Composite meteorological structure of flood events over the eastern mountains of South Africa

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Abstract

This study examines composite meteorological features of intense wet spells over the eastern mountains of South Africa during summer. Weather data for 14 five-day periods (pentads) with rainfall exceeding 50 mm were composited during the period October to March, 1980 to 1991. Historical summer means were subtracted from pentad composite maps to evaluate anomalies. A subtropical low is located over the western plateau of Southern Africa during flood events. Tropical moisture is converged and the South Atlantic High ridges south of the continent. Upper levels are dominated by south-eastward outflow around an anticyclonic anomaly to the east. Vertical uplift is most vigorous in the 700 to 500 hPa layer. A case study pertaining to peak flooding is analysed and a budget analysis of various influences demonstrates a mixed tropical - temperate character.

Introduction

Motivation

Southern Africa, within the southern subtropical belt of high pressure, is subject to large fluctuations in rainfall. Droughts and floods are common and skew the rainfall distribution. The background circulation is characterised by weak subsidence in the mid-troposphere and the region is regarded as arid (Tyson, 1986; Levey, 1993). However, the subcontinent's eastern flank next to the warm Indian Ocean is subject to increased rainfall (Harrison, 1986). KwaZulu-Natal and the adjacent mountain escarpment are susceptible to frequent flooding (Kovacs, 1988). This area supplies about 80% of the water resources of South Africa and runoff rates are over 20% (Schulze, 1982). The variability of streamflow is critical to the region's economy. Floods experienced in the eastern mountains of South Africa during the summer of 1995/96 prompted this study of contributing factors.

Background

The rainfall over Southern Africa has been analysed with respect to predictability of wet or dry seasons using precursors such as sea surface temperatures (Lindesay and Mason, 1989) and tropospheric winds (Jury, 1996). Other studies have focused on fluctuations in rainfall associated with changes in the frequency and type of circulation regimes (Tyson, 1986) or their composite anomalies (Jury and Pathack, 1993). Walker (1990) suggests that during wet spells the Indian Ocean Anticyclone is displaced south-west of its mean summer position, bringing the Inter-Tropical Convergence Zone polewards. There is also a relative increase in easterly winds in the western Indian Ocean. The increase in onshore winds accompanied by warmer, moister air masses results in increased convergence over the eastern mountains of South Africa which rise to 2 000 m in places.

Hurry and Van Heerden (1982) attribute good summer rains to an easterly wave regime supported by a ridge of high pressure south of Africa linking the Atlantic and Indian Ocean anticyclones. A strong pressure gradient over the eastern interior brings warm moist air from the Mozambique Channel. Over the eastern mountains it converges with cooler air flowing around a mid-latitude high. At the 500 hPa level a cut-off low may be situated over the south-western Cape, a trough to the north extends southward over the central interior towards this cut-off low. Convection to the east of the trough may result in flooding.

Harrison (1986) described cloud bands extending south-eastward from SW Zambia along the leading edge of a westerly wave as the major cause of rain events over Southern Africa. In truncated cases the cloud band contained a subtropical cold cored vortex embedded in deep easterly flow. These could take the form of cut-off lows during transition seasons (Taljaard, 1982).

The eastern seaboard of South Africa experiences more frequent flooding (Tyson et al., 1976) due to a combination of moist, unstable air from the warm Indian Ocean and orographic uplift. Due to their high frequency, Natal floods are well documented (Badenhorst, 1989; Van Heerden, 1989; Terblanche, 1989; Lindesay et al.., 1989). At the local scale summer thunderstorms are the largest contributor to rainfall over the eastern escarpment and occur in the mid- to late-afternoon about 100 days each year (Schulze, 1972). The storms are classified in two groups; large-scale squall-lines which move to the north-east and those that result from local slope convection along the escarpment (Tyson et al., 1976).

Scope

The aim of this study is to highlight meteorological features of flood events over the eastern mountains of South Africa. Common aspects of rain-producing systems are composite averaged to elucidate the convective dynamics. The hypothesis to be tested is that these flood events result from orographic uplift of tropical and Agulhas air into a deep low which tilts westward over the interior. It is expected that convergence and cyclonic vorticity at the lower level will be compensated by divergence and anticyclonic vorticity at upper tropospheric levels.

