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Links between rainfall variability on intraseasonal and interannual scales over western Tanzania and regional circulation and SST patterns

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Wth 14 Figures

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Summary

This study investigates the circulation anomalies associated with the intraseasonal evolution of wet and dry years over western Tanzania (29–37° E, 11.5–4.75° S) and how the onset and withdrawal of the rainy season as well as its wet spell characteristics are modified. It is found that for wet years, the rains begin earlier and end later, with strong wet spells occurring during the season, and there tend to be a greater number of moderate wet spells (although not necessarily more intense wet spells) than in dry years. In dry years, late onset and early cessation of the rainy season occur, often with an extended dry spell soon after the onset, and there tend to be a greater number of dry spells within the season. Large negative outgoing long wave radiation (OLR) anomaly values tend to be located between 20° and 40° E with anomalous westerly flow at 850 hPa occurring across the continent from 10° E to the tropical western Indian Ocean during wet spells in the anomalously wet seasons. Anomalously dry seasons are characterised by large positive OLR anomalies over 30–50° E as well as easterly anomalies at 850 hPa and westerly anomalies at 200 hPa. Eastward propagating intraseasonal anomalies are slower during the wet years implying that the convection remains over Tanzania longer. On the intraseasonal scale, Hovmoeller analyses of OLR and 850 and 200 hPa zonal wind indicate that convection over western Tanzania may be associated with a flux of moisture from the tropical southeast Atlantic and Congo basin followed by weak easterlies from the tropical western Indian Ocean.

On interannual scales, wet (dry) years are characterized over the Indian Ocean by weaker (stronger) equatorial westerlies and weaker (stronger) trades that lead to less (more) export of equatorial moisture away from East Africa and increased (decreased) low-level moisture flux convergence over southern Tanzania, respectively. These anomalies arise from an anticyclonic (cyclonic) anomaly over the tropical western Indian Ocean during wet (dry) austral summers that may be related to cool (warm) SST anomalies there. Large scale modulation of the Indian Ocean Walker cell is also evident in both cases, but particularly for the dry years.

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1. Introduction

The economy of Tanzania largely depends on agriculture, which in turn is highly vulnerable to variability in rainfall amount and distribution. Northern Tanzania, like the rest of East Africa, experiences a bimodal annual rainfall pattern, whereas the western Tanzania region (4.75–11.5° S, 29–37° E) studied herein, exhibits a single wet season from October to April. Within this period, the development over the western Indian Ocean of the NE monsoon and its transitions to and from the SW monsoon near the beginning and end of the wet season are important. Considerable intraseasonal variability and breaks in convective activity exist during the monsoon so that the wet season is typically characterised by a number of wet and dry spells. Spells of very heavy rain may cause floods and lead to outbreaks of disease such as malaria and rift valley fever whereas dry spells cause withering of crops and may lead to droughts and severe impacts on communities.

Despite the importance of such wet and dry spells to Tanzanian climate, relatively little work has been done on their frequency during the rainy season or its onset and withdrawal, or how these fundamental characteristics may vary on interannual time scales. In terms of interannual variability, Nieuwolt (1978) and Minja (1982) considered droughts in East Africa to be associated with weak monsoons and a number of authors such as Ogallo (1988; 1989), Hasternrath et al (1993), Kabanda and Jury (1999), Indeje et al (2000) have found evidence that the El Niño/Southern Oscillation (ENSO) phenomenon influences Tanzanian climate. A detailed analysis of the evolution of the ENSO signal over the Indian Ocean together with associated rainfall signals over eastern and southern Africa may be found in Reason et al (2000), and Allan et al (2003).

Other important SST patterns in the Indian Ocean, whose potential relationships with ENSO remain to be clarified, include the Indian Ocean Zonal mode (Saji et al, 1999; Webster et al, 1999) and subtropical south Indian Ocean dipole patterns (Behera and Yamagata, 2001; Reason, 2001). The former mode appears to influence the OND "short rains" over the Kenyan region whereas the latter sometimes influence JFM rainfall over a region of southern Africa stretching south from Zambia to Mozambique and eastern South Africa. However, whether or not either of these patterns directly impact on the western Tanzanian region of interest here is not clear.

Considerably more work has been done on the interannual variability of seasonal rainfall in various regions of East Africa than on the societally important and applications-oriented intraseasonal variability. In general terms, intraseasonal oscillations in the atmosphere are generally defined as fluctuations with periods longer than a week but shorter than a season and are a prominent feature of tropical weather particularly in the Indo-Pacific region (Madden and Julian, 1971; 1994; Vincent et al, 1991). This time scale of variability therefore falls between the synoptic weather scale and seasonal variations and is of fundamental interest to the water resources, agricultural, tourism and health sectors.

Initially identified by Madden and Julian (1971), intraseasonal oscillations have become widely studied in recent times over the Indo-Pacific and West Africa but less so over East Africa where the significant topography of the region complicates the signal. Also, intraseasonal convection anomalies tend to be smaller over Africa than those found over the Indo-Pacific region (Knutson and Weickmann, 1987). Such oscillations are known to be important for tropical rainfall, including East Africa (Anyamba, 1992; Camberlin and Wairoto, 1997) and are likely to influence wet and dry spell characteristics as well as onset and withdrawal of the season. Intra-seasonal oscillation studies which consider tropical Africa and the adjacent oceans include Zhu and Wang (1993) and Mpeta and Jury (2001). Zhu and Wang (1993) found a prominent centre of action in the central Indian Ocean with variability in convection on a 30 to 60 day time scale. Mpeta and Jury (2001) found that convective events over southwestern Tanzania were associated with an influx of northeasterly Indian Ocean monsoon flow followed by increased westerly flow from the Guinea/Congo region. Anyamba (1992) identified a 20–30 day oscillation in the tropical outgoing long wave radiation (OLR) spectra in the western Indian Ocean and found that while the 40–50 day ISO is characterized by an eastward propagating wave in the Indian and West Pacific Oceans, the 20–30 day ISO has a much weaker zonal propagation. Rui and Wang (1990) documented the development and dynamic structure of typical intraseasonal convection anomalies using pentad OLR and ECMWF derived 200 and 850 hPa wind divergence.

To help improve understanding of western Tanzanian rainfall variability, this study examines the intraseasonal evolution of anomalously wet and dry years and possible relationships with the surrounding oceans. In addition, the nature of the onset, withdrawal and wet spells during these wet and dry years is investigated.

2. Data and methodology

The data used in this study to investigate the evolution of wet and dry spells over western Tanzania includes pentad and monthly rainfall, NCEP/NCAR reanalyses (Kalnay et al, 1996), NOAA outgoing longwave radiation (OLR), and monthly Reynolds reconstructed SST (Smith et al, 1996). Moisture fluxes are calculated from the winds and specific humidity. The rainfall data consists of mean monthly records at 6 stations within the period 1968–1998 from the Tanzania Meteorological Agency and pentad (5-day mean) CMAP gridded rainfall (Xie and Arkin, 1997). The latter is a merge of satellite model and raingauge data with a spatial resolution of $2.5^\circ \times 2.5^\circ$.

The region of western Tanzania (4.75–11.5° S, 29–37° E) studied herein has a uni-modal rainfall regime with a wet season extending from October to April. A spatially averaged and normalised rainfall index was used to define anomalous wet and dry years during the 1968–1998 period for this season. Six stations were used for this purpose, namely, Kigoma, Tabora, Sumbawanga, Iringa, Mbeya and Songea (Fig. 1). Using a criterion of a standardised departure of at least 0.8 standard deviations from the mean, the anomalously wet seasons were found to be 1968/1969, 1970/1971, 1978/1979, 1979/1980, 1982/1983 and 1986/1987 and whereas dry seasons are 1969/1970, 1976/1977, 1987/1988, 1992/1993, 1993/1994 and 1998/1999. The selected years after 1979 are the same as those derived in the same way using CMAP data for western Tanzania.

Since the station data are only available as monthly totals, pentad (5 day) CMAP rainfall totals, averaged over 29–37° E, 11.5–4.75° S, are used to analyse the intraseasonal variability during the wet and dry seasons starting in 1979/80. Note that CMAP data are not available prior to 1979. Latitude-time sections of CMAP precipitation along 29–37° E were plotted to investigate onset, evolution and withdrawal of the rains over the Tanzanian region for the wet and dry seasons. Longitude-time section (Hovmoeller) plots of OLR anomalies and zonal wind components at 850 and 200 hPa levels were used to identify zonally propagating features over 15–5° S. To isolate intraseasonal oscillations such as Madden-Julian Oscillations (Madden and Julien, 1971; 1994) from synoptic features such as easterly waves, the data used in these Hovmöller analyses were first subjected to a 30–50 day band pass filter using the Dolph – Chebyshev convergence window (Doblas-Reyes and Déqué, 1998). This period of filtering was found to be optimal (20–40, 20–60 and 40–60 days were also tried) and roughly spans the 40–50 and near 30 day peaks in tropical convection and upper air parameters derived by Hayashi and Golder (1993). Visual inspection was used to determine when there was a "sudden increase" and "sudden decrease" of rainfall in each particular year. The pentads corresponding to the sudden increase and sudden decrease of rainfall were

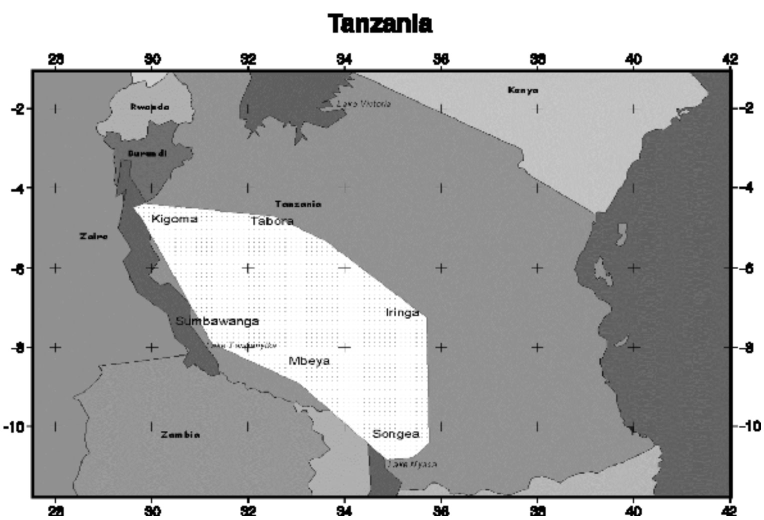

Fig. 1. The six rainfall stations in western Tanzania used for identifying wet and dry years during 1968–1999

