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Subseasonal Variability of the Belg Rains in Ethiopia

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Abstract

The February to May rainfall season, locally known as Belg, contributes up to 40% of the annual rainfall over northeastern, central and southwestern Ethiopia. Its contribution exceeds 50% over southern and southeastern Ethiopia. The Belg season is characterized by significant interannual and intraseasonal variability. However, there are only a few studies addressing the characteristics of this season. Interactions between extratropical and tropical systems across the Red Sea region play a major role in modulating the rainfall pattern during this season. It is shown in this paper that the North Atlantic Oscillation (NAO) seems to play a major role in the variability of the Belg rains on the subseasonal time scale. The Belg rains are negatively correlated with the NAO index over much of the region, with southern and southeastern Ethiopia exhibiting relatively highest correlation values. NAO rainfall anomaly composites also indicate that the negative (positive) phase of the NAO tends to enhance (suppress) the Belg rains. Two modes of regional circulation patterns that modulate Belg rainfall variability have also been identified in this study. A ridge/trough pattern, featuring two anomalous mid-to upper-level warm anticyclones and one cold cyclonic trough in the region between the Northeast Atlantic and the Arabian Peninsula, tends to suppress the Belg rainfall due to reduced tropical-extratropical interactions. In contrast, a tripole structure with two anomalous mid- to upper-level cold cyclonic troughs and one warm anticyclone tends to enhance rainfall during the Belg season of Ethiopia. It is further shown in this paper that the MJO tends to modulate rainfall during the Belg season.

Key words: Belg, Ethiopia, subseasonal, variability, NAO, MJO, tripole

1. Introduction and background

Ethiopia is a country in the Greater Horn of Africa with a complex topography and climate. According to research reports of the National Meteorological Agency of Ethiopia, NMA (1996) and NMA (2004), there are three rainfall seasons and three rainfall regimes in Ethiopia. The February to May rainfall, known as “Belg”, is a secondary rainy season in the northeast, central, and the highlands of the south and east. It is the primary rainfall season over the lowlands of South and Southeast Ethiopia. The June to September rains or “Kiremt” season is the main rainy season over much of the country, except for the lowlands of South and Southeast, which remains relatively dry during this season.

The western half of the country and the highlands of southern Ethiopia receive annual rainfall in excess of 1000 mm. In contrast, the annual total rainfall remains below 500 mm over the lowlands of northeastern and southeastern Ethiopia (Fig. 2a). There is a significant contribution of the Belg season to the annual rainfall totals in the eastern and southern half of the country (Fig. 2b). The Belg season starts slowly in February with monthly rainfall exceeding 40 mm across southwest and central Ethiopia (Fig. 2c). The rains increase both in amount and spatial distribution in March (Fig. 2d), covering much of the Belg areas in April (Fig. 2e). April is the peak month of the Belg season over northeastern, central, southern and eastern Ethiopia, and the monthly climatological rainfall exceeds 100 mm over southern and eastern Ethiopia. May is a transition period between the Belg and the succeeding Kiremt season. The Belg rains gradually decrease across the eastern and southern half of the country during this month, while the Kiremt rains increase across the western half of the country (Fig. 2f).

Ethiopia's economy is highly dependent on rain-fed agriculture, and climate variability has a big impact on the livelihood of its people. A previous study by Grey and Sandoff (2005) shows the existence of a significant relationship between rainfall variability and Gross domestic product (GDP) in Ethiopia. Many studies have been conducted to improve our understanding of rainfall variability in Ethiopia. However, most of these studies have focused on the "Kiremt" season for example: Sileshi and Demarée (1995), Bekele (1997), Wolde-Georgis (1998), Gissila et al. (2004), Segele and Lamb (2005), Korecha and Barnston (2007) and Diro et al. (2011a).

Nonetheless, the Belg rainfall season has its own importance to the economy of Ethiopia. It serves to grow crops in the northeastern, central, southern, and eastern highlands and is used for agro-pastoral activities in the lowlands of Northeast, South and Southeast Ethiopia. The Belg rainfall also helps in land preparation for the long cycle crops over western and southwestern Ethiopia. A dry Belg, as in the case of 2015, may result in drought with adverse impact on agricultural and pastoral activities in Ethiopia (USAIDa, 2016). In contrast, the excess rainfall during wet Belg may result in flooding related hazards (USAIDb, 2016). However, despite its importance in agriculture and other socio-economic activities, the Belg rainfall season is not widely discussed in the scientific literature. The major circulation patterns of the Belg season were documented by Kassahun (1986) and NMA (1996). Diro et al. (2008) studied the relationship between Sea Surface Anomalies (SSTA) and Belg rainfall. Shanko and Chamberlin

(1998) studied the influence of Southwest Indian Ocean Tropical Cyclones on Belg rainfall. The link between Belg rainfall, and NAO and quasi-biennial oscillation (QBO) was documented by Diro et al. (2011b).

Habtemichael and Pedgley (1974), Camberlin and Philippon (2002) and Diro et al. (2011b) described the roles of upper-level divergence associated with the southward bend of the subtropical westerly jet and mid-to-upper level cooling in enhancing rainfall over parts of northeastern Africa, including Ethiopia.

A number of earlier studies over different regions of the world have investigated the mechanisms of tropical-extratropical interactions. Elongated cloud bands connecting the Tropics and extratropics are referred to as tropical plumes (TP), and most TPs are rooted in the active segment of the ITCZ (McGuirk et al., 1987; Knippertz, 2007). According to Iskenderian (1995), a southwest-northeast oriented synoptic scale upper-level trough is often present poleward and westward of a TP in the northern hemisphere. Previous studies have shown the relationship between low-latitude troughs or cut-offs from fields of isentropic potential vorticity (PV) and convection associated with tropical-extratropical interactions (Waugh and Funatsu, 2003; Knippertz, 2007). Positive vorticity advection (PVA) ahead of the low-latitude upper-troughs quasi-geostrophically (QG) forces ascent and thereby triggers the eruption of cloud plumes (McGuirk et al., 1988; Kiladis, 1997; Knippertz, 2007). Moreover, deep mid-latitude disturbances associated with circulation that reaches far enough equatorward into the tropical moisture source can lead to considerable poleward moisture flux (Knippertz, 2007). This paper, describes how the low-latitude upper-level PV trough or cut-off, the upper-level divergence, and a poleward atmospheric moisture flux anomaly emanating from the tropics interact to modulate the Belg rainfall season.

Only a few studies discuss the influence of the North Atlantic Oscillation (NAO) on East African rainfall. Goswami et al. (2006) indicated the relationship between NAO and warmer upper tropospheric temperature anomalies over northern Africa and Asia. Diro et al. (2011b) described the mechanism by which the negative phase of NAO leads to enhanced Belg rainfall in Ethiopia in the following way. The Azores High in the vicinity of Northeast Atlantic becomes weaker than normal and gives way to the southward track of the mid-latitudes storms across the Mediterranean Sea into the Middle East. Circulation anomalies associated with these eastward propagating storms displace the Arabian High southwards into the Northwestern Indian Ocean. The shift of the Arabian High into the Indian Ocean increases moisture flux into Ethiopia, and lead to excess rainfall in the Belg season.

This paper focuses primarily on the subseasonal time scale roughly defined as variability between 10 and 90 days (Thiaw et al., 2017). A detailed description of the link between phases of the NAO and subseasonal variability of the Belg rainfall is provided. We propose an interaction between NAO and a mid- to upper-level tripole structure in the region between the Northeast Atlantic and the Red Sea, as a primary mechanism for variability within the Belg season. NAO modulation of the Belg rains is a case in point of this interaction such that positive (negative) phases of the NAO tend to decrease (increase) rainfall in Ethiopia.

Intraseasonal timescale systems such as the MJO also by way of altering the tropical component of the interaction are found to influence the Belg rainfall season. Pohl and Camberlin (2006), and Berhane and Zaitchik (2014) have studied the influence of MJO on the East African rainfall. However, their works mainly focus on the equatorial regions of East Africa not including the greater portion of Ethiopia.

According to Cassou (2008), interactions between the MJO and NAO have significant impact on the distribution and sequences of the NAO weather regimes. Jiang (2016) showed that negative (positive) NAO events are preceded by enhanced MJO convection over the tropical western and central Pacific Ocean (enhanced MJO convection over tropical Indian Ocean and Maritime Continent). Since Ethiopia is located close to an area of tropical-extratropical interactions, interactions between the MJO and NAO could also have an influence on the Belg rainfall. However, the lead/lag relationship between the MJO and NAO, and its influence on the Ethiopian Belg rainfall is outside of the scope of this paper.

In this paper, Belg rainfall and circulation anomaly composites during active MJO phases are constructed to document the influence of the MJO on this rainfall season and to better understand the tropical-extratropical circulation in modulating the Belg rainfall season.

Following this introduction, section 2 of this paper describes the data and methods, results are discussed in section 3, and summary and conclusions are provided in section 4.

2. Data and methods

Daily rainfall data used in this study cover 117 stations of the National Meteorological Agency (NMA) of Ethiopia for the 1980 to 2010 period, and February to May 2015 (Fig. 1). Stations used in this study are carefully selected so that information on major NAO and MJO events is not missed due to data gap. The proportion of missing daily data in this period is less than 25% for 115 of the stations. For the remaining two stations, their missing data proportion is 41% and 49%. We have included these two stations to improve the spatial coverage over the lowlands of Northeast and Southeast Ethiopia.

Moreover, this same rainfall dataset is used to identify the dry and wet events of the Belg season, construct composites of Belg rainfall anomalies for NAO and MJO phases, and analyze two case studies for dry and wet Belg rainfall seasons. Daily areal average rainfall over Ethiopia for the 1980 to 2010 period is sorted in ascending order and ranked to identify days that fall into the lower tercile (dry Belg) and upper tercile (wet Belg) categories. We then constructed composites of anomalous circulation patterns for the dry and wet Belg events.

