological fields being indicated.

Three atmospheric levels were used in detailed analysis, namely 850, 500 and 200 hPa. The 850 hPa coincides with the South African Plateau (1500 m above mean sea-level). The 500 hPa surface is used for representing vertical motion as this is generally the level of non-divergence and maximum vertical winds. The 200 hPa level is useful for observing how divergent flows interact with convection. In addition to map projections, Hovmöller plots and vertical sections along 25°S and 25°E are analysed for ISO structure and propagation. Composite anomalies are formulated by averaging pentad field data for each phase meeting the prescribed P-E criteria and subtracting a mean based on all phases of all cases.

Meteorological parameters discussed in this paper include, wind velocity and components, vertical wind, specific humidity, precipitable water, and integrated water vapour flux - the product of wind velocity and specific humidity integrated from the surface to 500 hPa. The computation of moisture flux is dependent on terrain elevation, being from 1000 hPa over the oceans and coast, and from 850 hPa over the plateau. The anomaly fields eliminate these discrepancies, as the mean is subtracted.

2.2 Results

Convective indices: OLR and P-E

The historical mean OLR and P-E summer distributions are shown in Figure 2. The OLR distribution (in the period 1975-1987) indicates preferred times during the season for convective events, knowledge of which will improve forecasts of medium-term weather. The P-E curve (1970-1991) is less obtrusive with a gradual upward trend throughout the entire summer and a peak around the end of January.

Mean spectra accumulated from both OLR and P-E time series indicate a prominent cycle in the range 20 to 35 days. The OLR spectrum exhibits a significant peak at 25.7 days, whilst the P-E index displays a flatter spectral distribution. Individual seasonal spectra have a tendency for longer ISO cycles in dry years and more rapid convective 'pulsing' in wet years. The frequency distribution of wet spells (>+0.5 standard deviation P-E, Figure 3a, b) yields a cycle in the range 20-35 days for > 75% of cases. Hayashi and Golder (1993) demonstrate that the 20-35 day ISO is independent of the 45-60 MJO and not a half-harmonic of it.

Hovmoller plots

A frequency analysis of oscillatory modes was conducted using hovmoller longitude-time plots for individual years for selected meteorological anomalies along 25°S. Figure 4 depicts the varied zonal propagation characteristics of ISO over southern Africa. The predominant mode is stationary and reflects the near equal influence of zonal easterly and westerly winds, and local generation of convection from sources of internal and surface heating. Almost half of ISO cases detected in the hovmoller plots are quasi-stationary, and grow and die over the sub-continent. Of the propagating modes, the majority (34%) move eastward in the same sense as the mid-latitude and tropical waves. A smaller percentage move westward (21%) from the Indian Ocean. Results of longitude/time plots at 25°S and latitude/time plots at 25°E. which intersect the study region, are discussed to determine structural evolution of the composite ISO. These plots were formulated from 16 cases over the summer season as previously outlined.

Figure 5 illustrates the composite u-wind component (a) at 200 hPa, v-wind component (b) at 850 hPa and precipitable water (c) for the time frame P-3 to P+2. The u-wind component highlights a tendency for the entire zonal band to become alternatively negative or positive. These abrupt changes refer to the advance and retreat of sub-tropical upper westerlies, as modulated by long-wave patterns. Weaker westerlies prevail during antecedent stages, but strengthen at P-1 where they are at a maximum and then weaken again. The v-wind component at 850 hPa shows westward propagation from the south west Indian Ocean near 80°E, westwards into southern Africa at 10°E from P-3 to P-0. The precipitable water anomalies show a dramatic increase of moisture towards the end of P-1 and at P-0 especially between 20°E and 35°E over southern Africa. Together these indicate the presence of a tropical easterly wave which moves in from the Indian Ocean.

Figure 6 shows the same variables, except in a north-south, time slice along 25°E. Southward propagation in the u-wind component anomalies at 200 hPa (a) is indicative of tropical penetration associated with upper anticyclonic outflow. Upper westerly anomalies shift southward from the equator to 40°S through the sequence. Low level southerly wind anomalies penetrate northward (b) after P-1 in the band 20-50°S. An interesting feature of the precipitable water anomaly plot (c) is the alternating dipole that exists between the equatorial and subtropical regions of Africa. The dipole initially shows increased moisture over the equatorial band and then reverses after P-1, such that precipitable water increases over southern Africa at the expense of the Congo during the wet spell. This evidences vertical (Hadley) overturning operating in conjunction with the ISO.

Composite anomaly fields

In the following section the evolution of the composite ISO over southern Africa is presented in map form using ensemble averages for phases from P-2 to P+2. Figure 7 shows the sequence of water vapour flux (WVF, left) and precipitable water from P-2 to P+2. During the dry and onset stages prominent easterly vector anomalies are seen over the tropical Indian Ocean 0-10° S, 40°-80° E and related to a sub-tropical anticyclonic gyre in the south Indian Ocean and relaxation of the equatorial monsoon. These conditions persist and shift westward into the Mozambique Channel by P-1. A mid-latitude anticyclonic gyre gradually shifts eastward from the South Atlantic to be situated south of Africa by P-0. Over the study area a cyclonic WVF vortex is evident during the wet spell. By P+1 mostly eastward and poleward fluxes of moisture dominate the region particularly over the south Indian Ocean. Following decay of the composite ISO over southern Africa, low level circulation anomalies reverse in the central Indian Ocean. The WVF is directed eastward there at P+2, heralding the re-intensification of the monsoon and a shift in convection to the Indian Ocean.

During antecedent phases precipitable water is anomalously negative across the sub-tropics (-5 to -10 mm at P-1). Precipitable water increases dramatically over most of the region at P-0. A moist axis lies NE-SW over Madagascar at the time of optimum convection, whilst a negative PW anomaly exists over equatorial Africa. It has taken about 10 days from P-2 to P-0 for moisture to penetrate from the central Indian Ocean to southern Africa. Wetter than normal conditions persist during the decay phase (P+1), suggesting a lingering of moisture. By P+2 PW anomalies are near zero over the plateau.

Figure 8 illustrates the sequence of 200 hPa wind (left) and vertical motion anomalies. In the early stages westerly anomalies occur polewards of 40°S. By P-1 a well-defined trough has advanced over the SW tip of the continent to be followed by an anticyclone at P-0. Relatively weak upper circulation anomalies are evident in the tropics. During the onset through decay phases, upper outflow anomalies over the study region are toward the northwest. Following the composite ISO event easterly anomalies are evident almost everywhere south of 15°S.

The vertical motion field at P-2 is relatively neutral over southern Africa. Alternating meridional axes of uplift and subsidence anomalies are found in the South Indian Ocean. By P-1 subsident anomalies are evident over the western Indian Ocean, Madagascar and most of southern Africa except the south-western tip. There negative anomalies (uplift) are associated with the eastward moving mid-latitude trough. In the wet phase uplift is vigorous over the study region and to the north (Zimbabwe). Sinking anomalies are evident to the south of Africa where the anticyclonic gyre is situated. Most of the southern Indian Ocean displays upward motion. During the decay phase uplift anomalies persist over the southeastern escarpment of South Africa, but by P+2 sinking motion anomalies have taken over.

Vertical sections

Figure 9 illustrates the sequence of zonal vertical sections for vertical motion anomalies (left) and specific humidity anomalies from P-2 to P+2. The most prominent feature is uplift (negative anomalies) at P-0 between 20° and 30°E in the layer around 500 hPa. This region exhibits positive anomalies at the onset phase (P-1) and decay stage (P+1). P-2 and P+2 patterns are anti-phase. The progression of specific humidity anomalies reveals negative anomalies in the surface layer over southern Africa at P-2 and P-1, as expected. At P-0 a build-up of moisture is evident over southern Africa between 10° and 40°E. During the decay phase negative anomalies are confined to the lower layers over southern Africa. In the Indian Ocean positive anomalies of specific humidity occur at P+1 and P+2, suggesting an eastward shift of convergence and convection.

Meridional vertical sections for composite ISO phases of vertical motion and specific humidity are illustrated in Figure 10. Vertical uplift anomalies occur in bands at 10°N, 20°S and 50°S during antecedent phases. They coalesce at P-0 into a Hadley distribution with prominent upward motion from 15-30°S and sinking anomalies either side at the equator and 40°S. The decay phases show sinking anomalies over southern Africa and increased uplift over equatorial Africa. Specific humidity anomalies are dominated by a north-south dipole. At P-2 and P-1 moisture is abundant over tropical Africa, whereas the southern African region exhibits a moisture deficit. A shift occurs at P-0 when moisture converges into the surface layer over southern Africa between 10° and 35°S and a marked deficit occurs over the Congo. The alternating north-south dipole is maintained up to P+2.

Conclusions of this chapter are summarised at the beginning of Chapter 4.

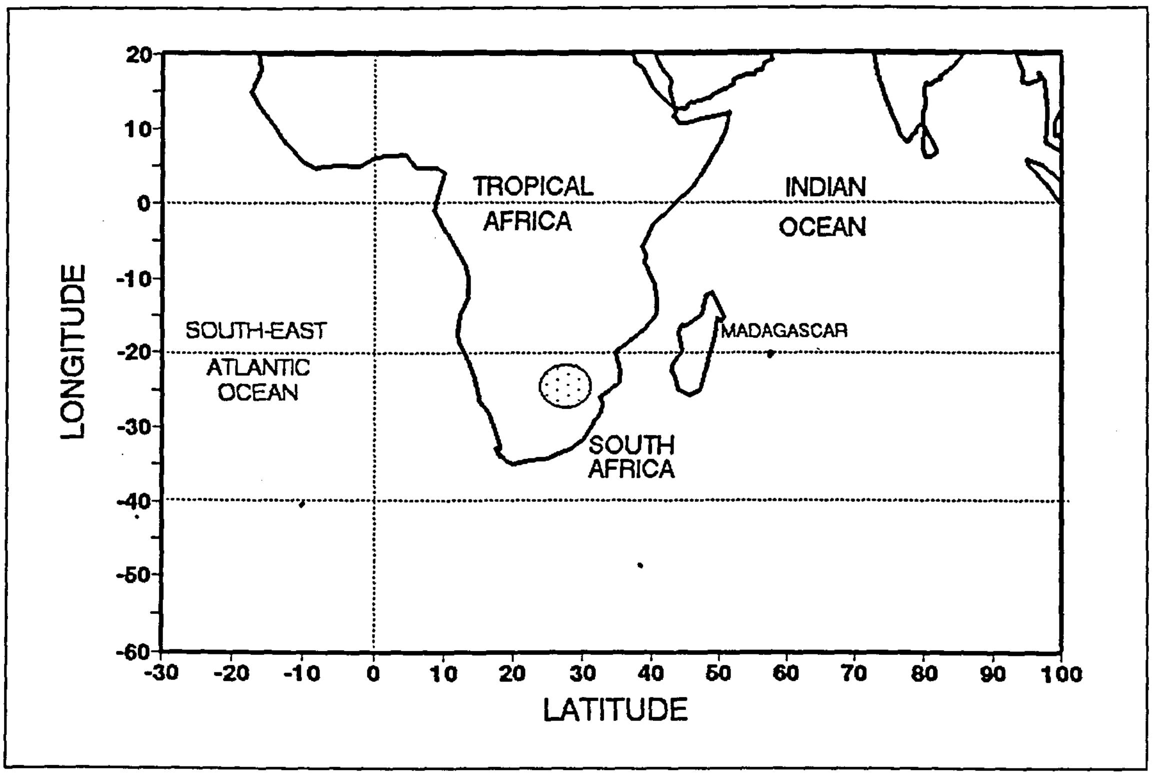


Figure 1 - Location map with domain 20°N-60°S, 30°W-100°E. Shaded circle identifies the study region of South Africa where OLR and P-E indices were extracted.

