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Transient Convective Waves in the Tropical SW Indian Ocean

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With 12 Figures

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Summary

Wave-organized convective features in the southwest Indian Ocean are described using Hovmoller composites of satellite imagery, OLR anomalies and ECMWF precipitable water departures during the southern summer. Westward movement of large convective elements is noted in the 10–20°S latitude band in about half of the years between 1970 and 1984. A study of 47 convective systems from satellite imagery establishes the climatological features, including zonal propagation speeds for maritime systems in the range -2 to -4 m s^{-1}, wavelengths of 25–35° longitude (3,000 km), lifespans of 10–20 days and convective areas of 7–10° longitude (800 km). Transient convective waves over the tropical SW Indian Ocean are slower and more diverse than their northern hemisphere counterparts. Interannual tendencies in the frequency and mode are studied. Wet summers over SE Africa correspond with an increased frequency of westward moving convective systems, whereas in dry summers convective systems tend to be quasi-stationary. INSAT data composites provide additional insight into the convective structure and show that tropical waves penetrated into southern Africa in February 1988. A more quantitative assessment of transient convective waves is provided by Hovmoller composites of OLR anomalies and precipitable water departures. Both display westward moving systems in 1976 and 1984 and highlight the wide variety and mixed mode character of convective waves. A case study is analyzed which illustrates the deepening of a moist, unstable layer coincident with the westward passage of a convective wave.

1. Introduction

Transient barotropic waves in low latitudes have received considerable attention in recent years, primarily as precursors to tropical cyclones which often bring rain and destruction to subtropical coasts. These waves require weak easterly winds through the troposphere (Riehl, 1954; Holton, 1971), conditions which are seldom met in the eastern Pacific and Atlantic sectors of the southern hemisphere as a result of the persistence of the subtropical westerly jet stream through the summer season (Arkin et al., 1986). However in the southwestern Pacific and Indian Ocean basins, sea surface temperatures exceed 26 °C and weak easterly shear is conductive to the development of transient convective waves and subsequent tropical cyclone formation (Krishnamurti, 1979). Upper easterly flow in the southern summer is reported throughout the south Indian Ocean across the intertropical convergence zone (ITCZ) in the 5–15 °S latitude band (Hastenrath, 1985) and across tropical Africa to 20 °S (Anyamba et al., 1982), and has been statistically correlated to rainfall over southern Africa (Harrison, 1986). It is our intention in this paper to demonstrate the existence of a wide variety of transient convective waves in the SW Indian Ocean (0–30 °S, 30–100 °E) through subjective analysis of satellite imagery composites over the mid-summer months of January and February.

Easterly waves were first identified in the Caribean (Dunn, 1940) and have since been studied using detailed synoptic and satellite observations (Yanai, 1968; Shapiro, 1986) and numerical models (Shapiro et al., 1988). The conceptual model of easterly waves as reviewed by Riehl (1979) includes a surface trough to the west (ahead) of the region of maximum precipitation, a zonal phase speed of $-8\,\mathrm{m\ s^{-1}}$, positive anomalies of temperature and water vapour across the 700–300 hPa layer, maximum geopotential and meridional wind departures near the 700 hPa level, convective wavelengths of 2,500 km and periods of 5 days.

Transient convective waves in the summer season over the tropical SW Indian Ocean have not previously been studied. Standing tropical waves and continental lows over southern Africa have been identified as contributors to summer rainfall (Vowinckel, 1956; Tyson, 1986 and Harrison, 1986). Asnani (1982) and Okoola (1989) have demonstrated the presence of easterly waves over the equatorial Indian Ocean and Kenya using spectral analysis and lag correlation techniques applied to routine radiosonde observations. Hall (1989) has shown that shallow easterly waves propagate westwards into the South Atlantic and cause rainfall fluctuations at Ascension Island. Padya (1989) describes the characteristics of transient convective waves in the SW Indian Ocean based on 30 years of forecasting experience. He mentions a wavelength of 1,500 km and a westward phase speed of $5\,\mathrm{m\ s^{-1}}$ as typical. Some attention has been focused on tropical cyclones in the SW Indian Ocean as part of global studies (Crutcher and Quayle, 1973). However, these mature cyclones usually recurve polewards, extracting moisture from the Mozambique Channel and reducing the rainfall potential over SE Africa (Dunn, 1985; Diab, 1988). Rather it is westward moving waves, linked to the ITCZ, which are potential contributors to rainfall over the plateau of southern Africa and form the focus of this paper.

2. Data

A synoptic climatology of transient convective waves is developed using NOAA satellite hemispheric mosaics in the visible band. Hovmoller (time-longitude) composites were constructed (as in Chang, 1970) in the latitude band 10–20 °S across the longitudes 10–100 °E. Daily images for the months of January and February for the period 1970 to 1984 were subjectively analyzed for highly reflective cloud distributions as in Garcia (1985). Indian Meteorological Satellite (INSAT) infrared imagery were digitally processed into Hovmoller composites for February 1986 and 1988 across similar domains.

An objective assessment of convective waves was provided by Hovmoller analyses of outgoing longwave radiation (OLR) and ECMWF precipitable water contructed over the period 1 December–31 March and domain 0–100 °E. The OLR data as in Gruber et al. (1986) were analyzed in a manner similar to Rui and Wang (1990). The mean and seasonal signal were removed and five day (pentad) OLR anomalies were computed to remove higher frequency fluctuations. Hovmoller plots were constructed over the 10 °S and 20 °S bands for the summers of 1976–1989. For brevity, the 1976 and 1984 summers were selected for presentation. Using the same summer period and SW Indian Ocean domain, ECMWF moisture fields were analyzed for precipitable water vertically integrated over the 850 hPa–300 hPa layer. The mean and standard deviation were computed and a Hovmoller plot of departures from the mean was constructed over the 15 °S band for the summers 1980–1988. The March 1984 period was chosen for presentation here. General agreement between the OLR and precipitable water Hovmoller plots was noted. Daily resolution OLR anomalies were analyzed for the 10–15 °S band for the 1976 case study, supported by 700 hPa synoptic weather analyses and radiosonde profiles at successive downstream stations, to better understand the evolution and structure of a westward moving convective wave.