The National Centers for Environmental Prediction NCEP Reanalysis (Kalnay et al., 1996), referred to as Climate Data Assimilation System (CDAS) daily data is used to produce the lower, middle and upper-level circulation anomaly composites for the dry and wet Belg. Daily NAO index data (Barnston and Livezey, 1987), for the 1980 to 2010 period are downloaded from the Climate Prediction Center (CPC) ftp site (ftp://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.index.b500101.current.ascii). Positive and negative NAO events are defined as days that are within the upper (lower) quartile calculated from 1980 – 2010 daily NAO index data following the method used by Sapiano and Arkin (2006). Out of the 11323 days in this period, we have found 735 and 1151 Belg days that fall into negative and positive phases of NAO, respectively. Rainfall anomaly composites for negative and positive NAO phases are then constructed based on this categorization. To better illustrate the mechanisms associated with Belg rainfall variability, two cases of a wet Belg season in 2006 and a dry Belg season in 2015 are examined. For each of the cases, NAO was in its positive or negative phase for at least 20 days during the season.

To better understand influence of MJO and its interaction with NAO during the Belg rains, daily Real-time Multivariate MJO series 1 (RMM1), and 2 (RMM2) data (Wheeler and Hendon, 2004), for the 1980 – 2010 period are used in this study. The RMM index is used for MJO classification following the method used by the CPC online MJO information. The method (CPC, 2010) suggests the following: (1), the MJO index must have amplitude greater than one standard deviation for 5 consecutive pentads.; (2) the MJO index must include phases that are in numerical order (i.e. phases 2, 3, 4, 5, 6, 7, 8, 1).; (3) MJO events must last longer than five pentads (25 days) and cannot remain stationary in one phase for more than four pentads (20 days). Rainfall anomaly composites are constructed for each of the MJO phases.

Student's t test is applied to the composites of dry and wet Belg circulation anomalies, and NAO and MJO related rainfall anomaly composites to determine their statistical significance.

Note that computation of correlation coefficient and construction of NAO and MJO rainfall composites along with their significant tests were performed using the gauge rainfall data. Results of these gauge based analyses are then converted into gridded values with a graphics package that uses the Cressman objective analysis scheme described in Cressman (1959). We have assumed that distribution of rain gauge stations used in this study (Fig. 1) is reasonably good for the application of the Cressman analysis scheme to obtain the gridded field. The horizontal resolution of the interpolated rain gauge data is 0.45°x0.45° lat-lon. All available data are used to compute Pearson Product-Moment Correlation coefficient (r) between NAO indices and Belg standardized rainfall anomalies. The standardized rainfall anomaly is computed by dividing the areal dekadal (10-day) rainfall anomaly by its standard deviation.

3. Results

3.1. Regional circulation anomalies

Because of the geographical location of Ethiopia, the Belg seasonal rainfall is modulated by both tropical and subtropical circulation anomalies. The subtropical circulation anomalies are associated with eastward propagating midlatiude frontal systems across the Mediterranean region (Diro et al., 2011b). These eastward propagating systems are parts of a trough/ridge circulation pattern between the Northeast Atlantic and the Red Sea.

As documented by Knippertz (2007), mechanisms of tropical-extratropical interactions that trigger the formation of tropical plumes (TP) include, upper-level divergence ahead of a low-latitude upper-level trough, upper-level troughs or cut-off lows from the fields isentropic potential vorticity (PV) and poleward moisture flux due to deep mid-latitude troughs penetrating southward into the tropical moisture source. These features are also evident in our composite studies, and are discussed here.

3.1.1. Horizontal tropospheric moisture convergence

According to NMA (1996) and Diro et al. (2011b), the moisture source for the majority of areas affected by the Belg rains is considered to be the Arabian Sea and the North Indian Ocean. Their argument holds true for the Belg rainfall activity that occurs over the central and northeastern parts of the country. However, their study gives little or no explanation on the abundant moisture carried by the East African Monsoon flow from the Western Indian Ocean. As shown in Fig. 2(b) – 2(e), a significant amount of Belg rainfall occurs over eastern and southern Ethiopia. Like in the neighboring East Africa countries, rainfall over the lowlands of South and Southeast Ethiopia is modulated by a north–south shift of the Intertropical Convergence Zone (ITCZ). Accordingly, we argue that contribution of the East African monsoon flow to the Belg rainfall over southern and southeastern Ethiopia is significant. To better illustrate this, we describe patterns of the vertically integrated tropospheric moisture flux and its associated horizontal convergence (divergence), and we further examine the link between tropical-extratropical interactions and moisture flux.

The dry Belg composites (Fig. 3a – 3d) show a stretch of vertically integrated horizontal moisture divergence across Ethiopia extending into the Arabian Peninsula across the Red Sea. Magnitude of the divergence and its areal coverage seems to decrease towards the end of the Belg season (Fig. 3d). The horizontal moisture flux shows a northerly to northwesterly direction across Ethiopia into the Western Indian Ocean. The southward flux is strong in February and March (Fig. 3a - 3b), mostly limited to central northern Ethiopia in April, and becomes weak in May (Fig. 3d). In contrast, the wet Belg composites (Fig. 3e - 3h) exhibit an area of moisture convergence stretching between Ethiopia and the Arabian Peninsula across the Red Sea. The magnitude of moisture convergence and its areal coverage decreases towards the end of the Belg season (Fig. 3h). During wet Belg, the atmospheric flux has a poleward direction across the Western Indian Ocean, the Horn of Africa, the Red Sea and the neighboring areas of the Arabian Peninsula. The poleward flux is mostly limited to areas north of Central Ethiopia in April (Fig. 3g), and it weakens significantly in May (Fig. 3h). According to Trenberth and Stepaniak (2003) and Knippertz (2007), a deep mid-latitude circulation pattern that reaches far enough equatorward into the tropical moisture source can lead to considerable poleward moisture flux. The broad area of moisture convergence anomalies and the associated poleward moisture flux is an evidence of excess Belg rainfall in Ethiopia induced by tropical-extratropical interactions. In contrast, the broad area of moisture divergence anomaly and the associated northerly flow across much of Ethiopia during dry Belg can be associated with reduced tropical-extratropical interactions. Occasionally, the tropical component can also be weakened by the formation of tropical cyclones in the Southwest Indian Ocean. According to Shanko and Camberlin (1998), occurrence of tropical cyclones over the southwestern Indian Ocean could suppress the Belg rainfall, by diverting moisture away from the Greater Horn of Africa region.

3.1.2. 500-hPa geopotential height, temperature and wind

Earlier studies by Camberlin and Philippon (2002) and Diro et al. (2011b) have shown that excess Belg rainfall over Ethiopia is associated with a mid- to upper-level dipole structure, with a warm anticyclonic anomaly over the Central Mediterranean Sea region and a cold cyclonic anomaly over the Red Sea region. They have associated the cold cyclonic anomaly over the Red Sea region with the southward bend of the subtropical westerly jet. The upper-level cold air advection may increase atmospheric instability through an increased environmental lapse rate.

Here, we propose a tripole structure in the region between Northeast Atlantic and the Red Sea (Fig. 4). The tripole structure is evident in the form of anticyclone-cyclone-anticyclone (ACA) anomaly in the case of a dry Belg, and cyclone-anticyclone-cyclone (CAC) in the case of a wet Belg. The dry Belg composites indicate two warm centers of positive height anomalies; the first one located over the Northeast Atlantic Ocean and the second one located across parts of Northeast Africa extending into the Arabian Peninsula across the Red Sea (Fig. 4a – 4d). The warm positive height anomalies over Northeast Atlantic and near the Arabian Peninsula are associated with amplified Azores high and Arabian high, respectively. Hence, Belg rainfall deficits are associated with a broad area of anticyclonic anomalies across Northeast Africa, the Red Sea and the Arabian Peninsula due to reduced tropical-extratropical interactions. In contrast, the wet Belg CAC tripole structure exhibits two centers of cold negative height anomalies located over the Northeast Atlantic and the Arabian Peninsula and the neighboring areas of the Red Sea. Between these two cold negative height anomalies, there is a zone of warm positive height anomaly located over the central Mediterranean Sea and Southern Europe (Fig. 4e – 4h). The cold negative height anomalies over Northeast Atlantic and near the Arabian Peninsula area are associated with weakened Azores and Arabian Highs, respectively. Moreover, the presence of these two areas of cold cyclonic anomalies is indications of southward penetration of extratropical systems across Northeast Atlantic and the Red Sea regions. The cyclonic trough anomalies and their southward penetration across the Red Sea region in wet Belg composites are consistent with earlier studies by Camberlin and Philippon (2002). The cold cyclonic troughs and negative height anomalies during wet Belg provide further evidence of extratropical influence on Belg rainfall in Ethiopia. Both the dry and wet Belg composites indicate that the tripole structure become less evident in May (Fig. 4d and 4h).

3.1.3. Upper-level circulation anomalies

Upper-level extra-tropical circulation anomalies and their influence on the spring rainfall of the Greater Horn of Africa region was documented by Habtemichael and Pedgley (1974), NMA (1996), Camberlin and Philippon (2002) and Diro et al. (2011b).

Fig. 5 and 6 show dry and wet Belg composites of upper-level circulation anomalies. The ACA and CAC tripole structures are still evident, but appear weaker at upper-level. The upper-level anomalies are stronger and cover broader areas over the eastern component of the ACA and

CAC tripole patterns, near the Red Sea region. Moreover, the upper-level circulation patterns provide additional dynamical evidence associated with tropical-extratropical interactions in the region. The presence of anomalous isentropic potential vorticity and 200-hPa stream function and divergence patterns in the Red Sea region has significant contribution in modulating the Belg rainfall.

The dry Belg composites show an area of negative potential vorticity cut-off at 350-K isentropic level, and positive stream function and anticyclonic anomalies at 200-hPa level in the Red Sea and neighboring areas (Fig. 5a – 5d). This structure is not conducive of enhanced rainfall due to reduced tropical-extratropical interactions in the region. Another interesting result from the dry Belg upper-level composite analysis is the southwest-northeast oriented area of anomalous convergence extending between the Greater Horn of Africa and the Persian Gulf (Fig. 6a – 6d). This area of upper-level convergence anomaly is located southeast of the anticyclonic ridge, and covers much of Ethiopia. It is one ingredient of the mechanisms that lead to rainfall deficits during Belg season.