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TABLE 1 12 UT ECMWF DATA AND DERIVATIVES USED IN THE STUDY		
Parameters	**Pressure level (hPa)**	**Units**
Geopotential height	850, 500, 200	gpm
Temperature	500	°C
Horizontal wind	850	$m \cdot s^{-1}$
Vertical motion	500	$Pa \cdot s^{-1}$
Divergence	200	$10^{-6} \cdot s^{-1}$
Vorticity	200	$10^{-5} \cdot s^{-1}$
Precipitable water	integrated from 1 000 to 300 hPa	mm
Water vapour flux	integrated from 1 000 to 500 hPa	10^{-1} $kg \cdot m^{-1} \cdot s^{-1}$

TABLE 2 RAINFALL AND PENTAD DATES		
Rainfall (mm)	**Year and pentad date**	
56.0	1980	15-19 February
53.8	1984	07-11 November
84.1	1984	22-26 March
171.8*	1985	05-09 February
85.1	1986	28-1 Oct / Nov
52.5	1986	16-20 January
56.9	1987	06-10 January
52.2	1989	18-22 October
72.6	1989	02-06 December
63.5	1989	19-24 February
52.2	1991	16-20 January
57.5	1991	21-25 January
72.7	1991	05-09 February
56.7	1991	15-19 February

* case study analysed; note: no cases in 1981 - 1983

Data and methodology

Data

The analysis considers European Centre for Medium Range Weather Forecast (ECMWF) data. The ECMWF model incorporates the usual suite of surface and satellite measurements to formulate a "best fit" weather analysis. The conventional observations come from radiosonde and pilot balloons, surface observations from land stations, ships and oceanic buoys, aircraft reports and extensive satellite observations in the form of temperature and moisture soundings and cloud-tracked winds (Levey, 1993). The quality of ECMWF data is well-known (D'Abreton, 1993; Parker 1994), having been employed in a number of studies of a similar nature.

The ECMWF III-b Global Analysis data set has been used for the period 1980 to 1991. The data analysis window is from 15° S to 40° S and 15° E to 40° E and the resolution of the data is 2.5° x 2.5°. The parameters, their derivatives, atmospheric levels and units used are shown in Table 1. The data are available at the usual standard pressure levels daily at 12 UT (14:00 local).

Daily rainfall data were gathered by Levey (1993) for stations with a mean annual rainfall > 1 000 mm, an elevation > 1 000 m, high runoff potential, and a high frequency of flood events. Inspection of data revealed that only nine stations met these criteria and daily records were processed from 1970 to 1991. The area containing these stations is shown in Fig. 1. Daily rainfall values were averaged for the nine stations into 5 d means (pentads).

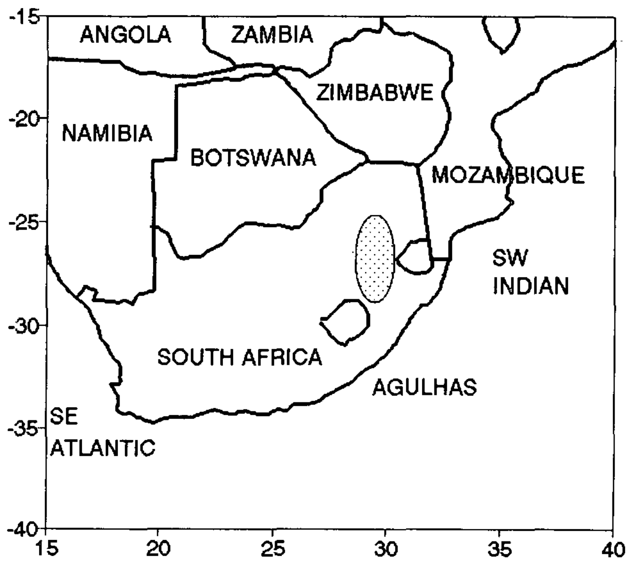

Figure 1
Map of Southern Africa showing political boundaries and the study region (shaded). Oceanic regions are defined.

Methodology

The circulation associated with flood events was evaluated using pentad mean weather data composites according to the rainfall statistics. Pentad area-mean rainfall > 50 mm was considered the threshold for case inclusion into a composite. This threshold value was chosen arbitrarily to limit the sample size in the period 1980 to 1991 to 14 pentads out of a possible 414. Known tropical cyclone cases were excluded (e.g. Domoina in 1984). The composite pentads are shown in Table 2.

