

Large Scale Features Affecting Ethiopian Rainfall

Gulilat Tefera Diro, D.I.F. Grimes, and E. Black

Abstract In this chapter we will discuss the large scale atmospheric and oceanic features associated with the long (Kiremt) and the short (Belg) rainy seasons. Considering the spatial variability of rainfall, the analysis was carried out for each homogeneous rainfall zones separately. Composite analyses on selected variables (wind, humidity, geopotential heights and sea surface temperature (SST)) from ERA-40 and HadISST reanalysis dataset were done based on excess/deficit seasonal total rainfall events. The result shows that during the Kiremt rainy season the large scale features associated with anomalous rains are the tropical easterly jet (TEJ), African easterly jet (AEJ), Quasi Biennial Oscillation (QBO), inter tropical convergence zone (ITCZ), East African Low Level Jet (EALLJ), Azores high, humidity anomaly over Red Sea and Gulf of Guinea and low level wind anomalies from Atlantic and Indian ocean to Africa and ENSO. Similarly for the Belg rainy season the large scale features associated with rainfall anomalies are the subtropical westerly jet (STWJ), ITCZ, ENSO, Arabian High, humidity anomaly over eastern Africa and low level wind anomalies from the Indian and Atlantic Ocean.

Keywords Ethiopia · Rainfall · Composite analysis · Large-scale features · Atmospheric circulation · Oceanic circulation · Jets · SST · QBO

1 Introduction

Ethiopia is situated in the Horn of Africa. It has complex topography, with altitudes ranging from hundreds of metres below sea level in the north east to over 4,000 m above sea-level in the northern highlands as shown in Fig. 1. The Ethiopian highlands are thought to be an important factor for the rainfall pattern over Ethiopia.

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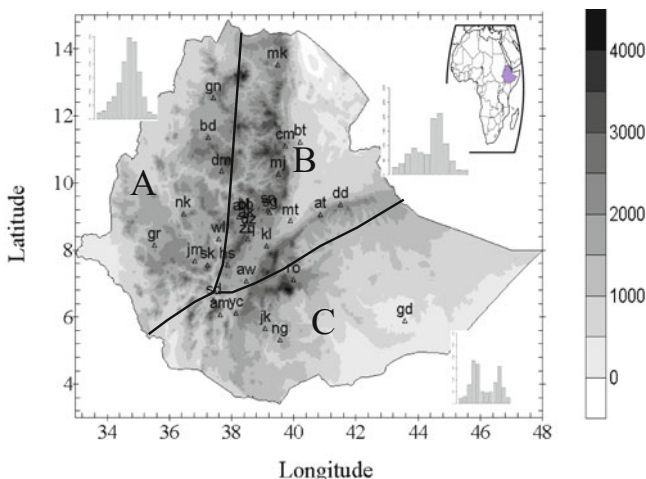


Fig. 1 Location, topography (in meters) and Rainfall regimes in Ethiopia. The small triangles represent the stations used in this study. The histograms are climatological monthly rainfall (January – December) averaged over the rainfall regimes A, B and C. (after Diro et al. 2009)

For instance the rainfall is generally higher over the highlands than over the lowlands. An idealised study by Slingo et al. (2005) using the atmosphere only GCM (HadAM3) forced with observed SST confirms the influence of the East African highlands on central and eastern Africa rains. They found that the rainfall over central and eastern Africa is systematically enhanced in all seasons by the presence of the East African Highlands.

Understanding the characteristics of Ethiopian rainfall is crucial because of its huge impact over the Ethiopian economy. For instance Fig. 2 shows how the GDP follows the rainfall pattern over Ethiopia, especially during the 1984 and 1990 dry years.

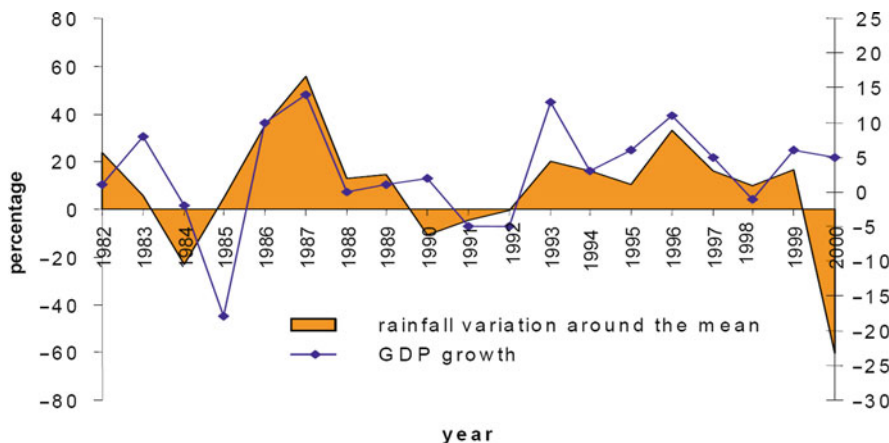


Fig. 2 Rainfall variability and GDP in Ethiopia (after Grey and Sadoff 2005)

The overall aim of this chapter is to understand the mechanisms behind the atmospheric and oceanic parameters that controls the Ethiopian rainfall anomalies at a seasonal time scale. This of particular relevance because previous studies (for example Gissila et al. 2004, Diro et al. 2008) have shown that seasonal forecasting systems based on oceanic teleconnections have skill.

This chapter starts with the description of the data methodologies used in the analysis. The large scale features associated with Kiremt (June–September) and Belg (February–April) rainfall anomalies will be discussed in Sections 3 and 4 respectively. Section 5 will discuss about the spatial variability and non-linearity in the process. Finally a summary and conclusions will be given in Section 6.

2 Data and Methods

2.1 Data

The type of data used in this study are rain gauge data over Ethiopia, global atmospheric reanalysis fields (except for precipitation) from ERA-40, and Sea Surface temperature (HadISST) from UK Met Office Hadley Centre.

2.1.1 Rain Gauge Data

The rain gauge data used in this study are the same as in Diro et al. (2008). i.e. 45 stations covering a period of 35 years (1969–2003). The data have been rigorously quality controlled for missing data and outliers (see Diro et al. 2008).

Clustering the Gauge Data into Homogeneous Rainfall Zones

As the rainfall over Ethiopia exhibits high spatial variation, it is necessary to divide the country into homogeneous rainfall zones. There are different ways of doing this. Many studies (e.g. Dyer 1975, Ehrendorfer 1987) have used principal component analysis for the reduction of the dimensionality and for grouping of station into homogeneous clusters. When the spatial variation of rainfall is complex and the first few principal components account for only a small percent of the variance then the reduction in dimensionality by this method does not work well for delineation of zones (Gadgil et al., 1993). Therefore an alternative method has been developed for Ethiopia involving comparison of the annual cycles and the interannual variability. The methodology is explained in detail in Gissila et al. (2004) and Diro et al. (2008) and described here briefly. The first criterion to identify homogeneous rainfall zones is to group gauges which show similar annual cycles. Based on this criterion six zones were identified.

The second criterion is based on the interstation correlation both within and across the different zones. In this method, zone boundaries were adjusted to ensure that the mean interstation correlation within each zone was higher than the mean

Table 1 Kiremt mean inter-station correlation within and across zones

Kiremt	ZoneI	ZoneIIa	ZoneIIb	ZoneIII	ZoneIV	ZoneV
ZoneI	0.26	0.16	0.02	0.16	0.16	-0.06
ZoneIIa	0.16	0.24	0.15	0.15	0.14	0.05
ZoneIIb	0.02	0.15	0.33	0.16	0.13	0.08
ZoneIII	0.16	0.15	0.16	0.25	0.17	-0.08
ZoneIV	0.16	0.14	0.13	0.17	0.31	-0.06
ZoneV	0.06	0.05	0.08	-0.08	-0.06	0.14

Note: bold values indicates statistical significance

Table 2 Belg mean inter-station correlation

Belg	ZoneI	ZoneII	ZoneIII	ZoneIV	ZoneV
ZoneI	0.50	0.30	0.10	0.21	0.09
ZoneII	0.30	0.36	0.19	0.21	0.11
ZoneIII	0.10	0.19	0.51	0.44	0.27
ZoneIV	0.21	0.21	0.44	0.50	0.26
ZoneV	0.09	0.11	0.27	0.26	0.40

Note: bold values indicates statistical significance

interstation correlation with any other zone. The interstation correlations are shown shown in Table 1 and 2.

The final homogeneous rainfall zones (as defined by these criteria) for the Kiremt and Belg rainy season are shown in Fig. 3. Six homogeneous rainfall zones for Kiremt and five zones for Belg are identified. Time series for each zone are obtained by taking the average of stations within Zone. If the number of missing stations within a zone for a given year is greater than 50% then it is regarded as a missing year.

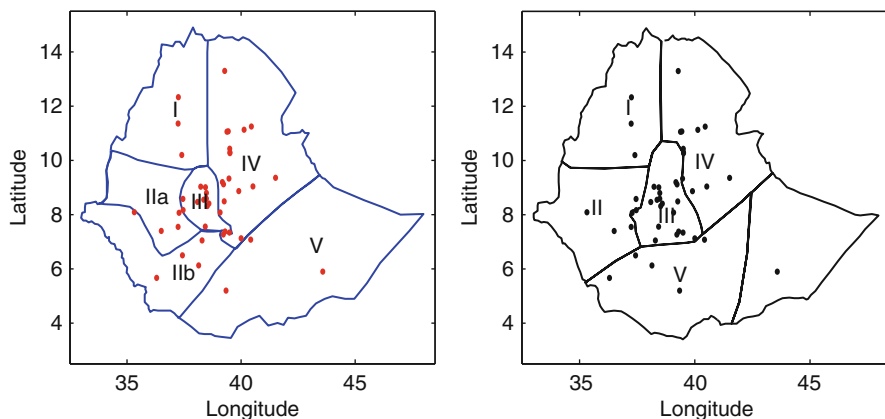


Fig. 3 Homogeneous rainfall zones for Kiremt (*left*) and Belg (*right*) seasons

2.1.2 Other Data

ERA-40 re-analyses covering 1969–2001 were used for this study. The reanalysis fields include wind (horizontal and vertical), humidity and geopotential height. More information on ERA-40 can be found in Uppala et al. (2005). Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) version 1.1 (Rayner et al. 2003) covering a period 1968–2003 were used. This product is monthly means with a resolution of $1^{\circ} \times 1^{\circ}$.

2.2 Methods

The purpose of this chapter is to investigate the mechanisms that give rise to rainfall in Ethiopia. The main method used focuses on the composite mean anomalies computed on selected variables from ERA-40 data based on samples of extreme rains over 1969–2001 (the common years for the gauge and ERA-40 data). Composites can be viewed as climatology based on specified conditions (Achter and Horn 1986). Composite analysis was used to summarize the large scale atmospheric features for the two extreme cases (excess and deficit rainfall years). Composite analysis has advantages over individual case studies because compositing emphasises commonly occurring features while smoothing more random fluctuations. Composite analysis is also better than correlation because it allows the study of non linearity. However it has disadvantages if the atmospheric fields considered vary substantially between events. A set of extreme (excess/deficit) seasonal total rainfall events have been selected for each homogeneous rainfall zones. Excess years are the five wettest years and deficit years are the five driest years. The Student's t-test was used to compare the means of the different composites on each grid points. A 0.1 significance level was used to reject the null hypothesis that the difference in the means is equal to zero. The significance test is used here only as a guidance because of the small dataset. The composite analyses have been done for Kiremt and Belg rainy seasons and the large scale features affecting the rainfall during these two seasons are discussed in the following sections. The anomalous dry and wet-rainfall years for the period (1969–2001) are shown in Tables 3 and 4 for Kiremt and Belg season respectively.

3 Large Scale Features Associated with Kiremt Rainfall Anomalies

According to the published literature Kassahun (1987), Grist and Nicholson (2001), Nicholson and Grist (2003), Asnani (2005), Camberlin (1995, 1997), Segele and Lamb (2005), the phenomena most likely to control the rainfall during Kiremt season are Tropical Easterly Jet (TEJ), Inter Tropical Convergence Zone (ITCZ), East African Low Level Jet (EALLJ), westerly wind from Atlantic, Azores High and humidity anomaly over Red Sea. Below is a discussion of how the large scale features affect the homogeneous rainfall zones.

Table 3 Excess and deficit Kiremt rainfall years selected for composite analysis for each zone

Zone	Deficit years	Excess years
I	1982	2001
	1987	1975
	1997	1974
	1992	1990
	1983	1973
IIa	1997	1988
	1982	1998
	1980	1973
	1969	2001
	1995	1970
IIb	1993	1970
	1985	1973
	1999	1981
	1990	1996
	1991	1974
III	1987	1996
	1982	1978
	1986	1993
	1983	1970
	1976	1992
IV	1987	1999
	1984	1994
	1982	1988
	1972	1998
	1991	1986
V	1993	1976
	1969	1981
	1990	1983
	1995	1975
	1973	1984

3.1 Upper Level Tropospheric Wind and Tropical Easterly Jet (TEJ)

The TEJ is a band of strong easterlies with a core around 150 mb extending from south East Asia across the Indian ocean and Africa as shown in Fig. 4. The development of the TEJ is related to the thermal wind pattern during the northern hemisphere summer (Hastenrath 1990). Related to the jet stream is the rainfall distribution, which is indicative of the vertical motion pattern in the lower troposphere. Air is accelerated into the jet and decelerated as it leaves the jet. This induces ageostrophic motion at the jet entrance and exit because of the imbalance between pressure gradient and Coriolis forces as shown in Fig. 5. At the jet entrance air is being depleted from the right hand side of the jet and is accumulated on the left hand side, leading to divergence and convergence in the right and left side of the jet respectively. From the Dines compensation model (Pettersen 1969) it can be shown that at lower levels the air should be ascending and pressure decreasing to the right

Table 4 Excess and deficit Belg rainfall years selected for composite analysis

Zone	Deficit years	Excess years
II	1988	1983
	1977	1992
	1999	1993
	1984	1969
	1973	1996
III	1999	1981
	1973	1983
	1994	1986
	1984	1969
	2000	1987
IV	1973	1995
	1999	1989
	1992	1990
	2000	1993
	1997	1987
V	1997	1970
	2000	1979
	1999	1982
	1973	1980
	1984	1981

(north) of the jet stream entrance and left (south) of the jet stream exit at low level. This ascending air is likely to induce rainfall.