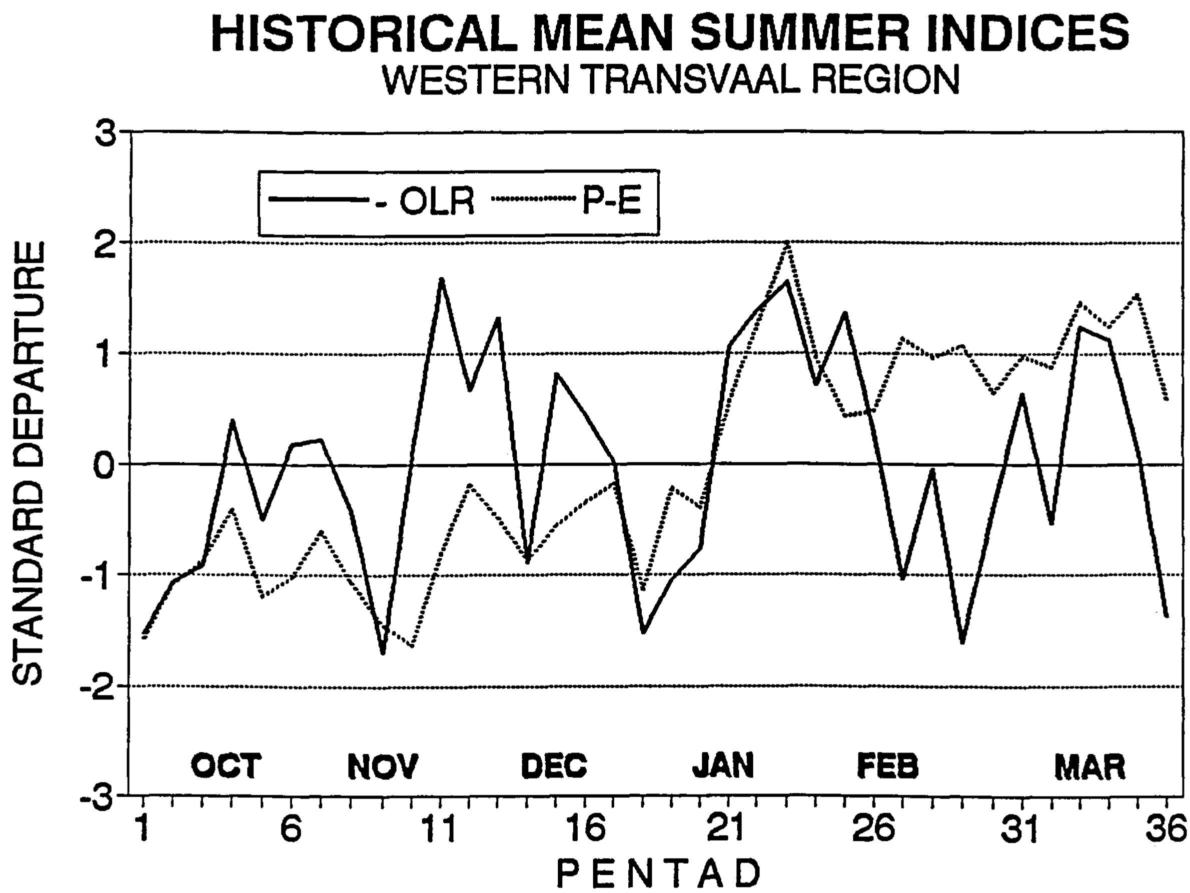
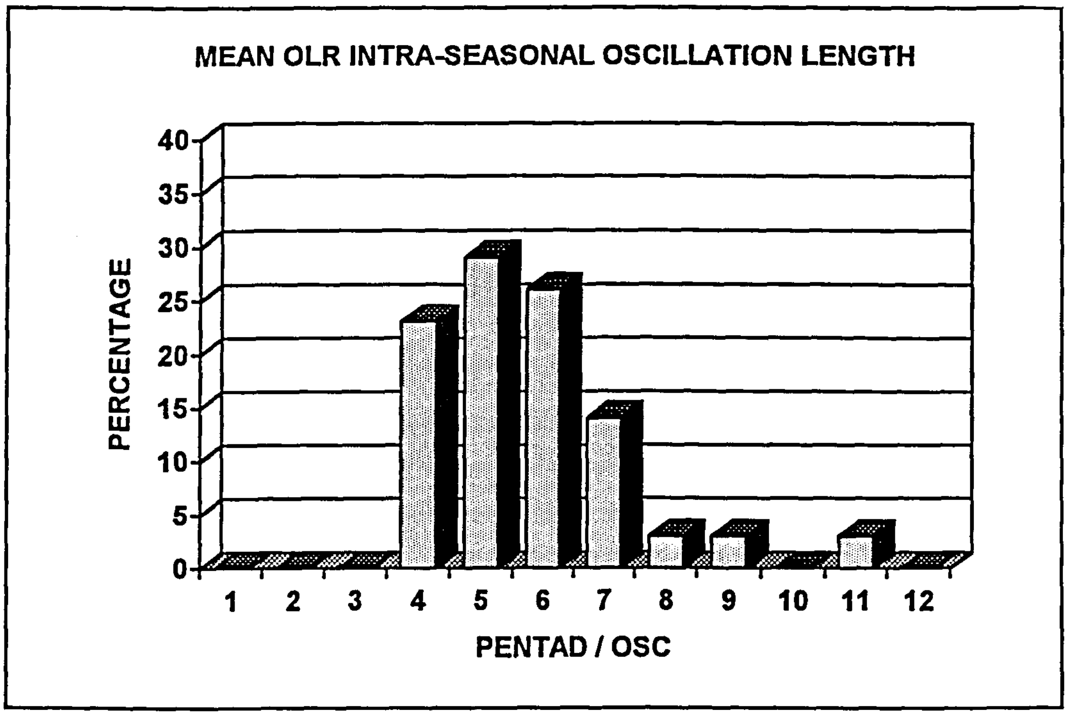


Figure 2 - Historical mean OLR and P-E summer indices. OLR (inverted) is bold line, P-E dotted; expressed as standardised departures for the October to March period.



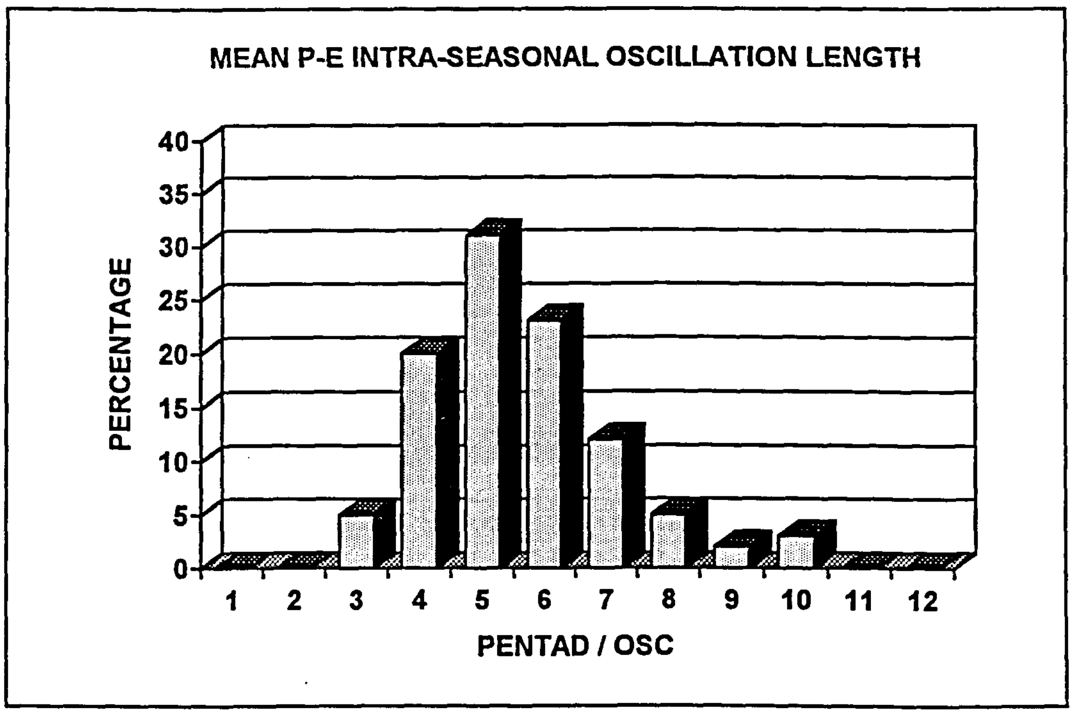


Figure 3 - Frequency distribution of ISO cycles expressed in pentads per oscillation, as identified by OLR (a) and P-E (b) time series.

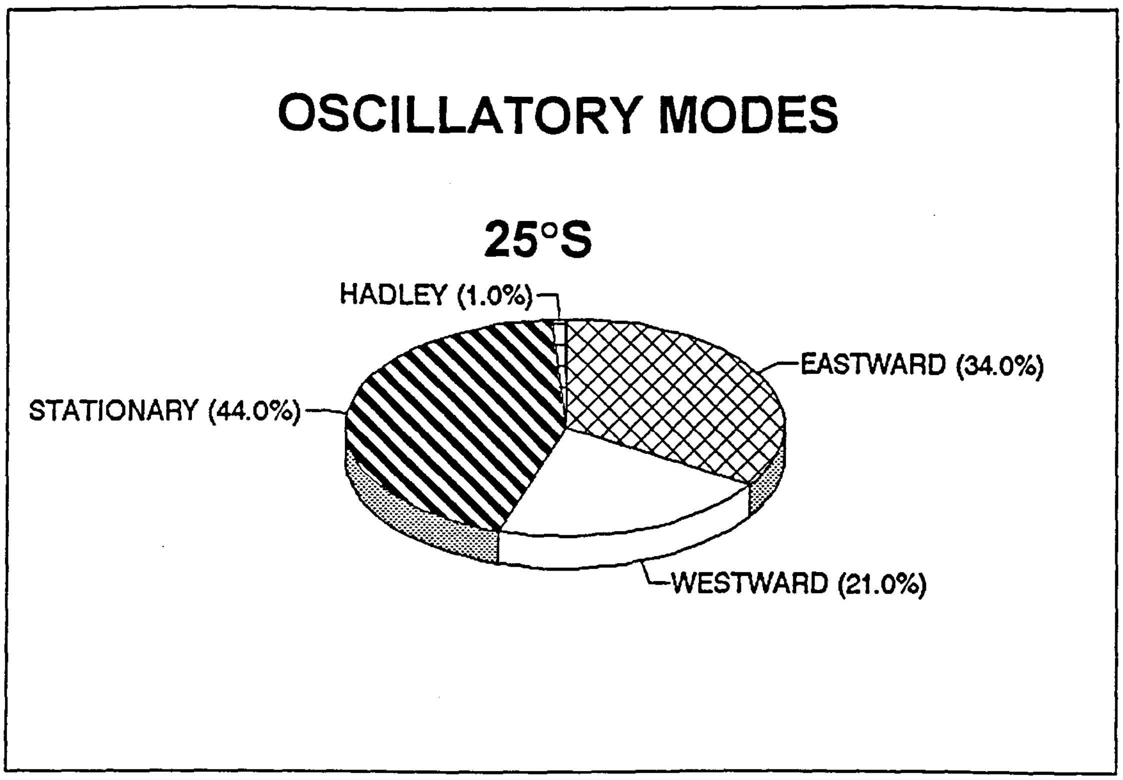


Figure 4 - Frequency distribution of ISO zonal propagation characteristics as identified in ECMWF Hovmoller analyses for the period 1986-1992.

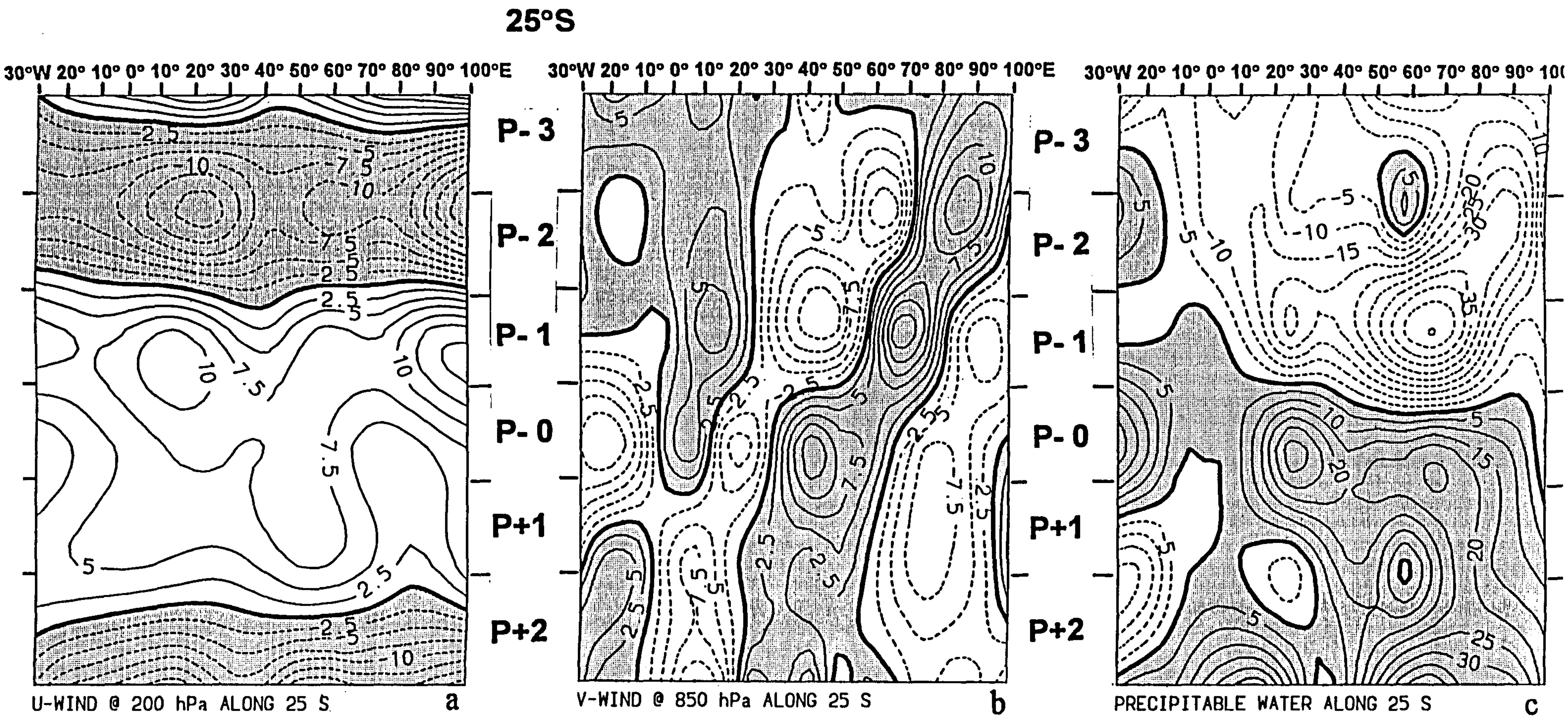


Figure 5 - Longitude/time plot along 25°S showing u-wind component 200 hPa anomalies (a, shaded = easterly); v-wind component 850 hPa anomalies (b, shaded = southerly) and precipitable water anomalies (c, shaded = positive) for the composite period P-3 to P+2.