3. Results

3.1 NOAA Composites

Hovmoller composites for January–February 1970–1984 in the 10–20 °S latitude band are shown in Fig. 1. Unlike the clear and distinct patterns of Chang (1970) for the North Pacific and Atlantic ITCZs, many different convective scales with both eastward and westward tendencies are noted. The wide variety of transient convective waves reflects the lack of consistent upper easterly support (Arkin et al., 1986), and the process of barotropic instability in the region appears to be neither unified or coherent. Interannual trends in zonal prop-

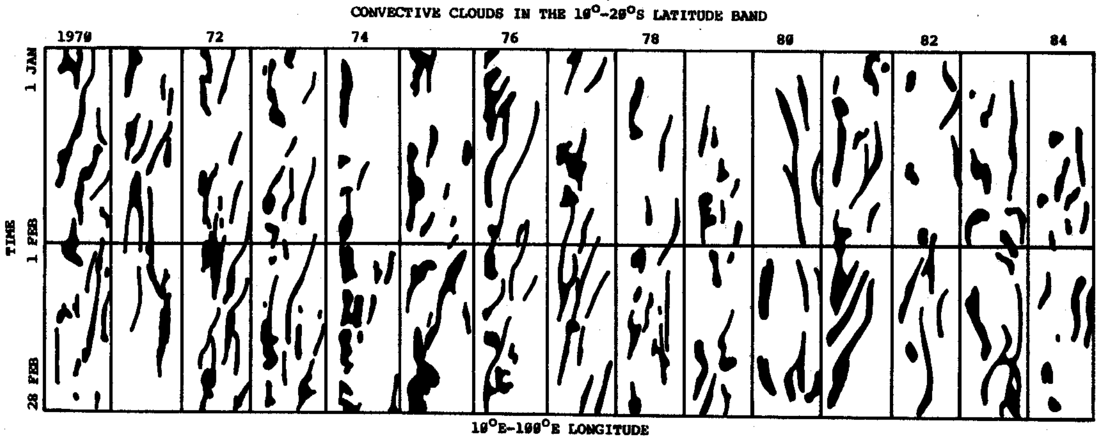


Fig. 1. Nephanalysis of NOAA visible imagery Hovmoller composites in the latitude band 10–20 °S for the months January and February 1970–1984. The longitude range is from 10–100 °E: west coast of Africa to the west coast of Australia

agation speeds in the 10–20 °S latitude band may be distinguished: transient convective waves moved generally westwards in the years 1970, 1972, 1974, 1976, 1977, 1981; convective systems were quasi-stationary in the summers of 1971, 1975, 1978, 1979, 1982, 1983, 1984, and transient convective waves moved eastward in 1980. During the summers of 1970, 1972, 1973, 1976, 1977, and 1981 convective wavelengths were relatively short and coincided with more rapid westwards propagation. Longer wavelengths during 1971, 1979, and 1982 were often stationary.

In the 20–30 °S latitude band (not shown) the convective systems were often quasi-stationary and long-lived. Westward moving convective waves were evident in the summers of 1971, 1974, 1975, 1976, 1981, and 1984. The 1974 and 1976 summers were noted for well above normal rainfalls over the plateau (Taljaard, 1987) and in 1981 a flood event occurred over the southern plateau (Estie, 1981) which appears to have been conditioned by the influx of moisture from a dissipating convective wave. The 1984 summer saw two intense cyclones strike the coast near Durban.

Figure 2 summarizes the climatological statistics for 47 zonally tracking convective disturbances in the SW Indian Ocean area. The probability distributions indicate a wide variety of transient convective waves. The zonal phase speed displayed probability peaks for transient waves of marine origin at -4 and $-2\ \mathrm{m\ s^{-1}}$. The lifespan of the convective disturbances ranged between 10 and 20 days. Of the 47 transient cases considered, most had a convective width of 7–10° longitude (800 km) and a wavelength of 25–35° longitude (3,000 km). Convective systems of continental (African) origin were either stationary or eastward-moving and zonal phase speed probabilities were peaked at 0 and $+1\ \mathrm{m\ s^{-1}}$. The continental systems had a greater convective area and longer wavelength possibly due to heating and topographic influences, but lifespans of 10 to 20 days remained common.