In Fig. 6, except for zone IIb (southwest), it can clearly be seen that there is a strong easterly wind anomaly at 200 mb in excess rainfall years composites and a westerly anomaly in deficit rainfall composites around a latitudinal band of 7° N–20° N starting from south Asia to Africa. This suggests that a stronger TEJ is

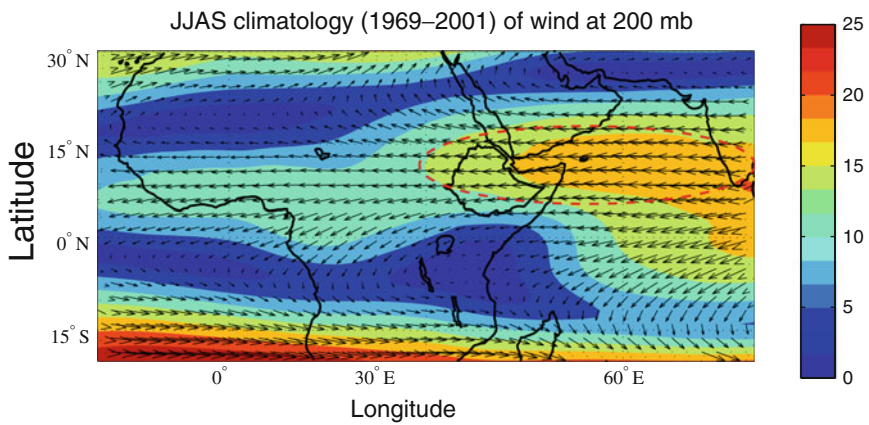
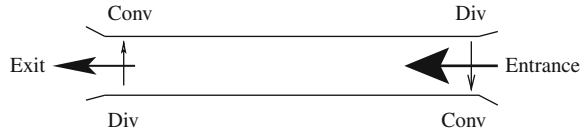


Fig. 4 Kiremt (JJAS) climatological wind at 200 mb. The filled contour represents the magnitude of the wind speed (m/s) and the vectors indicate the direction. The broken lines indicates the location of maximum wind speed region of TEJ

Fig. 5 Schematic diagram of jet stream and the associated area of cyclonic and anticyclonic regions



associated with excess rainfall and a weaker TEJ with deficit rainfall. The physical link between the TEJ and rainfall may be the upper level divergence associated with the jet stream, which could enhance the rainfall by promoting ascent at lower level beneath the jet core (Grist and Nicholson 2001). For zone IIb (the southwest), deficit rainfall is associated with a strong TEJ but it is not clear why this is so. The result for other zones agrees with the study of Segele and Lamb (2005), where they found strong (weak) jet is associated with short (long) dry spells in the Kiremt season over central Ethiopia. This may be due to a frequent appearance of stronger TEJ events during the Kiremt season. In addition to the zonal wind anomaly, there is a meridional wind anomaly at 200 mb associated with excess/deficit rainfall. Northerly (north-easterly wind) is associated with excess rainfall and southerly (south-westerly wind or south-easterly wind for zoneIIb) is associated with deficit rainfall (Fig. 6). This makes sense if we associate it with the Hadley circulation (the moist low level southerly and upper level northerly will enhance the Hadley circulation and induce more rainfall over Ethiopia).

3.2 Stratospheric Influence - Quasi Biennial Oscillation (QBO)

Reed et al. (1961), Veryard and Ebdon (1961) showed that the lower stratospheric wind above the equator changes on average every 26 months between easterly and westerly. These westerly and easterly regimes propagate vertically down ward as time progresses. This oscillation of wind from easterly to westerly is known as the Quasi Biennial Oscillation (QBO). The QBO is characterised by an alternating pattern of eastward and westward wind regimes in the lower equatorial stratosphere that repeat at an interval varying from 22 to 34 months with an average period of 28 months (Takahashi and Holton 1991). Holton and Tan (1980) suggested that successive regimes of westerlies and easterlies propagate downward at an average rate of about 1 km/month but with the westerly shear zone descending more rapidly and more regularly than the easterly shear zone. The oscillation is observed to have an approximate Gaussian distribution in latitude, with the maximum amplitude at the equator.

The Equatorial QBO is a non-linear Oscillation produced by vertical transfer of momentum by Kelvin and Rossby-gravity waves (Lindzen and Holton 1968, Holton and Lindzen 1972, Plumb 1977). The equatorially trapped Kelvin waves provide the westerly momentum and the Rossby-gravity waves are important for easterly momentum (Takahashi and Holton 1991).

Although these phases of the QBO are associated with excess and deficit rainfalls over Ethiopia, they are significant only for the west and south west parts of the

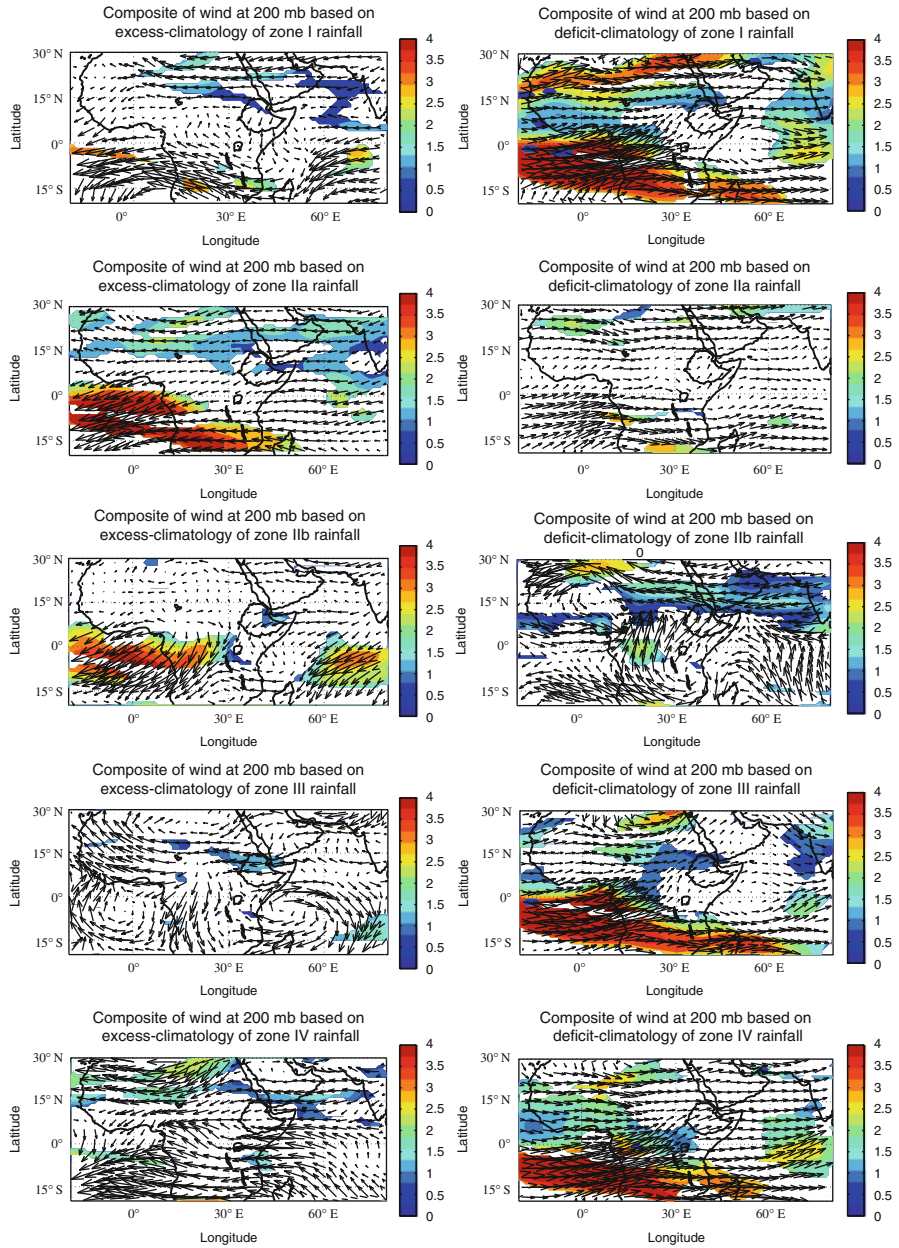


Fig. 6 Kiremt (JJAS) wind at 200 mb for excess-climatology (*left*) and deficit-climatology (*right*). The arrows indicate the direction of the wind anomaly and the filled contours represent the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

country (zones IIa and IIb). Strong positive zonal wind anomalies in the stratosphere (westerly phase of QBO) are associated with deficit rainfall years as shown in Fig. 7. The easterly phase of the QBO is associated with excess rainfall, however, this is not as strong as the deficit year composites. For these regions (zones IIa and IIb) the low level flow is predominantly westerly. During the easterly phase of the QBO the zonal circulation (which is westerly at low level and easterly aloft) becomes strong and this enhances the westerly influx of moisture from Atlantic and hence gives rise to above normal rainfall. During the westerly phase of the QBO, the zonal circulation becomes suppressed (because the low level westerly is not accompanied by an upper level easterly) leading to a weaker westerly influx of moisture from the Atlantic at low level (see Fig. 13 of Zone IIb), and in turn to a deficit in rainfall. For equatorial Africa, the association between rainfall and the QBO is documented for the long rains (MAM) by Indeje and Semazzi (2000). They found that in the absence of a strong El Niño, the westerly phase is associated with excess rainfall and the easterly phase with below normal rainfall. This implies that the westerly phase of the QBO is associated with deficit rainfall in summer and excess rainfall in spring season. This is due to the fact that for northeast Africa the structure of the mean low level wind is easterly in spring and westerly in summer.

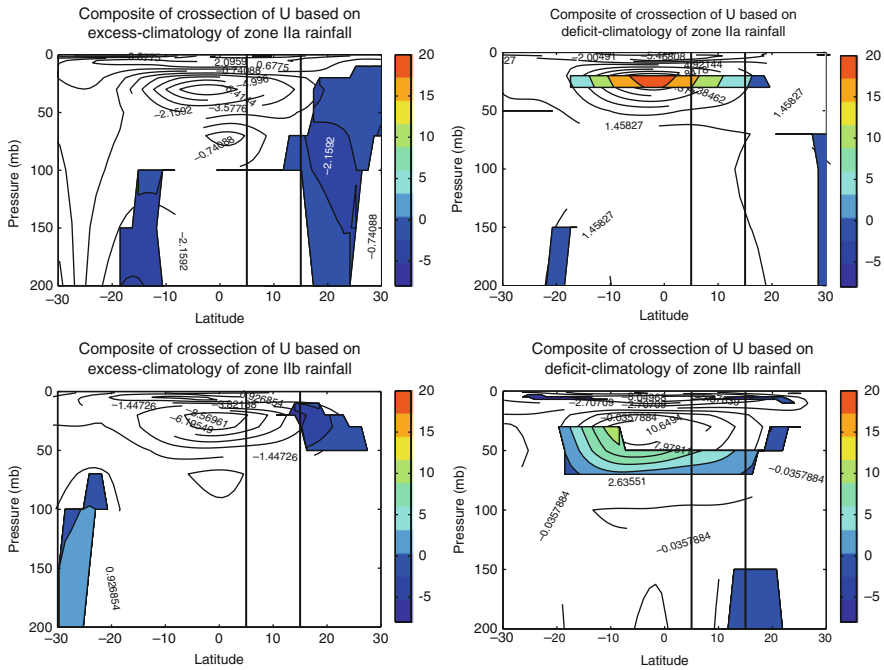


Fig. 7 excess-climatology (*left*) and deficit-climatology (*right*) composites of cross sections of zonal wind speed (m/s) during Kiremt season. The filled contour represents significant at 0.1 level

3.3 African Easterly Jet (AEJ)

The African Easterly Jet is a mid-tropospheric jet (at around 600 mb in ERA-40 data) located over tropical north Africa during northern hemisphere summer (Fig. 8). Cook (1999) suggested that the AEJ over west Africa during the northern hemisphere summer is formed as a result of the strong meridional soil moisture gradients, whereas Thorncroft and Blackburn (1999) suggested that AEJ is maintained by two diabatically forced meridional circulation patterns: The circulation associated with the dry convection in the Saharan heat low regions; and the one associated with deep moist convections in the ITCZ. Burpee (1972) showed that the AEJ is both barotropically and baroclinically unstable resulting in easterly waves which grow at the expense of the jet. This implies that the observed AEJ results from the combination of the diabatically forced meridional circulation that maintains it, and the easterly waves that weaken it (Thorncroft and Blackburn 1999). The vertical shear associated with the jet are crucial in organizing moist convection and the generation of squall lines, whereas the vertical and horizontal shears together are important for the growth of easterly waves (Thorncroft and Blackburn 1999).