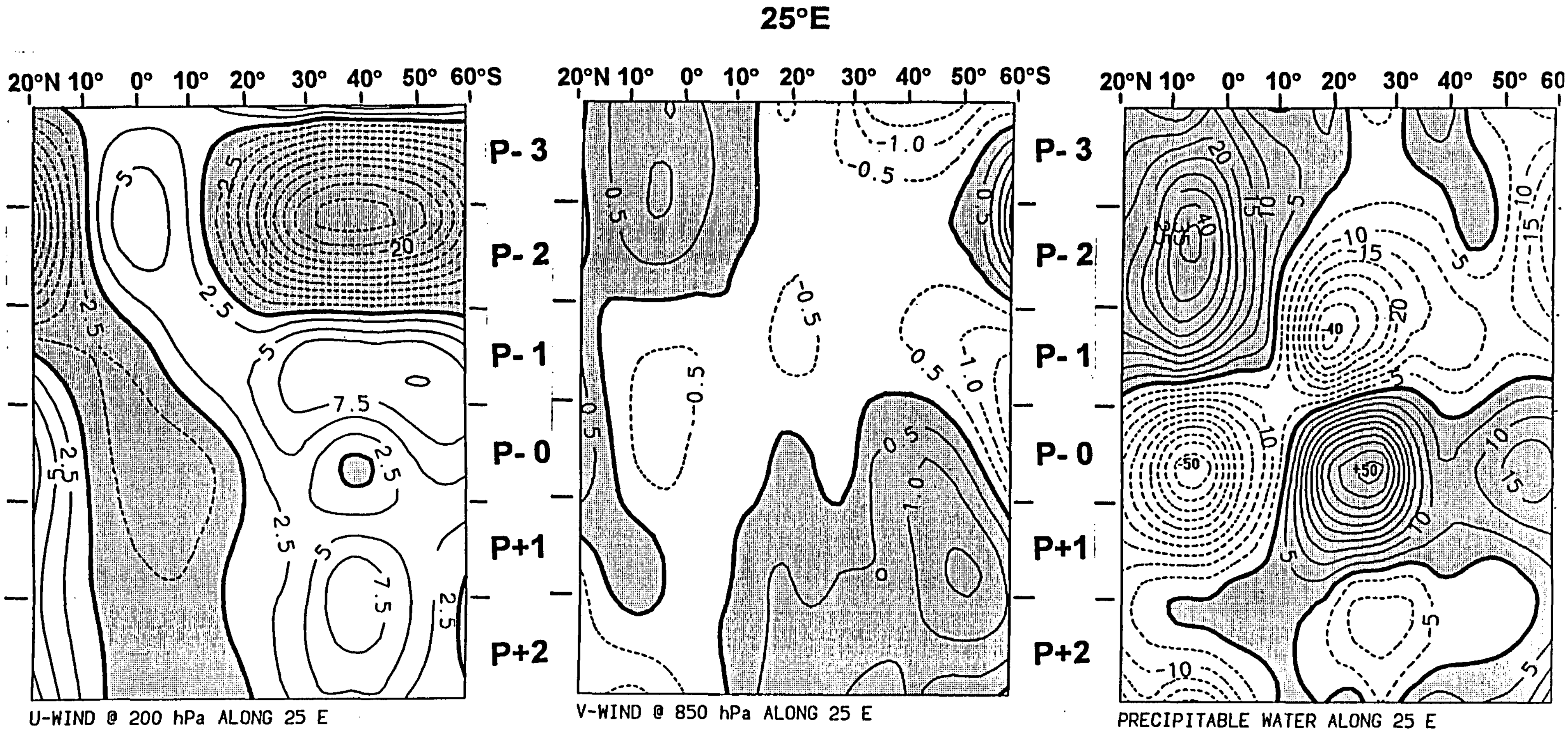


Figure 6 - As in figure 5, but a latitude/time plot along 25°E.

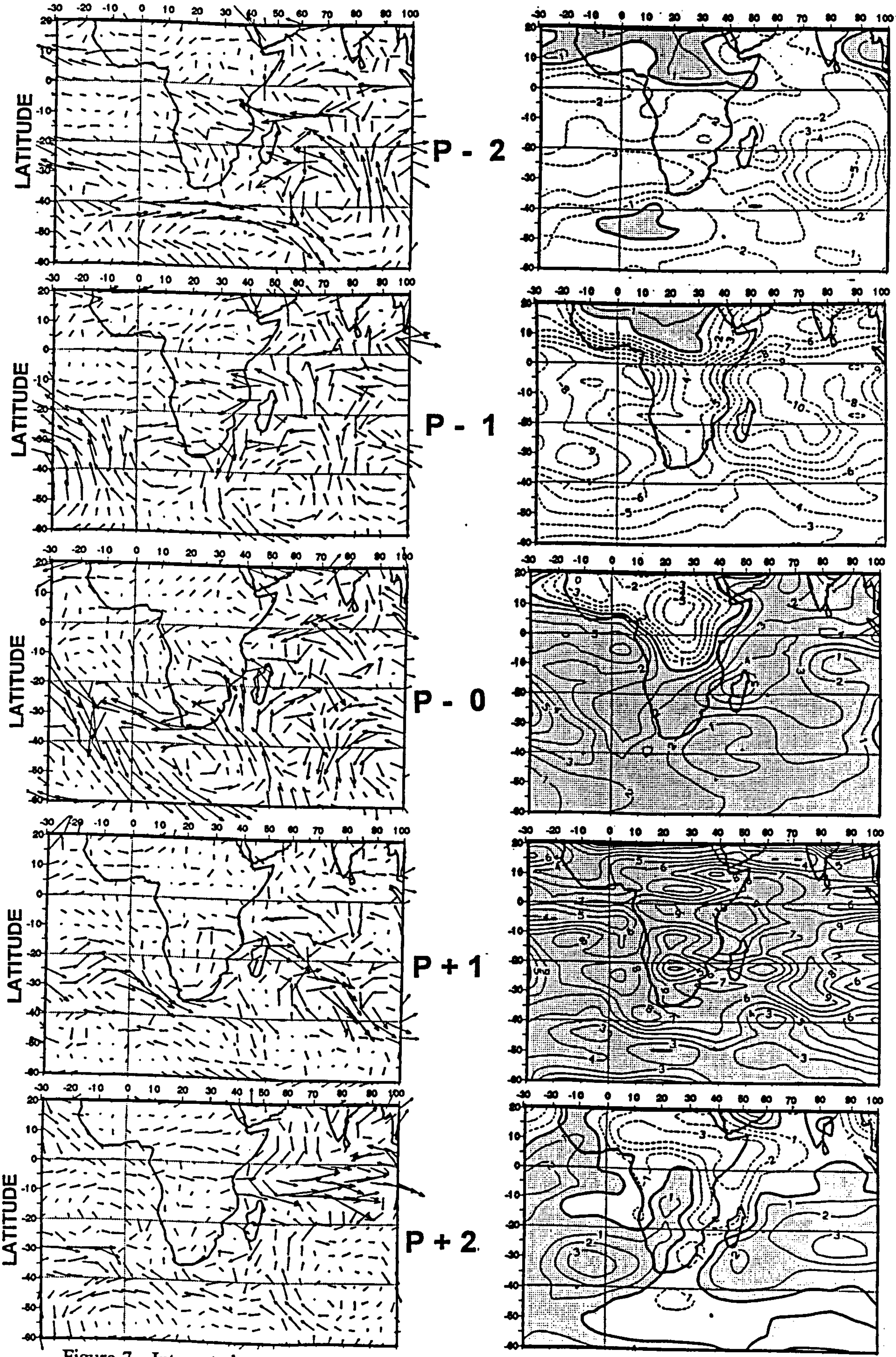


Figure 7 - Integrated water vapour flux anomalies (left) and precipitable water anomalies for the composite ISO sequence P-2 to P+2 (top to bottom). WVF vector → = 50 g kg^{-1} ms^{-1}.

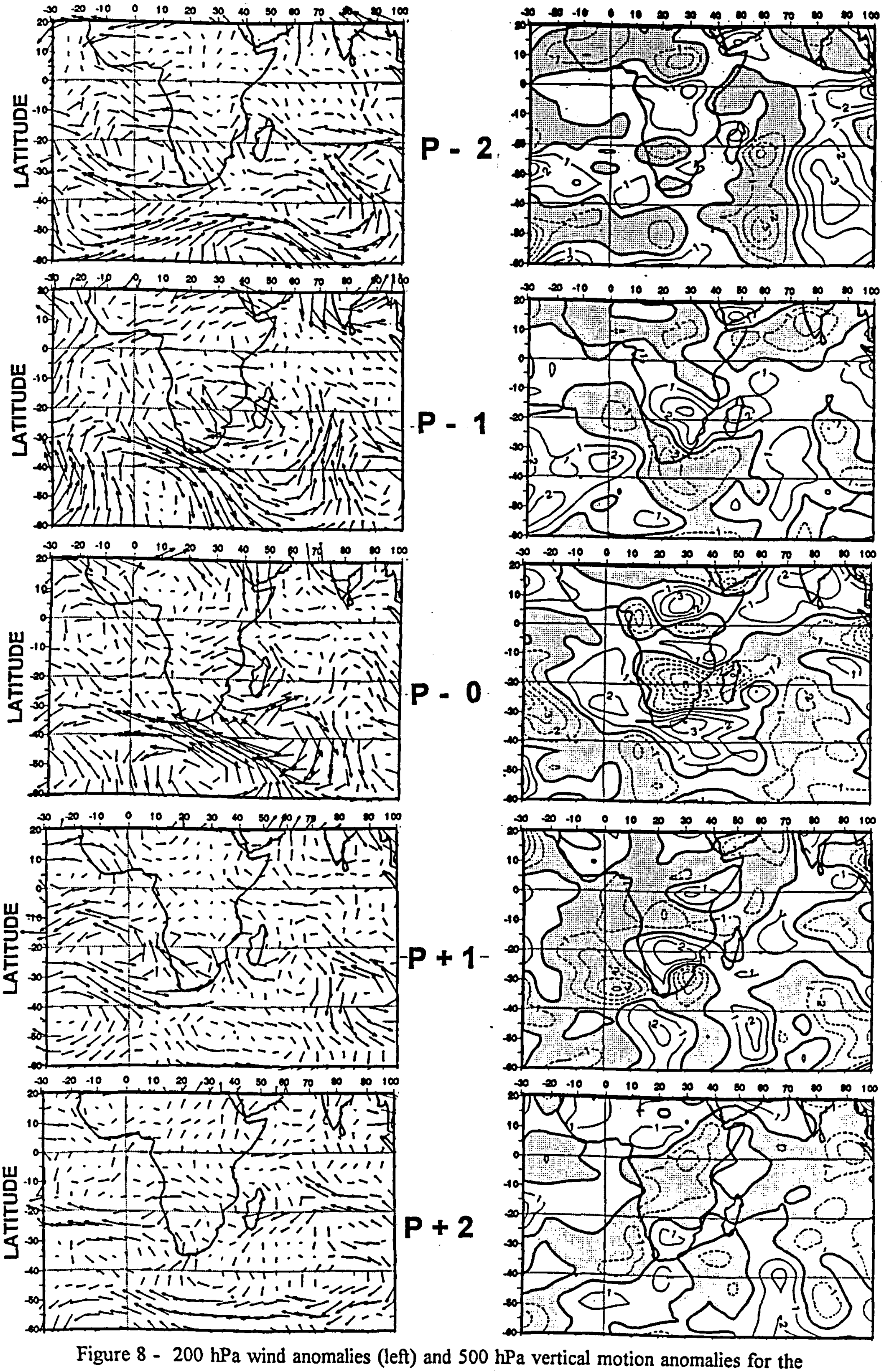


Figure 8 - 200 hPa wind anomalies (left) and 500 hPa vertical motion anomalies for the composite ISO sequence P-2 to P+2 (top to bottom), as in Figure 7. wind vector → = 10 ms^{-1}. Contour interval is 1×10^{-2} Pa s^{-1}. Shaded areas denote uplift.