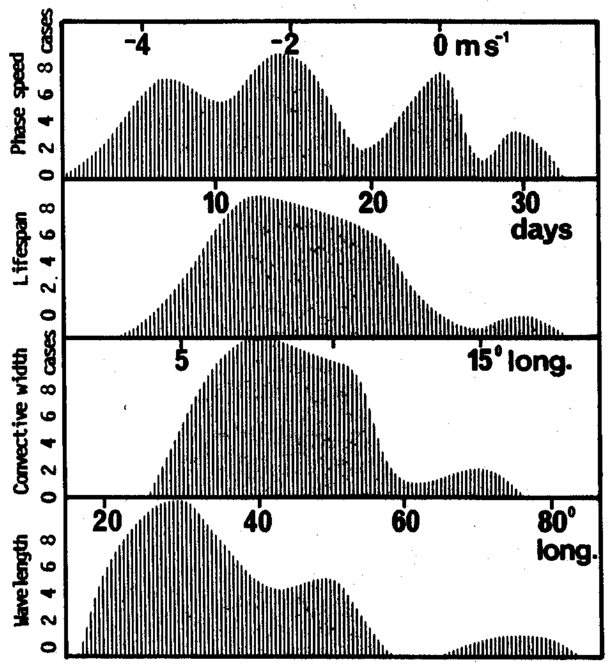
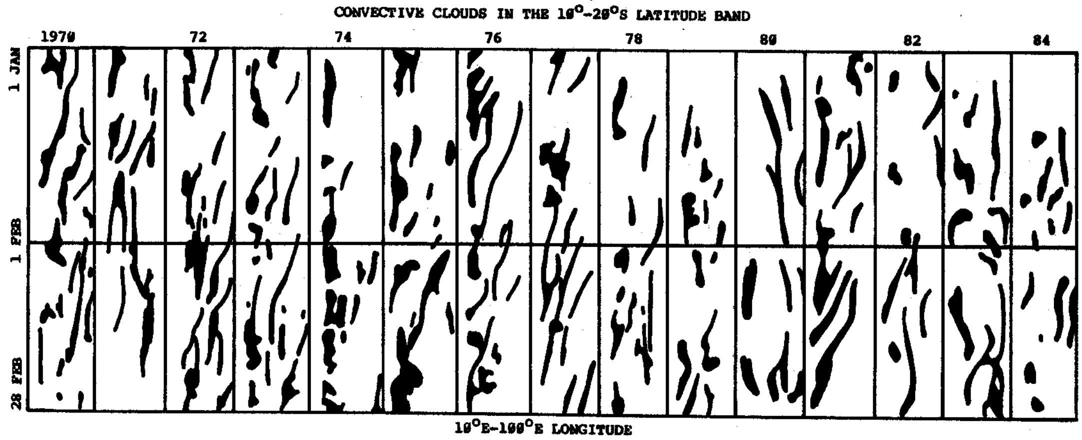


Fig. 2. Climatological statistics for 47 transient convective waves in the 10–20 °S latitude band from Figure 1. The lack of a singularly peaked or gaussian probability distribution indicates a wide range of convective structures



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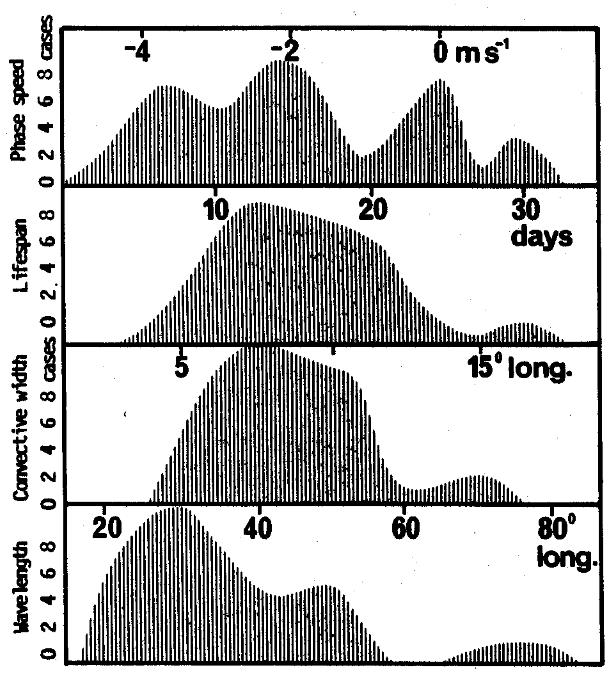

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3.2 INSAT Composites

INSAT infrared data were digitally extracted for the latitude bands 5–10, 13–18, and 21–26 °S across the entire Indian Ocean (Fig. 3) to construct Hovmoller imagery composites for February 1986 and 1988 (Figs. 4 and 5). In the low latitude band during February 1986 (left panel, Fig. 4) some eastward moving convective features were found in the central southern Indian Ocean. A region of minimal cloudiness was noted off the east coast of Africa, evidence for subsidence which could block the westward passage of transient waves. Convective systems in the subtropical latitude bands (middle and right, Fig. 4) appeared to be patchy, short lived and quasi-stationary.

In contrast the February 1988 Hovmoller composites display westward moving systems in the lower latitude bands (left and middle panels, Fig. 5). Wave trains became evident in the region of Cocos Island and were long-lived. The equatorial source region experienced a slow eastward moving convective wave (apparent in the right upper corner of the left panel in Fig. 5) which GMS imagery confirmed tracked eastward into the Pacific basin. No region of subsidence was evident off the east coast of tropical Africa, where sea surface temperatures were above normal (CAC Bulletin, 1988). The westward moving waves were seen to cross the southeast coast of Africa during February 1988 on the western rim of the INSAT field of view. The wave structures were characterized by convective widths of 1,000 km, wavelengths of about 3,500 km and zonal phase speeds of -3 to $-4\,\mathrm{m\,s^{-1}}$. Meteosat composites (not shown) indicated that three westward moving convective waves crossed into southern Africa from the SW Indian Ocean and dissipated near 20 °E, 20 °S. The tropical convective disturbances were steered westwards by a strong subtropical ridge

