Vertical structure of the atmosphere during wet spells over Southern Africa

Mark R Jury* and Kevin M Levey

Climate and Weather Research Laboratory, Oceanography Department, University of Cape Town, Rondebosch 7700, South Africa

Abstract

Vertical sections of atmospheric structure during wet spells over Southern Africa are analysed in terms of ECMWF meteorological variables. Six cases occurring between December and March 1986 to 1992 are averaged to form a single composite pattern and the mean is subtracted to highlight structure. Vertical uplift is vigorous over Southern Africa and compensated by sinking motions over the surrounding oceans and Congo basin. Temperature departures indicate predominantly barotropic easterly wave conditions and a cool dome near the surface. A warm region to the south is coincident with easterly wind anomalies. Evidence points to the need for both a mid-latitude ridge and tropical Hadley overturning. The requisite convergence of airstreams from the southern Mozambique Channel and Congo basin are viewed as a brief southward excursion of the ITCZ over Southern Africa. The wet spells help overcome large moisture deficits built up in the preceding winter and spring, and enable adequate crop yields and water resource replenishment over the dry sub-continent of Southern Africa.

Introduction

Water is a limited commodity in Southern Africa which constrains economic activity and resource availability. Summer rains over the central plateau are highly variable at all scales, and take the form of wet spells of 3 to 7 d duration at near-monthly intervals from November to March (Jury et al., 1996). Each major wet spell can contribute up to 25% of the seasonal total, so an understanding of their meteorological structure and wider climatic links would be of significant value.

The climate of Africa south of 15°S has received increasing attention since the devastating drought of 1982 to 1984, when maize crop yields declined to 10% of historical values and numerous sources of water dried up. Previous studies which have detailed the characteristics of multi-day rainfall events include (Lindesay and Jury, 1991; Lyons, 1991; Barclay, 1992; D'Abreton, 1992). Other research has analysed more sustained multi-week wet spells (Taljaard, 1981; Harrison, 1986; Matarira and Jury, 1990). Common features of intra-seasonal composite wet and dry spells have been identified (Taljaard, 1986; Matarira and Flocas, 1989; Levey 1993). However, detailed vertical section analyses of composite wet spells using high quality, model-interpolated weather data are limited.

Background and methods

Daily rainfall and class-A pan evaporation data were collected for stations within a 200 km radius of 25°S, 25°E; an agriculturally productive area prone to El Niño-induced drought (Fig. 1). The shortcomings of class-A pan data are recognised (Geiger, 1965; Wiesner, 1970). An area-averaged precipitation minus evaporation (P-E) index was calculated from the individual station data in the period 1970 to 1992. To limit random, short-term weather variability, the data were averaged into pentads (discrete 5 d means). Wet spells were designated when the normalised P-E index time series was in the range +1.0 to +2.0 times the standard deviation. This criterion was met six times in the austral summer (December to March) in the years 1986 to 1992 when overlapping gridded weather data were available.

Meteorological features of the composite wet pentad are illustrated using ECMWF (European Centre for Medium Range Weather Forecasts) data. The data are at a resolution of 2.5° at 12 UT each day. The atmospheric levels used for construction of vertical sections are: 1 000, 850, 700, 500, 300, 200 and 100 hPa, except for the moisture variable, which is from 850 to 300 hPa. Vertical sections are along 25°S and 25°E and extend from 30°W to 100°E and 20°N to 60°S. Composite *anomalies* are formulated by subtracting the 1986 to 1992 mean for the December to March period from the six-case ensemble average. Apparent inconsistencies at the crossing point for zonal and meridional sections are the result of mean and derivative calculations and differencing, and the smoothing and contouring routines applied.

Meteorological parameters include: geopotential height, temperature, wind components, vertical motion and specific humidity. Derivative variables include the velocity potential and stream