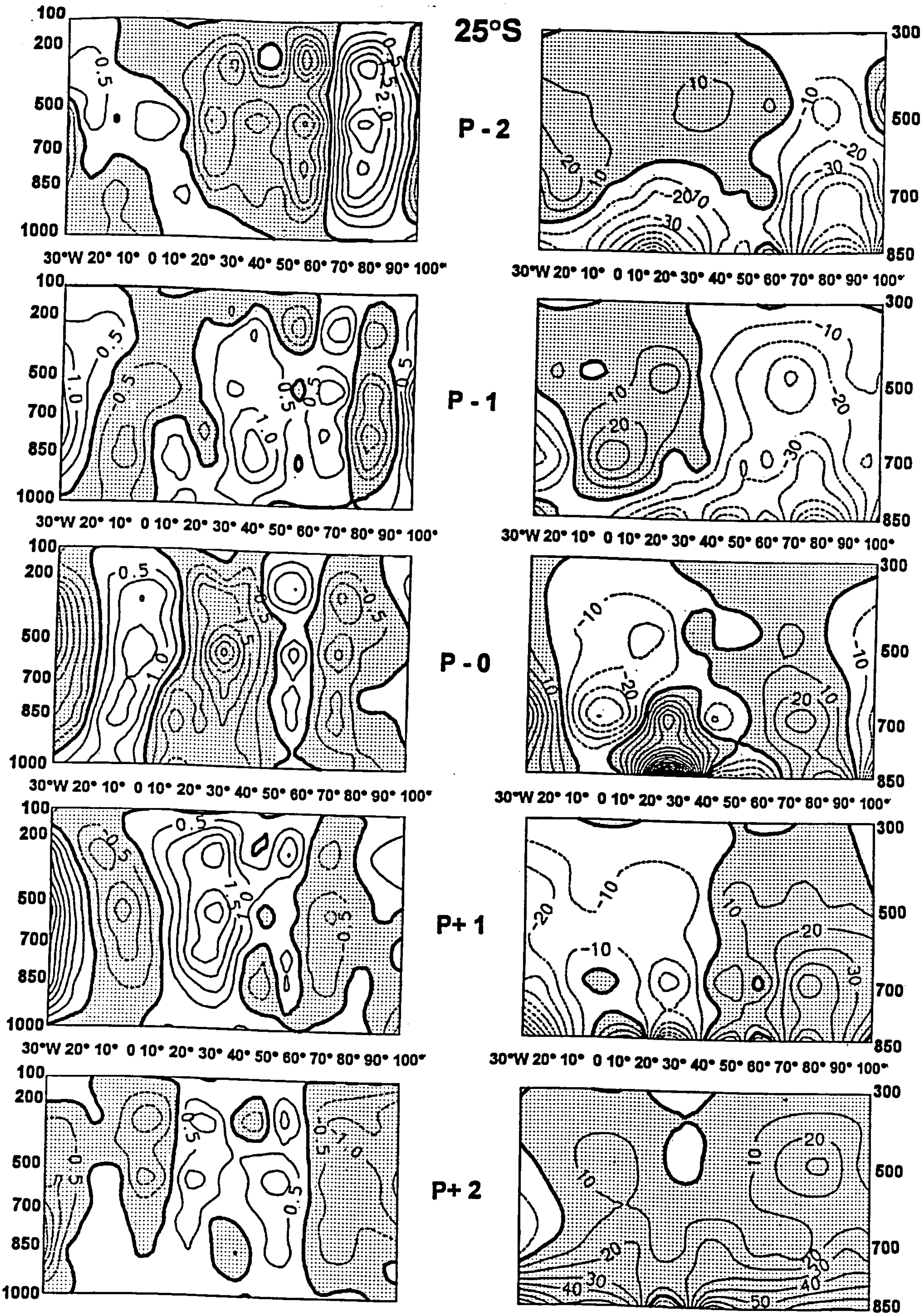


Figure 9 - Zonal vertical sections along 25°S showing vertical motion anomalies (left, contour 0.5 x 10^{-2} Pa s^{-1}) and specific humidity (contour 1 x 10^{-2} g kg^{-1}) for the composite period P-2 to P+2. Shaded areas in denote uplift and moisture. Vertical axis = pressure

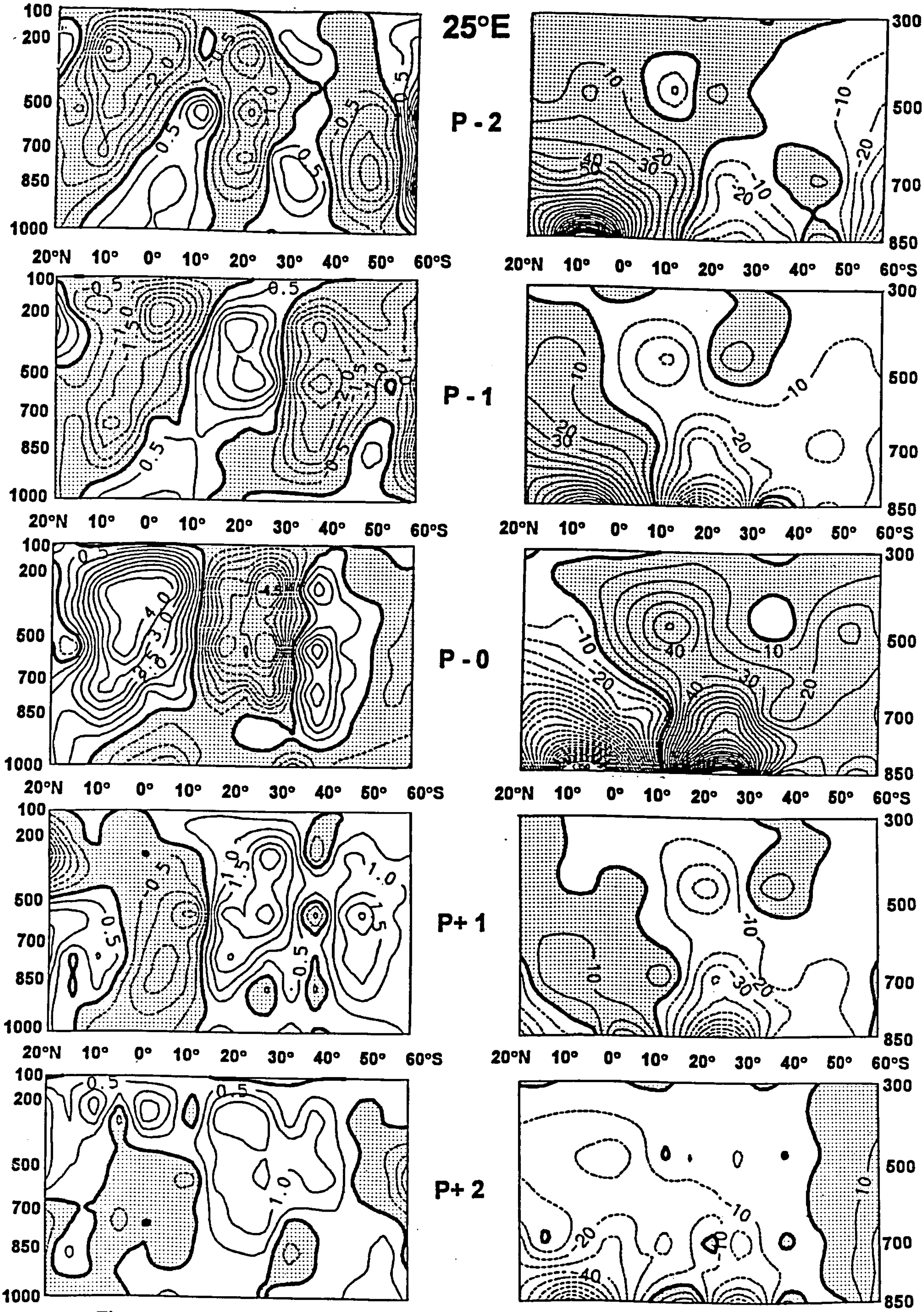


Figure 10 - Meridional vertical sections along 25°E showing vertical motion and specific humidity anomalies as in Figure 9. Vertical axis = pressure (hPa) where: 850~1.5km,500~5.5km

Chapter 3: Intra-seasonal convective phases

3.1 Background and Methods

In this chapter the characteristics of wet spells in early and late summer are contrasted. Wet spells are analysed from pentad (5 day mean) area-rainfall time series for the November-March season in the years 1987-1992. These are averaged from the standardised departures for 30 stations over central Zimbabwe (figure 11). It is useful to realise that results for this area are consistent with that found over northeastern South African and eastern Botswana. In a global warming scenario of doubled CO_2, GCM simulations predict that that the weather patterns over Zimbabwe will shift polewards towards South Africa (Joubert 1995) This ensures that the research has wider applicability.

For each season, pentad rainfall anomalies above one standard deviation are selected for grouping dependent on their month of occurrence. Using 12 UT ECMWF weather data and derived products, the spells are numerically averaged to illustrate meteorological structure at peak convection in the domain 20°N-40°S, 30°W-90°E. Results are presented for 700, 500 and 200 hPa levels, except for moisture fluxes and distribution which are vertical integrals from the surface to 500 or 300 hPa levels, respectively. Differences between wet spells centred on late-November and late-January are computed.

3.2 Results

<u>Rainfall</u>

Pentad rainfall anomalies for each summer of overlapping ECMWF data (1987-1992) are shown in figure 12. The onset, duration and cessation of the rainy season varies considerably from year to year. Wet and dry spells are non-stationary with respect to season and intra-seasonal oscillations may be investigated. During the dry summers of 1987 and 1992 there were only two wet spells in December and January. The relatively wet years of 1989 and 1990 exhibit continuously wet periods in January and February. Significant cycles are found at 45 and 22.5 days in 1987, at 45.5 and 13.5 days in 1988, at 12.9 days in 1989, at 13.9 days in 1990, at 33.4 days in 1991 and at 35.5, 18 and 14.5

days in 1992 (Makarau 1995). Zimbabwe pentad rainfall departures are well correlated with rainfall received over eastern Botswana and northeastern South Africa, so results presented here can be extrapolated to those areas (Jury et al 1993). In addition, the expected gradual southward migration of climatic conditions in the context of global warming, means that results for Zimbabwe may soon be applicable to northeastern South Africa.

Moisture distribution

In this section meteorological composites are presented for the sequence of wet spells. The water vapour flux (WVF) and precipitable water (PW) are shown in sequence from early to late summer in figures 13 and 14. At the onset of summer, moisture is advected around the Indian Ocean anticyclone onto eastern tropical Africa. WVF is confluent over the western Indian Ocean and over Angola. The WVF is eastward in the extra-tropics. During December and January monsoon recurvature gradually increases in the northern Mozambique Channel and cyclonic vorticies develop over the tropical Indian Ocean. Westerlies retreat over southern Africa and the WVF slackens in the mid-latitudes. An area of confluence gradually shifts westward from Zimbabwe in January to Namibia in March, as the monsoon in the Indian Ocean dies off and an anticyclone develops over southeastern South Africa. The WVF field demonstrates an important poleward trajectory of moist air sourced from the Congo Basin during mid-summer in the region 15-20°S, 25-30°E. The confluence between this tropical stream and westward WVF further south determines the area of low level convergence, uplift and rainfall.

Precipitable water is relatively low over southern Africa in the early summer (< 30 mm) and increases up to the February wet spell. Greatest amounts of PW occur over the equatorial Atlantic Ocean with a tongue extending into the Congo Basin. The tropical Indian Ocean is another region of PW > 50 mm which extends a tongue towards the Mozambique Channel by mid-summer in association with the advance of the monsoon and marine inter-tropical convergence zone (ITCZ). Both areas of high PW reflect underlying sea surface temperatures (SST) > 27°C. PW over southern Africa gradually increases through the course of summer to a peak in March when the 40 mm isoline reaches 15°S over Angola. Unlike the Indian Ocean, the band of high PW over the Atlantic remains quasi-stationary near the equator, consistent with the behaviour of an ITCZ constrained by cooler SST to the south. The eastern seaboard of southern Africa obtains a greater moisture content than elsewhere.

Significantly PW is < 30 mm over a large part of southern Africa south of 25°S throughout summer, particularly during the first wet spell in November. This indicates that moisture is a limiting factor in early summer. It is expected that kinematic forcing through the circulation must be more vigorous to overcome the water deficit. In late summer local PW values are higher and confluence of WVF from the Congo and the Mozambique Channel is notable.