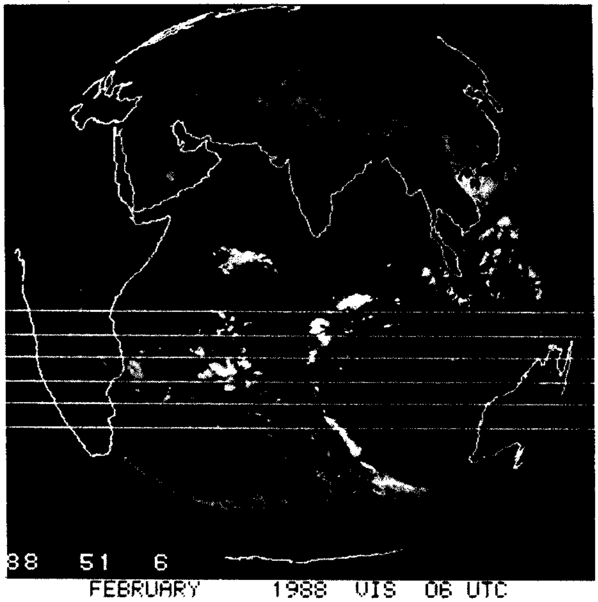

Fig. 3. Indian Meteorological Satellite (INSAT) field of view showing strips used for the construction of Hovmoller composites. The longitude range is from 10–140 °E

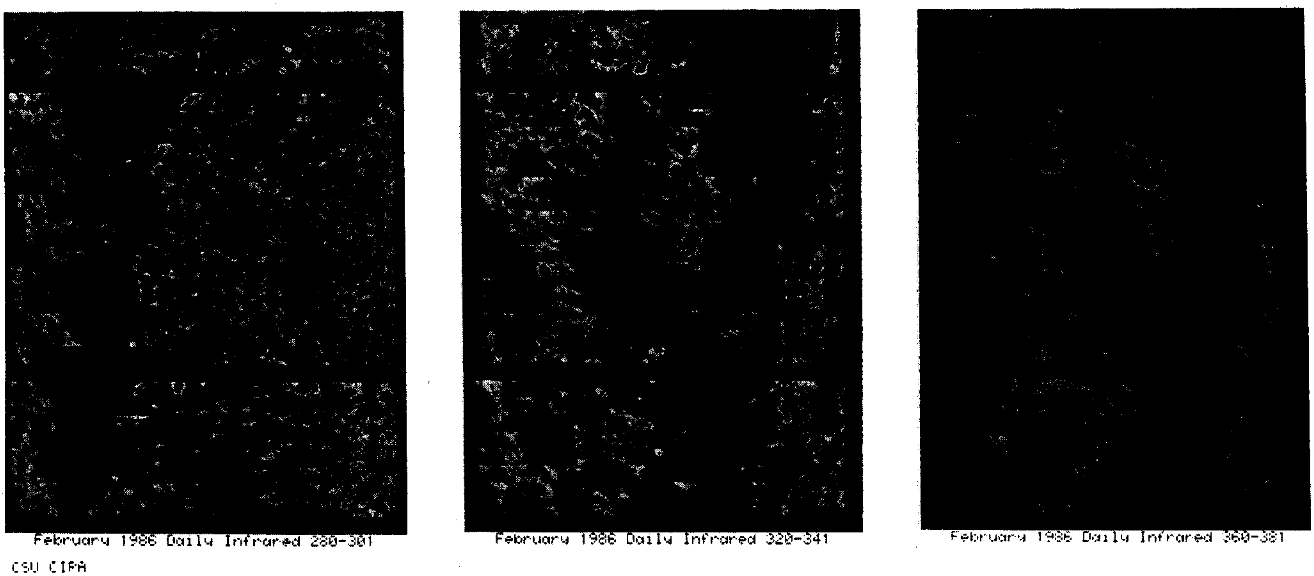

Fig. 4. INSAT infrared Hovmoller composite for February 1986 in the latitude bands (left to right) 5–10 °S, 13–18 °S, and 21–26 °S. Dark strips are missing data. Convective tops colder than $-40\,°C$ are dark