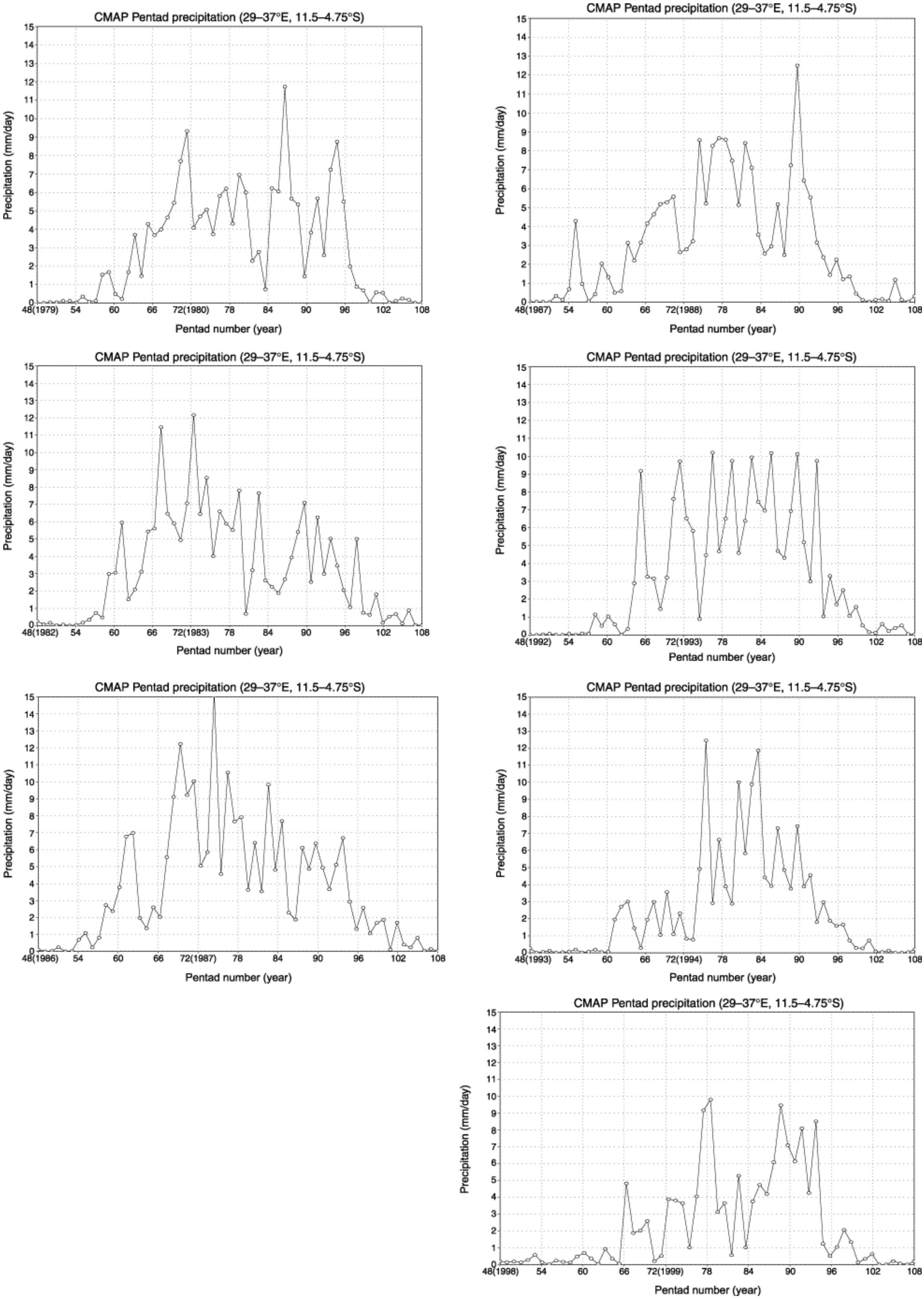

Fig. 2. Area averaged time series of pentad (5-day) CMAP rainfall over western Tanzania (1979/80, 1982/3, 1986/7 wet years on the left and 1987/8, 1992/3, 1993/4, 1998/9 dry years on the right)

Table 1. Mean pentad and dates of the onset and withdrawal of the rains for wet and dry years over western Tanzania during 1979–1999. Note that due to the rainy season straddling the calendar year (October–April), the pentad numbers for January–May have been added to pentad 73 (27–31 December) for convenience

Wet years			Dry years		
Year	Pentad and dates of the rain onset	Pentad and dates of withdraw of the rains	Year	Pentad and dates of the rains onset	Pentad and dates of withdraw of the rains
1979	57 (8–12 Oct.)	97 (26–30 Apr.)	1987	62 (2–6 Nov.)	90 (22–26 March)
1982	58 (13–17 Oct.)	100 (11–15 May)	1992	63 (7–11 Nov.)	92 (1–5 Apr.)
1986	57 (8–12 Oct.)	101 (16–20 May)	1993	60 (23–27 Oct.)	93 (6–10 Apr.)
			1998	65 (17–21 Nov.)	96 (21–25 Apr.)

regarded as the onset and withdrawal of the wet season, respectively. The period analysed each year started with pentad 48 (September) and ended with pentad 108 (June) so as to fully encompass any early start or late withdrawal of a particular season.

3. Intraseasonal analyses

It is evident from the CMAP pentad rainfall time series plots (Fig. 2) and Table 1 that the onset of the anomalously wet seasons for 1979–1999 occurs during the pentad range of 57–58 (mid October) whereas, for the unusually dry seasons, onset typically occurs around pentad 60–65 (late October to November). Anomalously wet seasons tend to end considerably later (pentad 97–101 – early May to late May) than the dry seasons (pentad 90–96 – late March to late April). Thus, the three anomalously wet seasons lasted 41–45 pentads whereas the duration of the four drier seasons ranges from 30 to 34 pentads, or about 2–3 months less in length. Note that due to the rainy season straddling the calendar year (October–April), the pentad numbers for January–May have been added to pentad 73 (27–31 December) for convenience in the calculations in Table 1. Inspection of the individual time series suggests that both wet and dry years experience pentads of relatively intense rainfall (8 mm or more per pentad) during the rainy season but that the wetter seasons tend to have more moderate wet spells (more than 4 but less than 8 mm per pentad) as well as lasting longer (Table 2). In addition, relatively dry spells (less than 2 mm per pentad) tend to be more common during the drier seasons. Thus, both the duration of the season and the frequency of moderate and light spells of rainfall within the season are important for determining the anomalous wet and dry years. It is important to emphasize that a dry year can still experience some pentads of very heavy rainfall. Such intraseasonal characteristics have important implications for local agriculture and water resources.

Table 2. Number of wet spells of various intensity during each anomalous season

Year	Moderate wet spells (between 4 and 8 mm/pentad)	Relatively dry spells (less than 2 mm/pentad)
1979/80	23	13
1982/83	23	11
1986/87	24	10
1987/88	19	11
1992/93	22	14
1993/94	14	18
1998/99	14	21

Further contrasts between these wet and dry years may be obtained by plotting latitude-time sections of precipitation averaged over the longitude band 29–37° E that extends over western Tanzania as well as Hovmoeller plots of OLR and 850 hPa and 200 hPa zonal wind. Note that these plots extend from northern Mozambique across the western half of Tanzania and up to northern Uganda/Kenya. We begin by discussing the first panel of Figs. 3–9 which show the evolution of the precipitation for each season and, later in this section, consider the Hovmoeller plots shown in the other three panels. Table 3 summarises some additional aspects of each season.

During wet 1979/1980 (Figs. 2 and 3), the rains started in pentad 57 (early/mid October) and started to withdraw in pentad 97 (late April). Strong wet spells occurred in the mid to late