For most parts of Ethiopia, rainfall anomalies are associated with a north-south displacement of the AEJ. A southward displacement occurs in deficit rainfall years and northward displacement in excess years, as can be seen by the dipole structure north and south of 15° N over northeast Africa (Fig. 9). Generally, positive zonal wind anomalies over Ethiopia (less easterly) at 600 mb are associated with excess rainfall and negative anomalies with deficit rainfall. This association of a north-south shift in the jet with excess and deficit rainfalls is also witnessed over west Africa and documented by Grist and Nicholson (2001), Yeshanew and Jury (2007). The mechanism by which the African Easterly Jet affects rainfall is by creating divergence of moisture below the level of condensation (Cook 1999), and hence a decrease in the rainfall. The latitudinal cross section of vertical wind speed (ω)

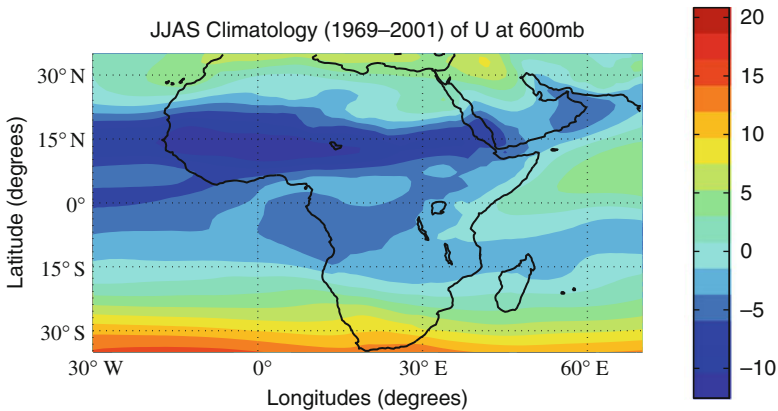


Fig. 8 Kiremt (JJAS) climatological zonal wind speed (m/s) at 600 mb. Negative values indicate easterly winds

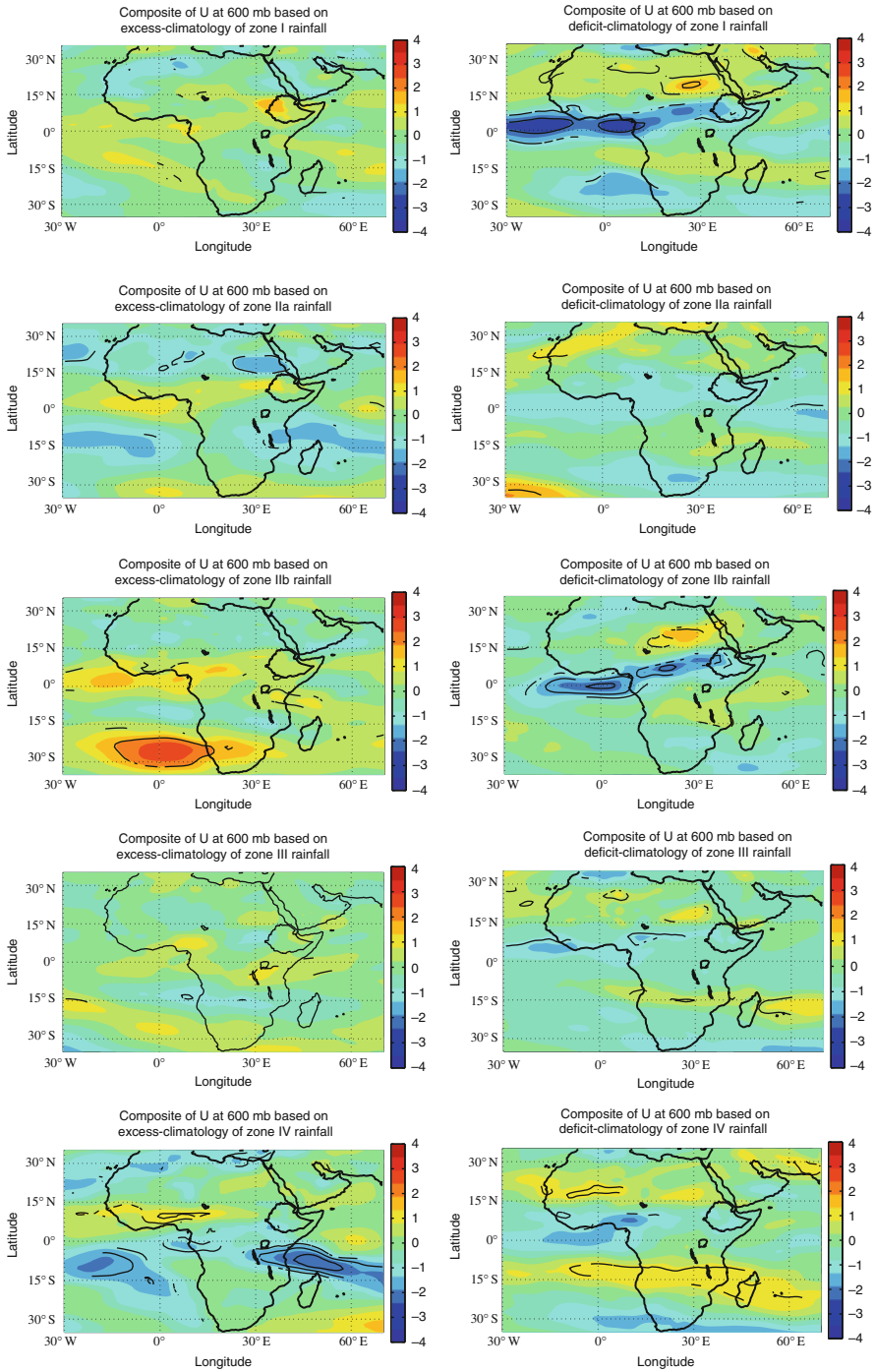


Fig. 9 Composite plot of zonal wind speed (U) in m/s at 600 mb for excess-climatology (*left*) and deficit-climatology (*right*). The contour lines represent significance at 0.1 level

also shows a shift in the region of divergence, creating a dipole structure below the 600 mb level (Fig. 11). This suggests that the shift in the location of the AEJ is associated with a shift of the region of moisture convergence (ITCZ) at lower levels.

3.4 Inter-Tropical Convergence Zone (ITCZ)

In Africa, the ITCZ oscillates annually between an extreme northward location of 15° N in July and an extreme southward location of 15° S in January (Asnani 2005). The passage of the ITCZ give rise to a bimodal rainfall pattern in southern Ethiopia (MAM (Belg) and OND), and a monomodal pattern in the northern Ethiopia (JJAS). Additionally in East Africa, there is a meridional arm of the ITCZ due to the difference in heat capacity of the land surface and the Indian Ocean. This produces rainfall over the south west of Ethiopia (zone IIb) in February/March even though the main ITCZ is still in the southern hemisphere (Kassahun 1987).

The ITCZ shows an interannual variation in location and strength. For the northeastern part of Ethiopia excess/deficit rainfall years are associated with northward/southward displacement of the ITCZ.

For the western part of Ethiopia, deficit rainfalls are associated with an east-west dipole in the mid-tropospheric ITCZ anomaly over Africa (Fig. 10 top). An active ITCZ over East Africa and the Red Sea is associated with excess rainfall; conversely a weak ITCZ is associated with a deficit rainfalls. For the eastern part of Ethiopia (zone IV), the mid tropospheric ITCZ shows a N-S dipole as can be seen from the vertical wind anomaly structure at 500mb in Fig. 10 (bottom), with deficit rainfall associated with southward displacement of the ITCZ. The latitudinal cross section

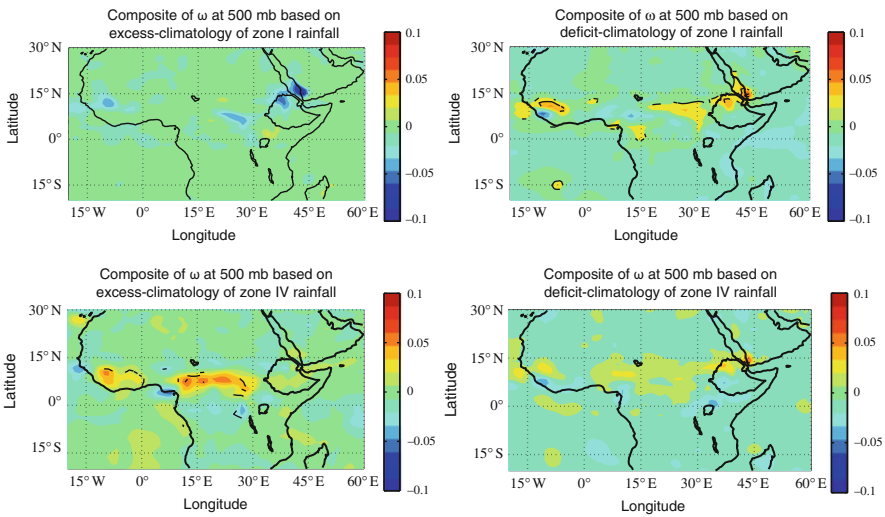


Fig. 10 Composite plot of vertical wind speed (ω) in Pa/sec at 500 mb for excess-Climatology (left) and deficit-climatology (right). The contour lines represent significance at 0.1 level. Negative value means upward motion

of vertical wind ω shows that, for most of the country, a north-south dipole occurs below 600 mb (as shown in Fig. 11) which may be associated with the north-south displacement of the AEJ. For the eastern part of Ethiopia (Zone IV) both below and above 600 mb, it shows north-south displacement.

3.5 Low Level Humidity

The composites of humidity based on excess/deficit rainfall identify two important locations: the Red Sea and the southeast Atlantic. For the western half of Ethiopia, a positive humidity anomaly over the Red Sea is associated with excess rainfall as shown in Fig. 12. The low level westerly wind from the Atlantic may be responsible for the humidity anomaly over southeast Atlantic. This is because a strong westerly inflow from the south Atlantic will advect moisture from the ocean into land and cause the humidity anomalies over the sea to be negative. For those regions (like Zone IIb) where excess rainfall years are associated with strong westerlies from Atlantic, excess/deficit rainfall is also associated with negative/positive humidity anomalies over the southeast Atlantic. Analogously for those regions whose excess rainfalls are associated with reduced westerlies (like zone IV), excess rainfall is associated with positive humidity anomaly over southeast Atlantic (since the moisture advected from the ocean is less).

The low level humidity also shows a low level shift from its climatological location for zone I (deficit composite), zone IIa (excess composite), zone III (deficit composite), and zone IV (excess and deficit composites). This north-south shift in the humidity can be related to the low level shift in the ITCZ (discussed in the previous section). This implies excess/deficit rains are characterised by a northward/southward shift in the low level moisture convergence associated with the ITCZ.

3.6 Low Level wind

The low level wind features affecting the rainfall are the westerly winds coming from the Atlantic, and the southerly winds from the south Indian Ocean which are associated with the East African Low Level Jet (EALLJ). For all regions except for the northwest (zone I) southwest (zone IIb), a strong EALLJ is associated with excess rainfall whereas a weaker jet is associated with deficit rainfall. For Zones IIa and III excess rains are associated with southerly anomalies from southwest Indian ocean associated with a stronger EALLJ. This is because southerly anomalies from the southwest Indian ocean mean a stronger influx of moisture from the Indian Ocean, which is a favourable condition for increased rainfall. For the south west (Zone IIb), in contrast, a strong/weak EALLJ is associated with a deficit/excess rainfall (Fig. 13). However excess/deficit rainfall years are associated with a stronger westerly/easterly anomaly from Atlantic suggesting the moisture source from Atlantic is important for the south west part of the country. Generally a stronger westerly anomaly from Atlantic is associated with excess rainfall except

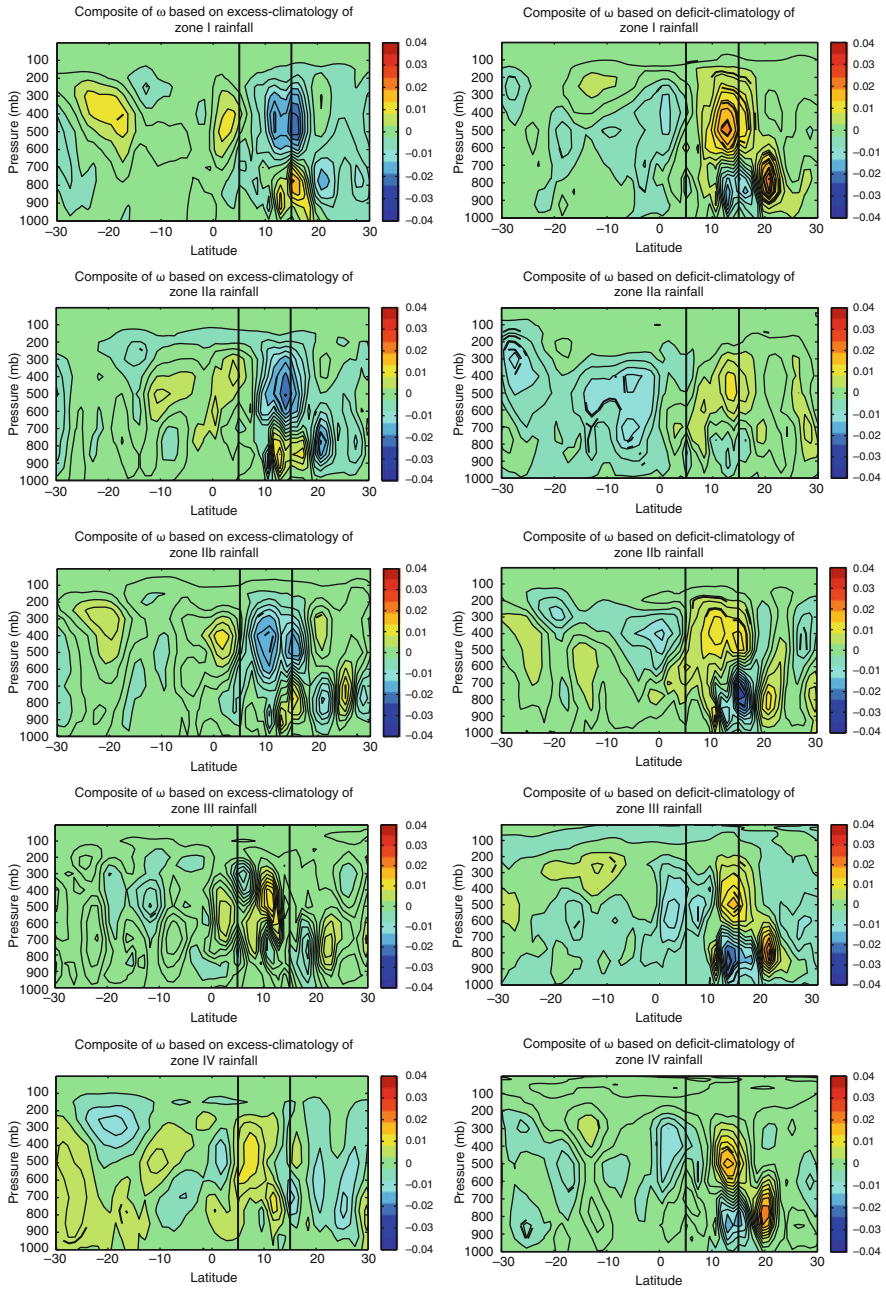


Fig. 11 excess-climatology (*left*) and deficit-climatology (*right*) composites of cross sections of vertical wind speed (in Pa/sec) during Kiremt season. The contour lines represent significance at 0.1 level. The vertical black lines represent the location of Ethiopia in terms of latitudes