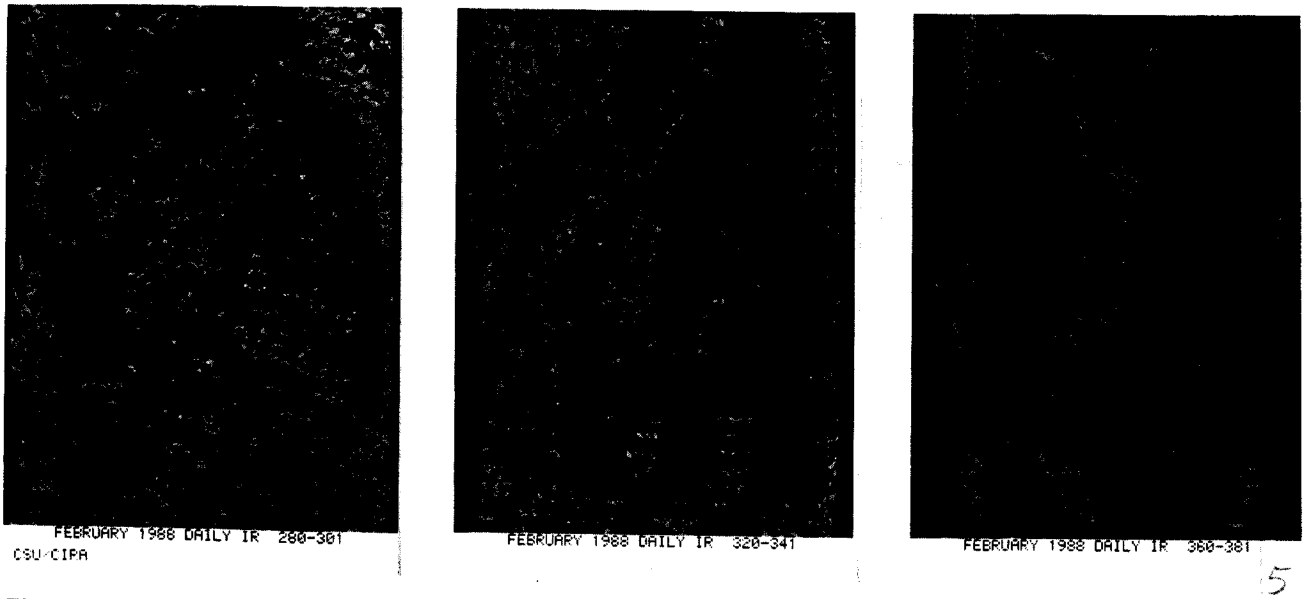

Fig. 5. INSAT composite for February 1988 as in Fig. 5

located to the southeast of Africa near 40 °E, 30 °S (Lindesay and Jury, 1991). In the mid-latitudes, westerly waves dominated the structure with zonal phase speeds of + 4 to + 6 m s^{-1} and wavelengths of 4,000 km prevalent. As the tropical easterly and mid-latitude westerly waves came into phase, conditions for flooding arose (Lindesay and Jury, 1990).

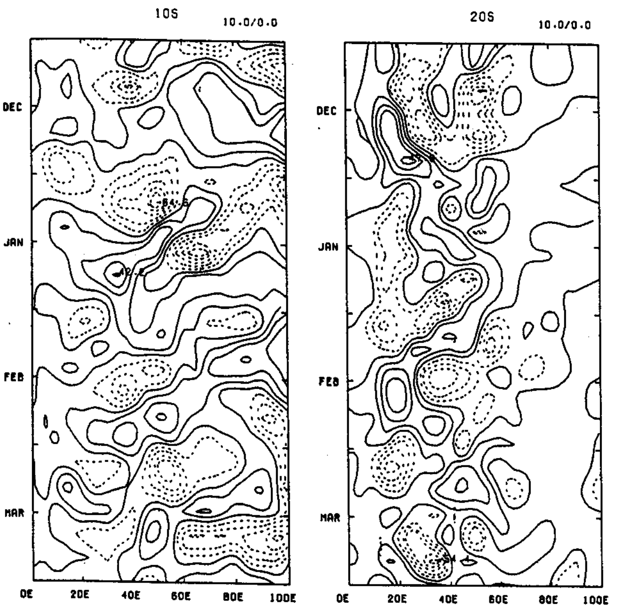

Fig. 6. Hovmoller analysis of pentad OLR anomalies for the 10 °S band (left) and 20 °S band (right) for the period 1 December 1975–31 March 1976 over the domain 0–100 °E. The east coast of Africa lies on the 40 °E longitude. Contour interval is 10 Wm^{-2} and negative (convective) areas are dashed

3.3 OLR and Precipitable Water Analyses

The OLR anomaly Hovmoller analyses for 1976 in Fig. 6 display westward moving convective waves (dashed areas). Four wave trains were seen in the 10 °S band while at 20 °S two westward moving systems were evident. The waves propagated 15–20° longitude per week or about 3 m s^{-1}. In the 1984 summer (Fig. 7) westward moving waves were less common and short-lived. A few short wavelength cases were noted in the 20 °S band, however in the 10 °S band longer wavelength eastward-moving disturbances prevailed, particularly in early February 1984 over the central South Indian Ocean. These intraseasonal oscillations have been documented by Rui and Wang (1990) who found a greatest amplitude and frequency of occurrence in this region at this time of the year.

The precipitable water 1980–1988 means and standard deviations are shown in Fig. 8 for the 15 °S band. A clear distinction is noted between continental and maritime convective regimes. Over Africa between 15°–35 °E, the mean 850–300 hPa precipitable water is near 33 mm and the standard deviation around 4.5 mm. The Mozambique Channel and Madagascar lie at the transition between the two regimes. Further to the east the standard deviations rise over 6 mm while the

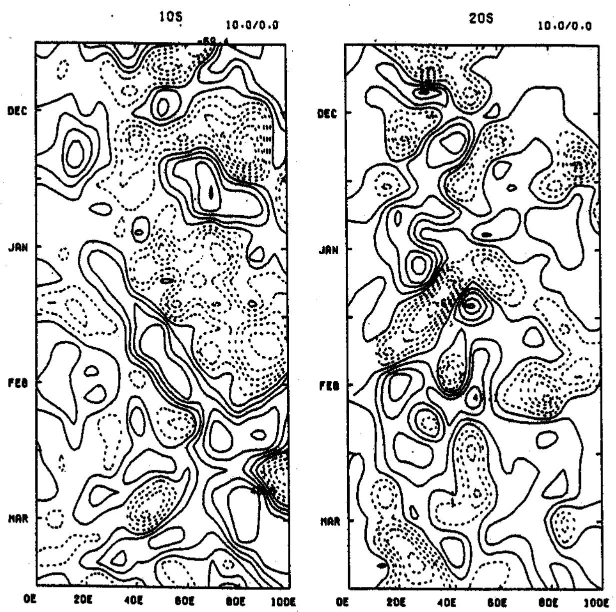

Fig. 7. Hovmoller analysis of pentad OLR anomalies as in Fig. 6 but for 1 December 1983–31 March 1984