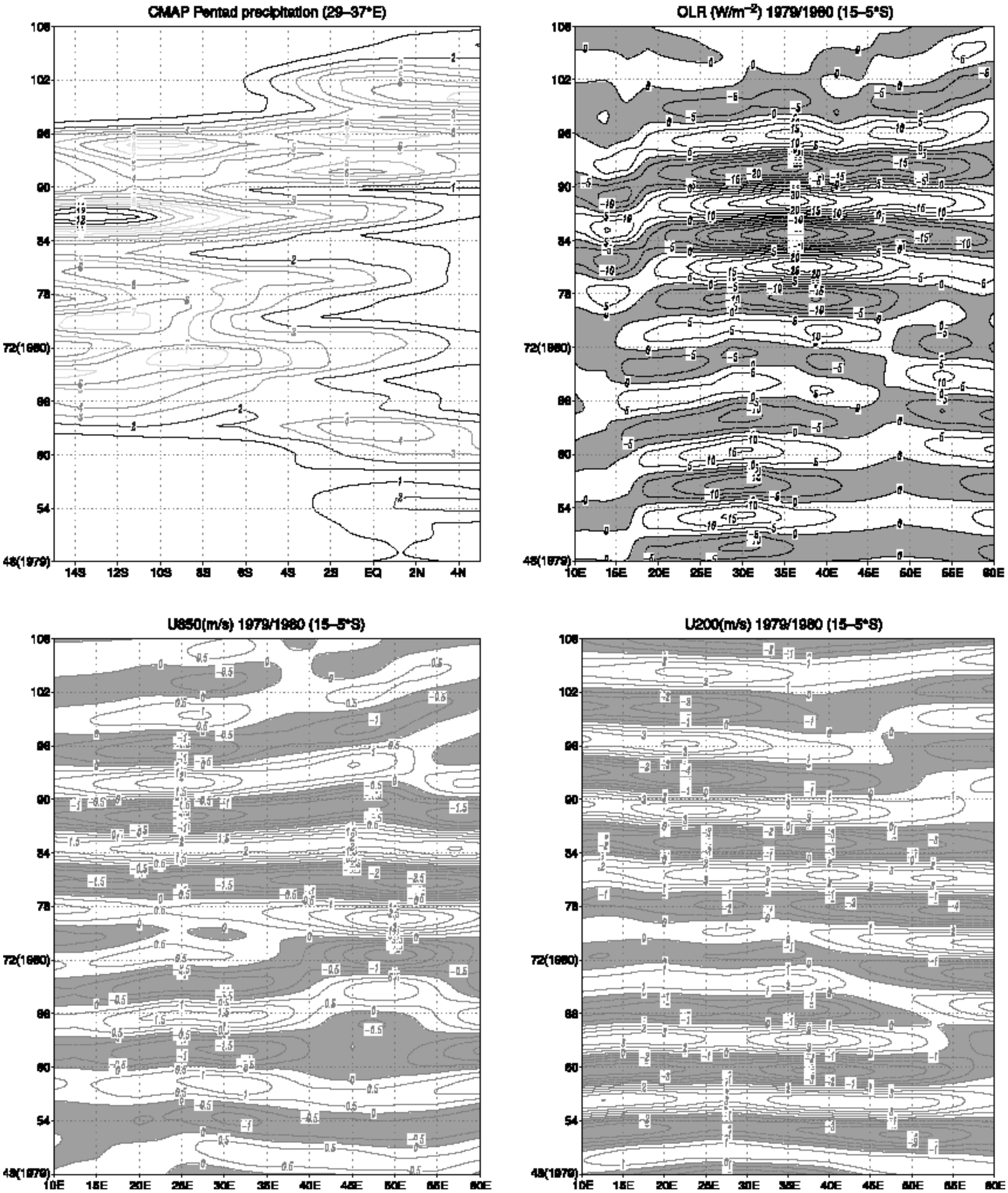

Fig. 3. Latitude time section of CMAP pentad rainfall (contour interval 1 mm/day) (upper left). The other panels are Hovmoeller plots for anomalies in OLR (contour interval 5 $\mathrm{Wm^{-2}}$), 850 hPa zonal wind (contour interval 0.5 $\mathrm{ms^{-1}}$), and 200 hPa zonal wind (contour interval 1 $\mathrm{ms^{-1}}$) for the 1979/1980 rainy season. All data except the rainfall have been 30–50 day bandpass filtered

part of the season while, early in the season, wet spells tended to propagate northwards from northern Mozambique, across Tanzania and into southern Kenya (Table 3). After pentad 78, wet spells tended to occur simultaneously. The 1982/1983 season (Figs. 2 and 4) was wetter than 1979/1980, although the rains started slightly later in pentad 58 (mid October). However, the season lasted until mid May (Table 1). Strong wet spells occurred during the middle third of the season (Table 3) with some northwards propagation of the wet spells from Mozambique to Kenya in the season. During the wet 1986/1987 (Figs. 2 and 5) season, rains

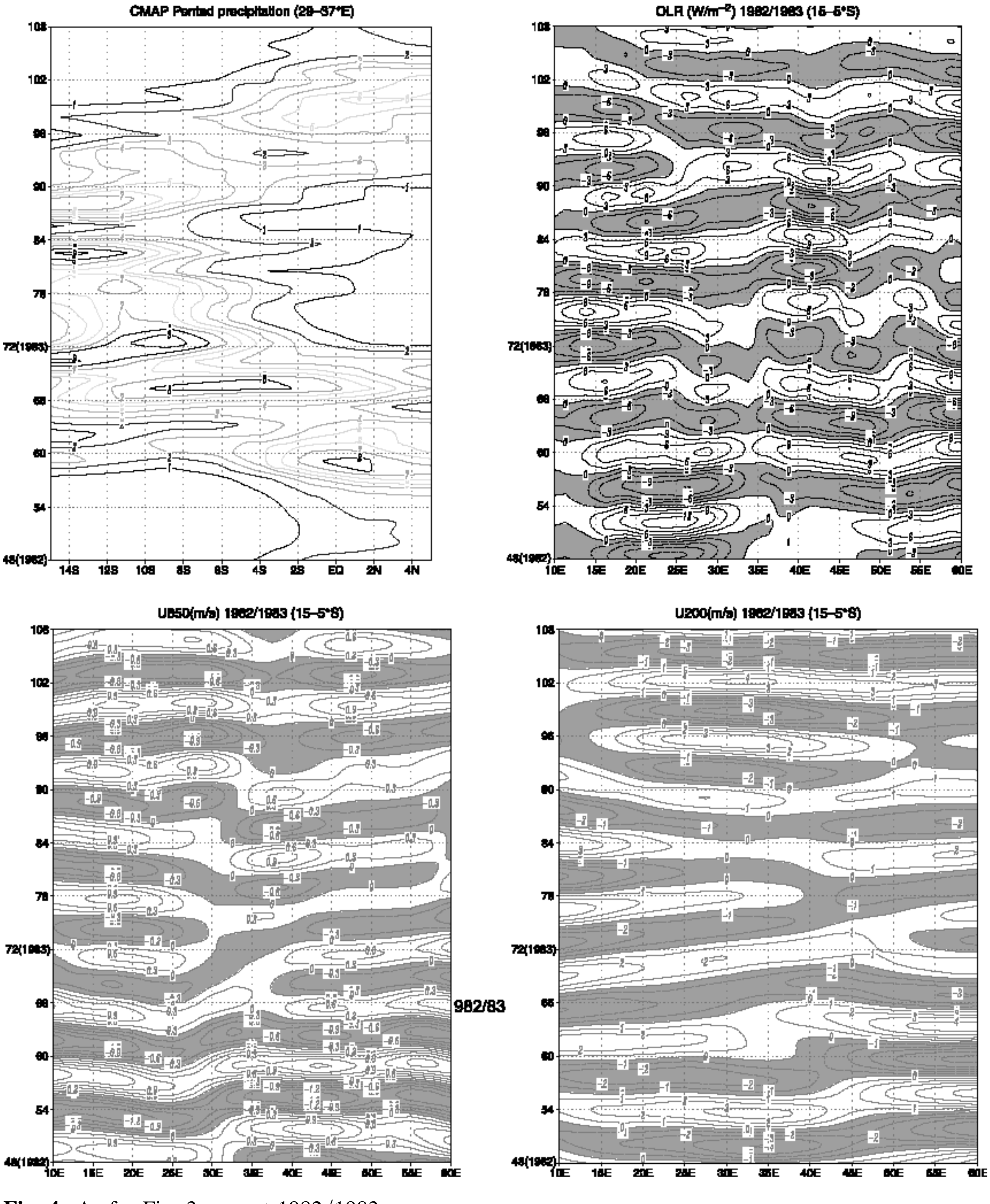

Fig. 4. As for Fig. 3, except 1982/1983

commenced in pentad 57 (early/mid October) and withdrew in mid- late May (Table 1). During this season, some wet spells had greater intensity compared to 1979/80 and 1982/83, and they tended to occur in the middle third of the season (Table 3). No obvious propagation of the wet spells occurred.

The dry 1987/88 season (Figs. 2 and 6) ended in late March (Table 1) although it was characterised by some pre-season rain very early in late September/early October. Some strong wet spells occurred in the latter half of the season and southward propagating wet spells occurred early in the season (Table 3). Rains started in early/mid November for the 1992/1993 dry season (Figs. 2 and 7) and ended in early April. This season was unusual in that it was characterised by several relatively frequent wet spells of similar intensity. These wet spells started more or less simultaneously across the region in the first half