In the case of wet Belg, the upper-level composites show a complete reversal in the sign of the anomalies and circulation patterns (Fig. 5e – 5h). The 350-K isentropic level anomalies show an area of positive vorticity cut-off. The 200-hPa stream function anomalies are negative and the wind anomalies become cyclonic in the Red Sea and neighboring areas. Moreover, there is evidence of a southwest-northeast upper-level divergence anomaly in the Greater Horn of Africa extending to the Persian Gulf (Fig. 6e – 6h). The presence of upper-level cyclonic trough and an area of positive PV anomaly cut-off north of Ethiopia in addition to the presence of a southwest-northeast oriented upper-level divergence anomaly ahead of the upper-level trough, covering much of Ethiopia, is consistent with the theory of formation of tropical plume (TP), as documented by Knippertz (2007). The circulation pattern shown in the upper-level wet composites are also consistent with earlier studies by Camberlin and Philippon (2002) and Diro et al. (2011b). The negative stream function anomaly and the associated cyclonic circulation near the Red Sea region is an indication of a southward bend of extratropical systems during wet Belg events. The upper-level divergence ahead of the upper-level cyclonic trough, as described by Diro et al. (2011b), creates conducive conditions for enhanced rainfall over the underlying areas in Ethiopia.

3.2. Influence of the NAO

The North Atlantic Oscillation (NAO) is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia. It is a large-scale seesaw in atmospheric mass between the Azores High and the Icelandic Low. The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years (Liftland, 2003; Barnston and Livezey, 1987). According to Thompson and Wallace (2001), NAO affects the day-to-day climate variability, modulating the intensity of mid-latitude storms and the frequency of occurrence of high-latitude blocking and cold air outbreaks throughout the northern hemisphere.

3.2.1. Correlation and composite analyses

Diro et al. (2011b) have indicated the possible link between the negative (positive) phase of NAO and wet (dry) Belg. Our results are overall in agreement with their assessment that the Belg rainfall is negatively correlated with NAO, with statistically significant correlation values over parts of eastern and southern Ethiopia (Fig. 7a –7d). The NAO influence tends to be more prominent during the peak of the Belg rains in March and April, especially in southern Ethiopia, where correlation values are highest.

The relationship between Belg rains and the NAO is further illustrated in the rainfall anomaly composites displayed in Fig. 8a - 8h with evidence of suppressed rainfall during the positive phase of NAO over central and southern Ethiopia and rainfall surpluses during the negative phase of NAO. This signal seems to be stronger in March, over a broad area in central Ethiopia stretching from north to south. This analysis further suggests that the influence of NAO on Belg rains: (1) is more pronounced during the negative phase than during the positive phase, and (2) is more significant during the month of March.

Both the correlation and composite analyses suggest the influence of NAO on Belg subseasonal variability. The link between phases of the NAO and Belg rainfall variability can be explained in terms of Mediterranean storm track. North Atlantic storm tracks reaching the Mediterranean are noticeably greater during the negative phase of the NAO (Nasr-Esfahany, 2011). According to Diro et al. (2011b), a southward deflection of the Mediterranean storms and their propagation across the Mediterranean and the Middle East areas during the NAO negative phase act to displace the Arabian High to the south over the Arabian Sea and northwestern Indian Ocean. The shift of this high pressure system leads to increased moisture advection into the Horn of Africa from the western Indian Ocean. In contrast, the positive phase of the North Atlantic Oscillation (NAO) is associated with a northeastward shift in the Atlantic storm track with enhanced activity into northern Europe and reduced activity over southern Europe and the Mediterranean region (Nasr-Esfahany, 2011). Results of our study further suggest that augmented Belg rains tend to be a response of an enhanced tropical-extratropical interaction between the North Atlantic Ocean and the Indian Ocean (Fig. 3 and 4, for example). This interaction is reduced during the positive phase of NAO due to a northward shift of the Mediterranean storm tracks that contribute to suppressed Belg rainfall.

3.2.2. Interaction between the NAO and regional circulation patterns

Results, discussed in section 3.1, are in agreement with earlier studies of Diro et al. (2011b). The tripole structure discussed in section 3.1.2 based on Figure 4, demonstrates quite well the connection between phases of NAO and regional circulation anomalies during the Belg season. In ACA tripole pattern (Fig. 4a – 4d), the anticyclonic ridge anomaly over Northeast Atlantic is linked with anticyclonic ridge anomaly in the Red Sea region via the tripole structure. As described by Diro et al. (2011b), the positive phase of NAO induces an anticyclonic anomaly over the Northeast Atlantic, which in turn is linked to the anticyclonic anomaly in the Red Sea to form a tripole pattern. Hence, the NAO positive phase acts to reduce Belg rainfall due to weakened tropical-extratropical interactions.

The connection between NAO negative phase and regional circulation patterns is reversed in the case of wet Belg. In CAC tripole pattern (Fig. 4e – 4h), the cyclonic trough anomaly over Northeast Atlantic is linked to the cyclonic trough anomaly in the Red Sea region via the tripole structure. As described by Diro et al. (2011b), the negative phase of NAO induces a cyclonic anomaly over the Northeast Atlantic, which in turn is linked to the cyclonic anomaly in the Red Sea to form a tripole pattern. Hence, the NAO negative phase acts to enhance Belg rainfall due to increased tropical-extratropical interactions.

It is important however to note that, the NAO and the regional circulation patterns belong to different scales of motion, and therefore may not always be in synchronic mode. North Atlantic storm tracks and the Mediterranean storm tracks are noticeably greater during the negative phase of NAO (Nasr-Esfahany, 2011). In the absence of active NAO, the regional circulation patterns are the dominant features that modulate the Belg rainfall patterns.

3.3. Influence of the Madden Julian Oscillation (MJO)

As discussed in sections 3.1 and 3.2, interactions between extra-tropical and tropical systems play a major role in modulating the Belg seasonal rainfall. In this section we discuss the influence of the MJO on the subseasonal variability of the Belg rainfall, by way of affecting the tropical component of the interaction.

The MJO is the principal mode of tropical climate variability on the intraseasonal timescale, affecting weather events in many areas in the global tropics and the mid-latitudes. The MJO is quasi-oscillatory, but known to have a period of around 30 to 60 days (Zhang, 2005).

Composites of daily rainfall anomalies constructed in this work show a significant relationship between phases of the MJO and Belg rainfall anomalies (Fig. 9). The Belg rains tend to be above-average over parts of Northeast and Southern Ethiopia, when the MJO is active during phases 7, 8, 1 and 2 according to the Wheeler-Hendon diagram (Fig. 9a – 9d). In contrast, the MJO seems to have an opposite impact when it is active during phases 4 to 6, with below-average rainfall prevailing over portions of eastern and southern Ethiopia (Fig. 9e - 9h). The construction of another set of MJO related rainfall composites for NAO-neutral and NAO-weak events was performed by removing days with NAO active events from the original composites. The new rainfall anomaly composites are displayed in Fig. 9i – 9p and show that the general pattern remains somewhat similar to the original composites, depicting scattered areas of enhanced rainfall during phases 7, 8, 1 and 2, and suppressed rainfall during phases-3, 4, 5 and 6. In the case of NAO-neutral and NAO-weak composites, areas of enhanced rainfall become very isolated during phases 7, 1 and 2. Particularly, removal of NAO active events from the original MJO composites didn't bring about significant changes in the MJO composites during phase-2, suggesting that MJO events during phase-2 dominate over NAO active phases in modulating rainfall over parts of southern and northeastern Ethiopia (Fig. 9d and 9l). No major differences are also noted during phases 4, 5 and 6 (Fig. 9n – 9p). Particularly, during phase-5, the MJO events seem to dominate over NAO in modulating the Belg rainfall over central and eastern Ethiopia (Fig. 9g and 9o).

Because of the complex topography of the region, we have chosen the 700-hPa level to show MJO composites of the lower-level wind anomalies (Fig. 10). Due to space limitation and to avoid redundancy, we have only included circulation anomalies of phases-2 (wet Belg) and phase-5 (dry Belg. During phase-2, northerly wind anomalies over Sudan turn into westerlies, inducing a cyclonic shear across Ethiopia. This westerly anomaly and its associated cyclonic shear contribute to the enhanced rainfall observed over Ethiopia during MJO phase-2 (Fig. 10a – 10c). In contrast, dry northeasterly anomaly prevails across Ethiopia and the neighboring areas and contributes to the observed drier than-average Belg rainfall during MJO phase-5 (Fig. 10b – 10d). The presence or absence of active NAO has little or no effect on the lower-level flow pattern in both phases (see figures 10a and 10b vs 10c and 10d).

3.4. Case Studies

3.4.1. Wet Belg Season in 2006

Much of the Belg areas in the eastern and southern half of Ethiopia received above-average rainfall during March 21 – April 10, 2006 (Fig. 11a and 12d). The northward stretch of the above-average rainfall across Ethiopia signals the influence of tropical-extratropical interactions. Consistent with our discussion in sections 3.1 and 3.2, the wetter than average rainfall observed during March and April 2006 can be attributed to a NAO negative phase and a CAC tripole mode (Fig. 11a, and Fig. 12a – 12d). The NAO index was negative from the second dekad of March through the first week of April, while the areal average rainfall was above-average during this same period. The NAO negative event may have contributed to the observed above-average rainfall via the CAC pattern (Fig. 12a – 12b).

The 500-hPa circulation anomaly (Fig. 12a) exhibits a CAC pattern, which is consistent with the wet Belg composites. The upper-level circulation anomalies are also consistent with the wet Belg composites, exhibiting an area of positive PV anomaly cut-off located in upper-level cyclonic trough north of Ethiopia (Fig.12b). Figure 12c shows an area of atmospheric moisture convergence across much of the Belg areas, extending into the Red Sea region. The associated moisture flux is generally southerly across East Africa including Ethiopia. The atmospheric moisture convergence also exhibited a south-north extent, but mostly limited to the eastern half of Ethiopia that include our case study area (Fig. 12d).

The MJO event that remained more or less active in January and February 2006, significantly weakened in the beginning of March 2006 and remained weak through early April 2006. Therefore, there was little or no influence of the MJO on the Belg rainfall anomaly observed during March 21 – April 10, 2006.

3.4.2. Dry Belg Season in 2015

The below-average rainfall observed during Belg 2015 and which preceded the El Nino related rainfall deficits in the June to September season led to a historical drought condition that caused displacements and a large number of people, livestock loss over northeastern and eastern Ethiopia (USAIDa, 2016). According to the time series plot (Fig. 11b), NAO indices were positive from around mid-February to about mid-April, while the areal average rainfall anomaly was negative. In general, periods of elevated NAO corresponds to higher rainfall deficits towards the end of February through mid-March, and also towards the end of March through the first dekad of April 2015. The above suggests that the positive phase of NAO contributed to the observed rainfall deficits in Belg 2015.