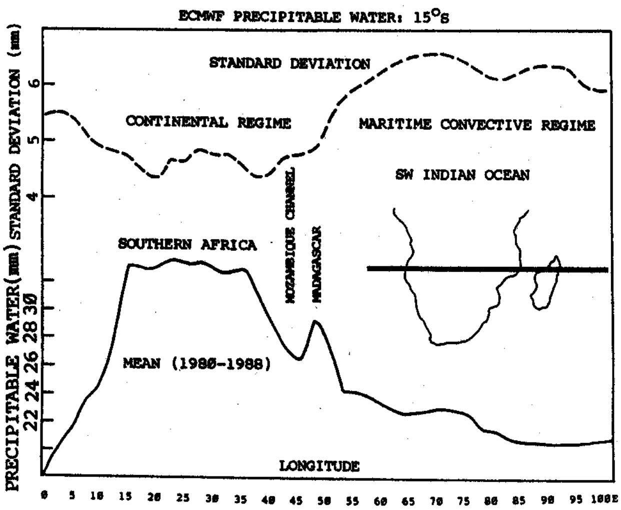

Fig. 8. ECMWF precipitable water (850–300 hPa layer) standard deviation (top) and mean for the 1 December–31 March summer period 1980–1988. Coastal outline and 15 °S reference is shown on right at smaller scale

mean drops to about 22 mm in the absence of large sensible heat fluxes over the ocean.

The precipitable water Hovmoller analysis for March 1984 (Fig. 9) identifies westward moving pulses of moisture. The wave trains exhibited departures of + 13 and − 19 mm with a wavelength of about 3,000 km and a propagation speed of 4–5 m s^{-1} to the east of 50 °E. The wave trains de-

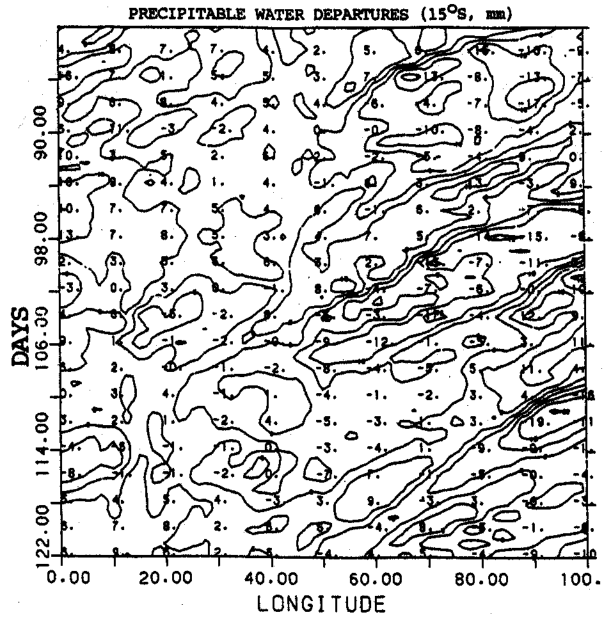

Fig. 9. ECMWF precipitable water (850–300 hPa layer) Hovmoller analysis for the period end February to end March 1984. Departures from the longitude mean are plotted and contoured at 5 mm intervals. A train of positive and negative departures is evident in the eastern half

cayed, slowed and dissipated over Madagascar and did not appear to reach the east coast of Africa in the 15 °S band. Synoptic reports revealed that an intense tropical cyclone devasted northern Madagascar in early April 1984.

3.4 Case Study

In this section the structure of a westward moving convective system (shown by the OLR anomaly

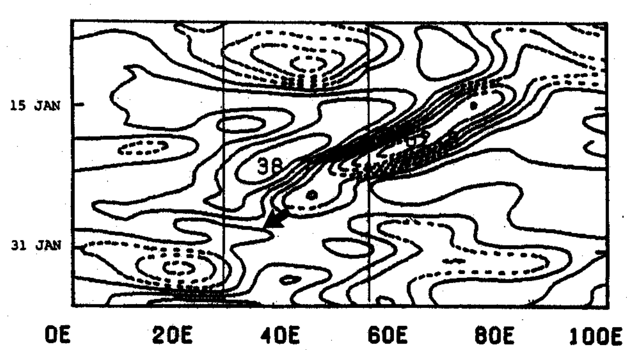

Fig. 10. Hovmoller analysis of daily OLR anomalies as in Figs. 6 and 7 but for the 10°–15 °S band for the period 5 January–5 February 1976. Vertical lines mark the longitude position of Mauritius and Zimbabwe data in Figure 12. Arrow shows propagation of the convective system. Contour intervals are 10 Wm^{-2} and negatives are dashed