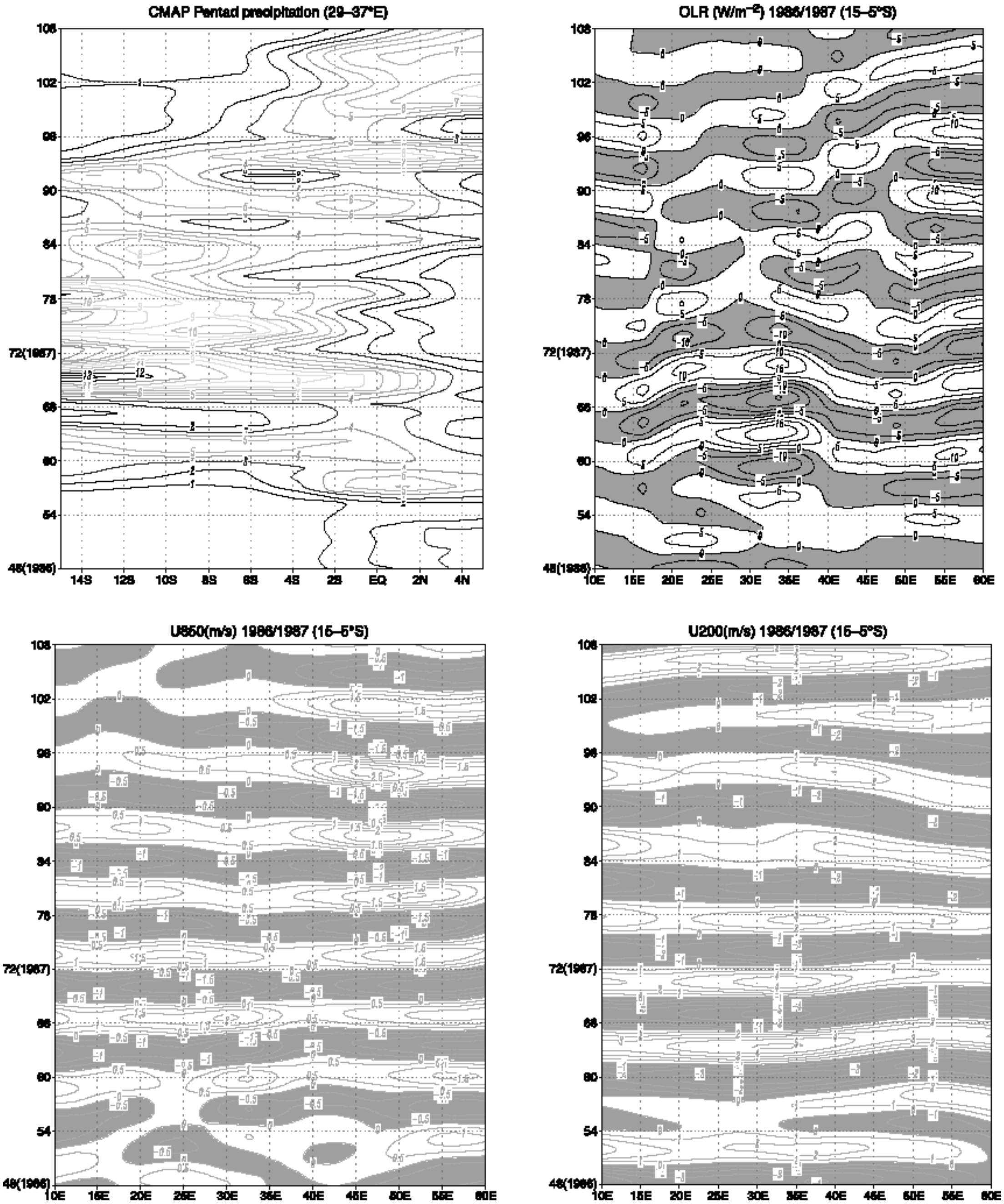

Fig. 5. As for Fig. 3, except 1986/1987

of the season, and then later, some northward propagation became apparent (Table 3). The 1993/94 season (Figs. 2 and 8) was relatively dry, with onset in late October followed by a dramatic increase in intensity in early/mid January. After this time, some northward propagation of the rains occurred over northern Mozambique and Tanzania up until early March (Table 3). A large number of dry spells occurred at the beginning of the season. Relatively strong wet spells occurred in the middle of the season (Table 3). In 1998/99 (Figs. 2 and 9), the rainy season started in mid-November (Table 1) with an extended dry period observed prior to this. Significant wet spells were experienced in the second half of the season with some northward propagation of weak wet spells from early to about midway through the season (Table 3).

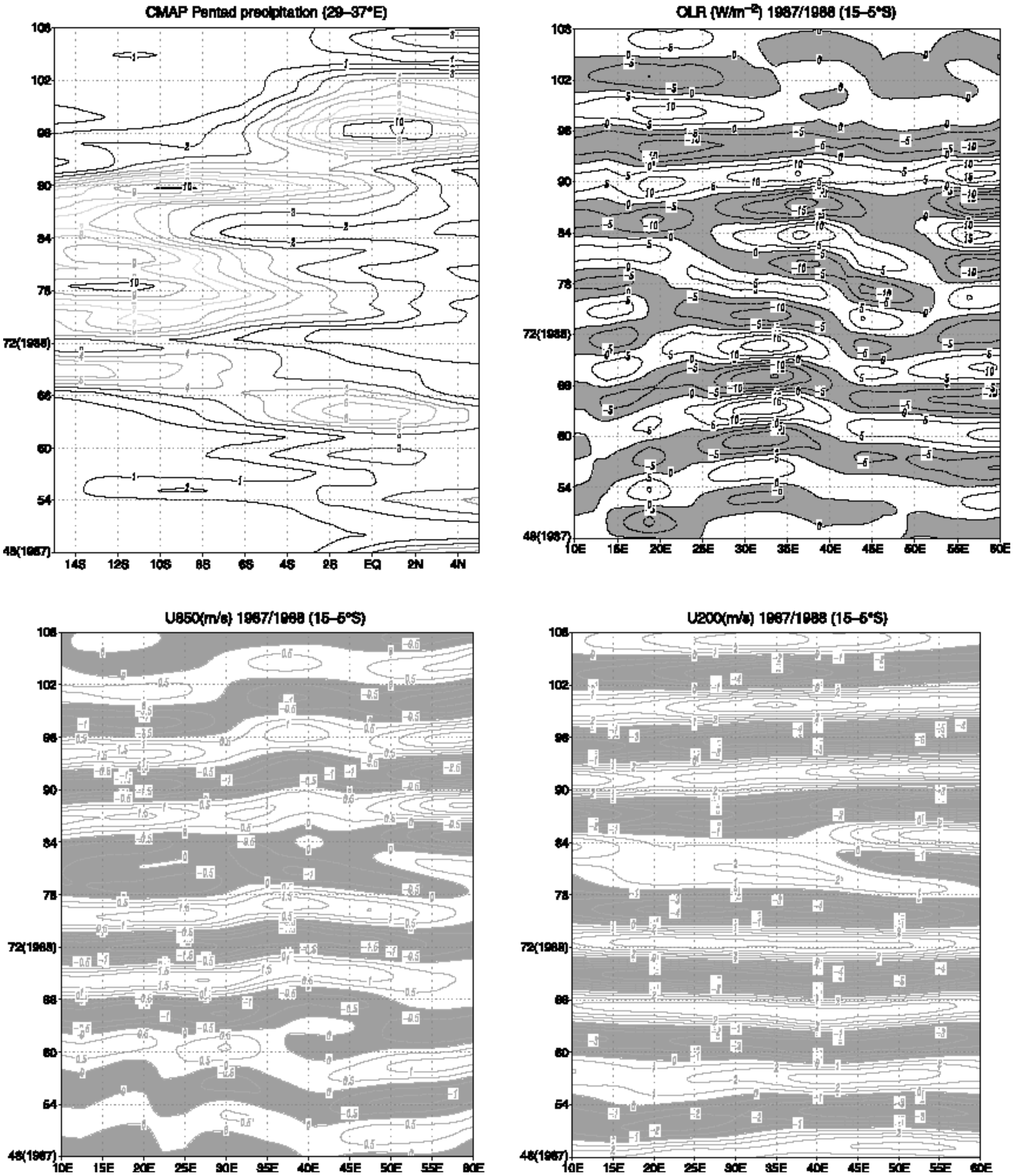

Fig. 6. As for Fig. 3, except 1987/1988

To consider the potential contribution of Madden-Julian and other intraseasonal oscillations (Madden and Julian, 1971; 1972; 1994) to the seasonal rainfall, longitude-time (Hovmoeller) plots of 30–50 day bandpass filtered OLR and zonal wind anomalies at 850 and 200 hPa were constructed for the 5–15° S zone (other panels of (Figs. 3–9)). Eastward propagating negative and positive OLR and zonal wind anomalies are evident in most wet and dry years although, early in some seasons, westward propagation is apparent (e.g., 1992/3; 1998/99). Propagating features may be convectively coupled equatorial Kelvin, n = 1 equatorial Rossby or mixed Rossby-gravity waves (Madden and Julian, 1994; Wheeler and Kiladis, 1999; Wheeler and Weickmann, 2001). Zonally stationary patterns are also apparent and reflect meridional shifts in the ITCZ. Some of the propagating OLR anomalies are seen to originate near 15° E over Angola and continue east to 40° E (Tanzanian coast), whereas others seem to originate between 20–40° E (central southern Africa)

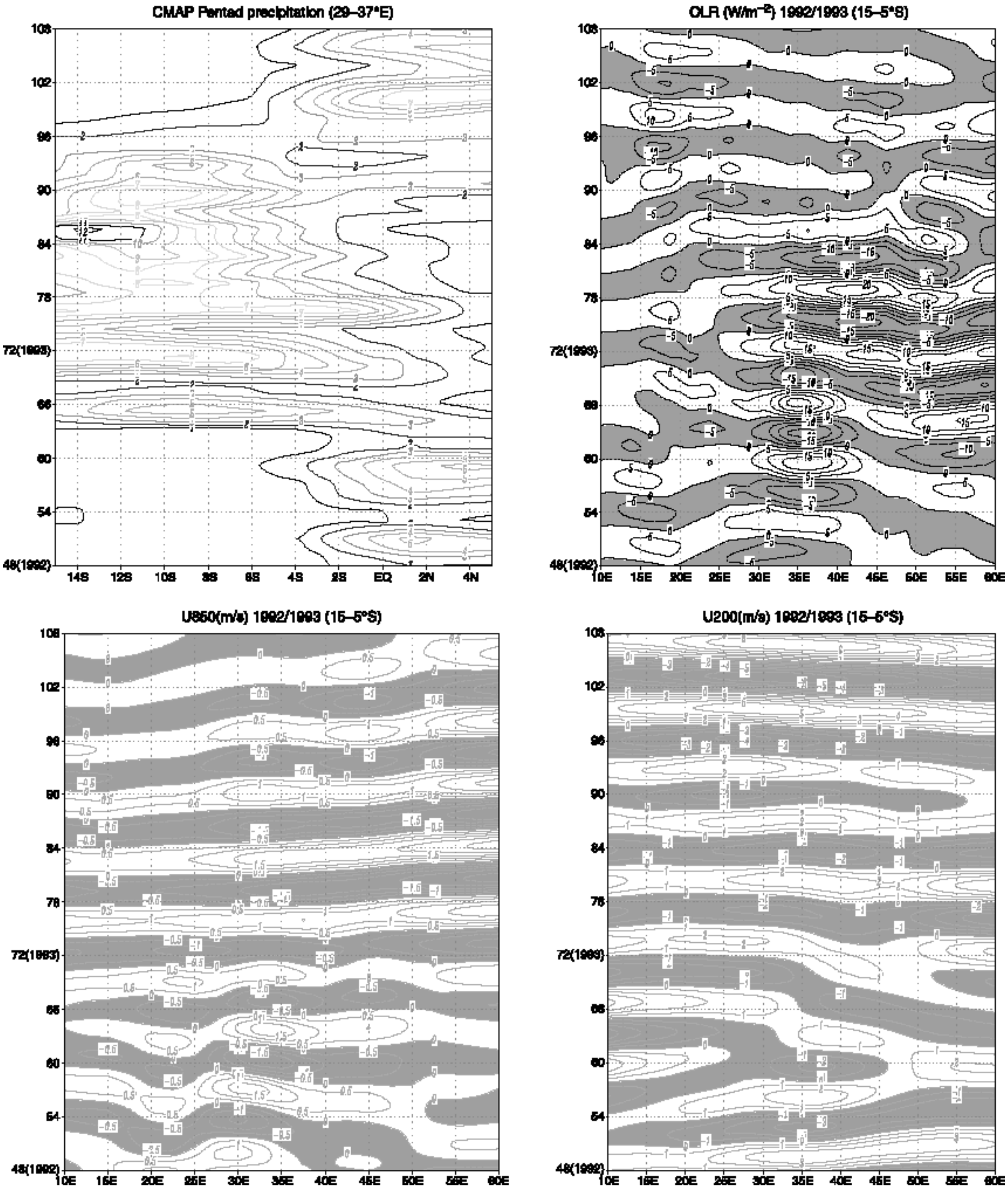

Fig. 7. As for Fig. 3, except 1992/1993

and continue beyond 60° E, well towards the central Indian Ocean. It is evident that most large negative OLR anomalies (i.e., strong convection) tend to be found in the range 20–45° E (i.e., southern Congo and Tanzania through to the near-shore western Indian Ocean) during the wet years together with anomalous westerly flow at 850 hPa extending across tropical southern Africa from 10° E (southeast Atlantic) to the western Indian Ocean. In dry years, negative OLR anomalies (convection) tend to be weaker than for the wet years and to be located further east as well as more likely exist over the Indian Ocean. Some dry years such as 1993/1994 and 1998/1999 experience few, if any, large negative OLR anomalies.