Gridded weather data for the specified rainfall threshold were averaged over the region and contour-analysed. Compositing or averaging of groups is useful in that it highlights common features for the different variables considered. The total number of maps is reduced so as to make the analysis and interpretation more manageable. The process of compositing also enhances data density. A disadvantage of this process is the loss of specific detail and the mixing of dissimilar weather types.

Fourteen pentads of ECMWF weather data were averaged at each grid location for the specific pressure surface and parameter considered. These comprise the pentad composites. Comparisons were made with the historical mean for the summer season based on a November to March average for the period 1980 to 1991 (total = 60 months). To highlight anomalies, the historical mean value at each grid point and pressure level, based on 1 820 d, was subtracted from the composite mean based on 70 wet d.

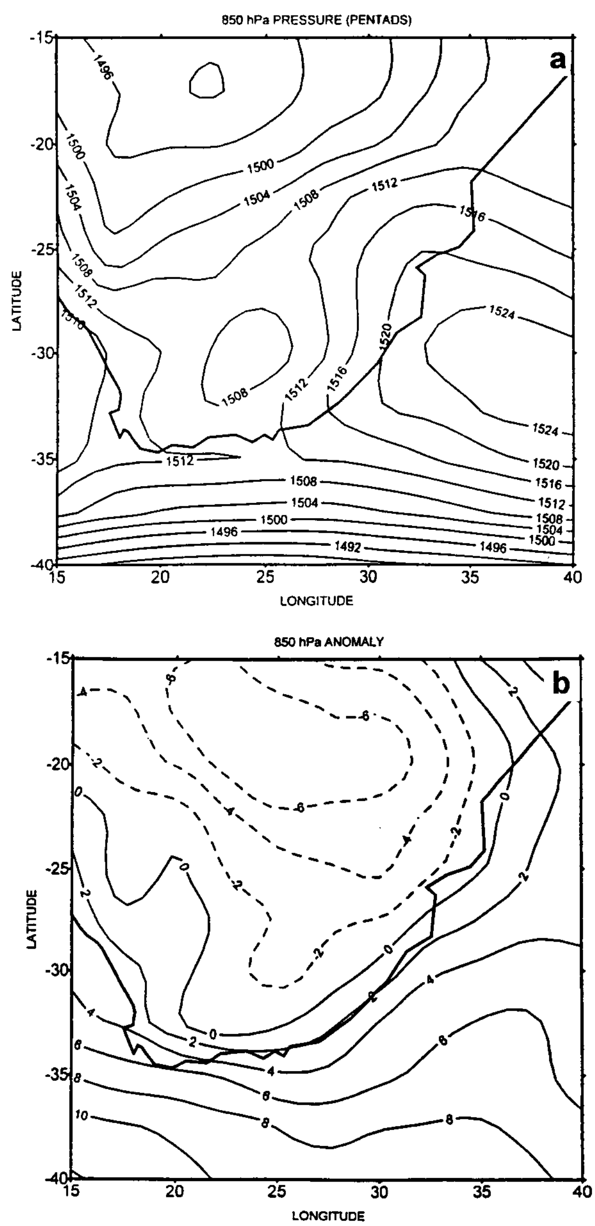

Figure 2

Geopotential heights at 850 hPa level. a) composite flood mean, b) anomaly w.r.t. historical mean. All units are listed in Table 1; contour intervals are 4 (a) and 2 (b) gpm.