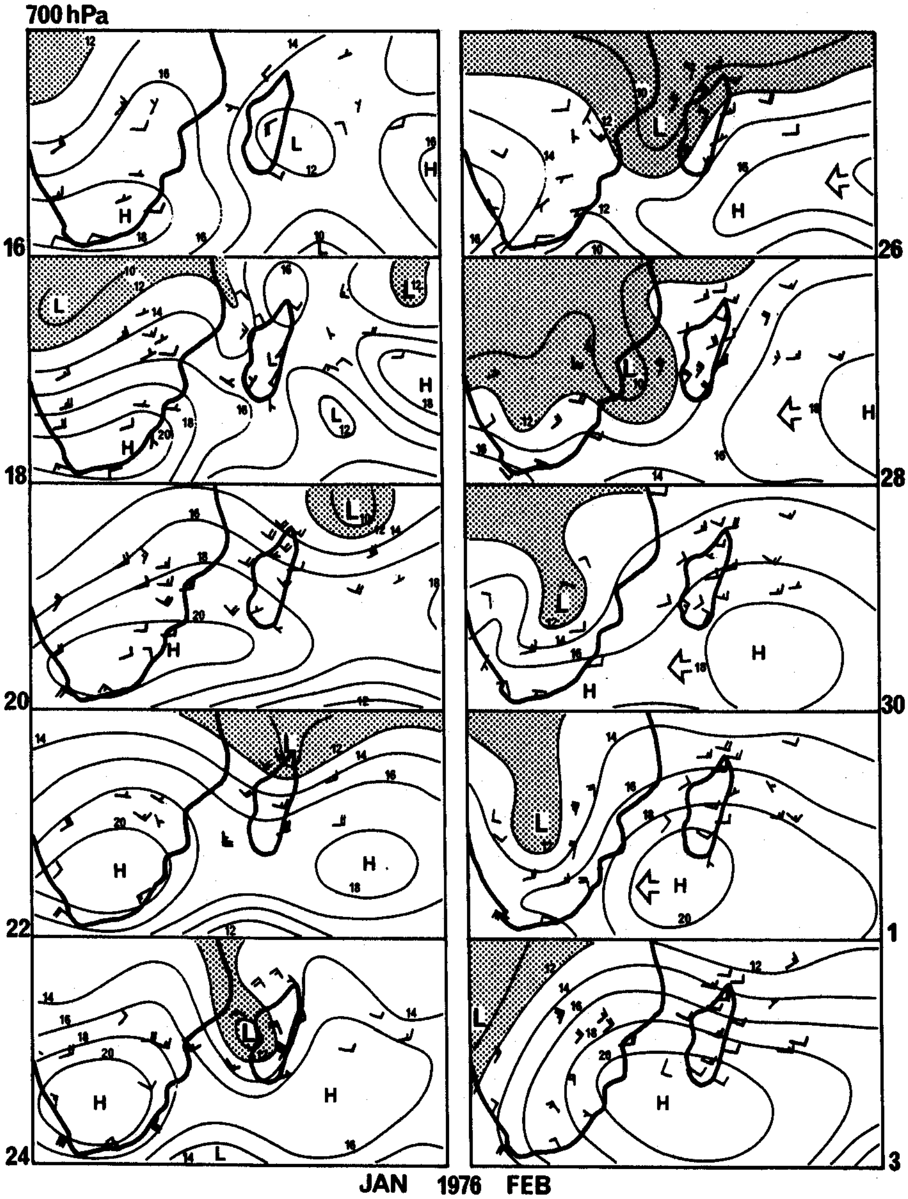

Fig. 11. Synoptic 700 hPa sequence of wind and geopotential observations for alternate days over the period 16 January–3 February 1976. Geopotentials below 3,120 gpm are shaded (adapted from Taljaard, 1987)

Hovmoller in Fig. 10) is analyzed. The system was first picked up in the Cocos Island radiosonde profile as a peak in upper easterly flow after 10 January 1976. By 12 January the perturbation had moved to 14 °S, 84 °E as a 700 hPa ridge developed along the 30 °S latitute (Fig. 11). A 300 hPa easterly surge was observed over Mauritius (near 20 °S, 55 °E) on 20 January, over Madagascar on 31 January and over Zimbabwe on 4 February 1976, coincident with a major rain event over the plateau of southern Africa (Taljaard, 1987). The 700 hPa meridional wind component revealed a growing signal along the path of the system. The OLR anomaly Hovmoller (Fig. 6, right panel) suggests a peak in development in the 20 °S band near 40 °E. As the system moved westward, the equatorial trough was brought poleward and 700 hPa geopotentials fell across much of SE Africa (Fig. 11) just prior to the convective outbreak.

Radiosonde profile time series at Mauritius and Zimbabwe (Fig. 12) reveal detailed circulation and thermodynamic features of the system. At Mauritius the system was distinguished by the temperature anomaly switching from − 3 to + 3 °C over the period 12–20 January 1976. A similar negative-positive anomaly was noted in the upper geopo-