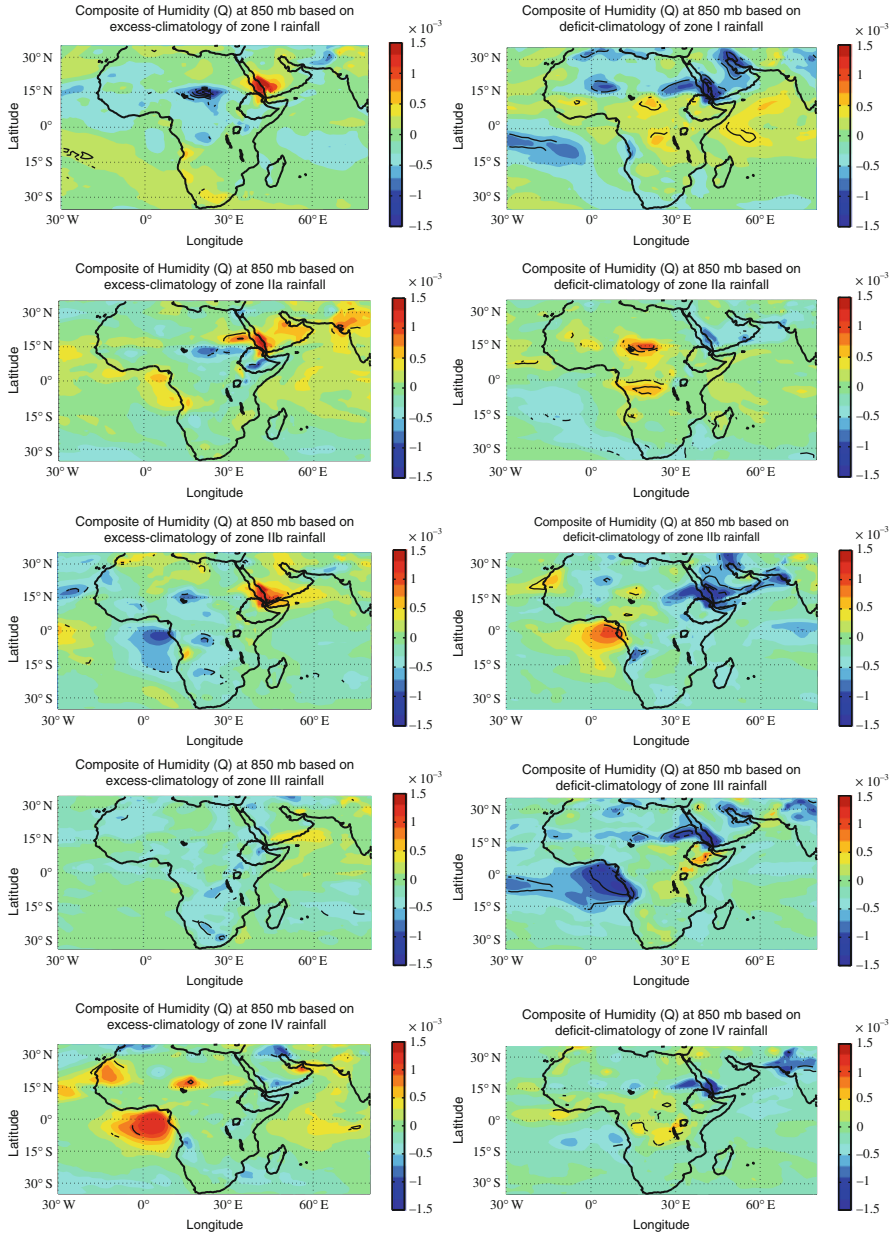


Fig. 12 Excess-climatology (*left*) and deficit-climatology (*right*) composite plot of Q (kg/kg) at 850 mb. The contour lines represent significance at 0.1 level

for the eastern part (zone IV). For the eastern part (zone IV) excess rainfalls are associated with weaker westerlies from south Atlantic but stronger westerlies from north Atlantic around $15^{\circ} N$ latitude. In Fig. 13 the excess composites of Zone IV shows that the westerlies from north Atlantic during excess rains are penetrating to northeast Africa and the north part of the Red Sea (well north of the climatological location of ITCZ) and this agrees with the northward shift of the vertical wind speed which also suggest the northward shift of ITCZ during excess rainfall years.

3.7 Low Level Pressure

The low level moisture sources during the Kiremt rainy season (JJAS) are the Atlantic and the Indian Ocean. The flux of moisture depends on the intensity and position of the St Helena and Mascarene highs (Kassahun 1987). For instance, the orientation of the Mascarene ridge axis is normally centered about $27^{\circ} S$ and $50^{\circ} E$ but if the ridge axis lies over the coast of East Africa the moisture flux decreases, leading to a decrease in rainfall (Kassahun 1986). The confluence between Atlantic/Congo air and Indian Ocean air defines a boundary zone, which extends northwards along western part of Ethiopia (Kassahun 1987). When the St. Helena high is weak or the boundary is displaced westwards of the western part of the country, a marked decrease in rainfall is observed (Kassahun 1987).

For the western part of Ethiopia (Zone I, IIa and IIb), excess/deficit rainfalls are associated with negative/positive height anomalies over Indian Ocean. Whereas for the eastern part (zone IV), both excess and deficit rainfalls are associated with positive geopotential height anomalies over all of the Indian Ocean except the northwest Indian Ocean and Arabian Sea. Low/high pressure anomalies over the northwest Indian Ocean and Arabian Sea are associated with excess/deficit rainfall years. Regarding the Highs over Atlantic ocean, for northwest, west and central regions (Zones I, IIa, III), a strong/weak Azores high (or a positive/negative NAO) is associated with excess/deficit rainfall as shown in Fig. 14. The link between a positive/negative NAO with excess/deficit rains can be explained by the tropospheric temperature (TT) over the Asia. Goswami et al. (2006) have shown that strong negative NAO events lead to a negative tropospheric temperature anomaly over the southern Eurasia via their influence on the storm tracks. These negative tropospheric temperature anomalies over Eurasia lead in turn to a weaker Tibetan high at upper levels. A weaker Tibetan high means the easterlies (i.e. the TEJ) associated with this anticyclone are also weaken. In section 3.1 it is shown that that a weaker TEJ is associated with deficit rains.

3.8 ENSO

Gissila et al. (2004), Korecha and Barnston (2007), Segele and Lamb (2005) have shown that SST over the Eastern Pacific is related to the Kiremt rainfall. In fact there is a significant relationship between Kiremt seasonal rainfall total and SST in several parts of the globe. The contemporaneous correlation between SST and

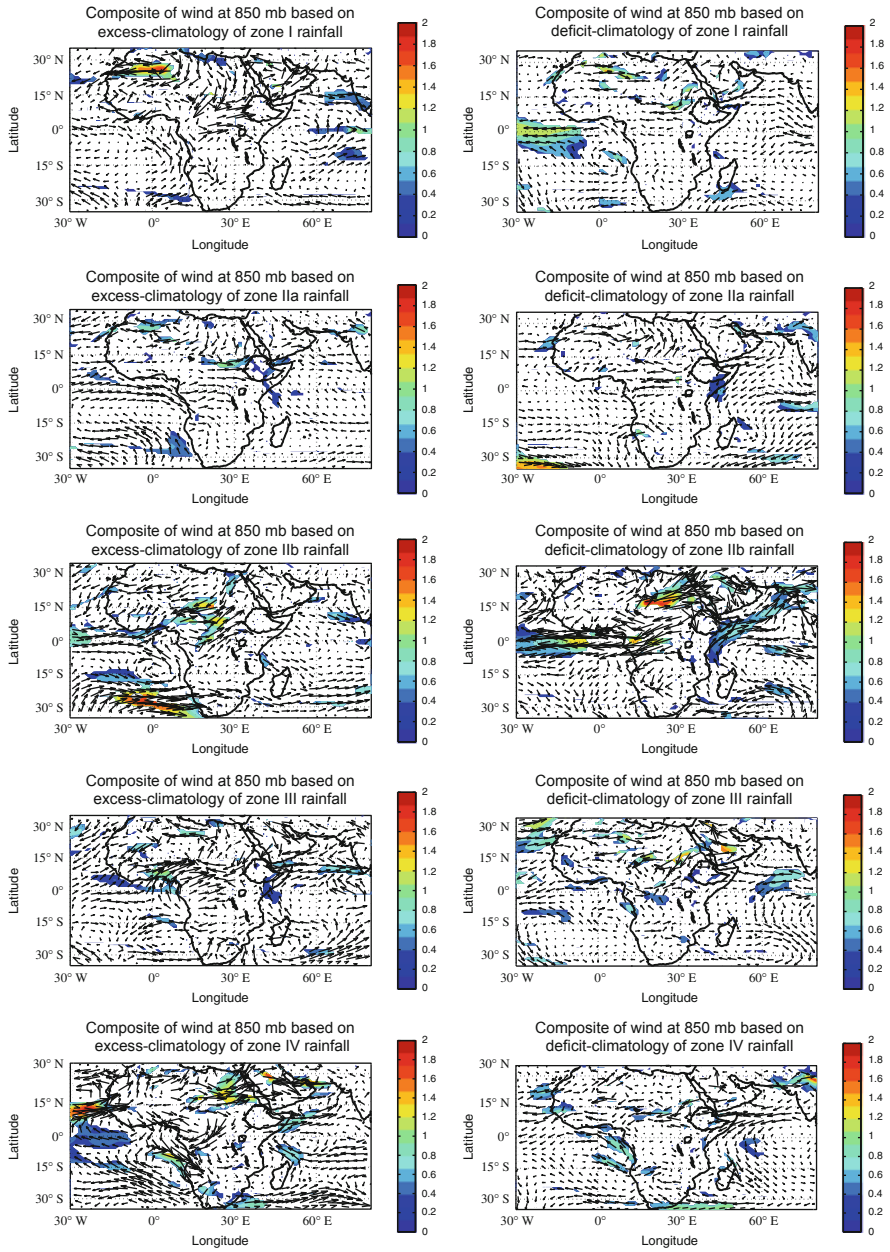


Fig. 13 Excess-climatology (*left*) and deficit - climatology (*right*) composite of wind at 850 mb. The arrows represent the direction of the wind anomalies and the filled contours represent the magnitude of the wind anomalies (m/s) that are significant at 0.1 level

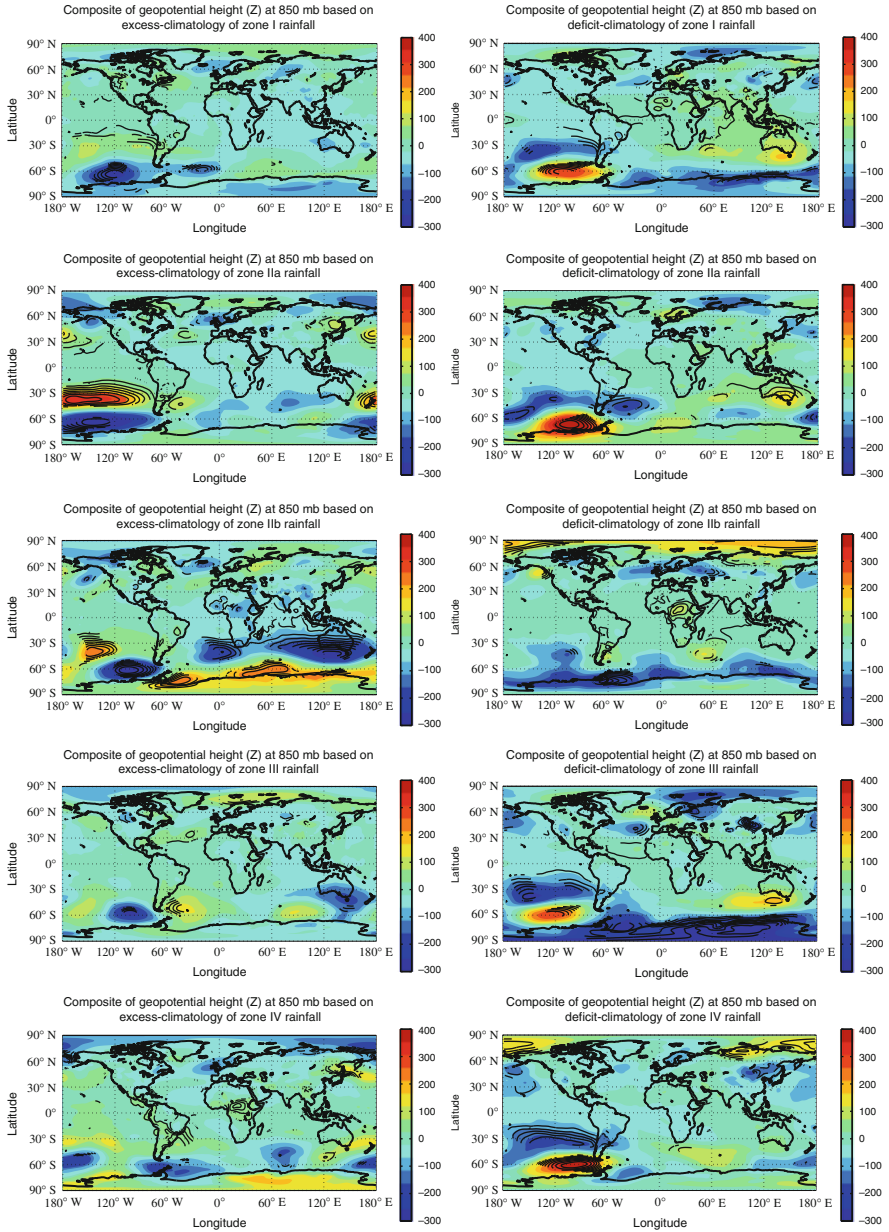


Fig. 14 Excess- Climatology (*left*) and deficit-climatology (*right*) composite plot of geopotential heights (m^2s^{-2}) at 850 mb. Contour lines represent significant at 0.1 level