The anomalous low, mid and upper-level circulation patterns during April 2015 are also consistent with dry Belg composites. At 500-hPa, the ACA triple pattern was evident (Fig. 13a). Reduced tropical-extratropical interactions near the Red Sea and the neighboring areas may have contributed to observed rainfall deficits during the season. The upper-level circulation anomalies are also consistent with the dry Belg composites (Fig. 13b). In contrast with the wet Belg case, an area of negative PV anomaly cut-off, within an upper-level anticyclonic ridge is located north of Ethiopia. Contrary to the case of wet the Belg, the direction of the moisture flux was mostly northerly across the Red Sea region and much of Ethiopia. Moreover, an area of moisture divergence prevailed across central and northern Ethiopia (Fig. 13c). The absence of a poleward moisture flux, mid-level anticyclonic anomalies and upper-level negative PV anomalies are indications of reduced tropical-extratropical interactions and suppressed rainfall during April 2015 (Fig. 13d).

The strong MJO event observed in the last two dekads of March 2015, dramatically weakened in the first dekad of April 2015 and remained weak through end of the month. Therefore, there was little or no influence of the MJO on the Belg rainfall anomaly observed during April 2015.

4. Summary

The Belg rainfall contributes significantly to economic activities in Ethiopia, but is also characterized by high temporal and spatial variability. This study identified synoptic and subseasonal features that lead to rainfall deficits and surpluses during Ethiopian Belg season. In particular, the theory of tropical plume formation (Knippertz, 2007) seems to hold true for Belg as tropical-extratropical interactions play a major role in modulating rainfall during this time of the year. This paper also complements earlier studies on seasonal variability of Ethiopian rainfall by (Habtemichael and Pedgley, 1974; Camberlin and Philippon, 2002, Diro et al., 2011b; Berhane and Zaitchik, 2014).

A tripole structure in a trough/ridge pattern in the region between the Northeast Atlantic Ocean and Red Sea regions is a dominant feature that is associated with Belg rainfall variability in Ethiopia. We have identified two modes of this tripole structure. In general, rainfall deficits (surpluses) in the Belg season are associated with the anticyclone-cyclone-anticyclone (cyclone-anticyclone-cyclone) modes. The ingredients summarized below contribute to rainfall deficits over Ethiopia during the Belg season due to reduced tropical-extratropical interactions: (1) the presence of an anomalous mid- to upper-level warm anticyclone over the Red Sea; (2) the absence of a poleward moisture flux and moisture convergence across the Horn of Africa; (3) the limitation of the southward extension of the mid-to-upper-level extratropical cyclonic trough; (4) upper-level negative PV anomaly north of Ethiopia; and (5) the prevalence of upper-level convergence across the Horn of Africa. Moreover, the presence of an anticyclonic anomaly across the Red Sea region and the neighboring areas of the Arabian Peninsula keeps the ITCZ south of its normal position during dry Belg events.

In contrast, factors that contribute to the enhancement of tropical-extratropical interactions and moisture surpluses during the Belg season include: (1) the presence of anomalous mid-to upper-level cold cyclonic trough over the Red Sea; (2) the presence of a northward moisture flux that extends deep into the Horn of Africa and the prevalence of horizontal moisture convergence over Ethiopia; (3) a southward penetration of mid- to upper-level extratropical cyclonic trough in the Red Sea region; (4) the presence of an area of anomalous upper-level positive PV anomaly cut-off north of Ethiopia; and (5) an elongated area of anomalous upper-level divergence across the Horn of Africa.

Both correlation and composite analyses suggest a possible link between phases of the NAO and rainfall surpluses or deficits during the Belg season. Belg rainfall tends to be below (above) average over many parts of Eastern and southern Ethiopia during the positive (negative) phase of NAO events. The influence of the NAO event is translated into the Greater Horn of Africa region through the Mediterranean storm tracks and the associated trough/ridge circulation pattern between the Northeast Atlantic and Red Sea.

The tripole pattern also plays a role in connecting NAO with circulation anomalies in the Red Sea region such that NAO induces an amplified (suppressed) Azores High in Northeast Atlantic (Diro et al., 2011b) resulting in enhanced (weakened) Arabian High via the tripole modes. However, the regional circulation patterns and NAO belong to different scales of motion, and may not always interact with each other constructively. Another mode of variability that may act to strengthen tropical-extratropical interactions is the MJO. A significant relationship between the phases of MJO and Belg rainfall anomalies has been documented in this paper. The Belg rainfall tends to be above-average over parts of Northeast and Southern Ethiopia during phases 7, 1, and 2 of the MJO and vice versa during phases 4 to 6 according to the Wheeler and Hendon diagram. Interactions between MJO and NAO may be complex and beyond the scope of this study. However, there is some evidence of interactions between phases of the MJO and NAO in modulating rainfall over Ethiopia. In particular, the presence (absence) of active NAO may increase (decrease) the magnitude and areal coverage of MJO related rainfall anomalies, especially during phases 7, 1, 4, and 6.

NAO and MJO each contribute to subseasonal rainfall variability during Belg. In the absence of active NAO and MJO, the tripole structure becomes the dominant feature that leads to subseasonal rainfall variability in the Belg season. Occasionally, two or three of these features are in phase to cause drier or wetter Belg events. For example, the presence of NAO negative phase and CAC tripole mode during active MJO ~~i~~n phase-2 can lead to wetter Belg. In contrast, the presence of NAO positive phase and ACA tripole pattern during active MJO in phase-5 tend to suppress rainfall during Belg season.

The National Meteorological Agency of Ethiopia (NMA) issues 10-day (dekadal) rainfall outlooks for decision support services in agriculture, hydropower energy, and health. The tools documented in this study can add value to subseasonal forecasting and improved climate services in Ethiopia.

Acknowledgements

The authors would like to thank the two anonymous reviewers for their insightful comments and suggestions. We would also like to extend our thanks to the National Meteorological Agency of Ethiopia for providing some of the data used in this study.

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Figure Captions

Figure 1. Locations of the 117 rainfall stations in Ethiopia used throughout this study (black circle marks).

Figure 2. (a) 1981 - 2010 annual rainfall climatology (mm), based on station rainfall data. (b) Percentage of 1981-2010 mean total annual rainfall contributed by the Feb to May season (%). (c) 1981-2010 February rainfall climatology (mm). (d), (e), and (f): same as (c) except for March, April, and May, respectively.

Figure 3. (a) – (d), Composites of daily average surface to 200-hPa vertically integrated moisture convergence anomalies: shaded negative is moisture convergence and positive is moisture divergence (unit: 10^{-3} g kg^{-1} s^{-1}); vector is moisture flux (g kg^{-1} m s^{-1}), for dry events, significant at the 95% confidence level (student's t-test). (e) – (h): same as (a) – (d) except for wet events.

Figure 4. (a) – (b) Composites of daily average 500-hPa circulation anomalies for dry events: shaded temperature anomalies (k); contours are geopotential height anomalies (gpm) and vectors are wind anomalies (m s^{-1}), significant at the 95% confidence level (student's t-test). (e) – (h), Same as (a) – (d) except for wet events.

Figure 5. (a) – (b) Composites of daily average upper-level circulation anomalies for dry events: shaded potential vorticity anomalies (unit:10^{-06} K m^2 kg^{-1} s^{-1}) at 350-K isentropic surface, contours of stream function (unit:10^{06} m^2s^{-1}) and vectors of wind anomalies (m s-1) at 200-hPa level, significant at the 95% confidence level (student's t-test). (e) – (h), Same as (a) – (d) except for wet events.

Figure 6. (a) – (b) Composites of daily average 200-hPa circulation anomalies for dry events; shaded divergence (unit:10^{-06} s^{-1}) and vectors of wind anomalies (m s^{-1}), significant at the 95% confidence level (student's t-test). (e) – (h), Same as (a) – (d) except for wet events.

Figure 7. Correlation coefficient between dekadal (10day) average NAO index and dekadal average standardized rainfall anomaly with respect to 1980 – 2010 period. The square patterns show statistically significant values ($p<0.1$).

Figure 8. (a) – (d), Composites of daily average rainfall anomaly (mm day-1) for NAO positive events, significant at the 95% confidence level (student's t-test). (e) - (h), Same as (a) – (d) except for NAO negative events.