Low level circulation

The WVF field is relatively consistent with 700 hPa flow, so circulation derivatives at this level are assessed in Figure 15. For the first wet spell of early summer there is low level convergence (mass influx) extending from southeastern Africa to the Congo. Local minima are located at 18°S, 30°E and at 0°S, 20°E. This zone of convergence is interrupted by a ridge of positive values extending from northeast Africa. Confluence in the ITCZ is well represented in mid-summer between 10 and 20°S over southern Africa. Initially this zone of values < 0 is oriented zonally, but tilts NW-SE in February and retreats towards the Congo Basin by March. Relatively strong positive divergence is noted over the Sahel region and to a lesser extent over southwestern Africa.

The seasonal cycle is more evident in the low level vorticity (spin) pattern. Anticyclonic rotation (+) is prevalent in early summer. A zonally elongated, cyclonic circulation (-) develops in the December, January and February wet spells between 10 and 20°S. The cyclonic centres shift and coalesce from one wet spell to the next and define a trough which extents from the Mozambique Channel to Angola. In the December spell cyclonic cells (-) are located over 15°S, 20°E and the Indian Ocean at 10°S, 75°E. In January and February these grow together in a zonal band with a minima over Madagascar. By March the zonally oriented cyclonic centres have dissipated. Throughout summer a band of strong anticyclonic vorticity is located across the mid-latitudes south of Africa. In the early and late summer this area encroaches over South Africa.

Mid-level circulation and vertical motion

Mid-level zonal and meridional winds are shown in figure 16 for the seasonal progression of summer wet spells. The '0' line separating tropical easterlies (-) from extra-tropical westerlies (+) is located near 15°S in November and retreats to near 25°S by January. However westerly winds in the mid-latitudes strengthen causing a sharp gradient across the sub-tropics in December and January. These gradient slacken in February and March. Tropical easterlies are located over the equatorial zone throughout summer and attain maximum velocity > 6 m s^{-1} at the 500 hPa level in December, January and March wet spells. The meridional wind flow displays a stationary pattern in the sub-tropics south of 25°S. Northerlies (< 0) occur over the SE Atlantic (20°W-0) and SW Indian oceans (45-65°E) whilst southerlies are evident to the south of Africa (15-35°E) during wet spells. This pattern is less evident during the February wet spell and tends to shift E-W by 10-20 degrees of longitude from month to month. During wet spells the equatorial band is affected by southerly flow over the western Sahel and northerly flow over the western Indian Ocean. Mid-latitude southerlies to the south of Africa extend northward toward Madagascar in the January and March wet spells.

Mid-level vertical motion is represented in figure 17. Rising motion (-) dominates the tropical band over Africa as expected. A NW-SE axis of uplift occurs in all wet spells. Centres of action (< -0.12 10^{-2} Pa s^{-1}) are located over Africa near 5°S, 15-20°E and 15°S, 30°E. Ascent is greatest and most organised in the December and January wet spells and gradually extends eastward toward Madagascar and the SW Indian Ocean. Centres of strong mid-level uplift overly regions of low level convergence and cyclonic vorticity, and identify diabatic heat sources where water vapour condenses to liquid creating excess energy. This may be channelled polewards over southern Africa. Prominent sinking motions are found over the tropical SE Atlantic and over the southwestern tip of Africa where anticyclonic divergence and cool SST are present.

Upper level circulation

The forcing of wet spells by upper level circulation features is inferred from the 200 hPa divergence and vorticity field in figure 18. Upper divergence, conducive to rainfall production, is prominent over Africa and exhibits a N-S alignment in the

November and March wet spells. In the mid-summer wet spell upper divergence is strong over Madagascar and the tropical Indian Ocean, which creates an E-W alignment. A centre of action (> +0.4 10^{-5} s^{-1}) is found throughout summer over southern Zambia (15-20°S, 25-30°E) which joins a second cell of upper divergence over northern Madagascar, except during the first wet spell in November. Upper convergence, which would suppress convection, is prominent in the Mozambique Channel in November. Upper convergence is present throughout the summer over the tropical SE Atlantic and just south of Africa.

Upper vorticity patterns are dominated by a persistent anticyclonic band (> +2 10^{-5} s^{-1}) across southern Africa from 10-25°S. This reflects the shearing effect of tropical easterlies and mid-latitude westerlies at the 200 hPa (12 km) level. Generally cyclonic vorticity is found over the southern Sahel and equatorial band. The cell of maximum vorticity shifts and changes intensity only slightly through the summer. The outflow from tropical thunderstorm clusters may be assisted by anticyclonic rotation in the upper troposphere.

Differences between early and late summer

Wet spells occurring in November and January are contrasted in this section through numerical subtraction of the composite fields. Figure 19 illustrates these differences for various meteorological parameters. The 500 hPa geopotential height (a) demonstrates lower values in the mid-latitudes in early summer. Greatest differences (-50 gpm) are located in the band 30-35°S and refer to increased baroclinic effects in the November wet spell. Slight increases in height are found in the tropics. In response to lower heights, zonal winds are > +5.0 m s^{-1} stronger across the sub-tropics (b). Enhanced equatorward penetration of westerly flow suggests that upper level shear plays a role in early summer convective systems. Differences between early and late summer meridional wind flow patterns are most evident in latitudes south of 25°S. There, increased southerly flow is found at longitudes 10 and 60°E, whilst increased northerly flow is located over the South Atlantic (c). Over the tropics meridional wind differences between early and late summer are small. In contrast, differences in the vertical motion field are rather large in the tropics. Uplift is greater over the western Congo and less over northern Madagascar in early summer (d). This pattern demonstrates the southeastward shift of an internal heat source as summer progresses. Another area of increased uplift in early summer is over the SW Atlantic.

In figure 20 differences between early and late summer circulation derivatives are illustrated. The low level divergence (a) exhibits relatively minor changes from early to late summer except over the Congo where convergence is considerably greater in early summer. At the 700 hPa level the vorticity is more anticyclonic in the early summer in the band 10-25°S. In the equatorial and mid-latitude bands on either side, the low level vorticity is more cyclonic in early summer (b). In the upper level, divergence is considerably greater in the equatorial band in early summer, and much less over northern Madagascar. Over southern Africa upper divergence is slightly greater in early summer (c). The upper vorticity differences between early and late summer are dominated by a band of increased cyclonic values in latitudes south of 25°S. The opposite holds true for the equatorial band, where anticyclonic vorticity is greater in early summer (d).

Vector differences of upper and lower circulation regimes for early and late summer wet spells are illustrated in figure 21. A key feature of the upper circulation is the equatorward penetration of the sub-tropical westerly jet stream in early summer. All across the band 10-25°S westerlies are up to 20 m s^{-1} greater in November than in January (top panel). In the WVF field greatest differences are confined to marine regions. Over the tropical Indian Ocean the seasonal onset of the monsoon circulation is evident. Westward WVF vectors there signify reduced monsoon recurvature in the early summer. Over southern Africa a sharp demarcation along 20°S separates early vs. late summer differences in westward tropical fluxes originating from the Indian Ocean; and eastward fluxes of moisture originating from the SE Atlantic.

Conclusions for this chapter are given in the second section of Chapter 4.

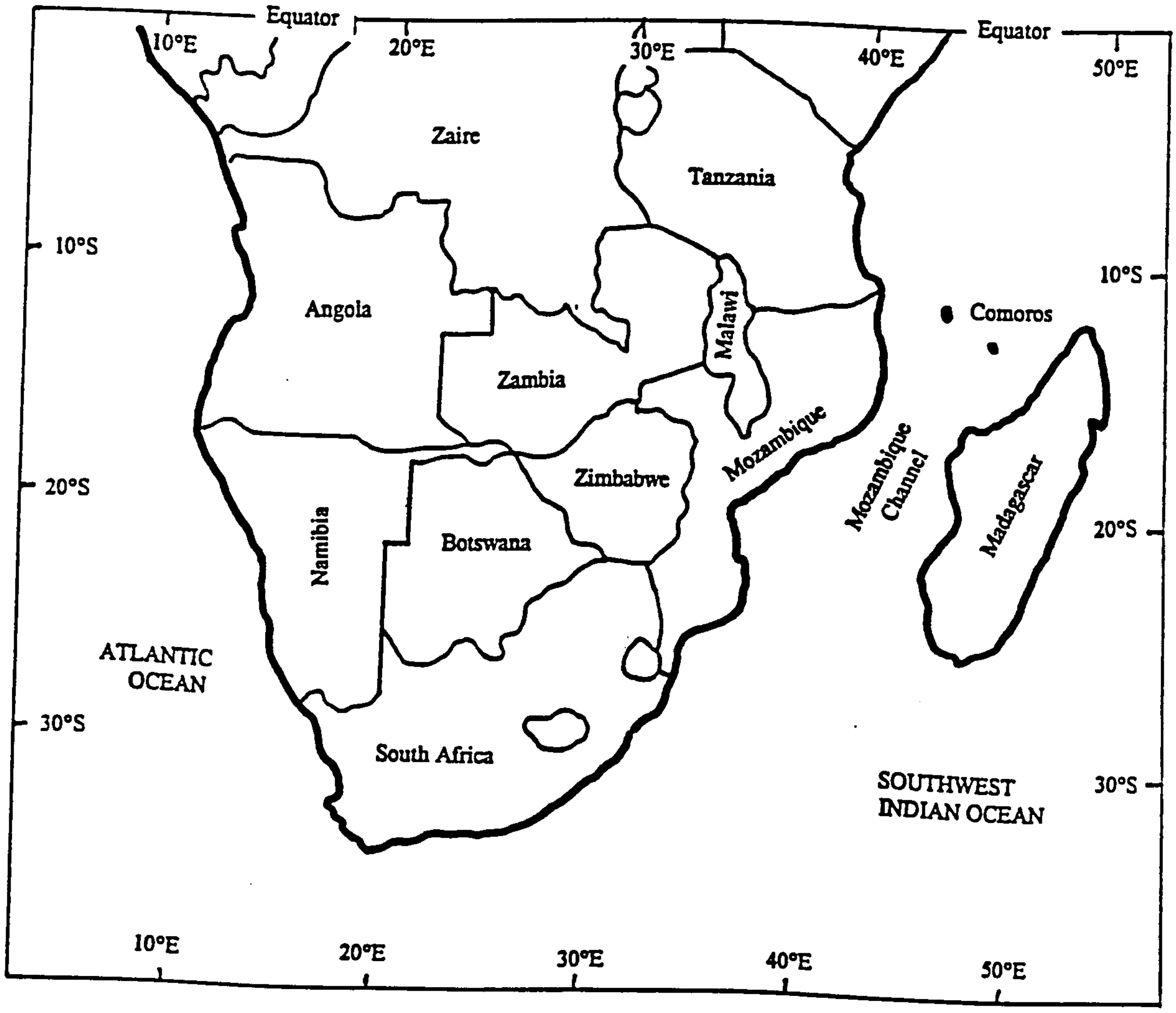


Figure 11 - Location map showing political boundaries and place names used in the text.

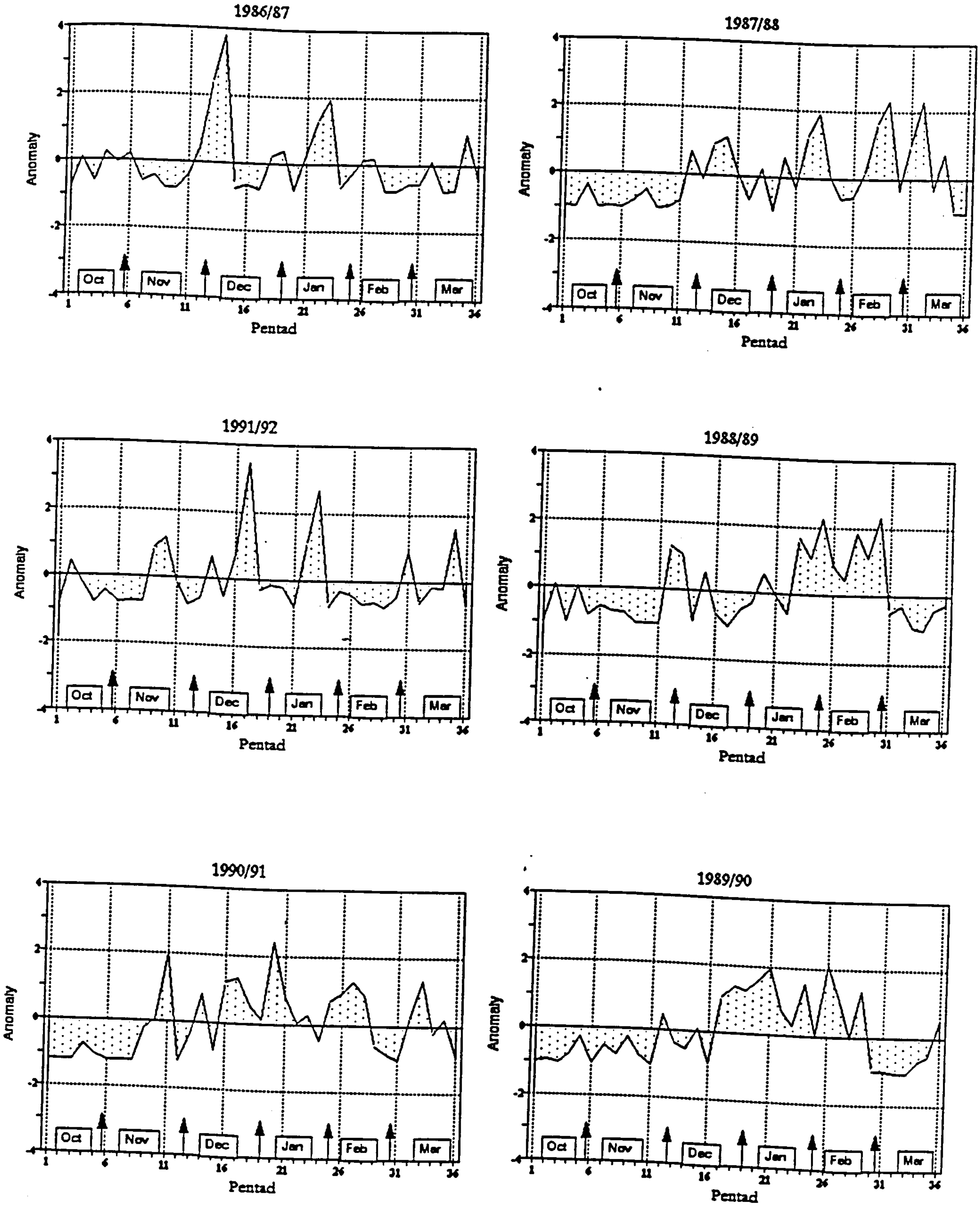


Figure 12 - Temporal distribution of pentad area-rainfall departures from the historical mean for the years 1987-1992 (clockwise).