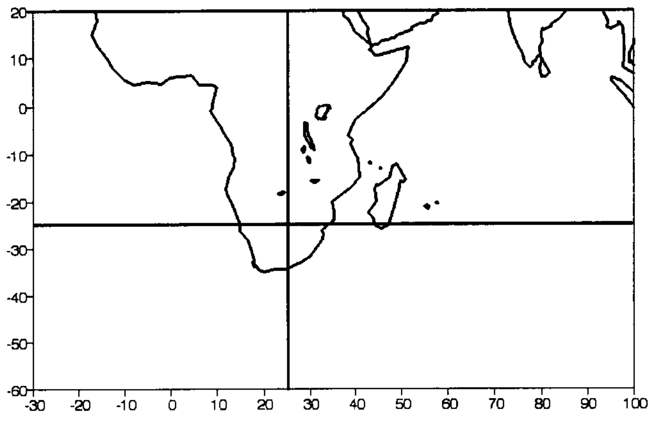

Figure 1

Location map of Southern Africa and cross-section lines

* To whom all correspondence should be addressed.
New address: Geography Department, University of Zululand, KwaDlangezwa 3886, South Africa
☎(021) 650-3979; fax (021) 650-3979; e-mail jury@physci.uct.ac.za
Received 29 March 1996; accepted in revised form 13 November 1996.

function which identify the large-scale mass flux divergence and rotational flow, respectively. The use of anomalies minimises topographic and surface-heating influences, and highlights composite convective structure and links to the background circulation. Whilst composite anomalies are illustrated for most variables, composite mean values are used for velocity potential and stream function.

Results

Zonal sections

The zonal vertical structure of the troposphere along 25°S over the South Atlantic, Southern Africa and South Indian Ocean is illustrated for the composite wet spell in the following figures. In the geopotential anomalies (Fig. 2a) negative values prevail over much of the region at all levels except below 700 hPa to the east of Southern Africa where positive values occur. The negative values indicate that a trough has penetrated or developed over the region and is undercut by a low-level anticyclone. In the temperature anomaly section (Fig. 2b), negative anomalies in the convective region (< -2°C) prevail over Southern Africa below 500 hPa, whilst positive anomalies in the lower troposphere occur over the adjacent oceans. Diabatic heating causes a small temperature excess of > +0.5°C in the 500 to 200 hPa layer. Near the tropopause, radiative cooling from penetrating cloud tops induces negative values. Although this three-cell system is typical of barotropic convection, there is a westward tilt of maximum temperature departures from 30°E in the lower levels to 20°E in the upper troposphere, indicative of some baroclinic influence.

The zonal vertical section of wind component anomalies for the composite wet spell is illustrated in Figs. 2c and d. Weak anomalies occur in the lower layers; however, above 500 hPa a westerly anomaly is present over and to the east of Southern Africa, bracketed by easterly anomalies over the adjacent oceans. The westerly shear assists upper convective outflows (Makarau, 1995). Meridional wind component anomalies indicate alternating cells of positive (northward) and negative (southward) values consistent with short-wave troughs. To the east of Southern Africa, southerly wind anomalies undercut air moving poleward above 700 hPa.

The vertical motion field (Fig. 2e) reveals the expected pattern of rising (negative) anomalies over Southern Africa and sinking anomalies over the adjacent oceans. The wavelength of the cells of alternating anomalous vertical motion is about 60° longitude, consistent with a wave-mode 6 pattern of the subtropical westerlies. The omega values over Southern Africa indicate composite uplift anomalies < -0.3 10^{-2} m s^{-1} extending from 25 to 40°E along 25°S in the mid-troposphere from 700 to 300 hPa. The specific humidity anomaly section is shown in Fig. 2f for the 850 to 300 hPa levels. The layer of excess moisture is confined below 600 hPa from 15 to 35°E. Decreased moisture is found to the west (5°W) at mid-levels and to the east (40 to 60°E) at lower levels. Most of the moisture anomaly structure is contained below 500 hPa as expected.

The velocity potential field is illustrated in Fig. 2g. The divergent circulation is dominated by a positive (convergent) layer from 700 to 500 hPa and a negative layer aloft which lies to the west of the main axis of uplift. The anomaly pattern for velocity potential (not shown) indicates upper convergent anomalies over the Indian Ocean (east of 60°E) in the 500 to 200 hPa layer which suppresses convection there. Rotational circulation is described by the stream function in Fig. 2h. A prominent area of positive (anticyclonic) values is found in the 850 to 300 hPa layer; however, this is considerably weaker than in the mean and dry phases, suggesting that a cyclonic trough weakens the quasi-permanent mid-level anticyclone during wet spells. This enables convection to penetrate through the mid-troposphere.