Eastward propagating anomalies have different phase speeds in different years (Table 4). These anomalies are slower moving in the wet years, leading to more prolonged convection over Tanzania, and hence increased rainfall with the

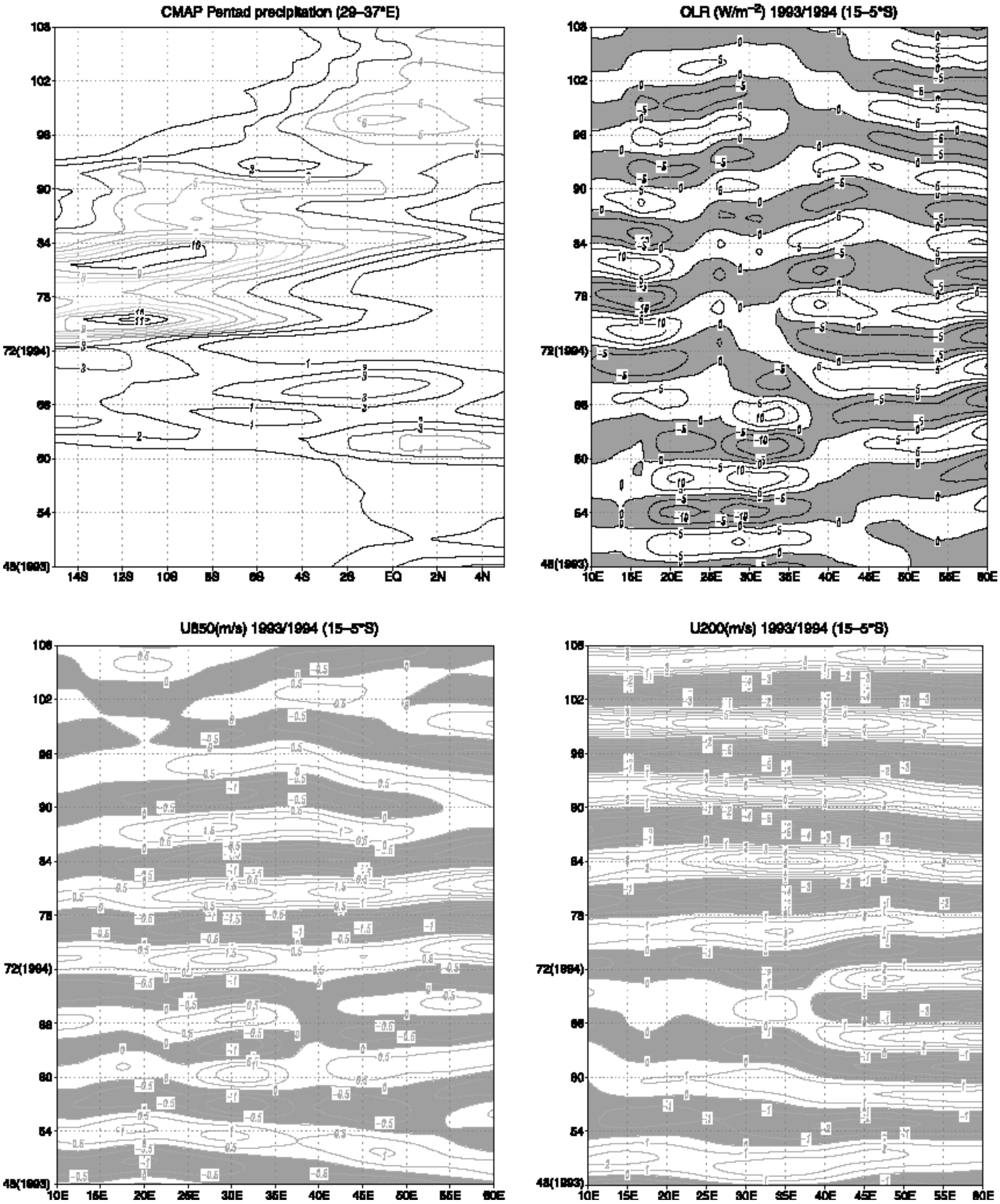

Fig. 8. As for Fig. 3, except 1993/1994

opposite tending to occur in dry years. During the wet years, the mean speed of the major eastward propagating features is 1.5 m/s, for dry years, this speed is about 3 m/s. In some cases, the features move slowly, become stationary, and then resume propagating in the same direction (e.g., 1979/80 and 1993/94). The elevated land surface of most of Tanzania as well as the low-level meridional monsoon flow may interfere with propagation across East Africa. It has been found that areas of strong convection lie just downstream of low-level westerly anomalies (Knutson and Weickmann, 1987; Rui and Wang, 1990), this pattern is also evident to some extent here.

Westward propagating features tend to be found over and east of Tanzania for the dry years whereas, during wet years, eastward propagation is more apparent over Tanzania and further west. It is evident that eastward propagating negative

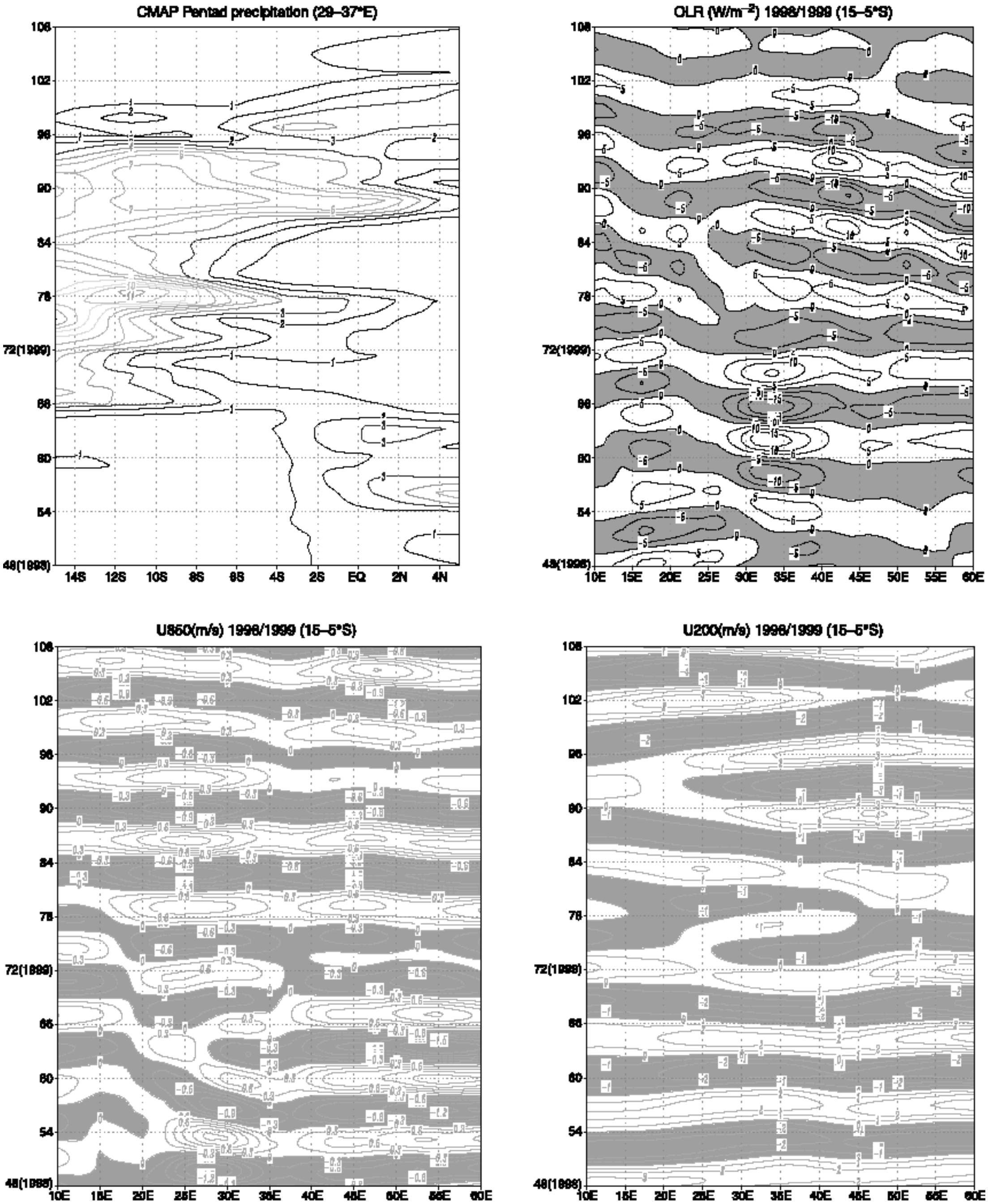

Fig. 9. As for Fig. 3, except 1998/1999

OLR anomaly values are consistent with the wet spells observed over the region for both wet and dry years, while the dry spells are linked with positive OLR anomaly values. In general, areas of negative OLR anomaly (strong convection) correspond with areas of westerly zonal wind anomalies at 850 hPa and easterly wind anomalies at 200 hPa level, while strong dry spells are characterised by the reverse. These results are consistent with previous observations of intraseasonal convective oscillations (e.g., Knutson and Weickmann, 1987; Hendon and Liebmann, 1990; Rui and Wang, 1990).