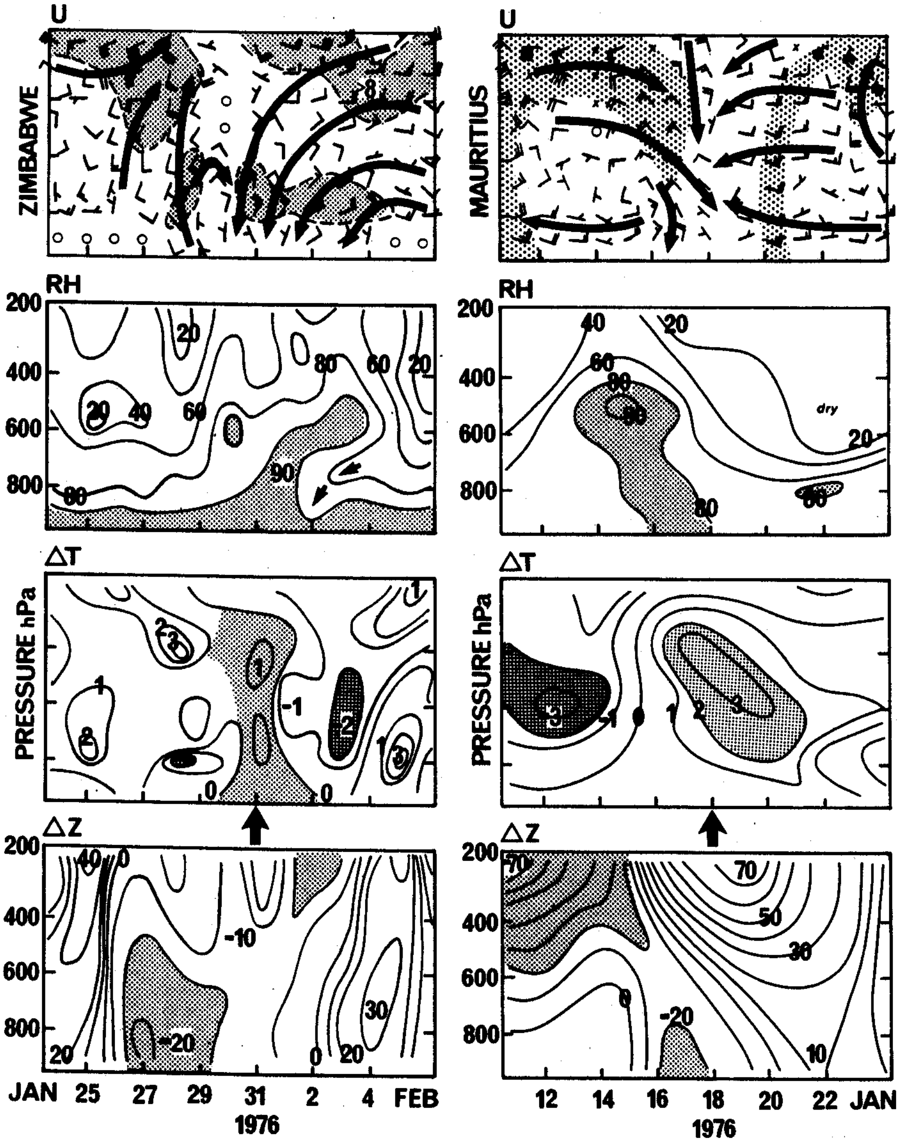

Fig. 12. Radiosonde time-height analysis of (top to bottom): wind, humidity, temperature departure, geopotential departure for Mauritius (10–24 January, right) and Harare, Zimbabwe (23 January–6 February 1976, left). Shading highlights high relative humidities and anomalies of temperature and geopotential. Arrows mark wave passage

tentials. Winds swung from NW to E and relative humidities rose to 80% up to the 400 hPa level on 15 January. An influx of very dry air followed the passage of the system over Mauritius in the SW Indian Ocean.

The wave evolved during westward passage across Madagascar and the Mozambique Channel and contrasts were noted in the Zimbabwe analysis (Fig. 9, right). Temperature and geopotential departures were less organized but the wind switch and moist lifting remained clear. Negative (positive) geopotential departures preceded (followed) the system and were best organized in the lower levels. NE winds originating from the northern Mozambique Channel, moved in on the back of the wave and acted to lift the 80 and 90% relative humidity levels by 5 km between 31 January and 3 February. The dry wedge trailing the system was maintained over SE Africa and 20% humidities were evident by 6 February in the layer down to 600 hPa. Heavy rainfall occurred over a wide swath of southern Africa between 2 and 4 February 1976 (Taljaard, 1987).

4. Summary

Through Hovmoller analysis of daily satellite imagery, OLR anomalies and ECMWF precipitable water departures in the mid-summer months, the presence of a wide variety of transient convective waves in the SW Indian Ocean has been demonstrated. In the 10–20 °S latitude band westward moving waves were prominent during the summers of 1970, 1972, 1973, 1976, 1977, 1981, and 1988 and in the 20–30 °S band in the years 1971, 1974, 1975, 1976, 1981, 1984, and 1988. Climatological characteristics of transient convective waves in the SW Indian Ocean from subjective analysis of satellite imagery, include a westward phase speed of 2 to 4 m s^{-1}, a lifespan of 10–20 days, a convective width of 800 km and a wavelength of 3,000 km. Autocorrelation analysis of 700 hPa meridional wind components at Mauritius (20 °S, 55 °E) indicates a 20 day period (Jury and Pathack, 1991), about three times longer than the tropical easterly waves of the northern hemisphere. The slower period reflects the longer wavelength and much slower phase speed. In "wet" summers over southern Africa (1974–1976, and 1988) the subtropical ridge acts as a waveguide for tropical waves. However in "dry" summers dominated by upper westerlies, such as 1983, convective ensembles remain in the SW Indian Ocean and tropical cyclones are less frequent.

The OLR Hovmoller analysis highlighted the wide variety and evolution of convective waves transiting the SW Indian Ocean. In 1976 both 10 °S and 20 °S bands exhibited westward moving waves, while in 1984 low frequency eastward moving waves dominated the 10 °S band. The ECMWF precipitable water data displayed a high (low) mean and low (high) standard deviation over SE Africa (the SW Indian Ocean). Pulses of moisture, driven by convergence and uplift in the easterly waves, were clearly defined and propagated westward at 4–5 m s^{-1} across the central South Indian Ocean. The waves appeared to dissipate or move out of the 15 °S band near Madagascar in March 1984.

The 1976 case study demonstrated that summer rainfall episodes over southern Africa can be traced to westward moving tropical weather systems originating in the south Indian Ocean. Upper easterly winds strenghtened on the back of the wave, first at Cocos Island in early January and finally over Zimbabwe in early February. A mid-tropospheric ridge guided the system westward, while convergence within the system lifted the moist unstable layer by 5 km, coincident with a major rainfall event.

Transient convective waves in the SW Indian Ocean exhibit a wide variety of structure and are slower and less coherent than in other tropical cyclogenesis regions. The waves contribute to summer rainfall by lifting moisture from the northern Mozambique Channel over the Zimbabwe escarpment and by pulsing the supply of latent heat energy and cyclonic momentum to the quasi-stationary tropical trough over Zambia. Further quantitative and dynamical studies of the causal mechanisms and structure of transient convective waves in the SW Indian Ocean is the goal of future research initiatives.

Acknowledgements

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