Meridional sections

The meridional vertical structure of the troposphere along 25°E over Africa and the southern Ocean is illustrated for the composite wet spell in the following figures. Figure 3a shows the geopotential anomaly structure and clearly decribes a lowering of heights across the tropics and positive anomalies over the southern Ocean. The 15 to 25°S latitudes have composite heights -1 gpm below the mean. The ridge to the south reaches a maximum anomaly of > +10 gpm in the 300 to 100 hPa levels. This suggests a poleward excursion of the mid-latitude jet stream. Temperature anomalies (Fig. 3b) highlight the cloudy region where evaporative cooling by rain and reduced insolation influence the layer below 500 hPa from 15 to 30°S. To the south of 40°S a warm anomaly is present which reaches maximum intensity of +3°C in the 850 to 500 hPa layer, where the ridge is present. Diabatic heating in the mid-level and radiative cooling of the tropopause over Southern Africa appear as relatively insignificant features.

The meridional section anomaly of zonal wind (Fig. 3c) is dominated by negative (easterly) anomalies in the latitudes 30 to 45°S particularly above 500 hPa. A small westerly cell is found equatorward of the convective area in the mid-troposphere. Together these offer cyclonic vorticity to the mid-troposphere. In the equatorial band at upper levels easterly anomalies are present and may be associated with a westward shift of tropical easterly weather conditions from the Indian Ocean to Southern Africa. In polar latitudes increased westerlies are present. The meridional wind component (Fig. 3d) identifies weak poleward flow through the mid-troposphere in the tropical band from 10 to 20°S, and equatorward anomalies in the mid- and upper levels in the mid-latitudes (35 to 50°S). Seen together, the upper southeasterly wind anomaly lies juxtaposed to the convective area as in Lyons (1991) and indicates equatorward penetration of a subtropical tough-ridge system. This is distinct from the poleward flow regime indicated by Harrison (1986) and Tyson (1986) as necessary for major wet spells over Southern Africa.

The meridional section of vertical motion (Fig. 3e) provides some indication of Hadley circulations. Strong upward motions are found over Southern Africa as expected. These reach a maximum in the 500 to 200 hPa layer between 25 and 30°S. To the south at 40°S and over a broad band north of 10°S, sinking anomalies are present. Overturning of the northern Hadley cell appears as a precondition for the southward shift of the ITCZ. Levey (1993) has shown that uplift associated with the composite convective system takes the form of a "pool" over Southern Africa and not a NW-SE aligned trough or cloud band linked to higher latitudes. The N-S section for specific humidity (Fig. 3f) supports the hypothesis that the northern Hadley cell acts as a 'sink' for convection further south. Specific humidity anomalies are strongly negative over the equator. Moisture is built up in the layer below 500 hPa from 15 to 30°S. This moist dome tilts northward with height, as does the equatorial deficit.

The N-S section of velocity potential and stream function (Figs. 3g and h) indicates lower convergence - upper divergence in the tropical band embedded in an anticyclonic environment. The strength of the mid-level anticyclonic cell over Southern Africa is weakened during the composite wet spell. A tongue of