In general, the Hovmoeller plots suggest that enhanced convective precipitation over western Tanzania may be associated with a flux of low-level moisture from the tropical southeast Atlantic and Congo basin followed by weak

Table 3. Characteristics of individual wet and dry years

Year	Strong wet spells	Propagation
1979/80	mid Dec, early March, mid April	Northward propagating wet spells early in season
1982/83	early Dec, late Dec, early and late Feb, mid Mar	Northward propagating wet spells early in season
1986/87	early/mid Dec, Jan, mid Feb	No obvious propagation
1987/88	late Jan, mid/late Mar	Southward propagating wet spells early in the season
1992/93	Several spaced throughout mid Dec–mid Mar	No obvious propagation in first half, northward propagation in second half
1993/94	Early/mid Jan, early and mid Feb	Some northward propagation in mid- to late season
1998/99	Late Jan, mid and late Mar, mid Apr	Some northward propagation early to midway through season

Table 4. Phase speed of major eastward propagating OLR anomalies for wet and dry seasons during 1979–1999

Year	Wet/Dry	Phase speed of eastward propagation
1979/80	Wet	1.5 m/s
1982/83	Wet	1.5 m/s
1986/87	Wet	1.5 m/s
1987/88	Dry	3.0 m/s
1992/93	Dry	2.5 m/s
1993/94	Dry	4.0 m/s
1998/99	Dry	2.3 m/s

easterly flow from the tropical western Indian Ocean. During dry seasons, large positive OLR anomalies are evident over about 25–50° E as well as easterly anomalies at 850 hPa and positive anomalies at 200 hPa. Westward propagating features tend to be evident during these periods. This suggests that, on intraseasonal scales, weakened convection over western Tanzania is associated with anomalous low level easterly flow from the tropical western Indian Ocean and westerly anomalies at 200 hPa.

4. Evolution of wet and dry seasons

This section uses NCEP re-analyses to discuss the composite anomaly evolution for the extended wet (1968/1969, 1970/1971, 1978/1979, 1979/1980, 1982/1983 and 1986/1987) and dry (1969/1970, 1976/1977, 1987/1988, 1992/1993, 1993/1994 and 1998/1999) years determined from the rainfall station data for 1968–1999. Monthly plots corresponding to the approximate onset, mid- and withdrawal periods of the rainy season over western Tanzania in October, December and April are shown. The other months tend to show anomalies that are a transition between those for October and December, and between December and April respectively, and are not shown for brevity.

In October, around the time of onset, the wet composite (Fig. 10) indicates anomalously positive SST anomalies over the western Indian Ocean, particularly east of Madagascar. Negative SST anomalies are apparent over the tropical southeast Indian Ocean. This SST anomaly pattern is reminiscent of the subtropical South Indian Ocean SST dipole pattern suggested by Behera and Yamagata (2001) and Reason (2001; 2002) as influencing southern African summer rainfall. Over the Atlantic Ocean, negative SST anomalies are observed in the Gulf of Guinea and along the Angolan coast. These negative anomalies are reminiscent of cool ENSO-like events in the tropical and southeast Atlantic (e.g., Zebiak, 1993; Florenchie et al, 2003), which are forced by equatorial upwelling Kelvin waves, and indeed the wind anomalies over the tropical Atlantic during the preceding July and August are suggestive of enhanced trades and generation of upwelling Kelvin waves.

During October, the moisture flux plot indicates a strong lower tropospheric anticyclonic anomaly over the western Indian Ocean on either side of the equator. This anomaly weakens the mean equatorial westerly export of moisture away from East Africa. At the same time, the northeasterly anomaly near the Tanzanian coast helps to increase moisture penetration into the western half of the country via the northeast monsoon as well as implying a deceleration of the mean low-level southeasterly tradewind flow over the western South Indian Ocean. As a result, increased low level moisture convergence is expected over western Tanzania as indeed is the case (not shown).

A secondary moisture source for southern Africa is the tropical southeast Atlantic. Anomalous northwesterlies in the South East Atlantic and extending into northern Namibia/southern Angola and Zambia (Fig. 10) oppose the mean easterly flux (Cook et al, 2004) that exists at this time of year from the South Indian Ocean across subtropical southern Africa and out over the Atlantic near 12–20° S. As a result, relative convergence of low level moisture (not shown) occurs over western Tanzania and northern Zambia. Negative OLR anomalies, and hence increased rainfall, are evident over Zambia and western Tanzania whereas the opposite is true over southern Angola, northern Namibia, and eastern South Africa consistent with the cool southeast Atlantic SST (Hirst and Hastenrath, 1983; Florenchie et al, 2003; Rouault et al, 2003; Cook et al, 2004).

Towards the peak of the wet season in December (Fig. 11), strong easterly moisture flux anomalies exist over the equatorial Indian Ocean region associated with an anticyclonic anomaly over the tropical South Indian Ocean. These act to increase (decrease) the climatological flux towards (away from) East Africa that exists roughly north (south) of about 2–3° S in December and hence increase the low level moisture reaching Tanzania. Over and just offshore of Tanzania, westerly anomalies act to decelerate the mean flow from the South Indian Ocean, leading to substantial low level moisture convergence over the country (not shown) and rainfall. Warmer SSTs near the Tanzanian coast act to increase the local evaporation (not shown), and hence the low level moisture over the land.

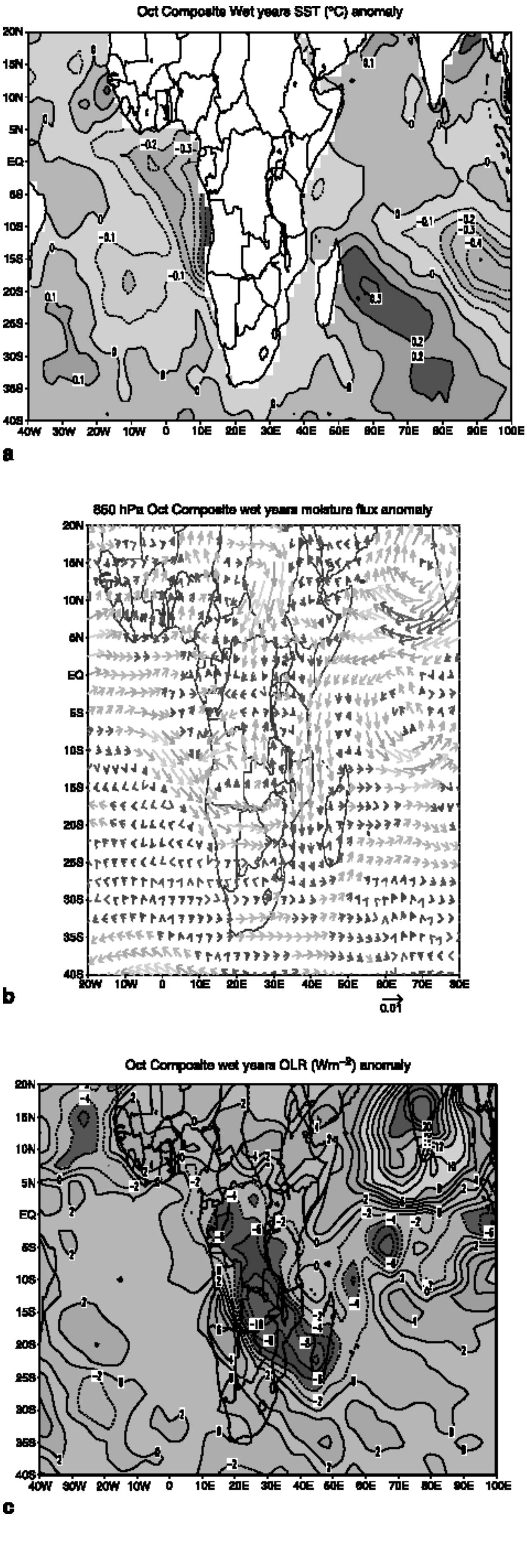

Fig. 10. Composite of wet year anomalies for October (onset of rainy season). Panel (**a**) shows SST (contour interval 0.1 °C) (**b**) 850 hPa moisture flux (a scale vector of 0.01 kg/kg m s^{-1} is shown), and (**c**) OLR (contour interval 2 Wm^{-2}). The wet years, determined from the monthly station rainfall data are 1968/1969, 1970/1971, 1978/1979, 1979/1980, 1982/1983 and 1986/1987