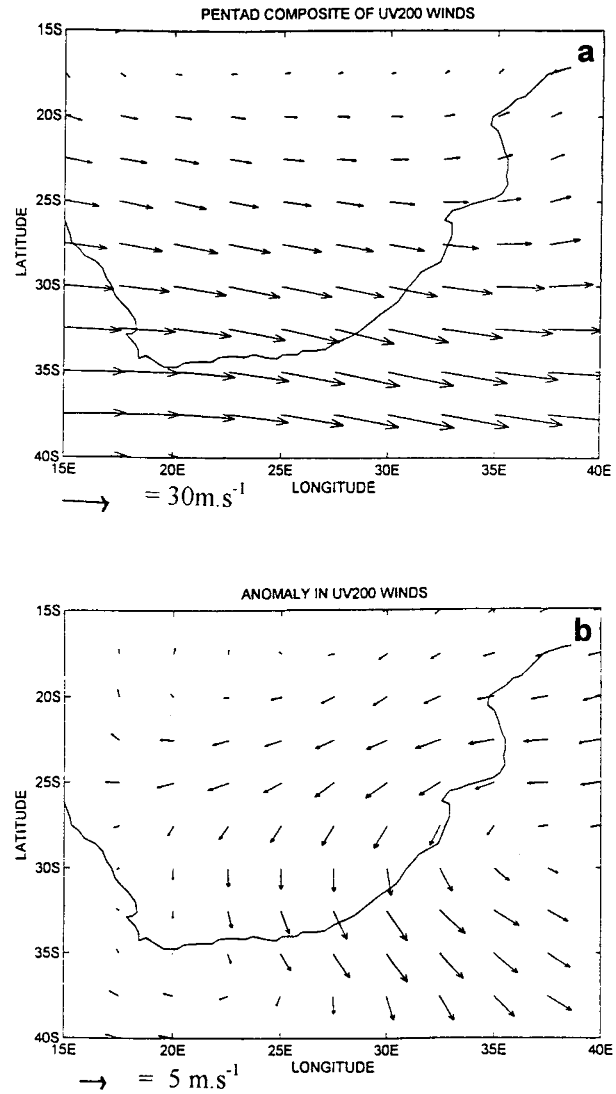

Figure 3

Horizontal winds at 200 hPa. a) composite, b) anomaly as in Fig. 2; vector key is provided.

Results

The composited ECMWF data for the rainfall events from 1980 to 1991 are described in this section. The composite average and its departure from the long-term mean are illustrated.

Kinematic fields

The pentad composite of 850 hPa geopotential height (Fig. 2a) shows a prominent high-pressure cell to the south-east and a trough over the central interior. The anomaly map (Fig. 2b) identifies a pattern of below-normal geopotential height over the central plateau, whilst the ocean areas to the south of Africa have higher pressures. The trough anomaly over the land has a 'T' shape with a zonal axis along 20°S and a meridional axis along 25°E.

The pentad composite map for 200 hPa winds (Fig. 3a) shows zonal flow from the west throughout. The speed of the winds increases in a polewards direction as expected. The anomaly map (Fig. 3b) illustrates a large anticyclonic anomaly to the south-east. Wind anomalies associated with this feature are about 5 $m{\cdot}s^{-1}$. From 20 to 25°S upper easterly anomalies are evident across the subcontinent. These circulation features suggest poleward momentum fluxes in the upper troposphere around a deep anticyclone east of South Africa.

The 200 hPa wind divergence for the pentad composite (Fig. 4a) demonstrates strong positive values over the south-east coast which are similar in strength to the anomaly values (Fig. 4b). The upper divergence takes on a NW-SE orientation with a maximum over Durban, South Africa. Upper convergence is noticeable to the extreme east and west.

Analysis of the 500 hPa temperature anomaly (not shown) indicates only weak departures from the historical mean and a pattern that is below-normal over the south-west and warmer than normal to the east.