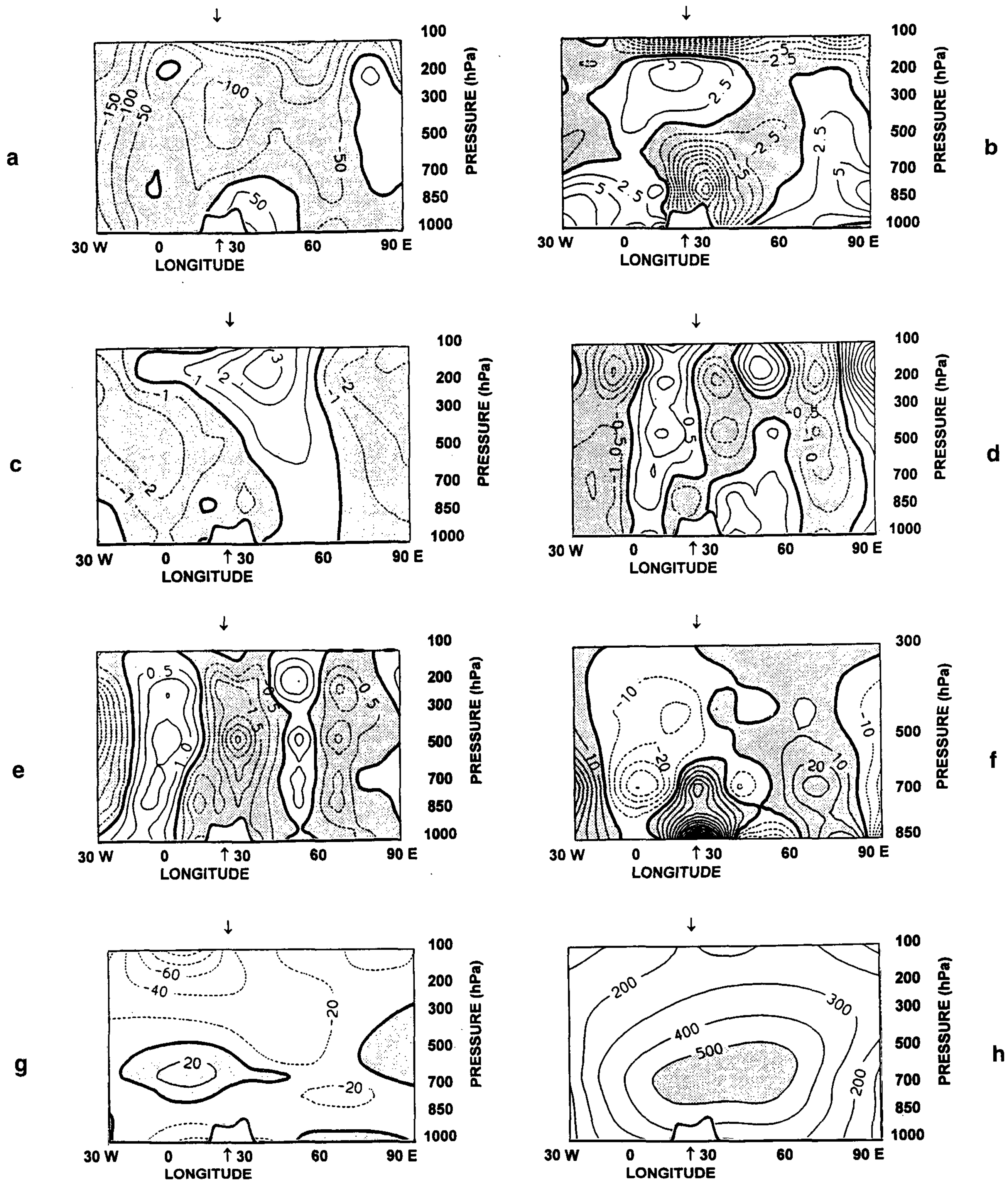

Figure 2

Zonal vertical section along 25°S of geopotential height anomalies for the composite wet spell.

***a.** contours at 50 x 10^{-1} gpm*
***b.** temperature anomalies; contours at 2.5 10^{-1} C*
***c.** zonal (U) wind anomalies; contours at 1 $m{\cdot}s^{-1}$*
***d.** meridional (V) wind anomalies; contours at 0.5 $m{\cdot}s^{-1}$*
***e.** vertical motion (w) anomalies; contours at 0.5 x 10^{-2} $m{\cdot}s^{-1}$*
***f.** specific humidity anomalies; contours at 10 x 10^{-2} $g{\cdot}kg^{-1}$*
***g.** velocity potential; contours at 20 x 10^{4} $m^2{\cdot}s^{-1}$*
***h.** stream function; contours at 100 x 10^{4} $m^2{\cdot}s^{-1}$*