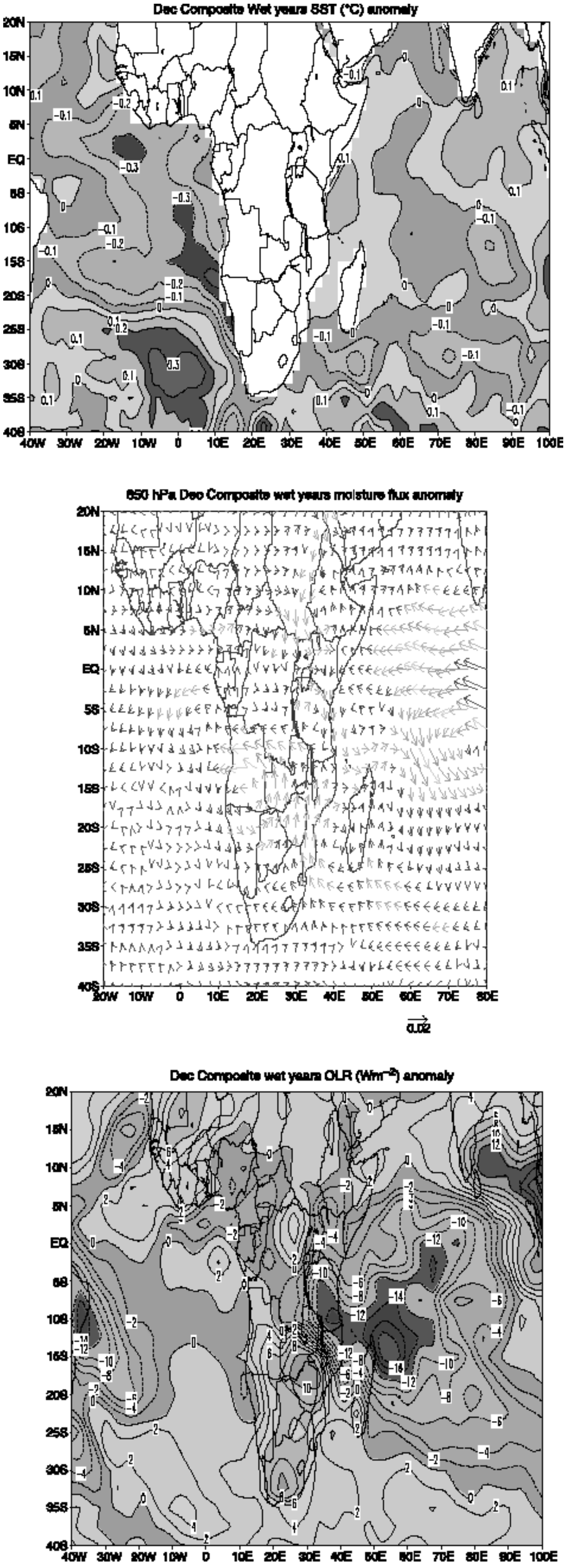

Fig. 11. As for Fig. 10, except for December (middle of

The lower tropospheric anticyclonic anomaly over the tropical South Indian Ocean is stronger than October and helps to reduce the equatorial (2.5–7.5° S) westerly mean export of moisture away from Tanzania at this time of year. It is possible that this anticyclonic circulation feature in October and December is part of the local atmospheric response to the cool SST anomaly in the tropical South Indian Ocean since it is what would be expected from linear quasi-geostrophic theory with some downstream advection (e.g., Gill, 1982; Fandry and Leslie, 1984), albeit this SST anomaly is weak. Such an atmospheric response to this type of SST anomaly pattern has also been proposed by Xie et al (2002) in a study of South Indian Ocean climate variability. These authors propose that a downwelling (upwelling) Rossby wave propagates as a warm (cool) SST anomaly near 10–15° S with a cyclonic (anticyclonic) atmospheric anomaly associated with it. The speed of propagation of the cool SST anomaly between October (Fig. 10) and December (Fig. 11) is around 10° in three months, or about 2 years to cross the entire basin, consistent with the typical phase speed of a Rossby wave at this latitude. Furthermore, strong, upwelling favourable, southeasterly anomalies occur along the Javan/Sumatran coasts in the previous winter and autumn in the wet composite (not shown) consistent with the generation of an upwelling Rossby wave and a propagating cool SST anomaly.

Low-level convergence and large negative (positive) OLR anomalies are apparent over Tanzania/northern Mozambique (Angola, Botswana, Zimbabwe) consistent with the South Atlantic (Rouault et al, 2003) and South Indian (Reason and Mulenga, 1999; Reason, 2002) SST patterns. Taken together this, together with the southward shift of the ITCZ over southern Tanzania during this month, suggests a substantial rainfall increase in December. The large anticyclonic anomaly over Angola reflects a substantial weakening of the mean near-surface low that exists in summer and is consistent with reduced rainfall and positive OLR anomalies over much of subtropical southern Africa (Cook et al, 2004) and enhanced convection (negative OLR anomalies) over Tanzania and the tropical western Indian Ocean (Tyson and Preston-Whyte, 2000).

Towards the end of the rainy season in April (Fig. 12), relatively weak anticyclonic (cyclonic)

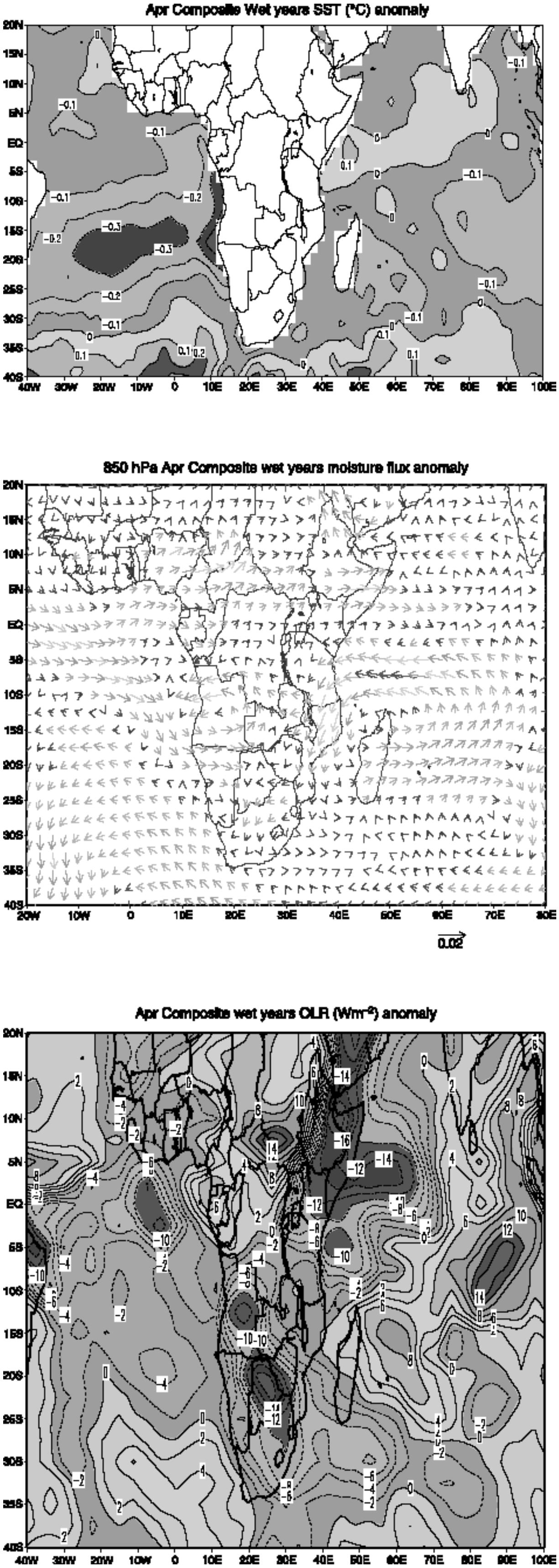

Fig. 12. As for Fig. 10, except April (end of rainy season)

moisture flux anomalies exist over the tropical southwestern (equatorial western) Indian Ocean consistent with the small cool (warm) SST anomalies in those regions. Relative to the mean flux, these anomalies imply less (more) low level moisture transport into Kenya (southern Tanzania) and reduced moisture export by the equatorial westerlies away from East Africa. Such conditions are favorable for ongoing wet conditions over western Tanzania during this month. Thus, the OLR anomalies show negative values over this region which strengthen considerably further north over East Africa, where the ITCZ is located at this time. A large area of increased evaporation (not shown) exists off the Tanzanian and Kenyan coasts, further promoting wet conditions over the neighboring land. Furthermore, low-level moisture convergence (not shown) is evident over western Tanzania where westerly anomalies emanating from the eastern tropical Atlantic converge over Congo and western Tanzania with easterly flow from the Indian Ocean.

Upper (200 hPa) and lower (850 hPa) level velocity potential plots (Fig. 13) were also examined and show evidence of increased low-level (upper level) convergence (divergence) and hence uplift over the western Indian Ocean/Tanzania, particularly for October and December. The mid-season (December) patterns are stronger, indicating pronounced development of favorable conditions for rainfall at this time.

Examination of the monthly dry composite 850 hPa moisture flux and OLR fields for October, December and April (and the intervening months) shows that the important modulations to the equatorial westerlies and South Indian Ocean trades discussed above for the wet case are essentially reversed. Thus, there are stronger equatorial westerlies taking more moisture away from East Africa, particularly in October and December of the dry composite as well as a cyclonic anomaly northeast of Madagascar that strengthens the tradewind flow towards southern Tanzania. Since the patterns are more or less opposite to the wet case, they are not shown for brevity; however, their reversal lends credence to the suggestion that the modulations of these Indian Ocean atmospheric circulations is important for influencing western Tanzanian rainfall. Over the tropical western Indian Ocean,