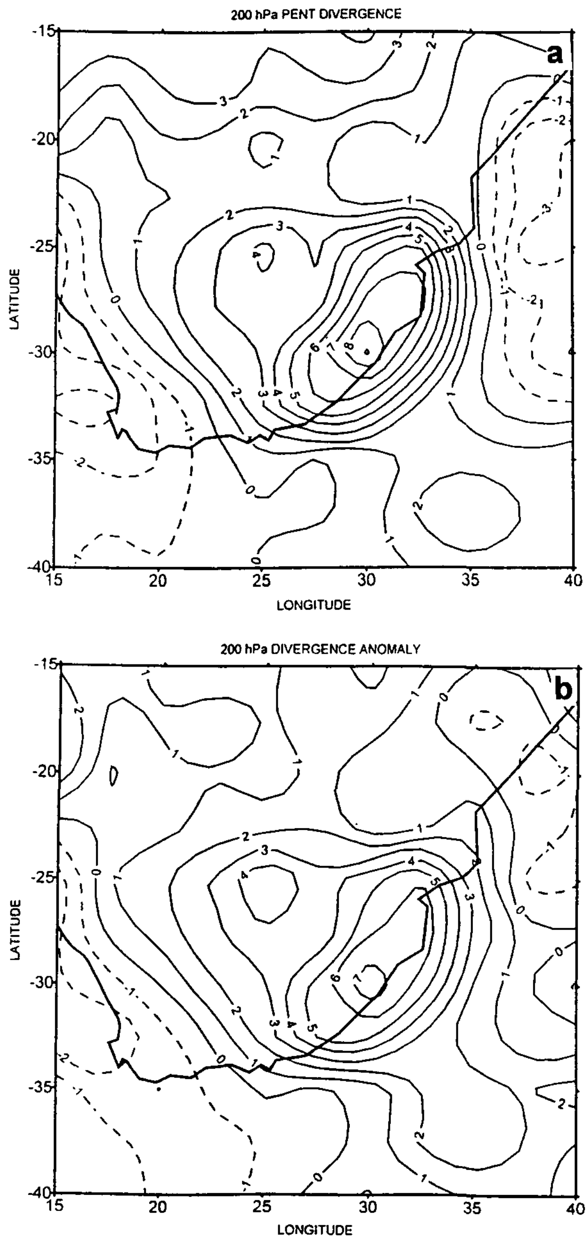

Figure 4

Divergence at 200 hPa level. Units are listed in Table 1; contour interval is 1 x 10^{-6} s^{-1}

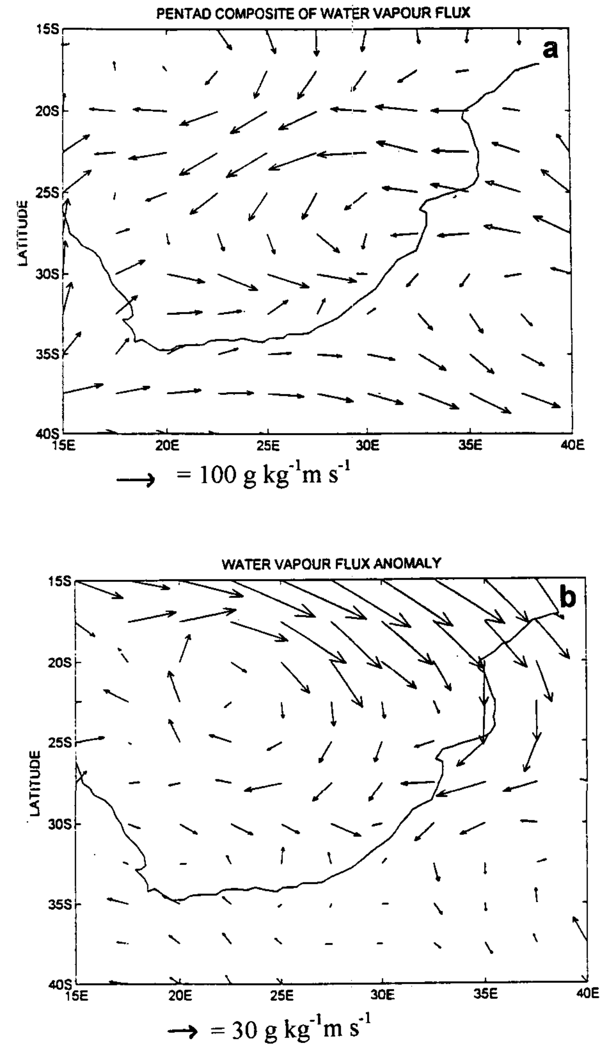

Figure 5

Water vapour flux, integrated from 1000 to 500 hPa. a) composite, b) anomaly as in Fig. 2; vector key is shown

Moisture and thermodynamic features

The horizontal water vapour flux ($\int_{1000}^{500} Vq$) in the pentad case (Fig. 5a) illustrates a westward stream of moist air from the Indian Ocean in the band 20 to 27°S. This ocean trade wind source is joined by southward flow from the tropical interior which recurves around a high pressure over the eastern seaboard. Water vapour streamlines are confluent over the eastern escarpment owing to eastward fluxes south of 30°S.