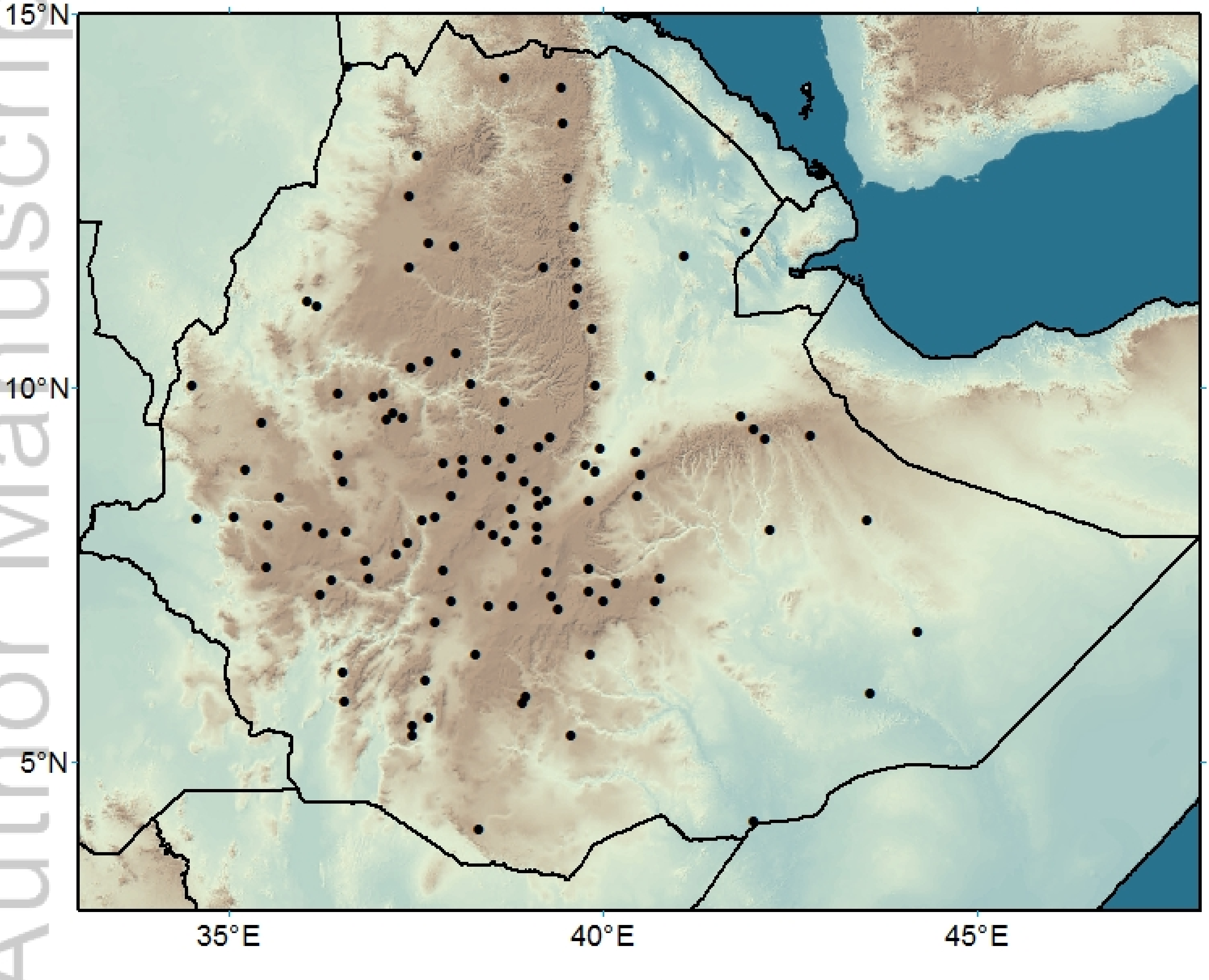
Figure 9. (a) – (h) MJO composites of daily rainfall anomalies (mm) for February to May season, with active NAO events. Active NAO events are defined as days that are within the upper (lower) quartile calculated from 1980 – 2010 daily NAO index, significant at the 95% confidence level (student's t-test). (i) – (p) Same as (a) – (h), except for NAO-neutral and NAO-weak events (days with active NAO events are removed from the composites).

Figure 10. (a) MJO pahse-2 composites of daily 700-hPa vector wind anomalies (ms^{-1}) for February to May season, with active NAO events, significant at the 95% confidence level (student's t-test). (b) Same as (a), except for NAO-weak events. (c) Same as (a), except for MJO phase-5. (d) Same as (b), except for MJO phase-5.

Figure 11. Top panel, time series of 7-day running mean NAO Index (blue) and 7-day running mean of the areal average rainfall anomaly (mm day-1) for February to April 2006 season (red). Areal average rainfall is computed for a box over eastern Ethiopia (39^{o}E to 43^{o}E & 8^{o}N to 13^{o}N). Bottom panel, same as in top panel, except for February to April 2015 season.

Figure 12. Circulation and rainfall anomalies for wetter than normal Belg period (March 11 – April 10, 2006). (a) Daily average 500-hPa circulation anomaly: shaded are temperature anomalies (k); vectors are wind anomalies (m s^{-1}). (b) Daily average upper-level circulation anomaly: shaded is the potential vorticity anomaly field (unit:10^{-06}K m^{2} kg^{-1} s^{-1}) at 350-K isentropic surface overlaid with 200-hPa wind anomaly in vector (m s^{-1}). (c) Moisture flux vector (g kg^{-1} m s^{-1}) overlaid with daily average surface to 200-hPa vertically integrated horizontal moisture convergence anomalies: Shaded in green is moisture convergence and in brown is moisture divergence (unit: 10^{-3} g kg^{-1} s^{-1})). (d) Rainfall anomaly (mm) during March 11 – April 10, 2006.

Figure 13. Same as Figure 12, except for the dry Belg period 1-30 April 2015.



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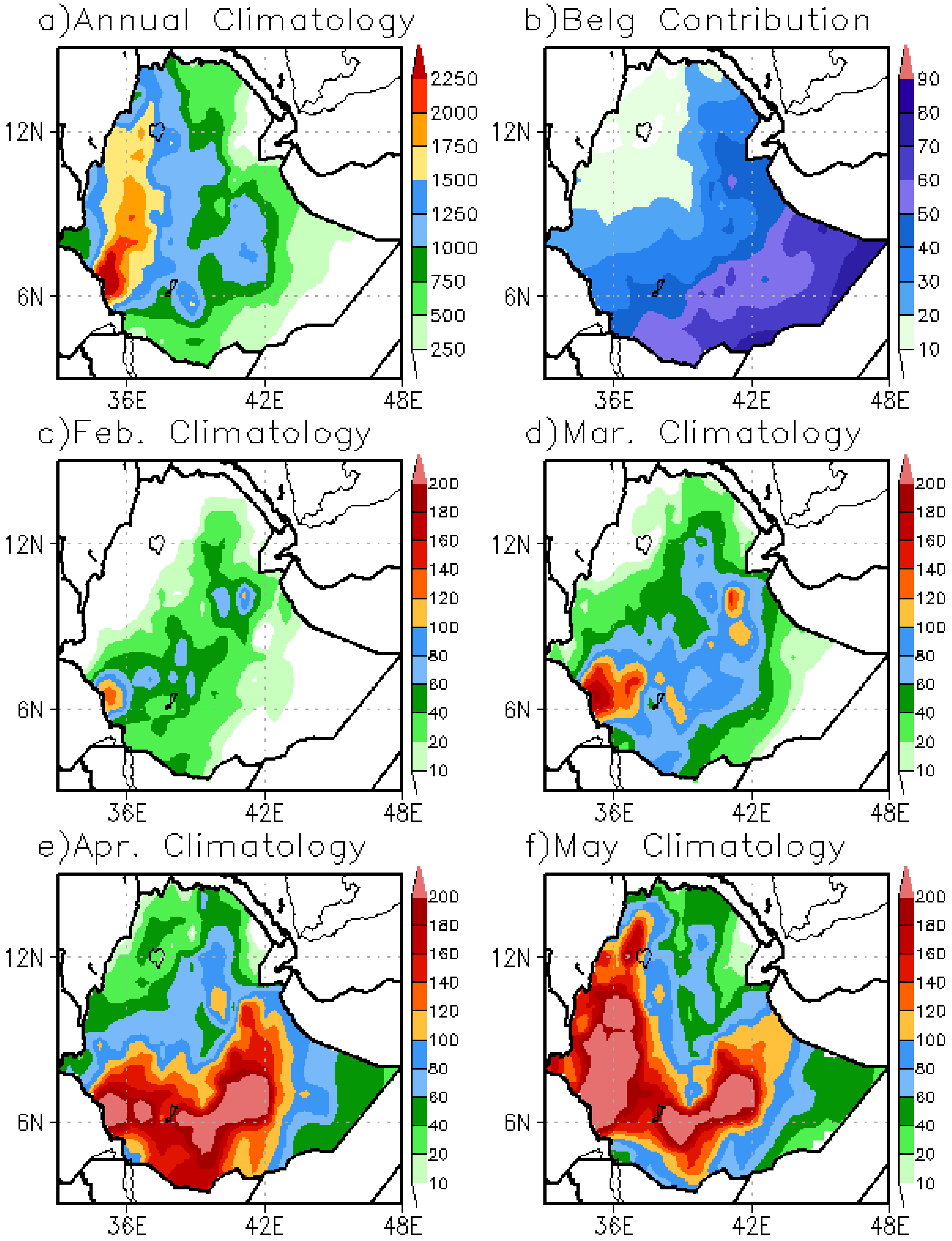
a)Annual Climatology
b)Belg Contribution
c)Feb. Climatology
d)Mar. Climatology
e)Apr. Climatology
f)May Climatology
12N
6N
36E
42E
48E
2250
2000
1750
1500
1250
1000
750
500
250
90
80
70
60
50
40
30
20
10
200
180
160
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120
100
80
60
40
20
10