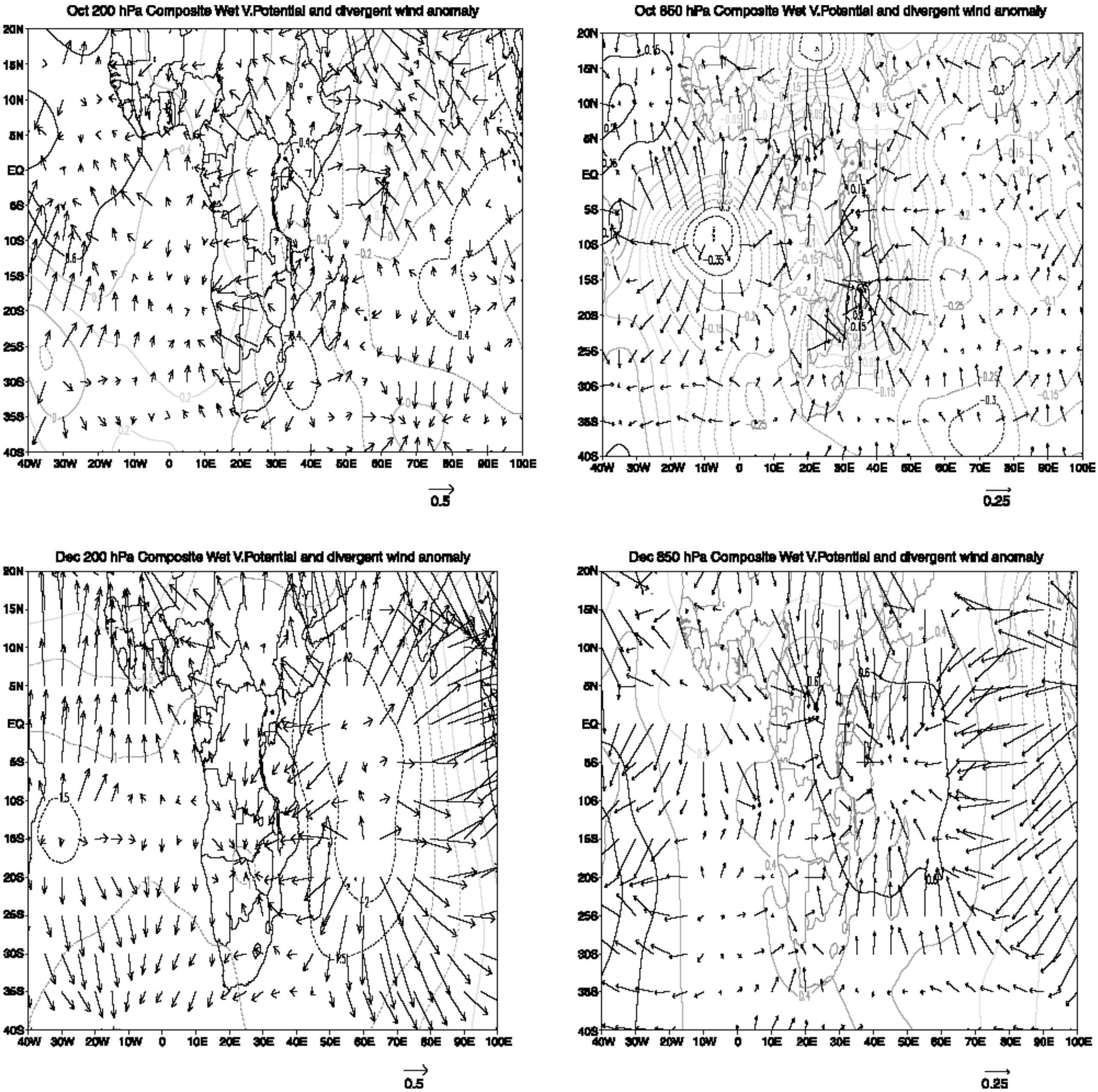

Fig. 13. Upper (200 hPa) (left panel) and lower (850 hPa) level velocity potential and divergent wind anomalies for the wet composite for October (top) and December (bottom) (contour interval is $0.1 \times 10^6\,m^2\,s^{-1}$). A scale vector is shown in m/s

SST anomalies are cool in October and December and then evolve to be cool (warm) off the Kenyan/Somali coast (near Mozambique and Madagascar) in January–April and therefore are also roughly opposite to the wet case. This lends support to the earlier suggestion of a link between western Indian Ocean SST, winds and Tanzanian rainfall. By contrast, there is little evidence of an influence of tropical southeast Atlantic SST on the rainfall variability.

The OLR patterns suggest that most of tropical eastern Africa (i.e., not just western Tanzania) will be dry during these years, particularly for October–December, whereas they imply enhanced convection over the eastern Indian Ocean. This suggests that the ascending branch of the local Walker circulation is located over the eastern Indian Ocean during dry years with relative subsidence over Tanzania, as indicated by upper and lower level velocity potential plots (Fig. 14).

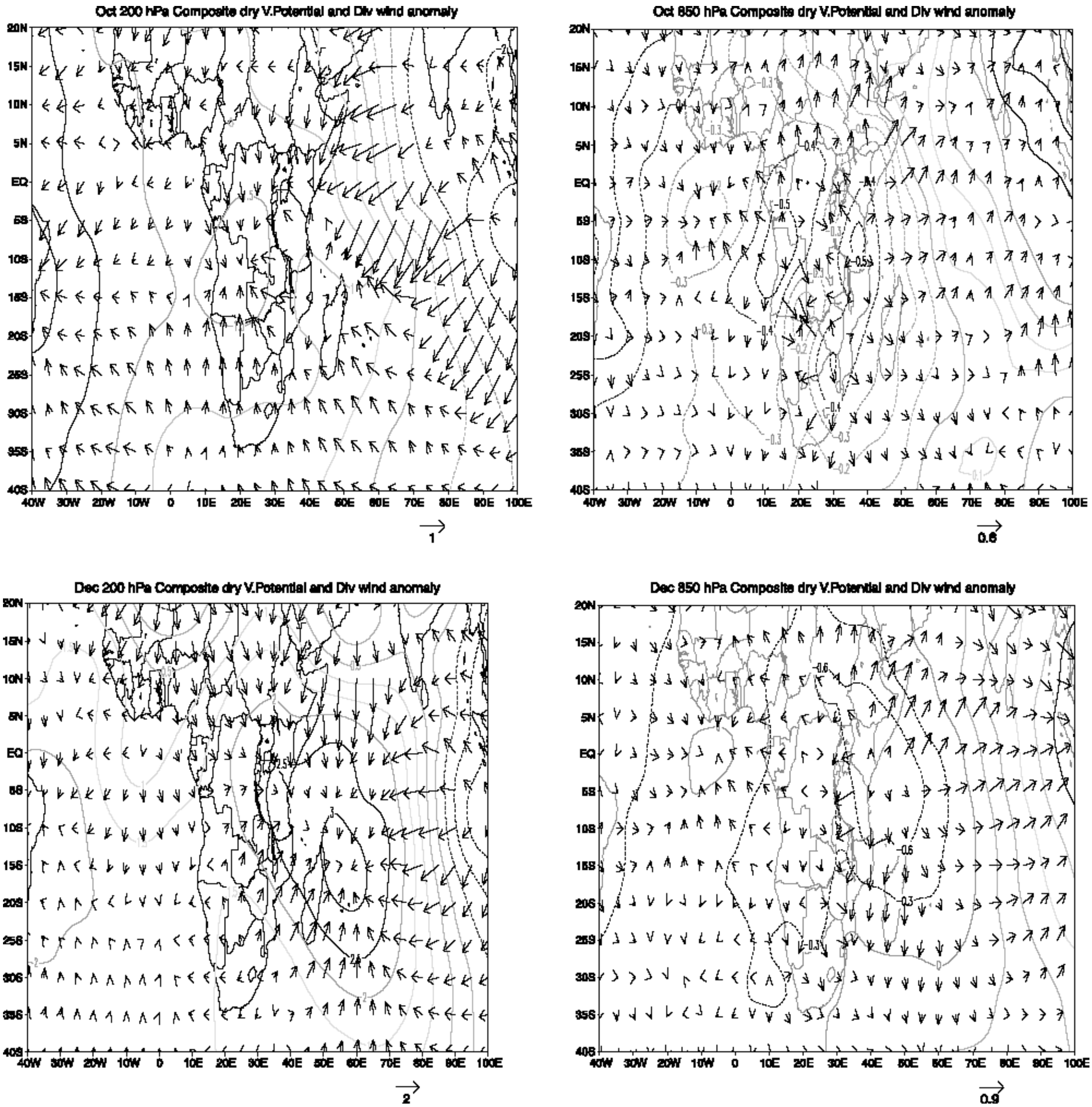

Fig. 14. As for Fig. 13, except for the dry composite. The dry years are 1969/1970, 1976/1977, 1987/1988, 1992/1993, 1993/1994 and 1998/1999

Such a coherent modulation of the Walker circulation across the Indian Ocean during these dry years is more pronounced than the reverse modulation during the wet composite.

5. Conclusions

The characteristics of intra-seasonal rainfall variability and evolution of the circulation anomalies associated with particularly wet and dry rainy seasons over western Tanzania has been investigated. It is evident that wetter than average seasons are characterised by an earlier onset of the rains and a later withdrawal such that the overall season may be 2–3 months longer than the drier than average seasons. Anomalously wet seasons are also typified by more evenly distributed rains with a greater number of wet spells occurring within the season whereas, for drier than average years, the reverse tends to be true.

An extended dry spell may occur after onset for the dry years which also tend to have more dry spells within the season itself than do the wet years. However, both wet and dry years may experience intense wet spells of short duration. Thus, both changes in season length and in the rainfall intensity tend to contribute towards determining a wet or dry year.

Intraseasonal and eastward propagating OLR and zonal wind anomalies are evident in most wet and dry years although early in some seasons westward propagation is also apparent (e.g., 1992/3; 1998/99). During wetter years, the eastward propagation speed is slower than the dry seasons implying that the convection remains over Tanzania for longer. These years are also characterised by large negative OLR anomalies (strong convection) located between 20° and 40° E over tropical Africa with anomalous westerly flow at 850 hPa occurring across the continent from 10° E to the tropical western Indian Ocean. This result suggests that, on the intraseasonal scale, convection over western Tanzania may be associated with a flux of moisture from the tropical Southeast Atlantic and Congo basin followed by weak easterlies from the tropical western Indian Ocean. During dry years, large positive intraseasonal anomalies are evident over about 30–50° E as well as easterly wind anomalies at 850 hPa and westerly wind anomalies at the 200 hPa level. Thus, weakened convection over Tanzania may be associated on intraseasonal scales with anomalous easterly flow from the tropical western Indian Ocean at 850 hPa and westerly anomaly flow at 200 hPa.

The interannual variability of October–April rainfall over western Tanzania appears to be associated with modulations of the equatorial westerlies and southeast trades over the South Indian Ocean. In wet (dry) years, weaker (stronger) equatorial westerlies and an anticyclonic (cyclonic) anomaly over the southern tropics act to reduce (enhance) the export of equatorial moisture away from East Africa and increase (decrease) the low-level moisture flux convergence over southern Tanzania, respectively. Some suggestions that western Indian Ocean SST anomalies may be forcing these low level wind anomalies were also found. Evidence for a large scale modulation of the Indian Ocean Walker cell was also found, particularly for the dry years.

These results suggest that improved monitoring of the tropical Indian Ocean is important for better understanding Tanzanian rainfall variability and for working towards improved seasonal forecasting in the region.

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