The water vapour flux anomaly map (Fig. 5b) highlights a cyclonic cell over the interior centred on 22°S, 22°E. On the north-eastern flank of the cyclonic anomaly, largest tropical fluxes are directed south-eastward. These recurve westward over the east coast to converge with eastward fluxes over the mountainous escarpment.

The pentad composite for vertical motion (Fig. 6a) illustrates intense uplift (negative) over much of the interior and east coast. Descending (positive) values occur over the oceans. Maximum uplift is over the eastern escarpment where easterly and westerly flow regimes meet. The anomaly (Fig. 6b) illustrates the enhanced (negative) vertical motion over the eastern escarpment with a magnitude and pattern similar to the composite. The uplift regions have two axes, one NE-SW over the mountains parallel to the south-east coast and another NW-SE axis across the southern plateau.

The pentad composite map for precipitable water (Fig. 7a) displays a N-S gradient of higher values over the tropics and a tongue of moist air (> 56 mm) extending southward along 30°E. The anomaly map (Fig. 7b) shows positive values for precipitable water over the east coast of Southern Africa, spreading in a pool into the interior plateau and over the SW Indian Ocean. Negative values are found over the western interior along 20°E.

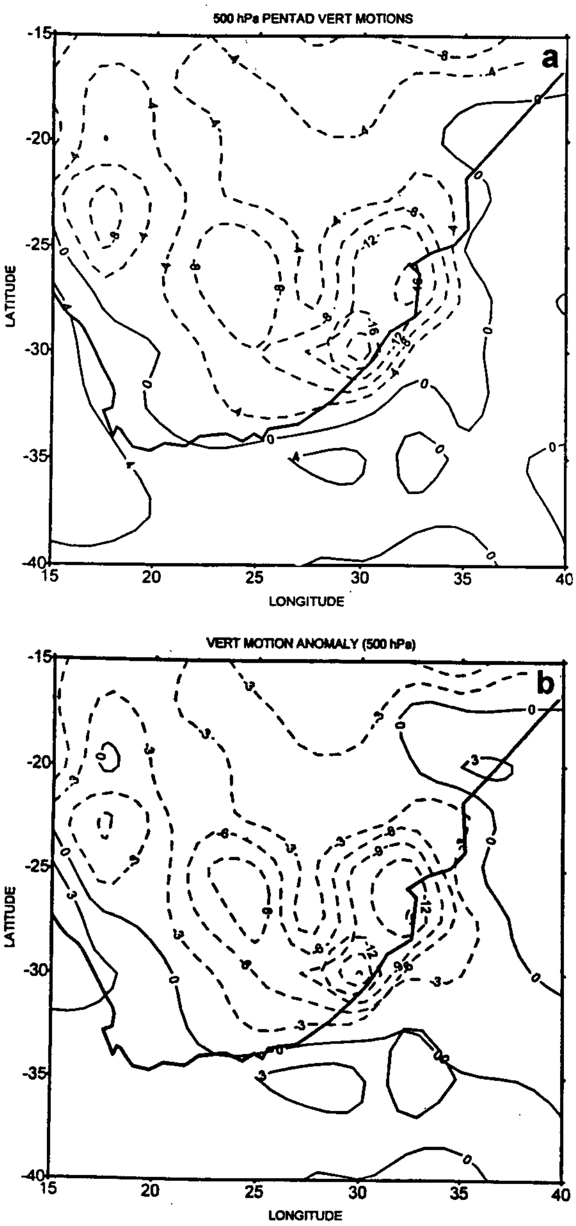

Figure 6
Vertical motions at 500 hPa. Units are listed in Table 1; contour interval is 3 x Pa s⁻¹, negative = uplift