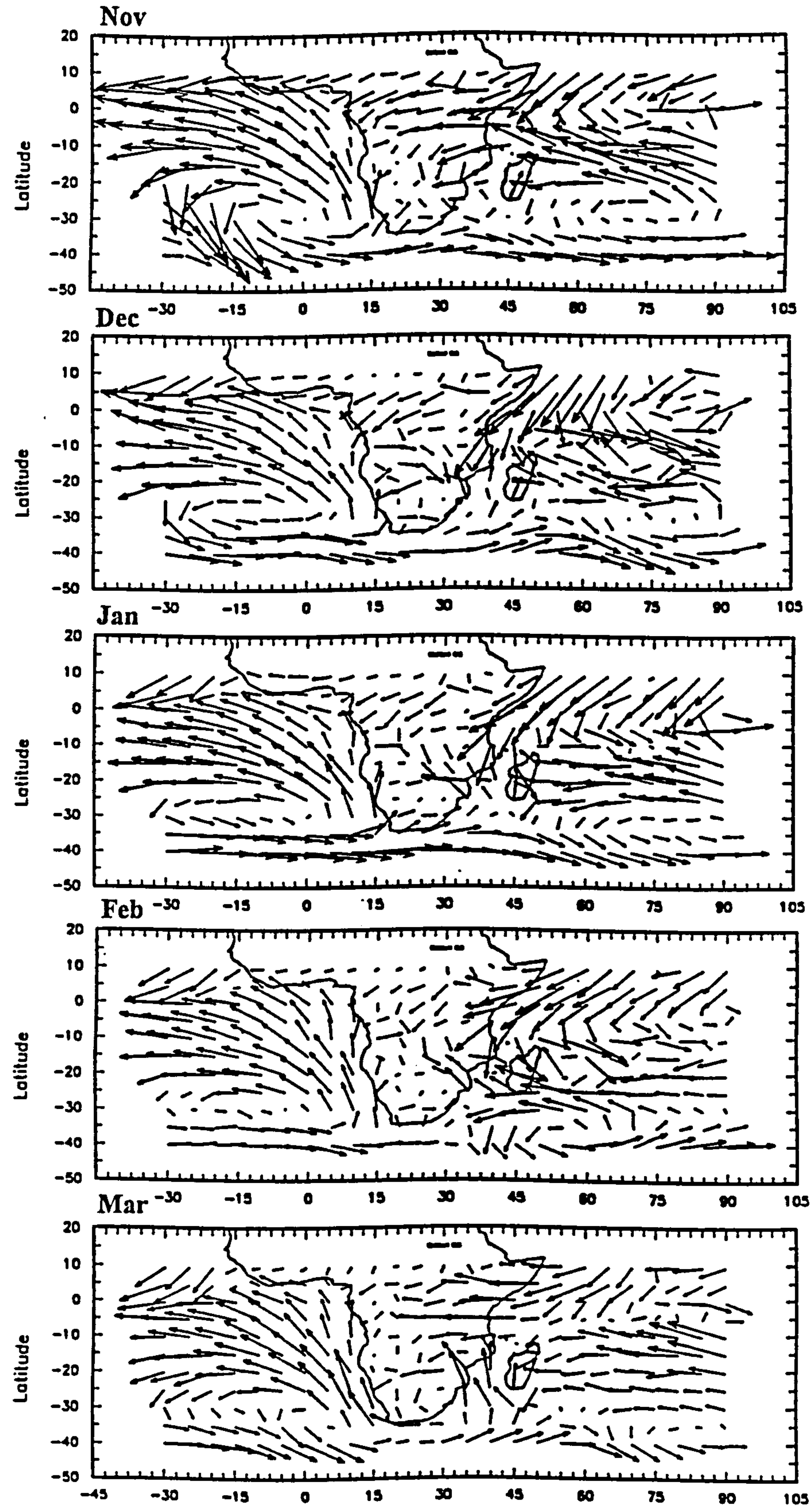


Figure 13 - Water vapour flux integrated from surface to 500 hPa for the sequence of composite pentad wet spells from early to late summer (top down). Longest vector is 225 g kg^{-1} m s^{-1}.

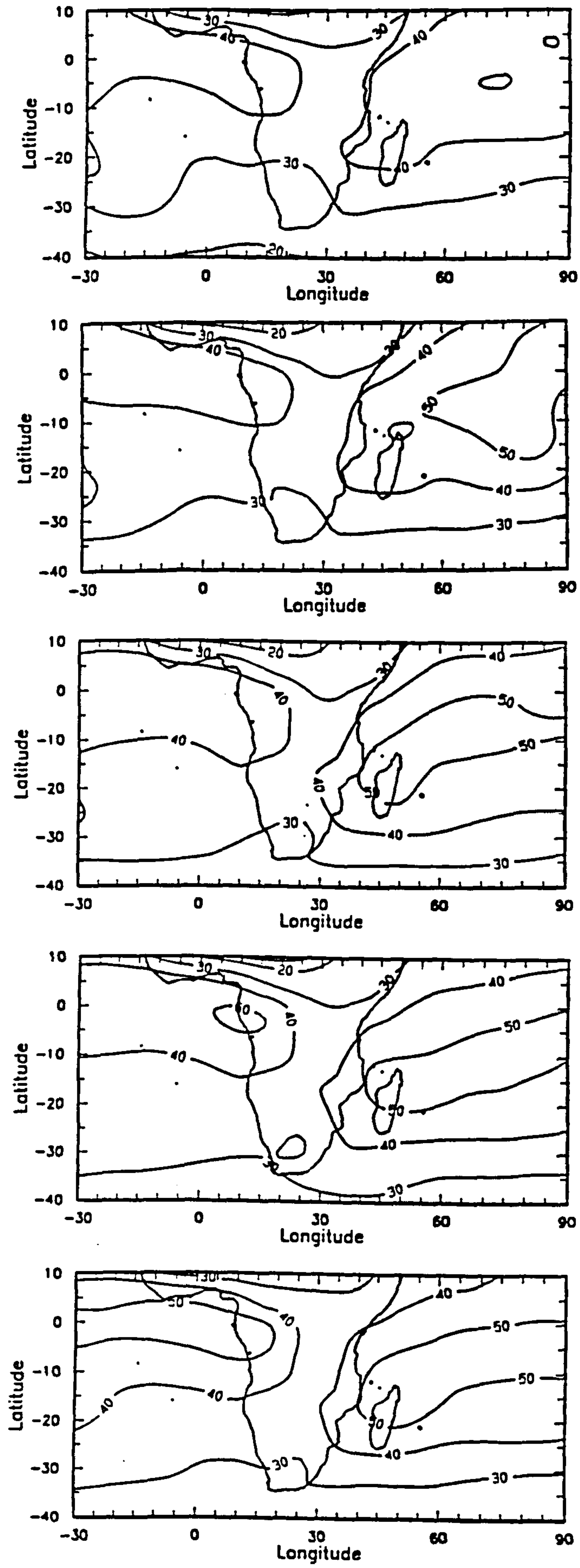


Figure 14 - Precipitable water for wet spells. Isolines are every 10 mm.

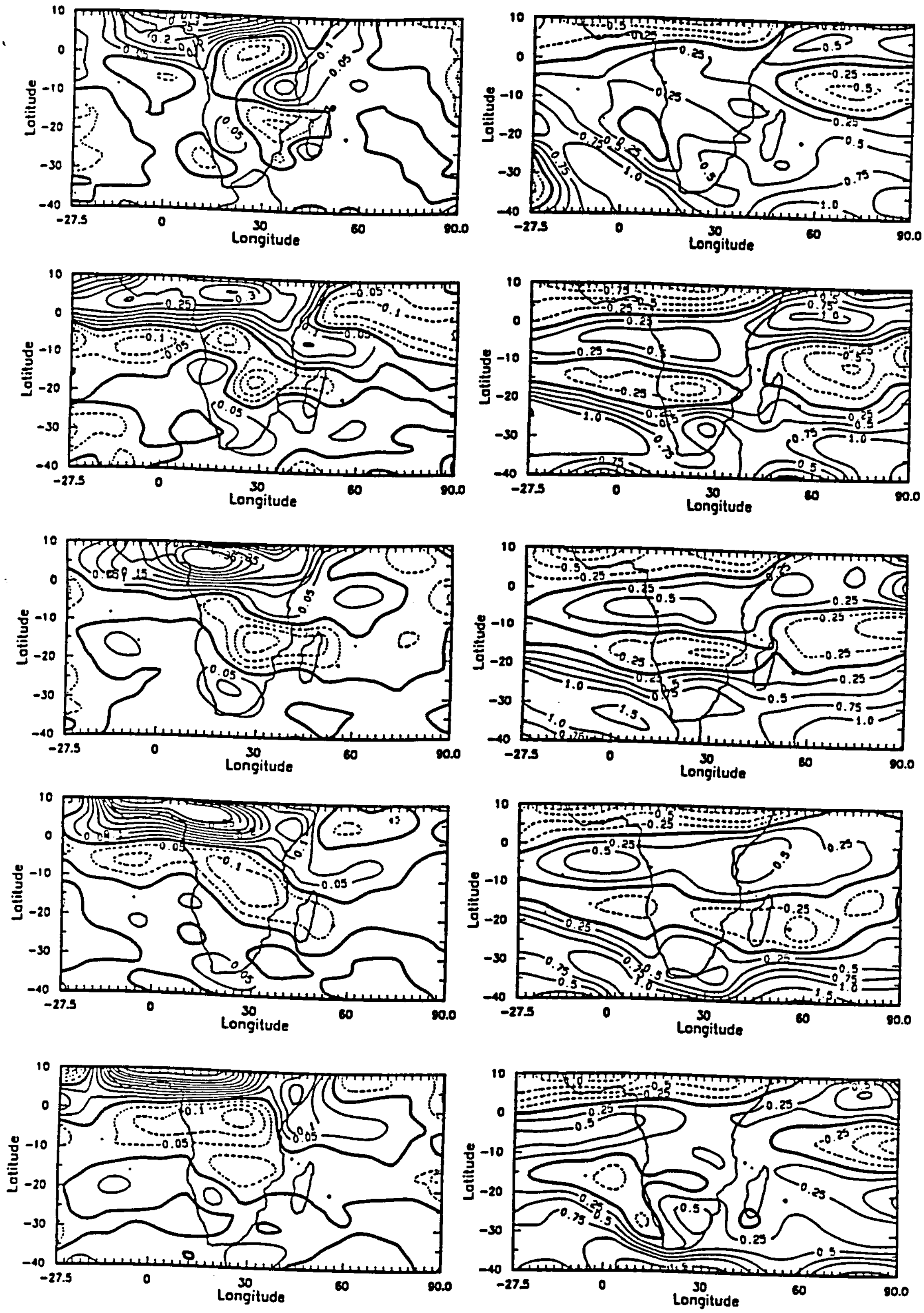


Figure 15 - 700 hPa divergence (left) and vorticity sequence for wet spells in units 10^{-5} s^{-1} . Negative areas are enclosed by dashed lines.