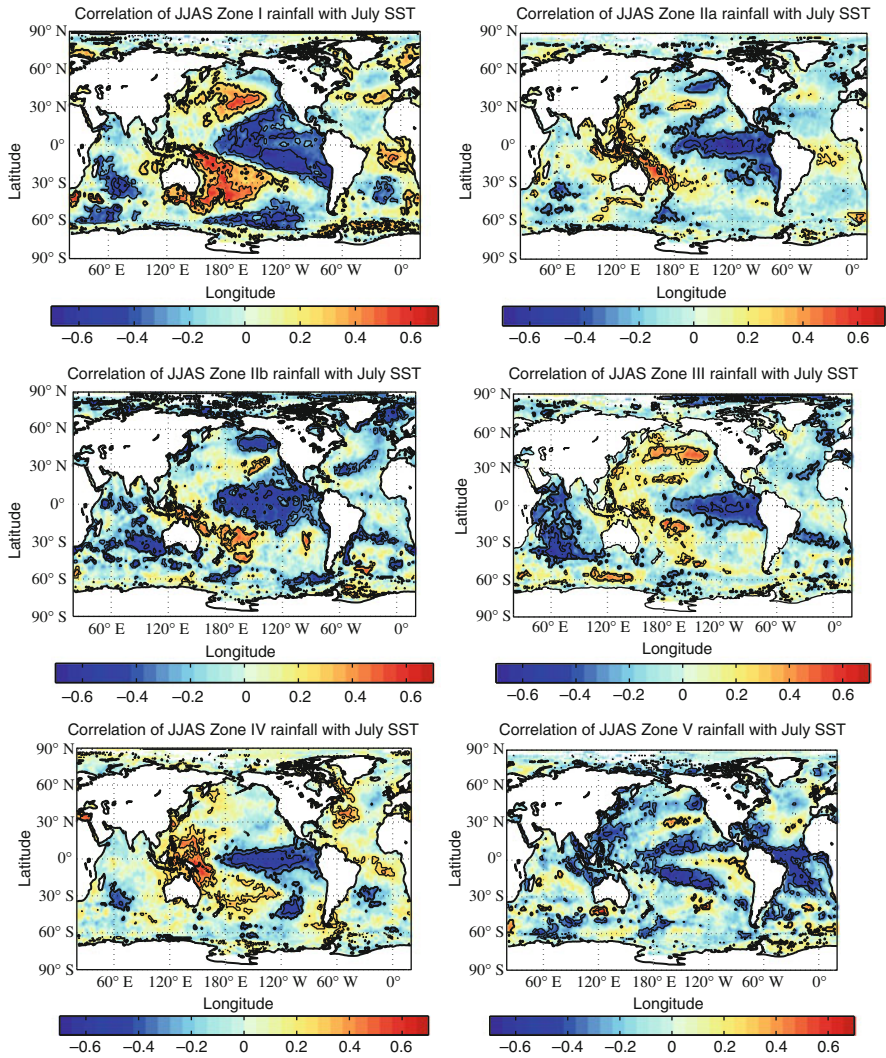


Fig. 15 Correlation of Kiremt rainfall in different zones with global SST in July. Contour lines represent significant at 0.1 level

rainfall (Fig. 15) shows that for all regions except for zone V (which is dry for this time of the year) the correlation values are highest over tropical Pacific, suggesting a strong link with ENSO. The strength of the link however varies between zones. The mechanisms by which the warming of equatorial Pacific is leading to a deficit rainfall has been discussed in (Diro et al. 2010).

The effect of a warm equatorial eastern Pacific (El-Niño) depends on the season of occurrence and the region of Ethiopia. Specifically, El-Niño in the previous winter is associated with excess Kiremt rainfall whereas El-Niño in the contemporaneous

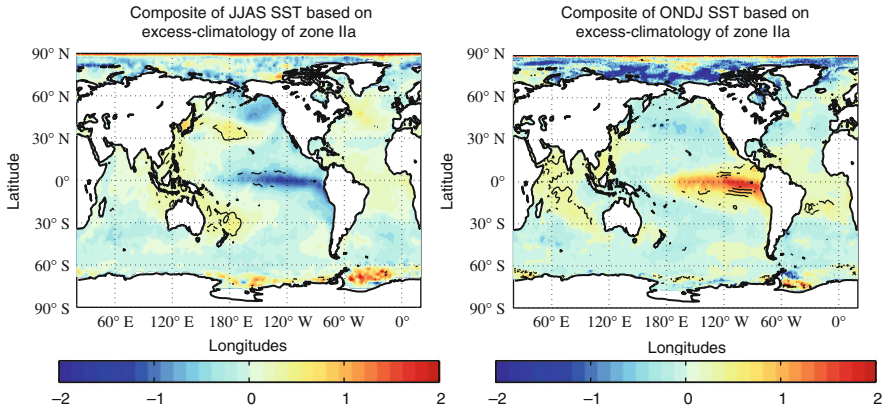


Fig. 16 Excess-climatology composites of SST (K) in Kiremt season (*left*) and in Bega season (*right*) based on Kiremt Zone IIa rainfall years

summer is associated with deficit Kiremt rainfall as shown in Fig. 16 for all zones except Zone I (northwest). For the northwest, El-Niño is always associated with deficit Kiremt rainfalls irrespective of season of occurrence.

3.9 Discussion on Kiremt Large Scale Features

From the previous studies, the large scale features we expect to affect the Kiremt rainfall are the ITCZ, TEJ, Highs over Mascarene and St Helena, winds from Atlantic and Indian Ocean and ENSO. From this chapter we have seen the large scale features associated with Kiremt rainfall anomalies are ITCZ, TEJ, AEJ, QBO, the Azores High (NAO), ENSO, winds from Atlantic, and Indian Ocean, EALLJ, humidity anomalies over the Red Sea and over the Southeast Atlantic Ocean. We have also seen the response of these large scale features for the different homogeneous rainfall zones are not entirely the same. Here are some examples:

- Low level circulation: Deficit rains over the southwestern part of Ethiopia (Zone IIb) are associated with weaker westerlies from the Atlantic even if the EALLJ is stronger suggesting the moisture source from the Atlantic is most important (Fig. 17 left), whereas for the eastern part (Zone IV), excess rains are associated with stronger EALLJ and this suggests that the moisture from the Indian Ocean and the Atlantic Ocean also play a role (Fig. 17 right).
- Upper level circulation: a westerly anomaly at 200 mb indicative of a weaker TEJ is linked to deficit rainfall in all areas except Zone IIb (Fig. 18), probably via reduced upper level divergence associated with the weaker jet. For Zone IIb, it is likely that the effect of the jet is less important than other factors such as the effect of the QBO on the westerly moisture flux as described in Section 3.2.

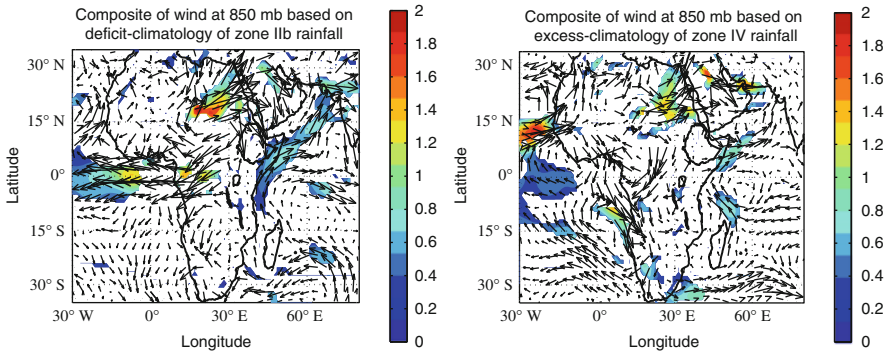


Fig. 17 Composites of wind at 850 mb for deficit-climatology of Zone IIb in (*left*) and excess-climatology of Zone IV (*right*). The arrows indicate the direction of the wind anomaly and the filled contours represent the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

- ENSO: for the contemporaneous season deficit rains in all zones (except Zone V) are associated with El-Niño. However, the influence of a previous winter El-Niño in the following Kiremt is opposite between Zone I and the rest of the regions as shown in Fig. 16.
- There is an opposite pattern between Zone IIb and Zone IV in terms of geopotential height (Fig. 19). A positive geopotential height anomaly over central Africa is associated with deficit rains of Zone IIb and excess rains of Zone IV. For Zone IIb this positive geopotential height anomaly relates to a weaker westerly anomaly. For Zone IV this positive height anomaly over central Africa is associated with westerly inflow from the north Atlantic (around 15°N) and a northward shift of the ITCZ, which in turn leads to high rainfall.

The schematic of the large scale features associated with rainfall anomalies in Kiremt season is shown in Fig. 20.

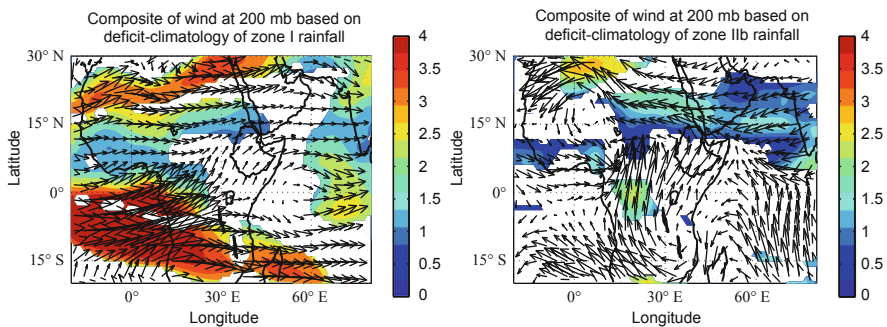


Fig. 18 Deficit-climatology composites of wind at 200 mb for Zone I in (*left*) and Zone IIb (*right*). The arrows indicate the direction of the wind anomaly and the filled contours represent the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

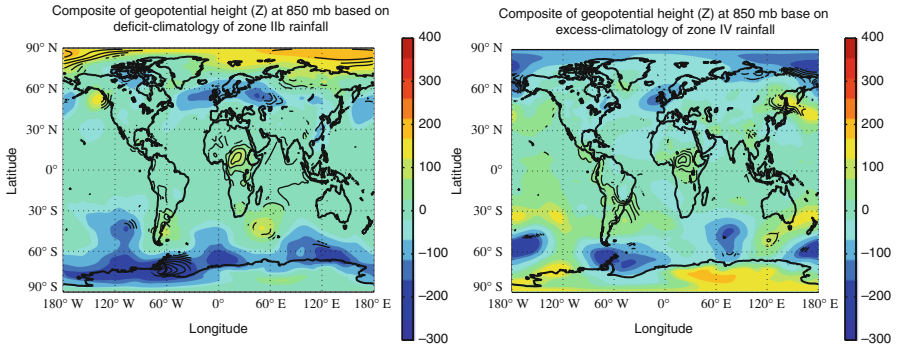


Fig. 19 Composites of geopotential height (m^2s^{-2}) at 850 mb for deficit-climatology of Zone IIb in (left) and excess-climatology of Zone IV (right). Contour lines represent significant at 0.1 level

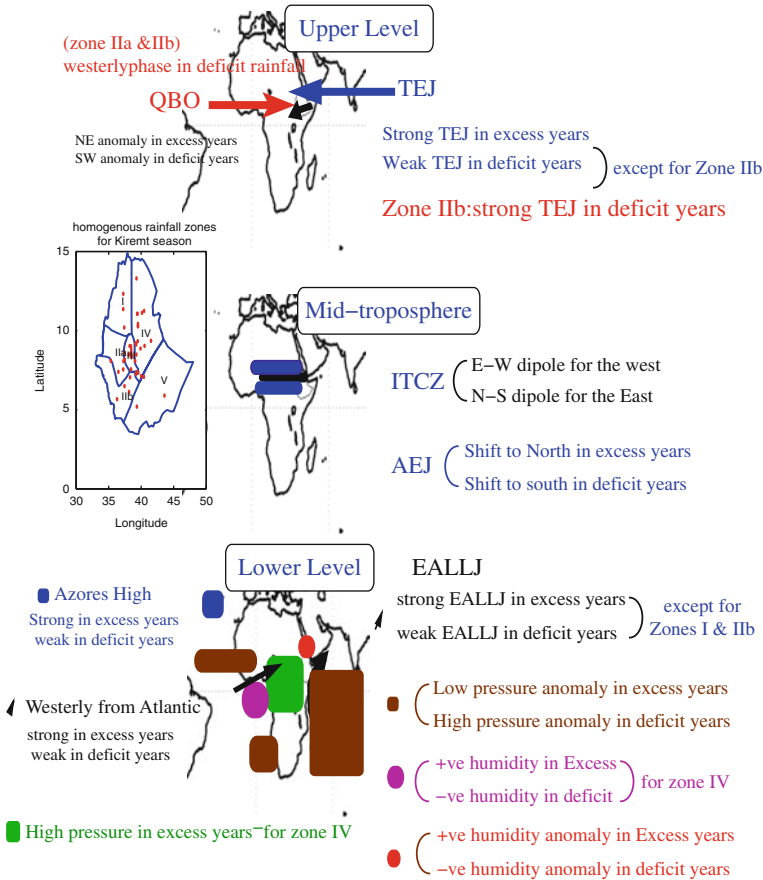


Fig. 20 Summary of large scale feature associated with rainfall anomaly in kiremt season

4 Large Scale Features Associated with Belg Rainfall Anomalies

Belg (FMAM) is the main rainy season for the southern part of Ethiopia (Zone V) and is the short rainy season for the rest of the country except for the northwest (Zone I). Zone I is dry for this time of the year. The large scale features associated with excess and deficit rainfalls during the Belg season will be discussed in the following section. From previous studies, the large scale features which affect Belg rains are the ITCZ, Subtropical westerly jet streams, Arabian High, NAO and the frequency of tropical cyclones over the southwest Indian Ocean. Now we will look at the wind, geopotential height, humidity at 850mb, 200mb and the height-latitude cross section to examine some of these features and also check how they vary over the different homogeneous rainfall zones.