figure_2.tif

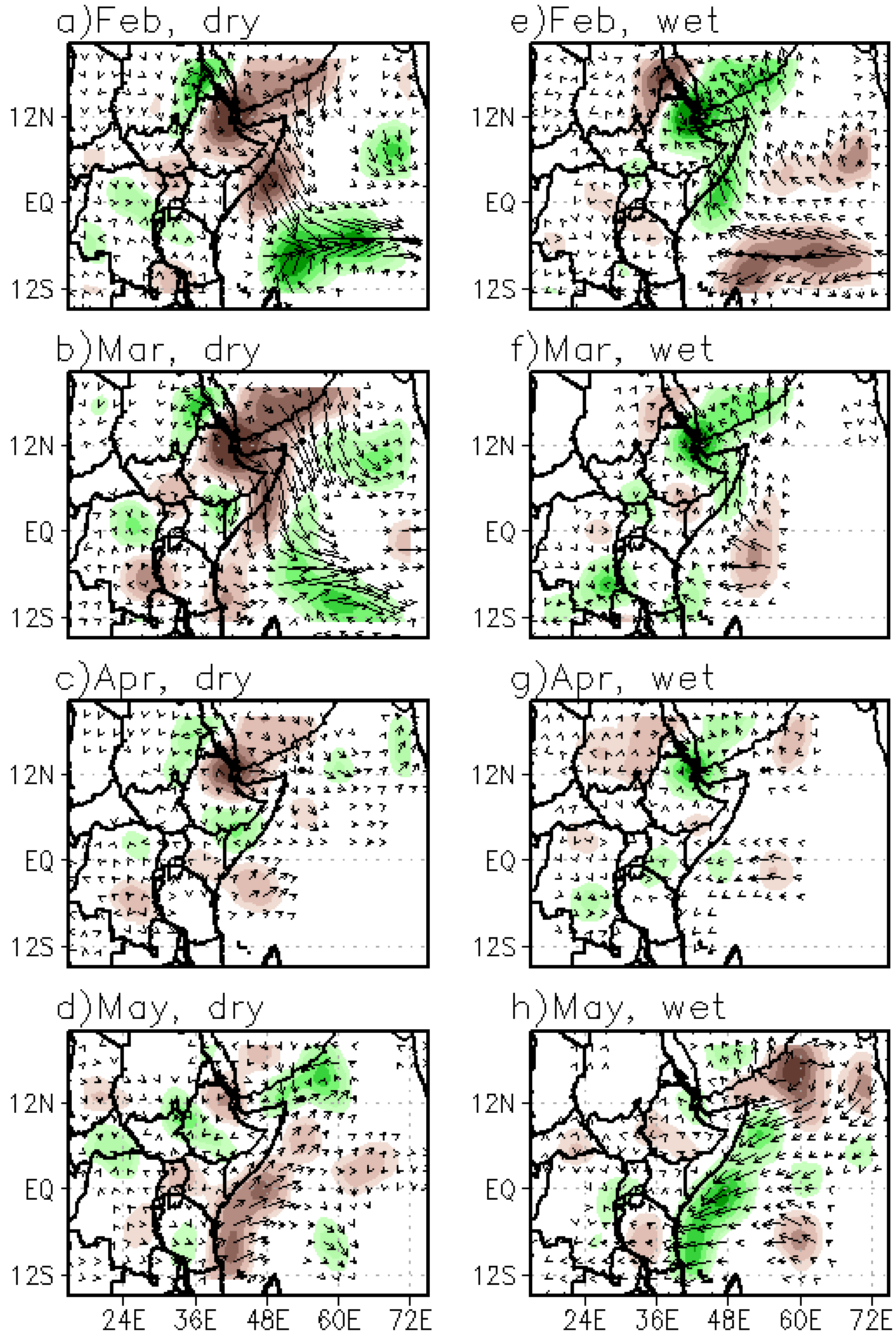

a)Feb, dry
e)Feb, wet
b)Mar, dry
f)Mar, wet
c)Apr, dry
g)Apr, wet
d)May, dry
h)May, wet
12N
EQ
12S
24E
36E
48E
60E
72E
30000
−16
−12
−8
−4
−2
2
4
8
12
16

figure_3.tif

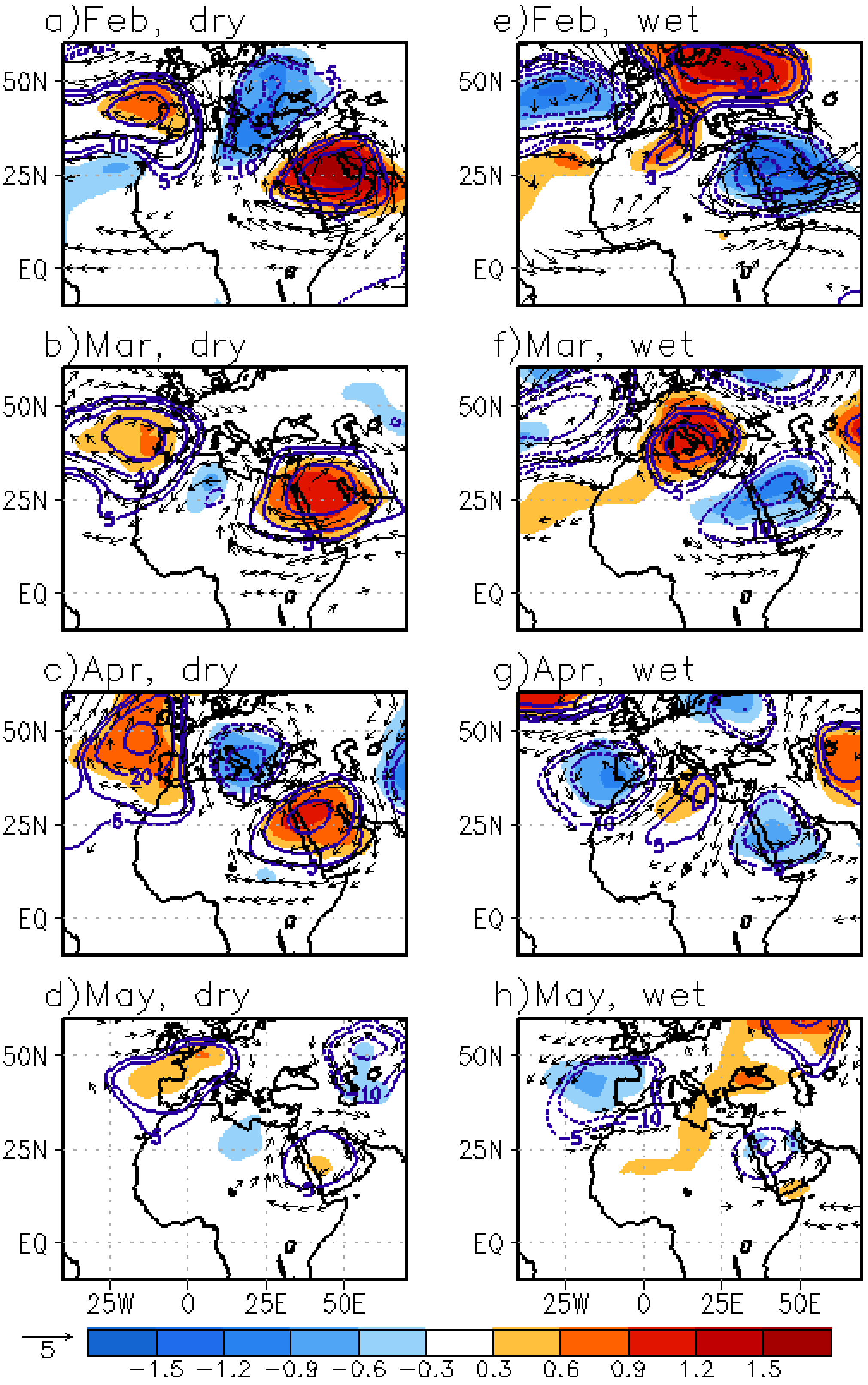
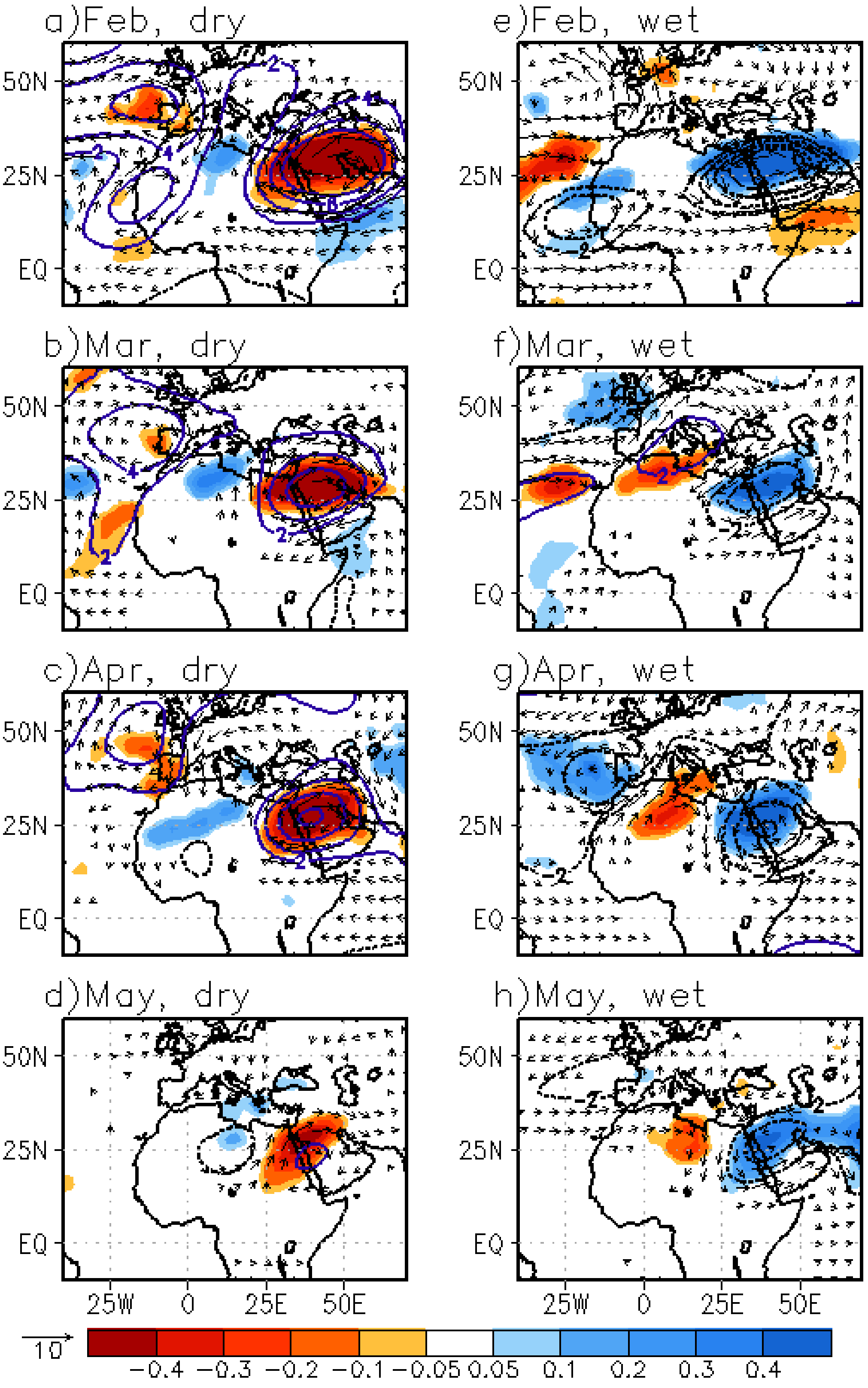

a)Feb, dry
b)Mar, dry
c)Apr, dry
d)May, dry
e)Feb, wet
f)Mar, wet
g)Apr, wet
h)May, wet
50N
25N
EQ
25W
0
25E
50E
5
-1.5
-1.2
-0.9
-0.6
-0.3
0.3
0.6
0.9
1.2
1.5