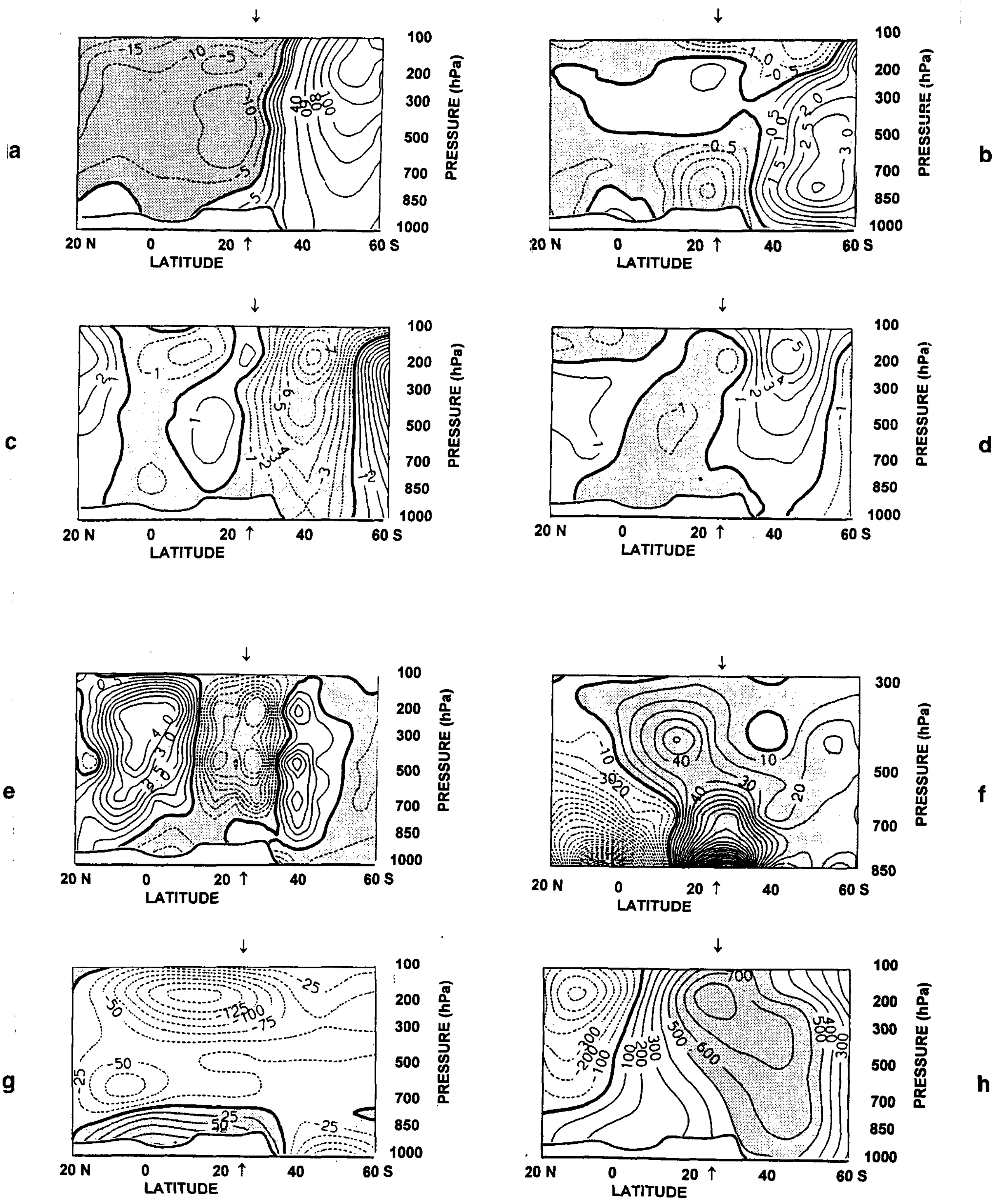

Figure 3

Meridional vertical section along 25°E of geopotential height anomalies for the composite wet spell.

a. *Contours at 5 x 10^{-1} gpm except above 20, at 20 x 10^{-1}*

b. *temperature anomalies; contours at 0.5°C*

c. *zonal (U) wind anomalies; contours at 1 m·s^{-1}*

d. *meridional (V) wind anomalies; contours at 1.0 m·s^{-1}*

e. *vertical motion (w) anomalies; contours at 0.5 x 10^{-2} m·s^{-1}*

f. *specific humidity anomalies; contours at 10 x 10^{-2} g·kg^{-1}*

g. *velocity potential; contours at 25 x 10^{4} m^2·s^{-1}*

h. *stream function; contours at 100 x 10^{4} m^2·s^{-1}*

cyclonic stream function anomalies (not shown) extends from upper levels into the mid-troposphere in the latitudes 20 to 40°S. A cell of divergent circulation is located between 0 and 20°S at 200 hPa. The upper divergent region lies equatorward of the convection, and signifies that upper outflow anomalies are directed toward the tropics, down the stream function gradient.

Conclusions

Recent studies have demonstrated that 75% of large amplitude wet spells over Southern Africa occur at intervals of 20 to 35 d, consistent with the second mode of global variability found by Hayashi and Golder (1992). Nearly half of all wet spells appear quasi-stationary (Levey and Jury, 1996). In this research the impact of intra-seasonal oscillations of convection has come to the fore. The composite vertical structure of major wet spells over Southern Africa has been analysed in terms of departures from the mean. Convective intensity is related to Hadley overturning, anticyclonic ridging and a localised increase of moisture and uplift. Temperature departures are indicative of barotropic easterly wave conditions with a slight north-westward tilt consistent with more remote baroclinic westerly influences. A detailed knowledge of the vertical anomaly structure of composite wet spells over Southern Africa, based on ECMWF gridded data, has been afforded in this study of six cases in the period 1986 to 1992. Structural features which have been revealed include:

- the temperature pattern is dominated by a cool dome near the surface and a warm region to the south where a geopotential ridge and easterly wind anomalies are present
- meridional wind anomalies suggest a short wave pattern of alternating subtropical flow regimes
- uplift over Southern Africa is compensated by sinking motions over the adjacent oceans and Congo basin, where moisture deficits are found
- the mid-tropospheric flow regime over Southern Africa becomes less anti-cyclonic during the wet spell
- upper divergent motions are found equatorward of the convection near the 200 hPa layer, and
- low-level convergence and moisture surpluses occur in a relatively shallow layer over the plateau.

Influences of both a mid-latitude ridge and tropical Hadley overturning are found in the N-S sections. The requirement for sustained convection over Southern Africa is the forced juxtaposition of a tropical trough with a ridging mid-latitude anticyclone. The requisite convergence of airstreams from the southern Mozambique Channel and Congo basin are viewed as a brief southward excursion of the ITCZ over Southern Africa. These wet spells bring life to the Kalahari plateau and ensure the continued survival of agriculture in the face of enormous water deficits accumulated during austral winter and spring. If certain components of the convective forcing do not arrive in-phase, the wet spell may be weak or short-lived. Failure of mid-summer wet spells results in potential evaporation of the order 10 $mm \cdot d^{-1}$ lasting a month or more, damaging maize yields and limiting water resources. Knowledge of how Southern African wet spells link to the background climate and associated phase of the global El Niño forms the basis for further work.

Acknowledgements

This study was jointly supported by the Foundation for Research Development and the Water Research Commission project on short-term rainfall variability.

References

BARCLAY JJ (1992) Wet and Dry Troughs Over Southern Africa During Early Summer. Unpublished M.Sc. Thesis. University of Cape Town. 178 pp.

D'ABRETON PC (1992) The Dynamics and Energetics of Tropical-Temperate Troughs over Southern Africa. Unpublished Ph.D. Thesis. University of Witwatersrand. 231 pp.

GEIGER R (1965) *Climate Near the Ground.* Harvard University Press, Cambridge. 611 pp.

HARRISON MSJ (1986) A synoptic climatology of South African rainfall variations. Ph.D. Thesis, University of Witwatersrand. 341 pp.

HAYASHI Y and GOLDER DG (1992) Tropical 40-50- and 25-30-day oscillations appearing in realistic and idealized GFDL climate models and the ECMWF Dataset. *J. Atmos. Sci.* **50** 464-494.

JURY MR LEVEY KM and MAKARAU A (1996) Mechanisms of short-term rainfall variability. WRC Report 436/1/96. 50 pp.

LEVEY KM (1993) Intra-seasonal oscillations of convection over Southern Africa. Unpublished M.Sc. Thesis, University of Cape Town. 236 pp.

LEVEY KM and JURY MR (1996) Composite intra-seasonal oscillations of convection over Southern Africa. *J. Climate.* **9** (8) 1910-1920.

LINDESAY JA and JURY MR (1991) Atmospheric circulation controls and characteristics of a flood event in central South Africa. *Int. J. Climatol.* **11** 609-627.

LYONS SW (1991) Origins of convective variability over equatorial Southern Africa during the Austral summer. *J. Climate.* **4** 23-39.

MAKARAU A (1995) Intra-seasonal oscillatory modes of the Southern Africa summer circulation. Ph.D. Thesis. Oceanogr Dept, Univ. of Cape Town. 324 pp.

MATARIRA CH and FLOCAS AA (1989) Spatial and temporal rainfall variability over SE central Africa during extremely dry and wet years. *J. Meteorol.* **14** 3-9.

MATARIRA CH and JURY MR (1990) Contrasting atmospheric structure during wet and dry spells in Zimbabwe. *Int. J. Climatol.* **12** 165-176.

TALJAARD JJ (1981) The anomalous climate and weather systems of January to March 1974. *SAWB Newsletter* 397 51-53.

TALJAARD JJ (1986) Change of rainfall distribution and circulation patterns over Southern Africa in summer. *J. Climatol.* **6** 579-592.

TYSON PD (1986) *Climatic Change and Variability in Southern Africa.* Oxford University Press, Cape Town. 220 pp.

WIESNER CJ (1970) *Hydrometeorology.* Upman and Hall, London. 227 pp.