4.1 Sub-Tropical Westerly Jet (STWJ)

During the short rainy season, Camberlin and Philippon (2002) have shown the existence of a trough over the Red Sea at about 200 mb. This trough pattern corresponds to an anomalous southerly extension of subtropical westerly jet streams (STWJ) over Northeast Africa. The STWJ is relatively narrow and shallow streams of fast flowing air in the upper troposphere with maximum speed at about 200 mb level as shown in Fig. 21. The STWJ is formed as a result of conservation of angular momentum as the air moves from the lower latitudes to the higher latitudes (Mcilveen 1998). The Jet speed is largest in the ridge and weakest in troughs (Hastenrath 1990). This means that the west of the trough can be treated as the exit of the jet, and hence the ageostrophic component points to the high pressure. The east of the trough can be taken as the entrance of the jet, meaning that the ageostrophic component points to the low pressure. Therefore the area of divergence will be ahead of the trough as shown in Fig. 22. This divergence ahead of the trough is likely to induce

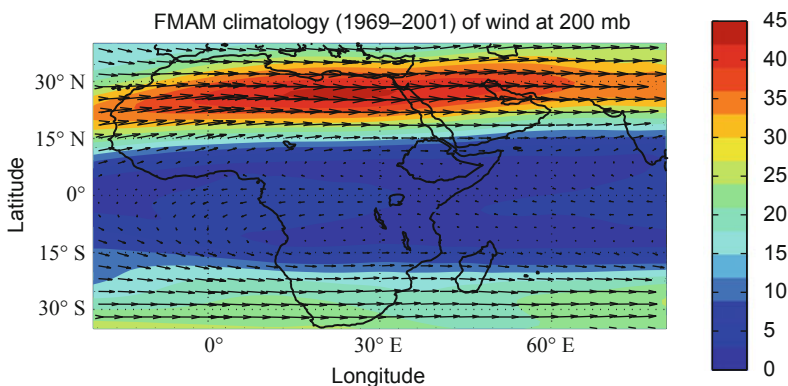
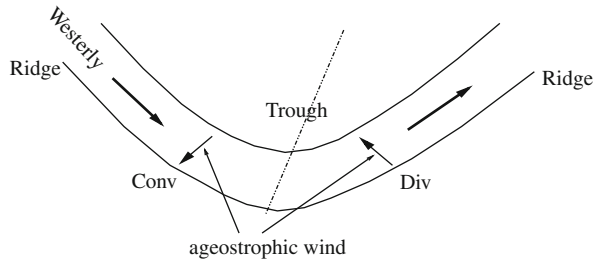


Fig. 21 Wind climatology at 200 mb during the Belg (FMAM) season. The colours represent the magnitude of the wind (m/s) and the arrows indicate the direction of the wind

Fig. 22 Schematic diagram of the path of the downward bend of the subtropical westerly jet stream and associated area of divergence



upward motion (Hastenrath 1990) and hence be conducive to the generation of precipitation.

The most prominent features at upper levels (200 mb) are the wind anomalies associated with excess and deficit rainfall years (Fig. 23). During deficit rainfall years, the STWJ shows a dipole pattern, with easterly anomalies over NE Africa $\sim 15^{\circ}N$ and westerly anomaly $\sim 30^{\circ}N$. This suggests that the STWJ is shifted to the north from its climatological location during deficit rainfall years. Excess rain in all zones is associated with upper level trough over Africa (Fig. 23) which could be linked to the south ward tilt of the STWJ. For Zone IV, the location of the trough (cyclonic anomaly) is placed further west over the Sahara compared to the trough for other zones in excess composites, which is located around northeast Africa. For Zone IV, there is an anticyclonic anomaly over the Horn of Africa during excess rains. This upper level anticyclonic flow anomaly ahead (east) of the trough could be the one that enhances ascent flow and trigger convection. For deficit years the wind anomaly forms an anticyclonic pattern over Arabian peninsula. This wind anomaly pattern for excess and deficit rainfalls is in agreement with the Camberlin and Philippon (2002) study over north Ethiopia and Eritrea.

4.2 Low Level Humidity

For all zones, deficit rainfall years are associated with significant negative humidity anomalies over NW Indian Ocean, the Arabian peninsula and East Africa, and positive humidity anomalies over the eastern Indian Ocean and the southeast Atlantic (Fig. 24). Looking at the wind anomaly at 850 mb during deficit rainfall years (Fig. 25), which shows an westerly anomaly over Indian ocean, the westerly anomalies in the Indian ocean will advect humidity to the eastern Indian ocean and at least explaining the observed positive anomalies over eastern Indian ocean and negative anomalies over western Indian Ocean and over the Horn of Africa. The easterly anomaly over west Africa and the Atlantic also means less moisture is advected to the African continent from south Atlantic, which means positive humidity anomalies over Atlantic Ocean.

For all zones except Zone V, excess rains are associated with positive anomalies of humidity over the western Indian Ocean, the Arabian peninsula, the Red Sea and Eastern Africa and negative anomalies over the eastern Indian Ocean. Again except

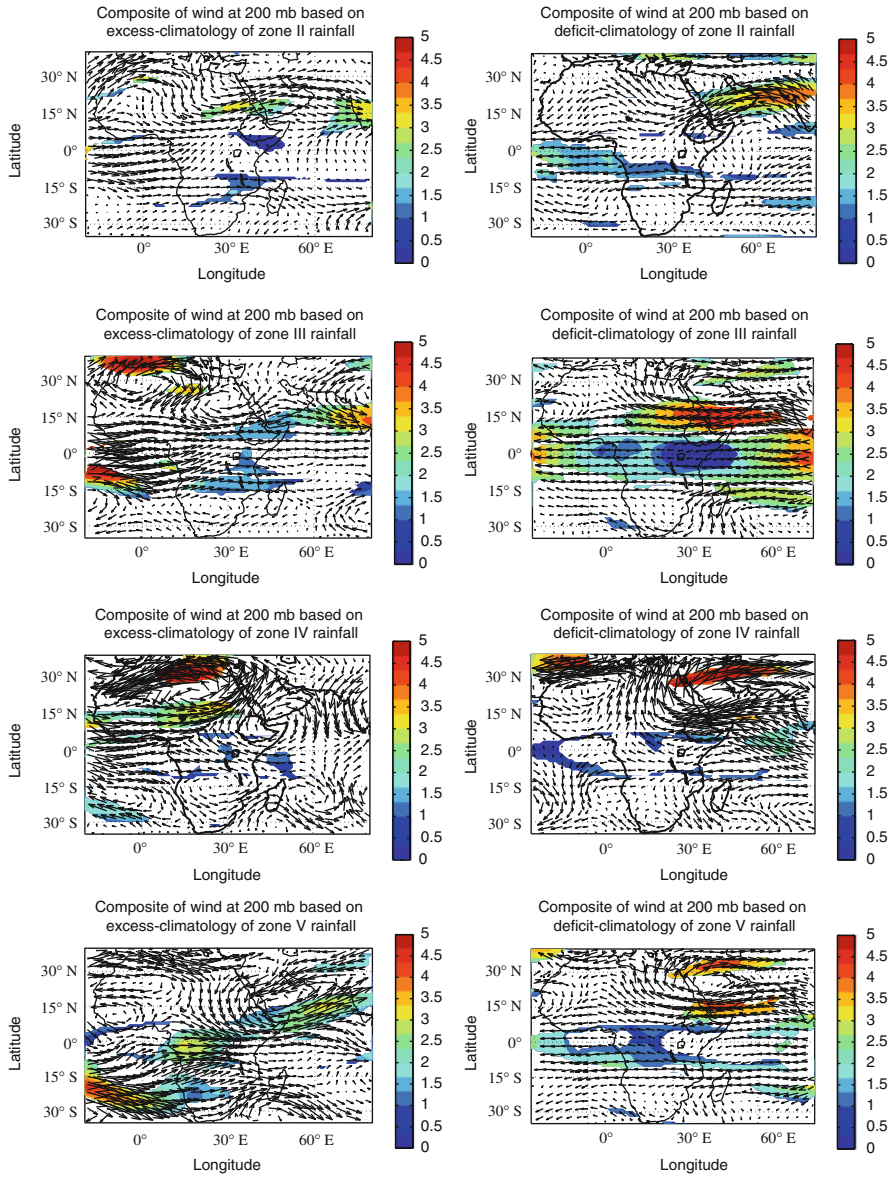


Fig. 23 Belg (FMAM) wind at 200 mb for excess-climatology (*left*) and deficit-climatology (*right*). The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

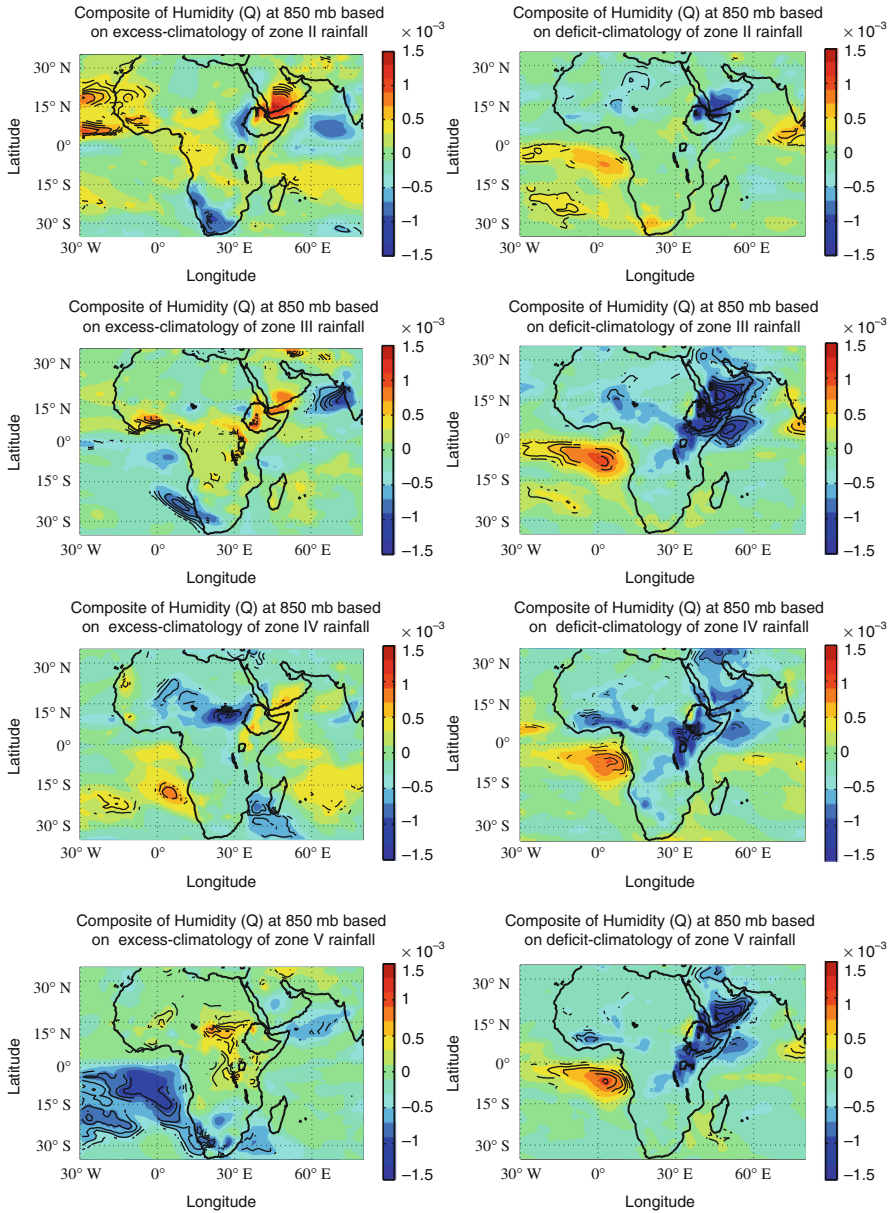


Fig. 24 Belg (FMAM) specific humidity (kg/kg) at 850 mb for excess-climatology (*left*) and deficit-climatology (*right*). Contour lines represent significant at 0.1 level