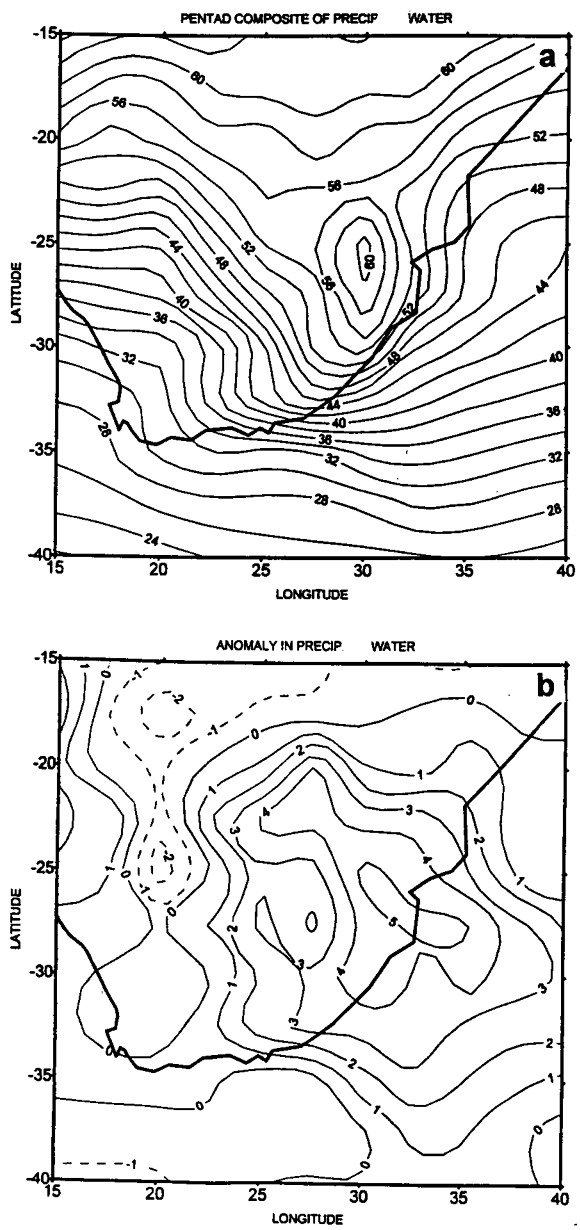

Figure 7
Precipitable water, integrated from 1 000 to 300 hPa. Contour interval is 2 (a) and 1 (b) mm

Discussion

Composite results

The composite anomalies for 850 hPa geopotential height and water vapour flux indicate an anomalous low situated over the central plateau of Southern Africa during flood events over the eastern mountains. The geopotential minimum tilts to the south-west with height and weakens. The composite anomalies indicate higher pressure over the oceans to the south (low level) and east (upper level) of Southern Africa. This implies increased ridging of the south Atlantic high into the Indian Ocean, consistent with Hurry and Van Heerden (1982) and Preston-Whyte and Tyson (1988). 200 hPa wind anomalies are westward and poleward around an anticyclonic anomaly located at 27°S, 37°E. The WVF and 200 hPa vorticity composites (not shown) all emphasise anticyclonic rotation over the eastern seaboard.

Although there is a westward stream of moist air over the interior during flood events, water vapour flux anomalies reveal a cyclonic cell over the north-western interior with anomalous poleward fluxes around its eastern flank. The main source of anomalous moisture is tropical central Africa, when a low level trough is situated over the south-western plateau. The fluxes are channelled by the upper anticyclone over the Mozambique Channel (D'Abreton, 1993).

The water vapour flux vorticity anomaly (not shown) is predominantly cyclonic over the tropics. Anticyclonic vorticity is prevalent at the upper level over the east coast and indicates the westward penetration of a deep anticyclonic cell from the Mozambique Channel. The WVF is confluent over the eastern escarpment where orographic uplift is strong. Convective outflows are aided by intense upper divergence. Precipitable water increases 10% above mean values across the 10^{12} m^2 study area and adjacent Indian Ocean region during flood events, as in Harrison (1988).

Temperature anomalies are weak indicating a predominantly barotropic character. A closed cell of lowered temperatures overlies the south-western interior, suggesting a small influence from cold-cored, cut-off lows in the subtropical westerlies in early and late summer. Above-normal temperatures are found within the deep anticyclone to the east.