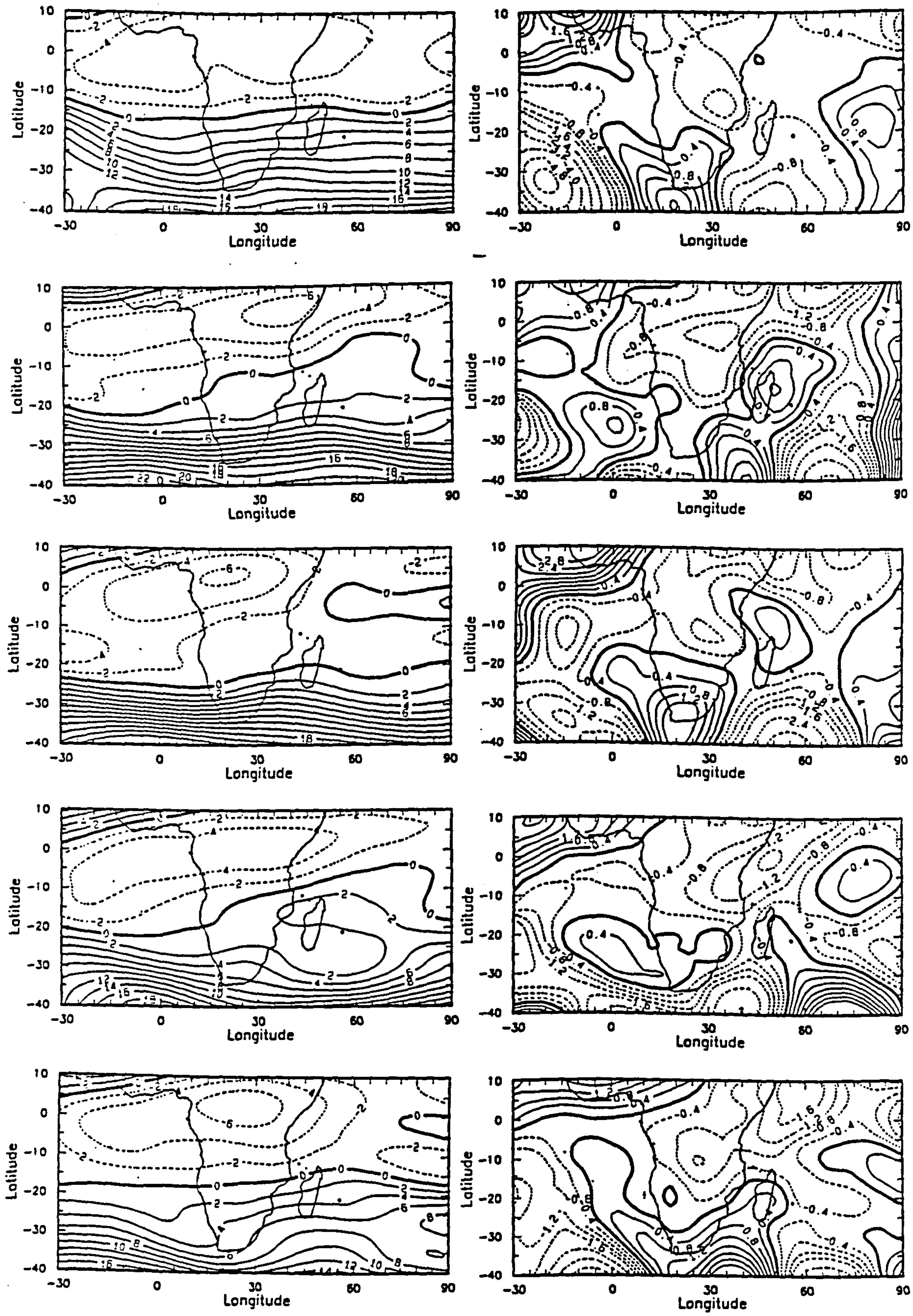


Figure 16 - 500 hPa zonal (left) and meridional winds for wet spells in m s^{-1}.

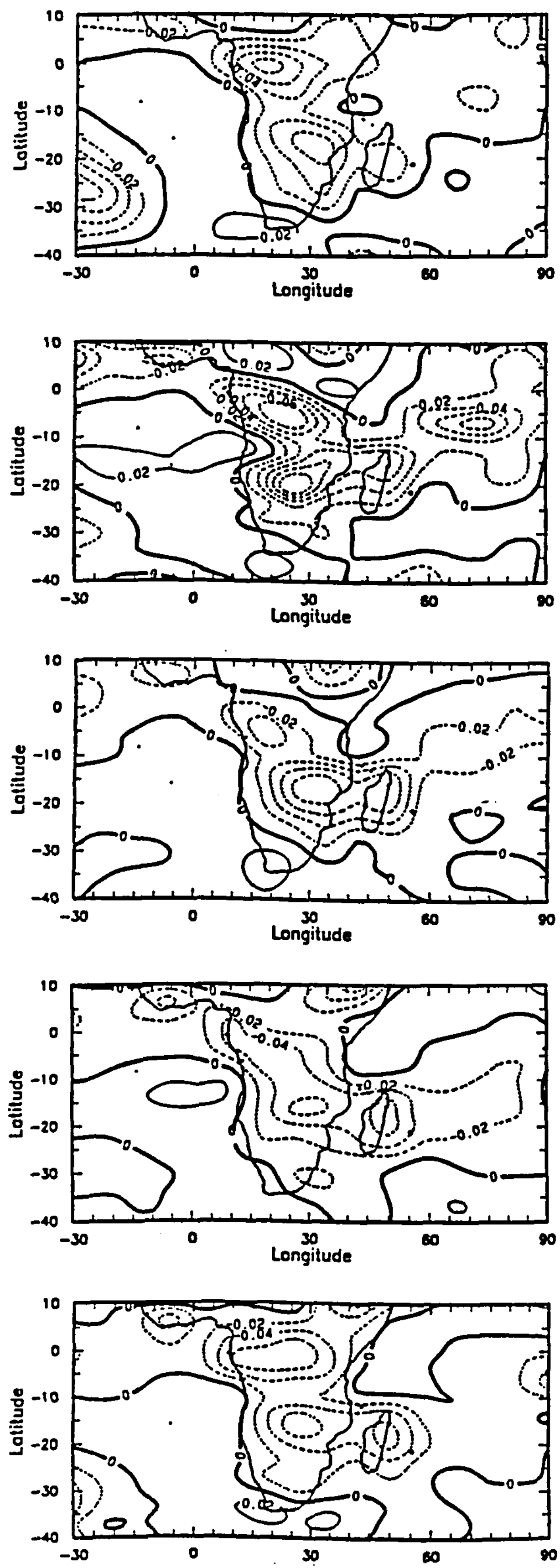


Figure 17 - 500 hPa vertical motion for each wet spell in sequence from early to late summer. Contours are at 0.02 10^{-2} Pa s^{-1} intervals. Negative values refer to upward motion and are dashed.

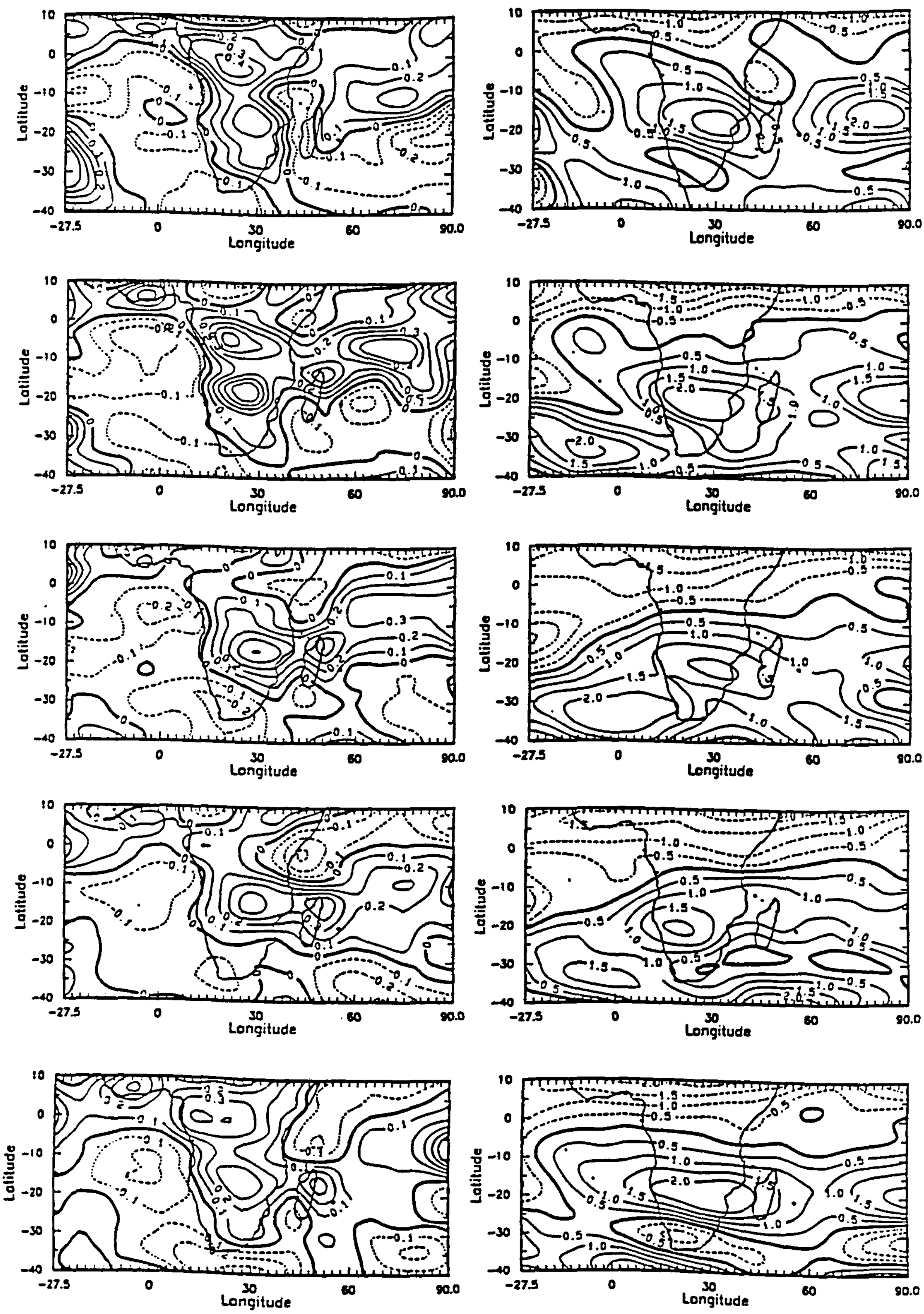


Figure 18 - 200 hPa divergence (left) and vorticity sequence for wet spells in units 10^{-5} s^{-1}

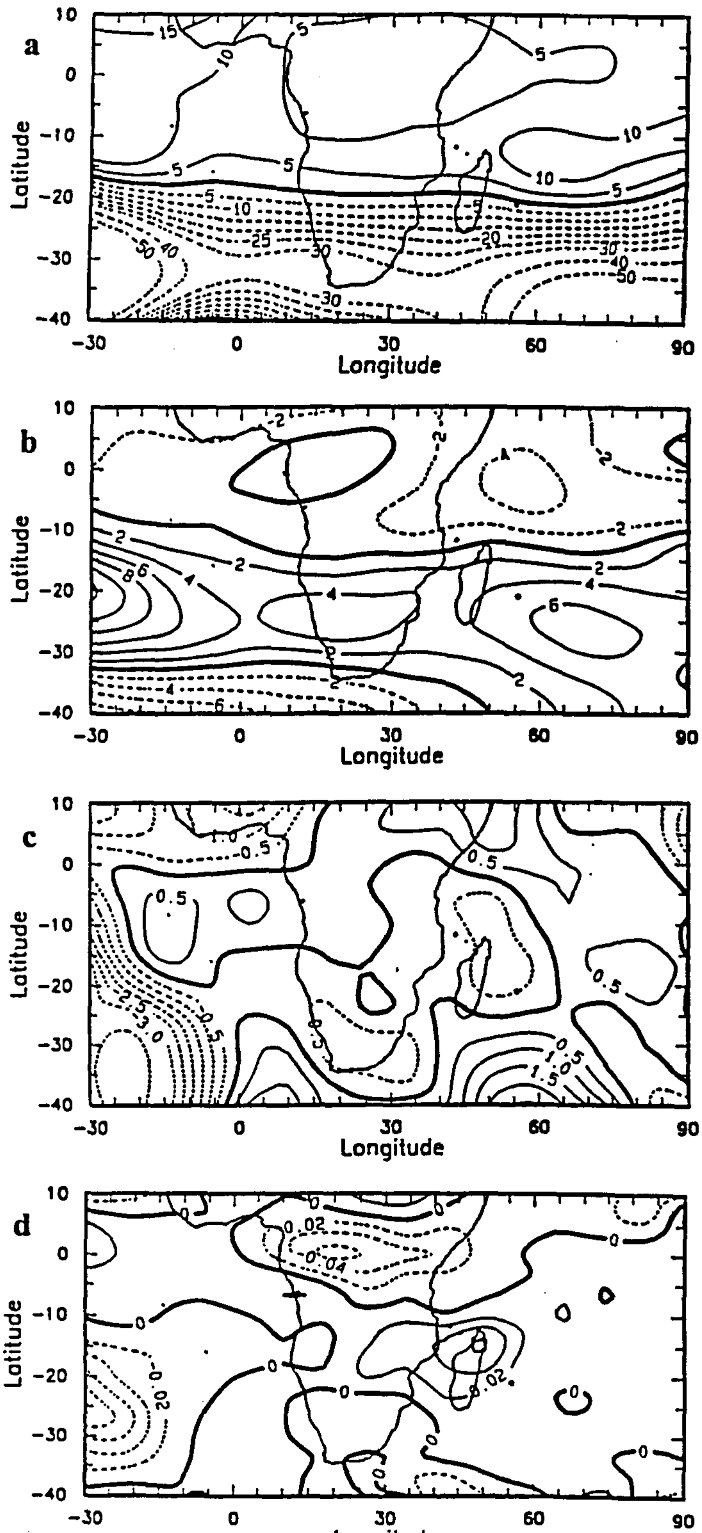


Figure 19 - Differences between early and late summer wet spells for 500 hPa geopotential height (a), 500 hPa zonal wind (b), 500 hPa meridional wind (c), and vertical motion (d); all expressed in units as in preceding figures. Values are derived by subtracting late summer from the early summer conditions during respective wet spells.