figure_4.tif


a)Feb, dry
e)Feb, wet
b)Mar, dry
f)Mar, wet
c)Apr, dry
g)Apr, wet
d)May, dry
h)May, wet
50N
25N
EQ
25W
0
25E
50E
10
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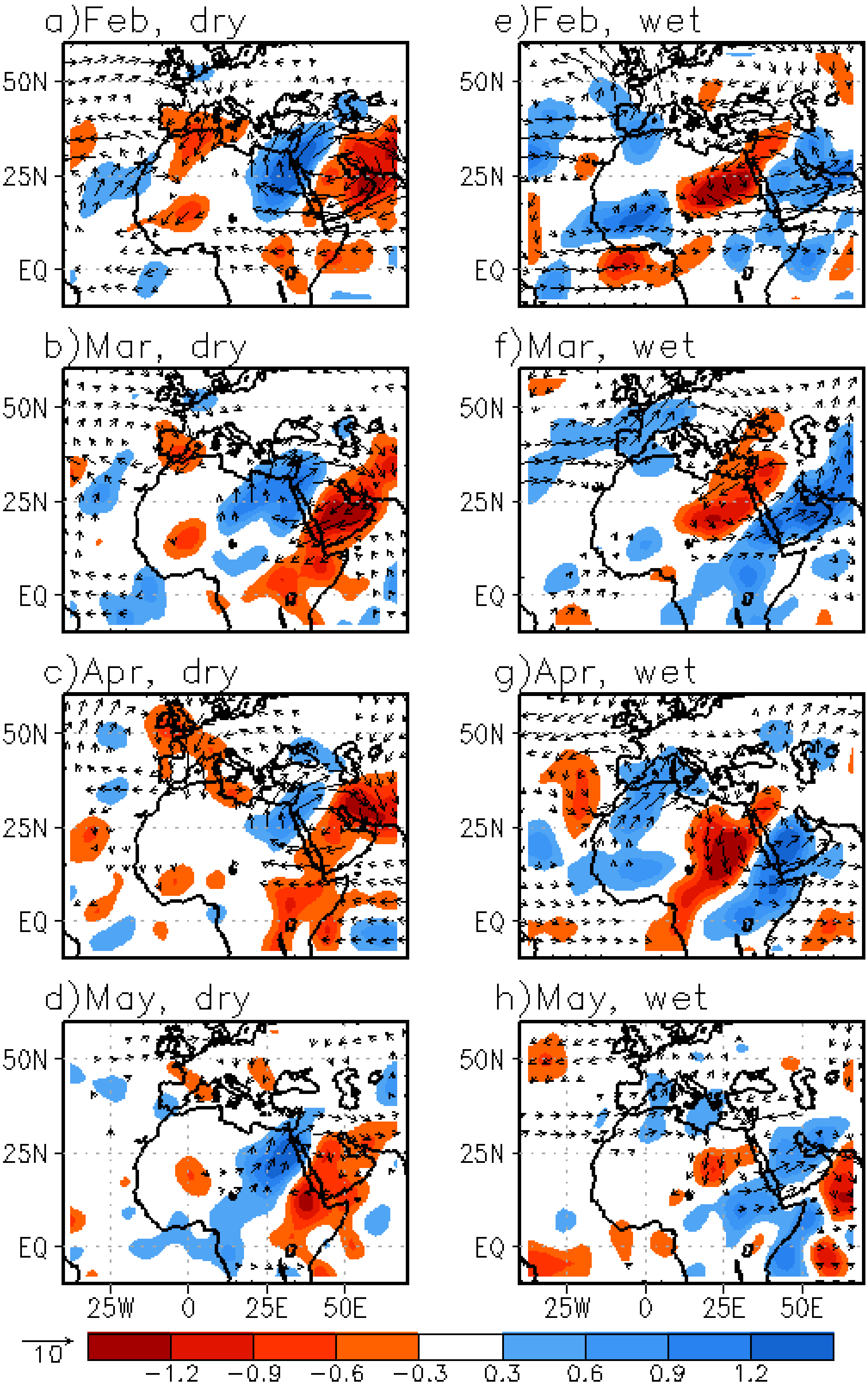
−0.2
−0.1
−0.05
0.05
0.1
0.2
0.3
0.4

figure_5.tif


a)Feb, dry
e)Feb, wet
b)Mar, dry
f)Mar, wet
c)Apr, dry
g)Apr, wet
d)May, dry
h)May, wet
50N
25N
EQ
25W
0
25E
50E
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−0.6
−0.3
0.3
0.6
0.9
1.2

figure_6.tif

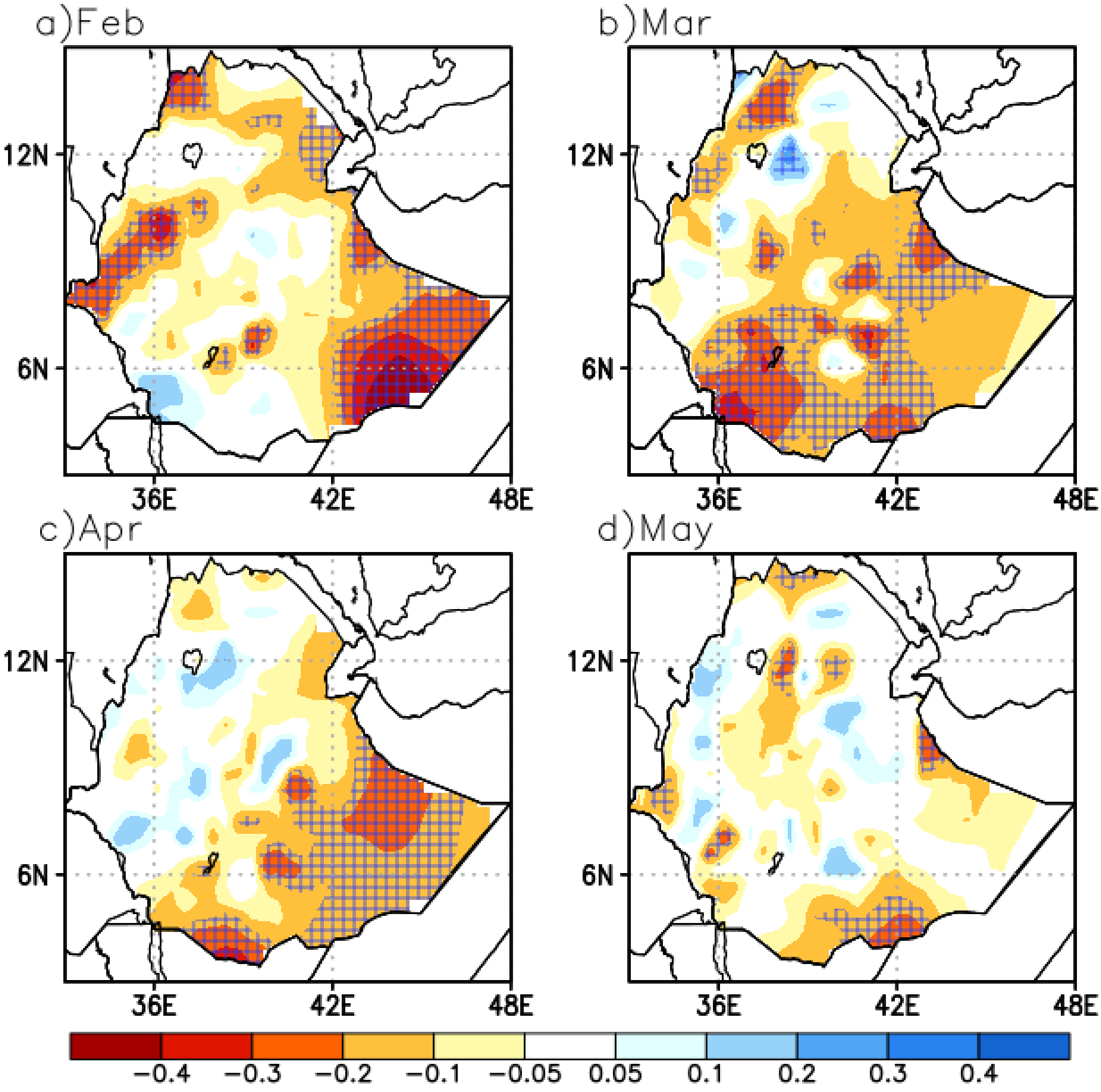

a)Feb
b)Mar
c)Apr
d)May
12N
6N
36E
42E
48E
−0.4
−0.3
−0.2
−0.1
−0.05
0.05
0.1
0.2
0.3
0.4