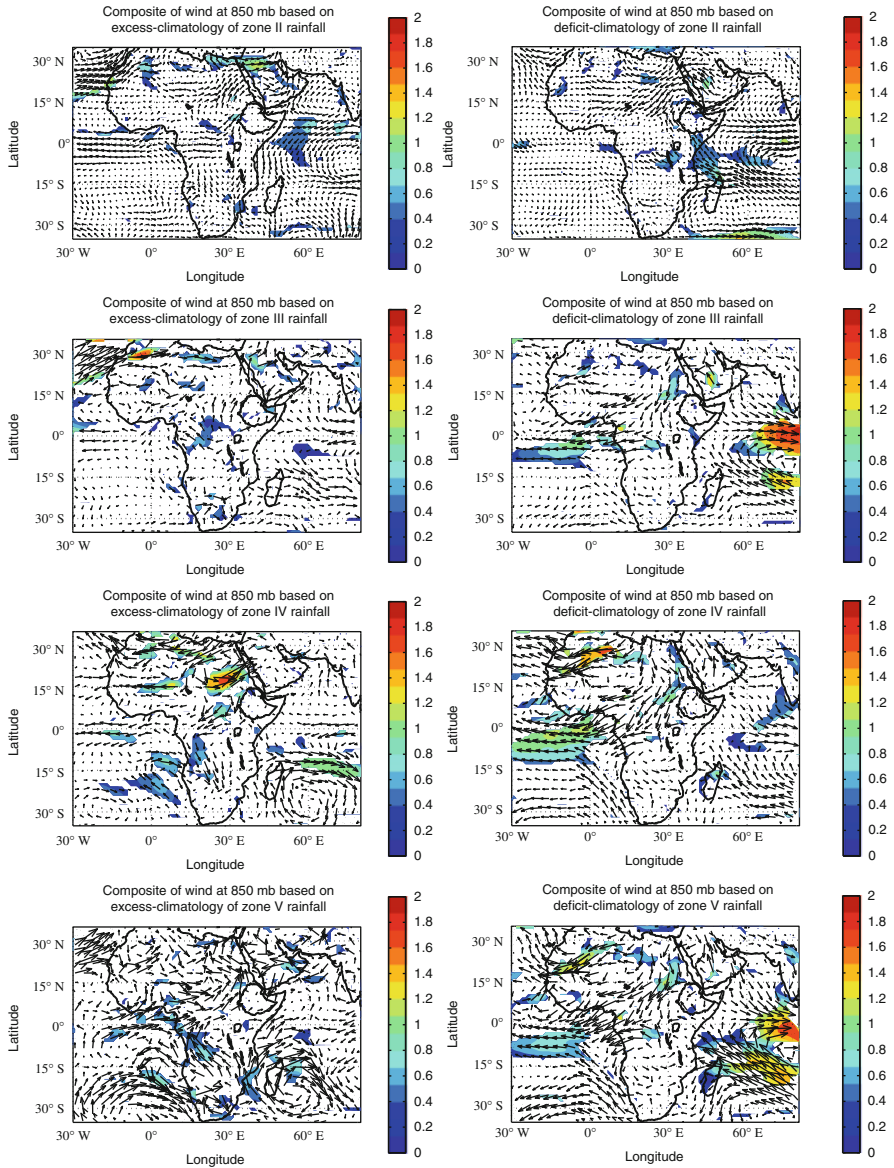


Fig. 25 Belg (FMAM) wind at 850 mb for excess-climatology (*left*) and deficit-climatology (*right*). The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

for Zone V the humidity anomalies over Africa during excess rainfall years show a dipole over Ethiopia and Sudan with positive values over Ethiopia and negative values over Sudan. The alignment of the dipole of humidity anomalies suggests that the meridional arm of the ITCZ may be shifted to the east (to Ethiopia) during excess rainfall years.

4.3 Low Level Wind

During deficit rainfall years there is a consistent wind anomaly at 850 mb for all zones (Fig. 25) namely westerly anomalies over the Equatorial Indian Ocean and easterly anomalies over the Atlantic. If we consider the zonal (Walker) circulation, the westerly anomalies to the east of the Horn of Africa and easterly anomalies to the west of the Horn of Africa make the region an area of divergence (and hence deficit rainfalls). For excess rainfall years (except for zone V), there is an easterly anomaly over the Indian Ocean, which advects moisture and makes a favourable environment for excess rainfall. For zone V, there are cyclonic anomalies over the western Indian Ocean that hinder the easterlies delivering moisture to the continent from the Indian Ocean. However there are strong westerly anomalies over the Atlantic and over Africa, suggesting that the moisture influx for the southern part of Ethiopia comes from the Atlantic during excess rainfall years. These observations for Zone V i.e. the association of moist south Atlantic westerly flow with the excess rains is in agreement with studies made for the equatorial east Africa regions eg. McHugh (2006), which suggest that these westerlies from Atlantic are linked to ENSO with stronger/weaker westerlies associated with El Niño/La Niña periods.

In summary, for the northern part of Ethiopia the easterlies associated with the Arabian Anticyclone are important in bringing moisture from Indian ocean, whereas for the southern part it is the westerlies from Atlantic that are more favourable for excess rain.

4.4 Low Level High Pressures

During the Belg (FMAM) season, easterly to north easterly outflow on the southern periphery of the Arabian anticyclone, which lies over the Arabian sea for this time of the year, carries moisture into East Africa (Camberlin and Philippon 2002). In the previous section i.e. Section 4.3, it is shown that the easterlies from the Indian Ocean are the main source of moisture and cause rain over most of the northern and central part of Ethiopia.

Figure 26 shows the composites of geopotential height at 850 mb based on excess and deficit rains and it suggests that a stronger signal is observed over extra tropical Atlantic and Pacific Oceans. Again from Fig. 26, it can be seen that in most cases negative North Atlantic Oscillation (NAO) i.e. negative anomaly around Azores and positive anomaly over Iceland is associated with excess rains and positive NAO with deficit rains. The link between the high over the north Atlantic and Belg rainfall over

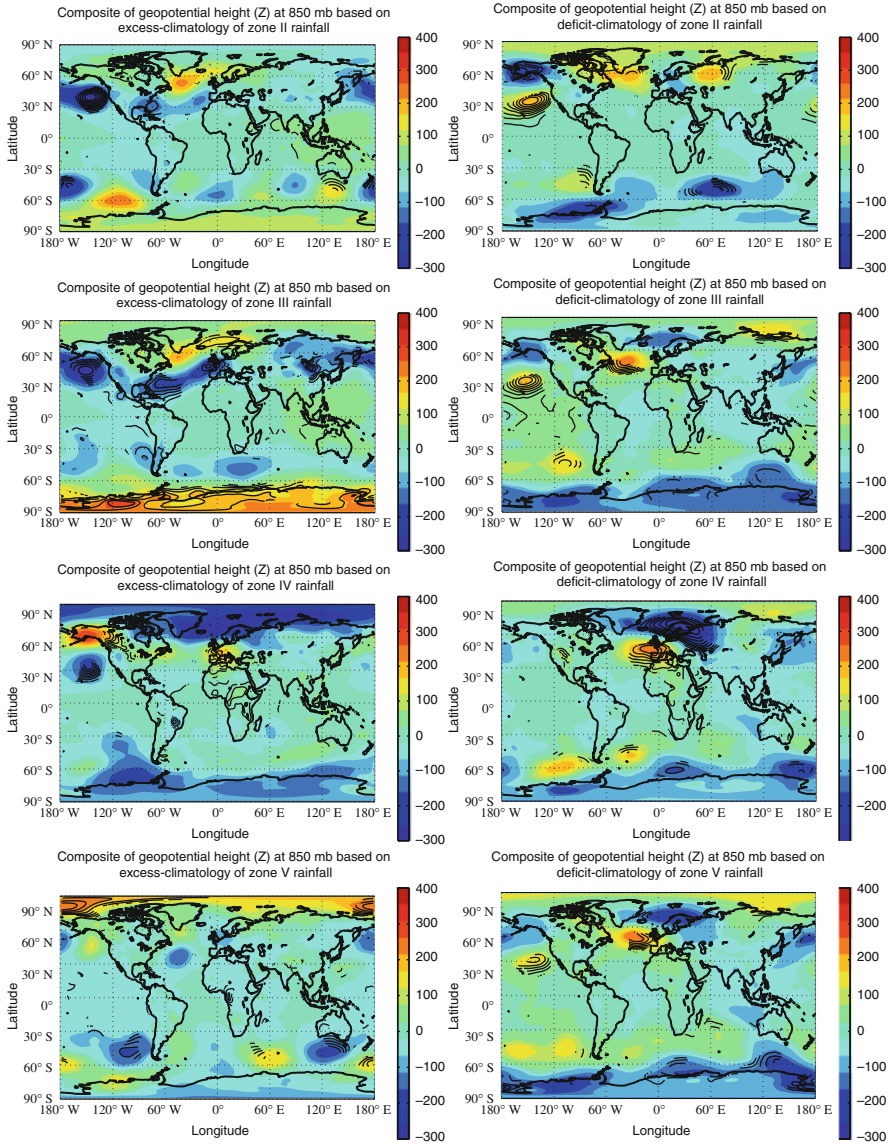


Fig. 26 Belg (FMAM) geopotential height (m^2s^{-2}) at 850 mb for excess-climatology (*left*) and deficit-climatology (*right*). Contour lines represent significant at 0.1 level

Ethiopia could be via the easterlies in the Indian Ocean which advects moisture to East Africa. A weaker Azores High (or a negative NAO) implies the storm tracks are deflected to the south (i.e. penetrate to the Mediterranean and to the middle east) and this will displace the Arabian High to the south over the Arabian Sea which means

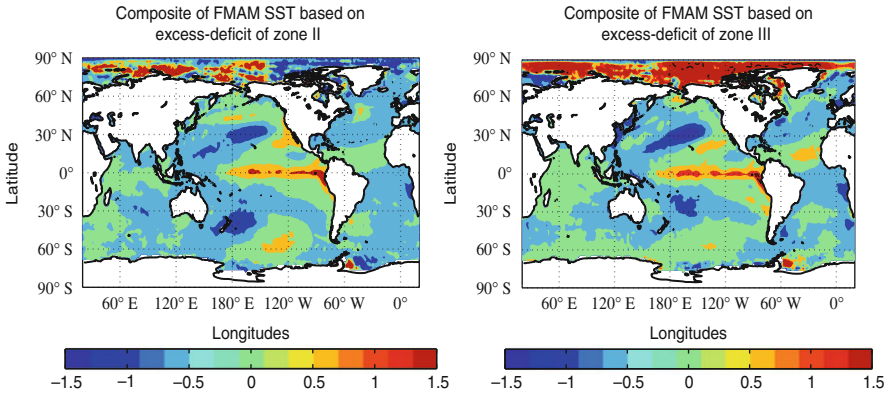


Fig. 27 Excess-Deficit composite of SST (in K) Belg season for Zone II (*left*) and Zone III (*right*)

that more moisture is advected to the horn of Africa from the western Indian ocean by the easterlies south of this anticyclone. Although the signal is weak, the excess composites in Fig. 26 also shows a positive height anomaly over the Arabian Sea especially for the north and central (Zones II and III) which agree with the above possible extra tropical-tropical interaction.

4.5 ENSO

Unlike the Kiremt season where rainfall is correlated negatively with the tropical Pacific (i.e. El Niño is associated with deficit rains), for the Belg (FMAM) season, rainfall is correlated positively with the tropical Pacific (though the strength is lower than the Kiremt-SST correlation). The strongest signal of ENSO is shown over western and central part of Ethiopia, where warm/cold equatorial eastern Pacific is associated with excess/deficit Belg rainfalls as shown in Fig. 27.

The one season lag in the SST-rainfall relationship (i.e. ONDJ SST correlates with FMAM rainfall) is similar to the contemporaneous rainfall-SST relationship but weaker in strength. In other words both contemporaneous (Belg) and the previous Bega (winter) warming/cooling of Equatorial Pacific are associated with excess/deficit rainfall although the contemporaneous relation is stronger.

For the two season lag SST-rainfall relationship (the previous JJAS SST correlating with FMAM rainfall), warming of Eastern Pacific (coast of S. America) during the previous Kiremt (which is accompanied by warming of the Indian Ocean) is associated with deficit Belg rainfall. In other words, the occurrence of El Niño (accompanied by warming of Indian ocean) in the previous summer is associated with deficit Belg rains, but the occurrence of El Niño / La Niña in the previous Bega or contemporaneous Belg is associated with excess/deficit Belg rains as shown in Fig. 28.

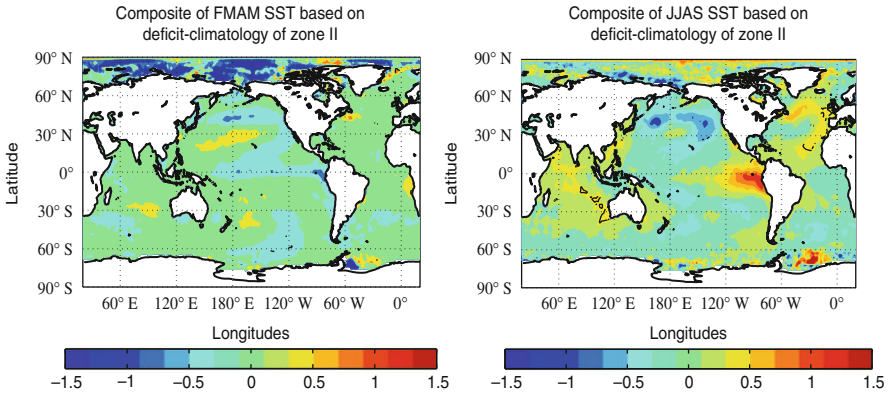


Fig. 28 Deficit-Climatology composite of (*left*) SST (in K) in Belg season (*right*) SST in previous Kiremt season for Zone II

Generally for Zone V, The ENSO teleconnection is weak and located over the central Pacific, whereas in other zones the strongest correlation is associated with the equatorial eastern Pacific.