Composite budget and case study

The budget of various influences can be evaluated for the composite flood event by comparing magnitudes of the pentad composite and its anomaly. Meteorological fields displaying greatest departures from the long-term mean, in descending order, are:

- Vertical motions in mid-troposphere **(10^0)**
- Upper wind, its vorticity and divergence **(10^0)**
- Precipitable water and 500 hPa temperature **(10^{-1})**
- Water vapour flux, its vorticity and divergence **(10^{-2})**
- Geopotential height at 200, 500 and 850 hPa **(10^{-3})**

(note: where departure magnitude is bold)

Significant meteorological features on 8 February 1985 may be isolated to study a particularly heavy rainfall case. Representative ECMWF data are extracted in Table 3. Surface south-easterly flow was particularly strong over the eastern mountains owing to ridging of the South Atlantic high pressure cell and the development of a weak cut-off low over the interior. The airflow had a long trajectory from SE to NW around the leading edge of an advancing high pressure cell. 700 hPa temperatures were cold (+2°C) to the south of Durban (30°S, 30°E) creating an unstable atmospheric boundary layer over the warm Agulhas Current. Surface temperatures and specific humidities were significantly higher, indicating a vertical flux of moisture from east coast waters of the order of 10^7 MW. A second source of moisture was a 700 hPa cyclonic gyre overlying Zimbabwe which brought tropical air poleward over Mozambique. This flow recurved westward to join the Agulhas air over the study area: 27 to 30°S, 30°E. Vertical motions estimated from the ECMWF model were greater at 3 km (700 hPa) than further up in the troposphere, pointing to orographic effects. Comparisons of synoptic-scale vorticity and divergence values reveal the rotational component to be an order of magnitude greater than the divergent part.

Conclusion

Sustained floods in the eastern mountains of South Africa may be attributed to a combination of factors which are consistent with a poleward cloud band (Tyson, 1986) undercut by a ridging marine anticyclone; an easterly continental low coupled with a weak subtropical wave-trough. A summary of the synoptic patterns contributing to floods includes:

- A deep cyclone is situated over the interior and tropical moisture flows poleward on its north-eastward flank. Widespread cyclonic vorticity and low level convergence is associated with this feature.
- The South Atlantic anticyclone ridges south of Africa, whilst a deeper anticyclone intensifies over the Mozambique Channel.
- The moisture is sourced from tropical Africa, the Mozambique Channel and the Agulhas region. Water vapour flux anomalies in the temperate band are an order of magnitude smaller than the tropical fluxes.
- The eastern escarpment plays a major role in forcing convection; vertical motion increases above the mean by an order of magnitude at 700 hPa.

A diagnostic analysis of 14 summer flood events over a 12 year period has elucidated the underlying meteorological processes. Vertical motions are forced when easterly surface layer winds impinge on the eastern mountains of South Africa. Upper north-westerly winds induce rapid convective overturning and outflow. The mixing of barotropic and baroclinic weather influences is attested by below-normal temperatures in the trough to the west. The trough tilts westward, so enabling the mid-latitude high to undercut the subtropical low. Convective rainfall is sustained and intense, resulting in a substantial pulse of streamflow runoff into regional water supply systems.

Acknowledgments

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TABLE 3
REGIONAL ECMWF DATA FOR 12 UT 8 FEBRUARY 1985 CASE STUDY

Parameter	Feature, position, value
Geopt. ht 500 hPa Geopt. ht 850 hPa	Cut-off low, 30°S 20°E, 5730 gpm. Ridging high, 40°S 12°E, 1616 gpm.
Temperature 700 hPa Temp 500 hPa	cold low to west, 30°S 20°E, +2.0°C warm high to east, 27°S 40°E, +11.1°C cold trough to southwest, 32°S 22°E, -13.6°C
Wind 200 hPa Wind (surface)	jet stream over eastern mtns: 320° 60 - 70 m s^{-1} equatorward flow from Agulhas: 140° 20 - 25 m s^{-1}
Divergence 200 Divergence 850	upper outflow over Durban: +25.2 x 10^{-6} s^{-1} convergence over eastern mtns: -19.4 x 10^{-6} s^{-1}
Vorticity 300 Vorticity 700	Cyclonic trough, 30°S 20°E, -12.6 x 10^{-5} s^{-1} Cyclonic cells, 30°S 27°E and 25°S 30°E
Vertical motion 700 hPa 500 hPa 300 hPa	Maximum uplift occurs 27 - 30°S, 30°E -0.63 Pa s^{-1} -0.45 Pa s^{-1} -0.32 Pa s^{-1} less uplift with height
Dewpoint 850 hPa 700 hPa streamlines	moist over eastern mountains, 30°S 27°E, 17.7°C from NE Mozambique, from SE Agulhas

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