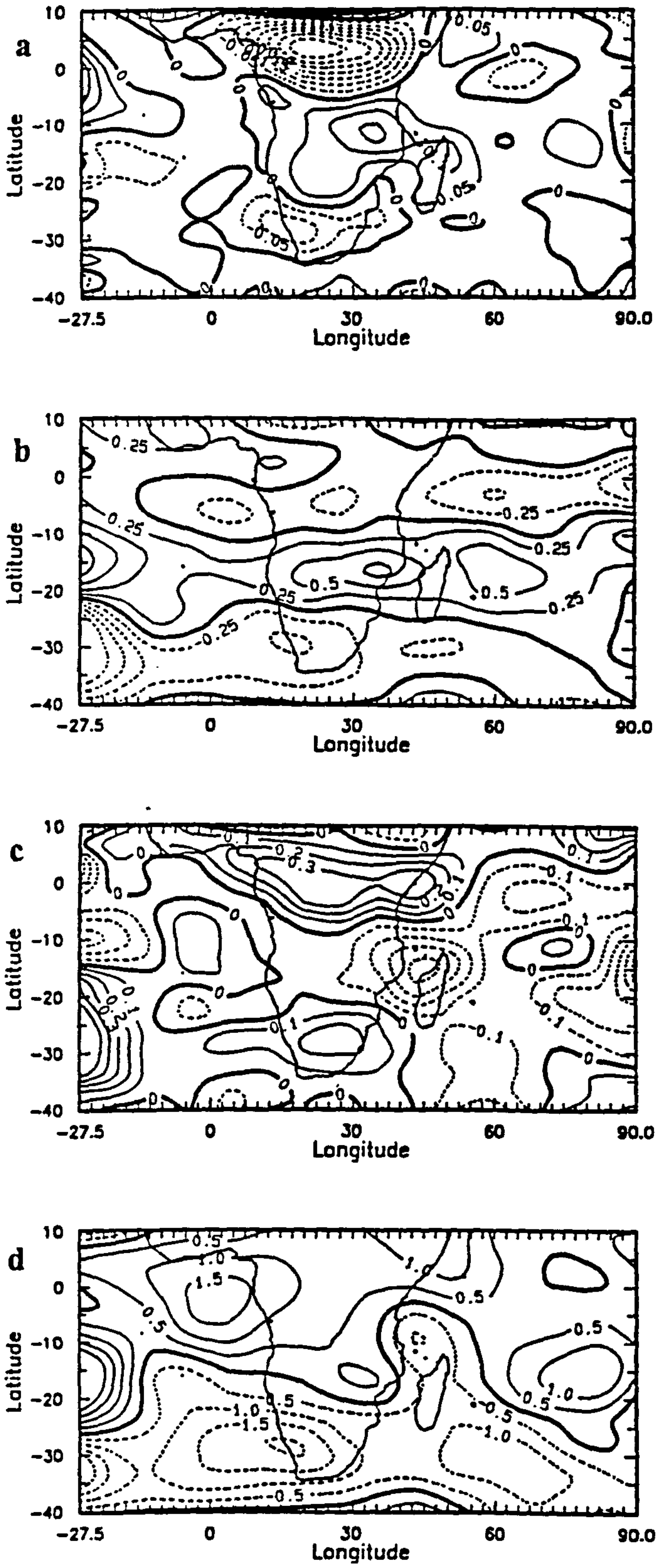


Figure 20 - Differences between early and late summer wet spells for 700 hPa divergence (a), and vorticity (b), and 200 hPa divergence (c), and vorticity (d);

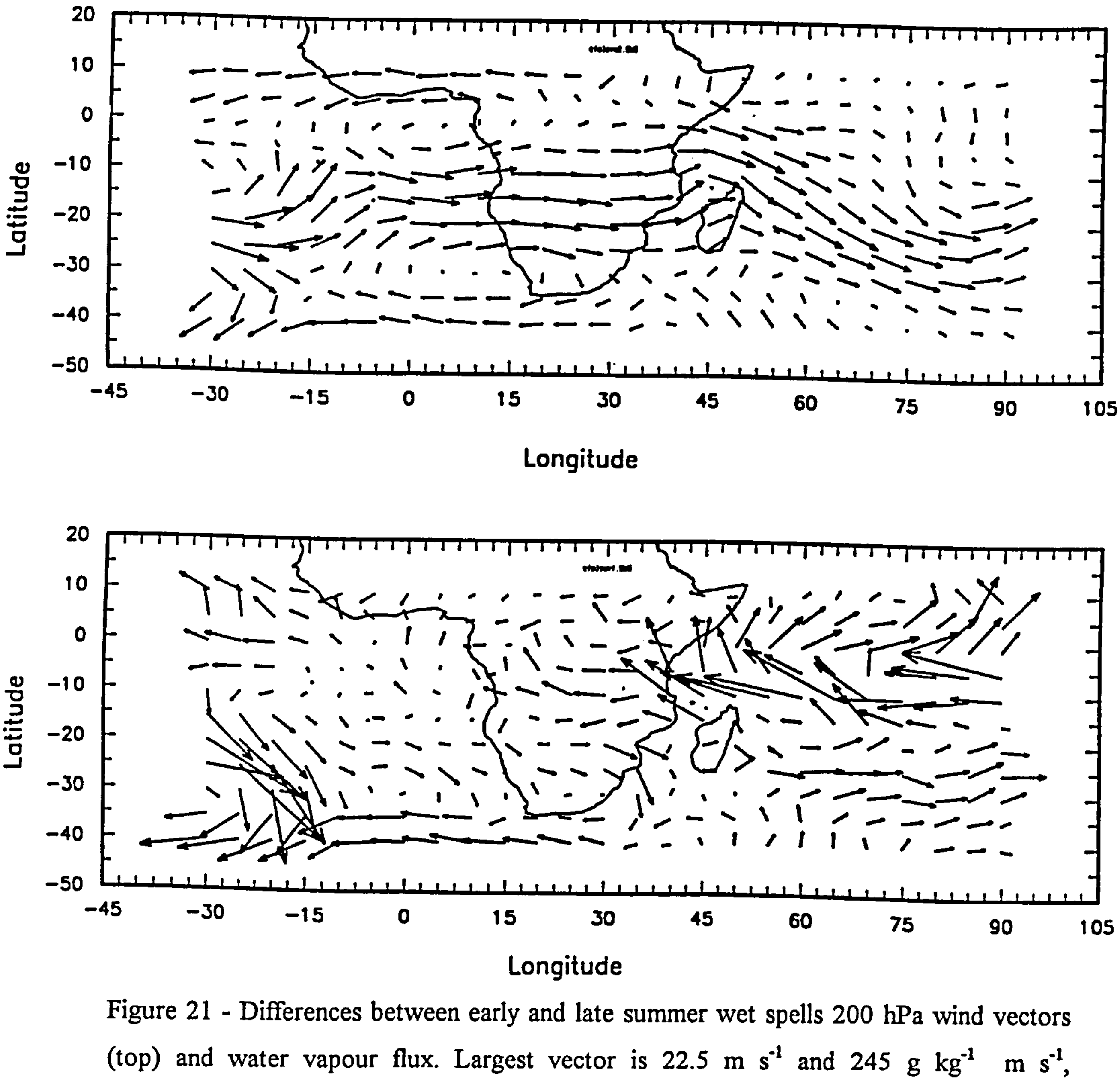


Figure 21 - Differences between early and late summer wet spells 200 hPa wind vectors (top) and water vapour flux. Largest vector is 22.5 m s^{-1} and 245 g kg^{-1} m s^{-1}, respectively.

Chapter 4: Conclusions

Chapter 2

In chapter 2 the common features of major wet spells over central South Africa have been outlined. Summer convection over southern Africa is 'pulsed' at cycles of 20-35 days by regional scale ISO which are externally modulated by tropical and mid-latitude waves. These competing influences provide a variety of ISO characteristics with zonally propagating and stationary modes, whose convective intensity is related to Hadley overturning, anticyclonic ridging and moist inflows from the Indian Ocean.

The study has identified a number of key features of the intra-seasonal convective cycle:

- the 20-35 day ISO is significant in spectral analysis and 75% of large amplitude cases exhibit cycles in this range;
- about half of all ISO cases are quasi-stationary over southern Africa as a result of standing tropical-temperate interactions and variations in Hadley overturning;
- about one third of all ISO cases propagate eastward, in the same sense as the tropical and mid-latitude waves;
- moisture fluxes from the central Indian Ocean lead the ISO, and are related to a relaxation of the equatorial monsoon;
- an upper trough shifts eastwards in the mid-latitudes towards southern Africa in the onset phase followed by a ridging anticyclone;
- uplift during the wet phase is widespread over southern Africa and compensated by sinking in the tropics and mid-latitudes;
- WVF anomalies in the central Indian Ocean at P-2 and P+2 exhibit opposing patterns, suggesting that the local ISO is embedded within the 45-60 day cycle of the tropical wave.

The 20-35 day cycle found in this study is a dominant mode of convective variability over the central region of sub-tropical southern Africa. The conspiring influences of mid-latitude and tropical circulation systems modulate the succession of wet and dry spells. Being in-phase at times and producing larger amplitude events. When external forcing is weak the convection is locally generated and more stationary. Further work includes the analysis of composite ISO distinguished by month of occurrence to determine interactions with the annual cycle. Principal components analysis may define contributions from differing synoptic weather types to intra-seasonal events. From a forecasting perspective, the anomaly patterns offer statistical guidance out to 20 days. An early warning of the intensity and timing of wet and dry spells may prove useful in rain-fed agricultural practices in southern Africa, thereby improving food security. In addition, knowledge of mechanisms yielding substantial run-off is useful in managing water resources.

Chapter 3

In chapter 3 differences between early and later summer wet spells were illustrated. Comparisons of circulation fields indicate that confluence associated with the ITCZ is relatively deep over southeastern Africa and Madagascar following onset of the summer monsoon in the northern Mozambique Channel. Convective uplift in the tropical zone is most active in January between 10 and 20°S in agreement with Janowiak (1988) and Jury and Pathack (1991). The WVF field indicates that the sub-tropical SE Atlantic is a sink region for moisture and that the circulation regime there is stable with respect to the annual cycle. Elsewhere the external forcing of wet spells by the regional circulation is more variable. When anticyclonic circulation anomalies shift eastward into the SW Indian Ocean, moisture fluxes emanate from the Mozambique Channel. A poleward stream of warm moist air is sourced from the Congo Basin which produces confluence along an E-W trough lying from Angola to Mozambique.

In the sub-tropics a standing wave pattern was evidenced by alternating meridional winds in the mid-levels south of 25°S. Channels of poleward flow occurred in the central ocean basins, whilst equatorward flow was evident around 30°E. Further north over tropical Africa generally poleward flow was observed to increase through the summer owing to the presence of monsoon circulations. Vertical motion analyses revealed two centres of action, one active over the Congo Basin in the first and last wet spells and a second over northern Madagascar in the mid-summer which extends toward Zimbabwe. These two centres of convective heating interact over southern Africa during peak wet spells such that the ITCZ and sub-tropical troughs are constructively aligned in a manner similar to that outlined by Lyons (1991).

During the early summer upper level westerlies are stronger and precipitable water values are relatively low. There is some 'reluctance' on the part of early summer weather systems to produce extensive precipitation. External forcing from baroclinic disturbances becomes more important. Large amplitude, cold-cored troughs which are embedded in a diffluent sub-tropical upper westerly flow encourage convection in November. By late summer the atmosphere has become moister, and upper westerlies retreat. In the band north of 25°S a trough lying from Angola to Mozambique may develop a 'V' shape and produce copious rains to its south. With sufficient repetition these wet spells can offset water deficits accumulated during early summer, and enable food and water resources to be replenished to a level which will support the growing population of southern Africa.

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