4.6 Indian Ocean Related Teleconnections

For the central part of Ethiopia, consistent with the ENSO teleconnection, correlation of Zone III rainfall with the Indian Ocean shows is positive in the contemporaneous season and negative in the previous summer. In other words, warming of the Indian Ocean in the contemporaneous season is associated with excess Belg rainfall but warming of the Indian ocean in the previous summer is associated with deficit Belg rainfall as shown in Fig. 29.

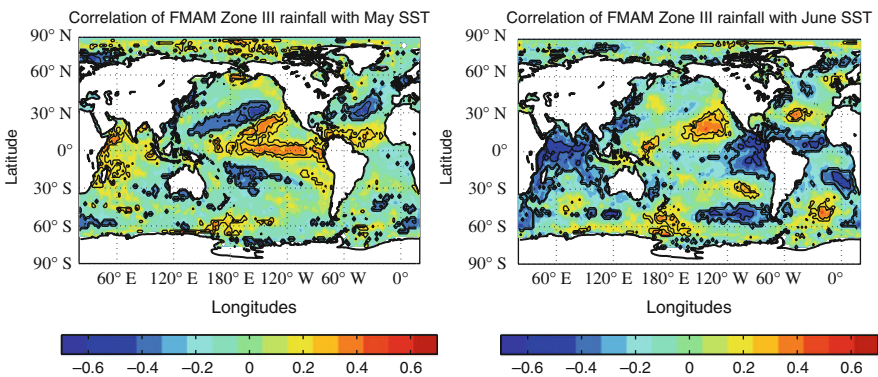


Fig. 29 Correlation of Belg rainfall with SST in (*left*) May (*right*) previous June

Shanko and Camberlin (1998) have examined the relationship between the tropical cyclones over the southwest Indian Ocean and rainfall for the short rainy season (FMAM) and found that low/high frequency of Tropical cyclone is associated with heavy/deficit rainfall in the Belg season.

4.7 Discussion on Belg Season Large Scale Features

From the literature it is known that Belg rainfall is affected by upper level troughs associated with the subtropical westerly jet, the ITCZ for the southern part of Ethiopia, the easterly anomaly from the Indian Ocean, and the frequency of tropical cyclones over the southwest Indian Ocean. The composite analysis not only confirmed the association of the above features (except the effect of tropical cyclones) with the Belg rains but also reveals additional features. The following are some of the additional features:

- Low level circulation: although for deficit rains there is a consistent westerly anomaly over the Indian ocean for all zones, the excess composites suggests that there are regional differences on the impact from the Atlantic. For instance excess rains are associated with easterly anomaly for the eastern and western part of Ethiopia but associated with westerly anomaly for the southern Ethiopia as shown in Fig. 30. This suggest that the easterly anomaly associated with the anticyclonic flow over the Arabian Sea is crucial for wet conditions over the western and eastern Ethiopia (Fig. 30 left) whereas the moist southwesterly anomaly from the Atlantic is responsible for wet conditions over southern Ethiopia (Fig. 30 right).
- The upper level features affecting the Belg season are the trough related to the southward shift of the subtropical westerly jet in excess years and the weaker or northward shift of subtropical westerly jets in deficit rainfall years. There is, however, a slight variation over the location of the trough for different regions For example the location of the trough or cyclonic anomaly is located further west during excess years of zone IV rainfall compared to say Zone V as shown in Fig. 31.

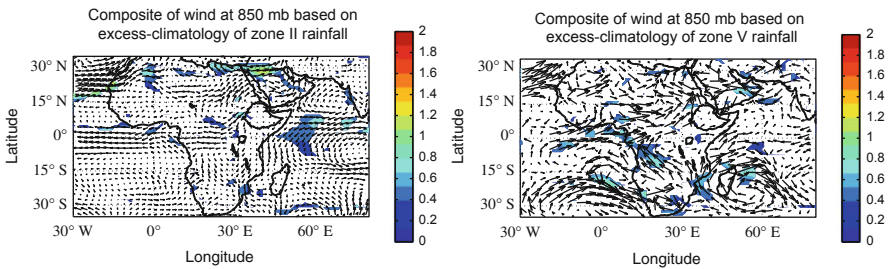


Fig. 30 Excess-climatology composite of wind at 850 mb for Zone II (left) and Zone V (right) of Belg season. The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

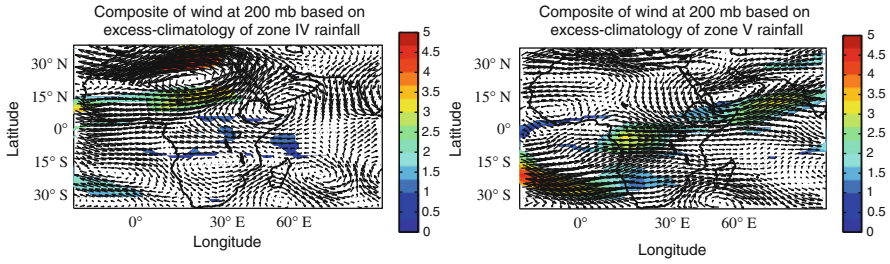


Fig. 31 Excess-climatology composite of wind at 200 mb for Zone II (*left*) and Zone V (*right*) of Belg season. The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

- It is interesting that the impact of ENSO on Belg rainfall is the opposite to the impact of ENSO on the Kiremt rainfall. In Section 3.8, it is shown that in Kiremt, El-Niño is related to deficit rains, however in the Belg season, El-Niño is related to excess rains.

Another interesting feature is that the lag relationship between ENSO and Belg rains. At zero lag (contemporaneous season) the occurrence of El-Niño is associated with excess Belg rains, However, the occurrence of El-Niño at two season lag (the previous summer) is associated deficit Belg rains.

- There are also opposite patterns between Zone V and the rest of the zones in terms of the geopotential height (Fig. 32). Negative geopotential height over Africa and positive geopotential height over Atlantic Ocean are associated with excess rains of Zone V. For the rest of the zones excess rains are associated with a positive height anomaly over Africa and Atlantic ocean. This might explain the westerly inflow from Atlantic during excess rains over the southern Ethiopia. For Zone V (the southern part of Ethiopia), the zonal pressure gradient between the Atlantic ocean and African continent might be responsible for the the westerly influx from the Atlantic during excess rains.

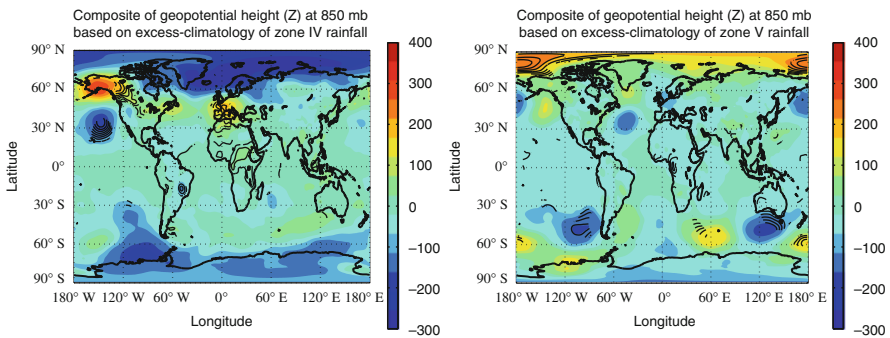


Fig. 32 Composites of geopotential height (in m^2s^{-2}) at 850 mb for excess-climatology of Zone IV in (*left*) and Zone V (*right*) of the Belg season

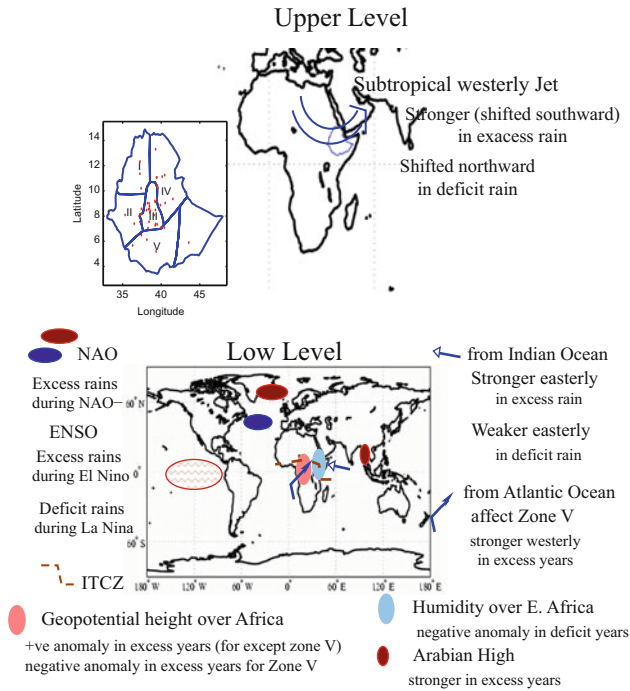


Fig. 33 Summary of large scale feature associated with rainfall anomaly in Belg season

The schematic of the large scale features associated with rainfall anomalies in the Belg season is shown in Fig. 33.

5 Summary and Conclusions

In this chapter the large scale atmospheric and oceanic controls on Kiremt and Belg rainfall have been studied and the main points are summarised below.

For Kiremt, in most cases excess (deficit) rainfalls are associated with:

- a stronger (weaker) Tropical Easterly Jet (TEJ). A stronger (weaker) jet implies a strong (weak) divergence associated with the jet and hence more (less) convective activity over Ethiopia.
- a northward (southward) shift in African Easterly Jet (AEJ). The climatological location of the jet is around 15° N and the geostrophic component of the Jet transports the moisture from east Africa to west Africa and ultimately to the Atlantic (since the flow is easterly). This implies that the weaker (stronger) jet or the northward (southward) shift of the jet means less (more) moisture is taken away from east Africa and hence to more (less) rainfall.
- a stronger (weaker) East African Low Level Jet (EALLJ). A stronger (weaker) EALLJ means more (less) moisture from southern Indian Ocean penetrating into

east Africa and hence giving rise to more (less) favourable conditions for high rainfall.

- stronger (weaker) westerly moisture influx from the Atlantic.
- a cold (warm) summer SST over the equatorial Pacific, which alters the circulation over Africa (see Diro et al. 2010) in such a way that there is more (less) rainfall over Ethiopia.
- a positive (negative) phase of North Atlantic Oscillation (NAO). The positive NAO is associated with warmer upper tropospheric temperature (TT) anomalies over north Africa and Asia (Goswami et al. 2006). This warm TT anomaly over Asia leads to a stronger Tibetan High (at upper level) and hence a stronger easterlies south of this High – in other words a stronger TEJ. Positive NAO conditions may also lead to a stronger EALLJ by strengthening the meridional TT gradient between Asia and the Indian Ocean.
- an easterly (westerly) phase of the Quasi Biennial Oscillation (QBO). Since the mean low level flow is westerly and if the upper level flow is easterly (easterly phase of QBO) then the zonal circulation gets stronger and hence more moisture is injected from Atlantic. This implies that during a westerly phase of the QBO, the zonal (east-west) circulation is reduced meaning less westerly influx from Atlantic, which in turn may mean less moisture and less rainfall.

There are, however, exceptions. For instance, the southwestern part of Ethiopia (Zone IIb), deficit rains are associated with stronger EALLJ but weaker westerly influx from Atlantic this may suggest it is the moisture influx from the Atlantic which is important for this region. Again for this region (Zone IIb) unlike the other parts of Ethiopia deficit rains are associated with stronger TEJ and westerly phase of QBO. This also suggest the upper level feature important for this region is the QBO rather than the TEJ.

Another interesting point is the relationship between Kiremt rainfall and ENSO in the previous winter. For Zone I (northwest) El Niño in the previous winter is associated with deficit rainfalls but for zone IIa (west), El Niño in the previous winter is associated with excess rain.

For the Belg season, excess (deficit) rains are associated with:

- a stronger (weaker) and southward shift in the subtropical westerly Jet (STWJ). A trough is associated with the southward shift of subtropical westerly jet. Convection is likely to occur to the east of this upper level trough.
- a warm (cold) equatorial Pacific (El Niño). Warm SSTs over central equatorial Pacific excites stationary Rossby waves, which propagate eastward and northward, entering the subtropical westerly jet in the Atlantic and reaching north Africa (Shaman and Tziperman 2005). This means convective anomalies generated from the eastern Pacific reach north east Africa via subtropical westerly jets linked to Rossby waves. We have already seen that a stronger or southward shift in the subtropical westerly jet is associated with excess rainfall.
- a negative (positive) phase of the North Atlantic Oscillation (NAO). Negative phase of NAO (weaker Azores High) mean the mid latitude depressions can propagate via the Mediterranean sea and displace the Arabian High to the south (to the Arabian Sea). When the Arabian High is displaced south the easterlies (associated

with the anticyclone) bring moisture to the Horn of Africa and contribute to the excess rains.

- a stronger (weaker) easterly anomaly from Indian Ocean. The easterlies in the Indian Ocean are associated with the Arabian High, the Arabian High in turn may be associated with the Azores High (or the NAO). Excess rains are associated with negative phase of NAO (weaker Azores High), stronger Arabian High, and stronger easterly anomalies from the Indian Ocean.
- less (more) frequent tropical cyclones over southwest Indian ocean. The effect of the tropical cyclone is through the diversion of moisture to the cyclone region (Shanko and Camberlin 1998).

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