figure_7.tif

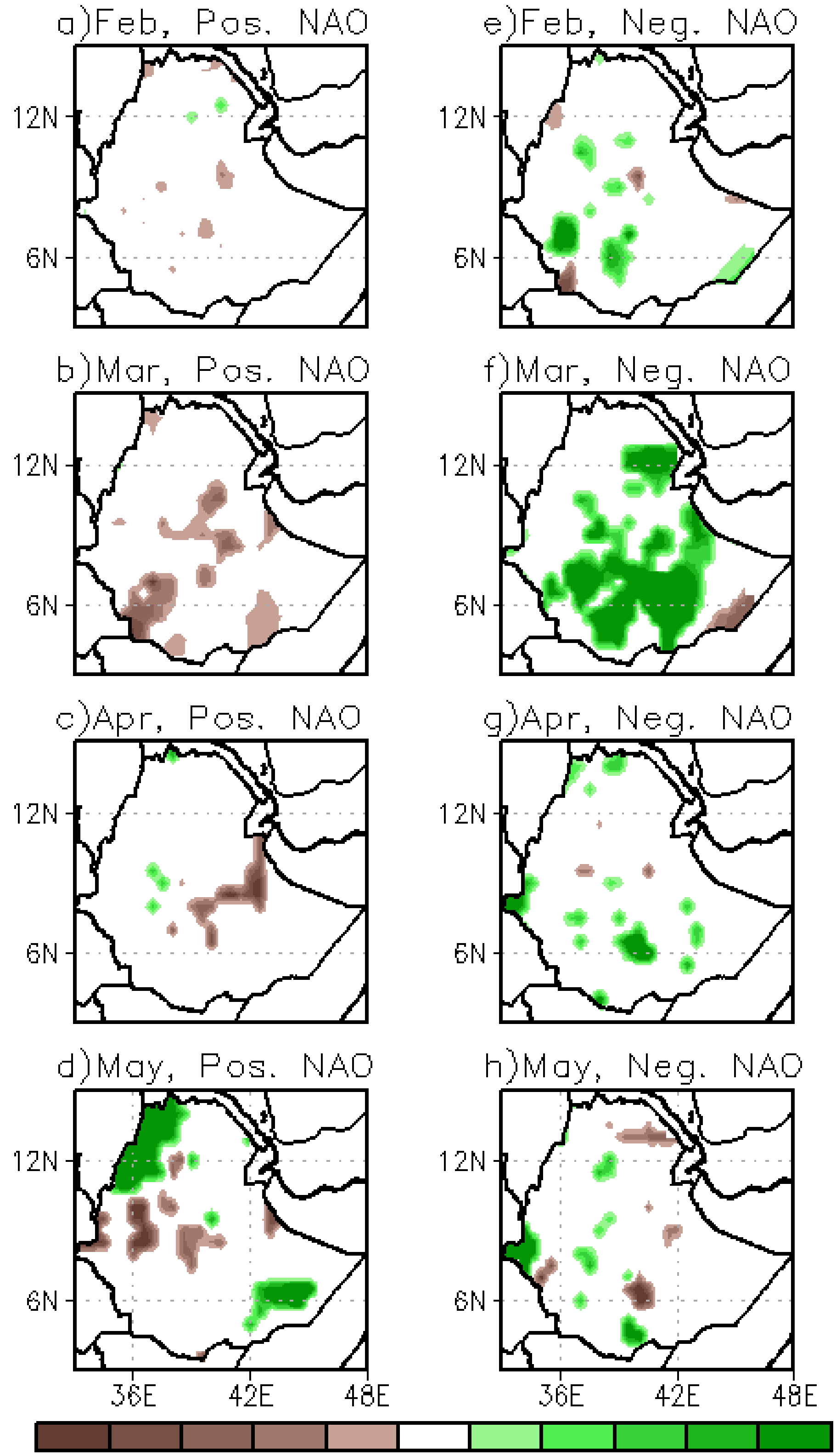

a)Feb, Pos. NAO
b)Mar, Pos. NAO
c)Apr, Pos. NAO
d)May, Pos. NAO
e)Feb, Neg. NAO
f)Mar, Neg. NAO
g)Apr, Neg. NAO
h)May, Neg. NAO
12N
6N
36E
42E
48E
−1.25
−1
−0.75
−0.5
−0.25
0.25
0.5
0.75
1
1.25

figure_8.tif

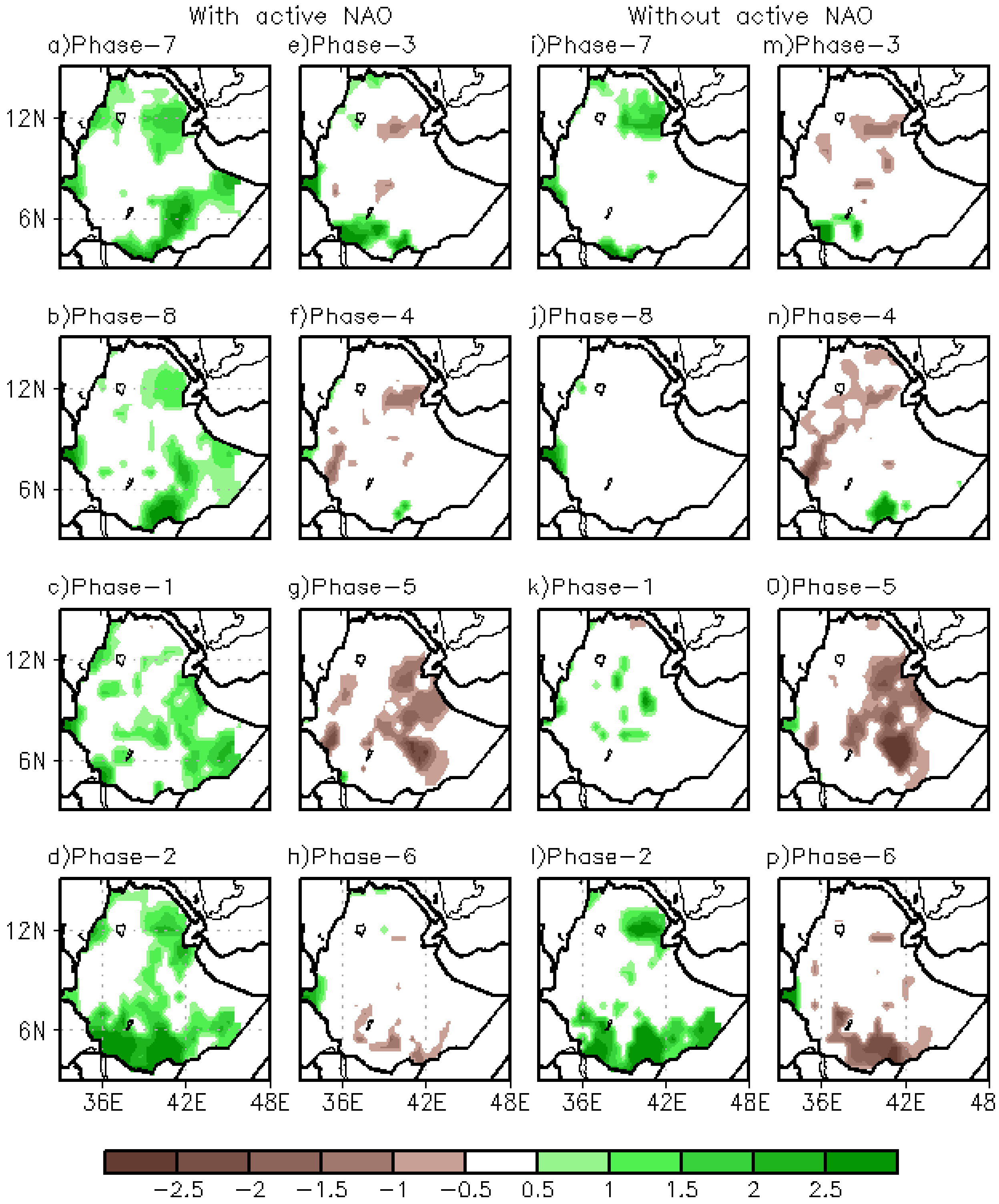

With active NAO
Without active NAO
a)Phase−7
e)Phase−3
i)Phase−7
m)Phase−3
b)Phase−8
f)Phase−4
j)Phase−8
n)Phase−4
c)Phase−1
g)Phase−5
k)Phase−1
0)Phase−5
d)Phase−2
h)Phase−6
l)Phase−2
p)Phase−6
12N
6N
36E
42E
48E
48
−2.5
−2
−1.5
−1
−0.5
0.5
1
1.5
2
2.5

figure_9.tif

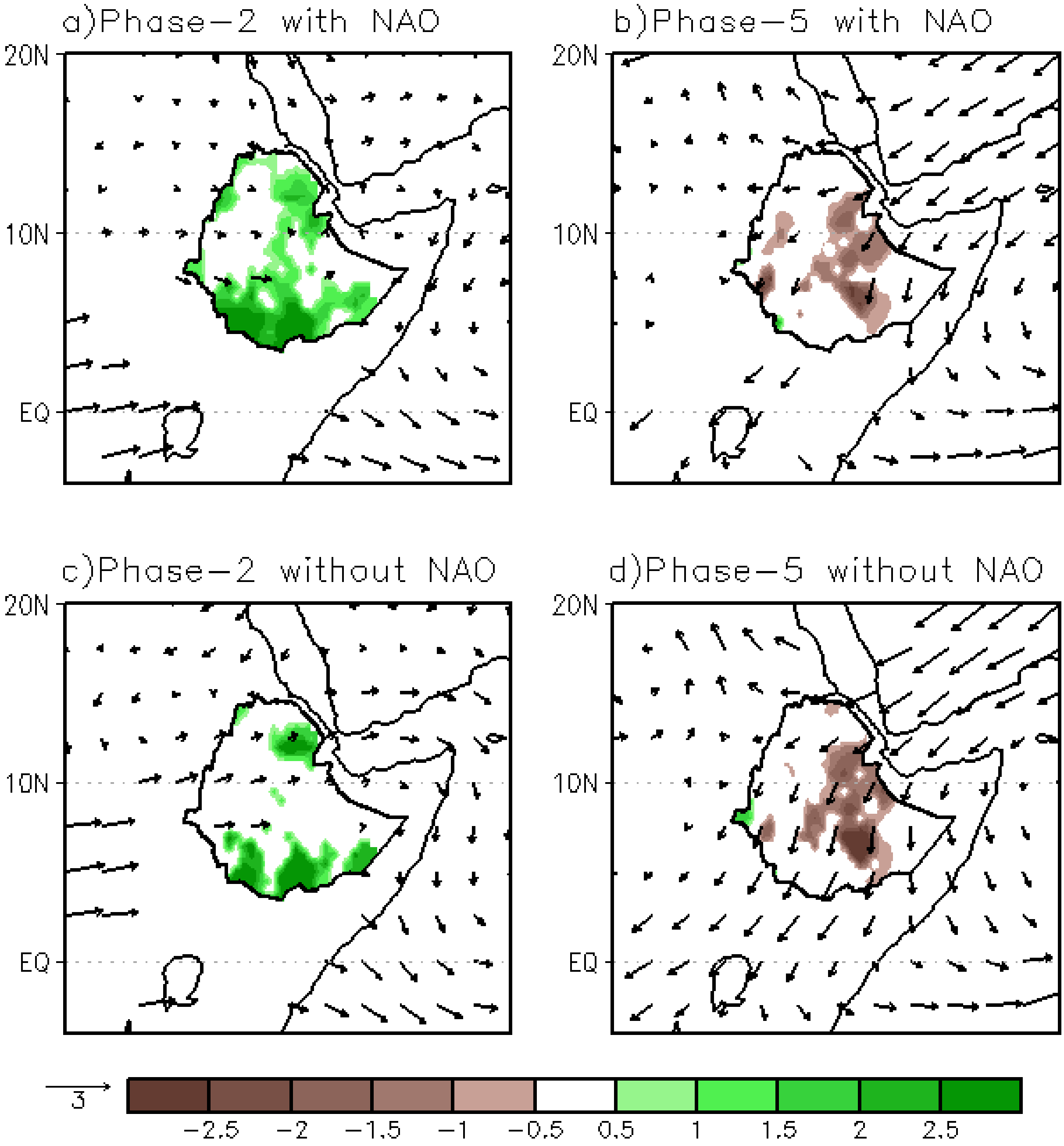
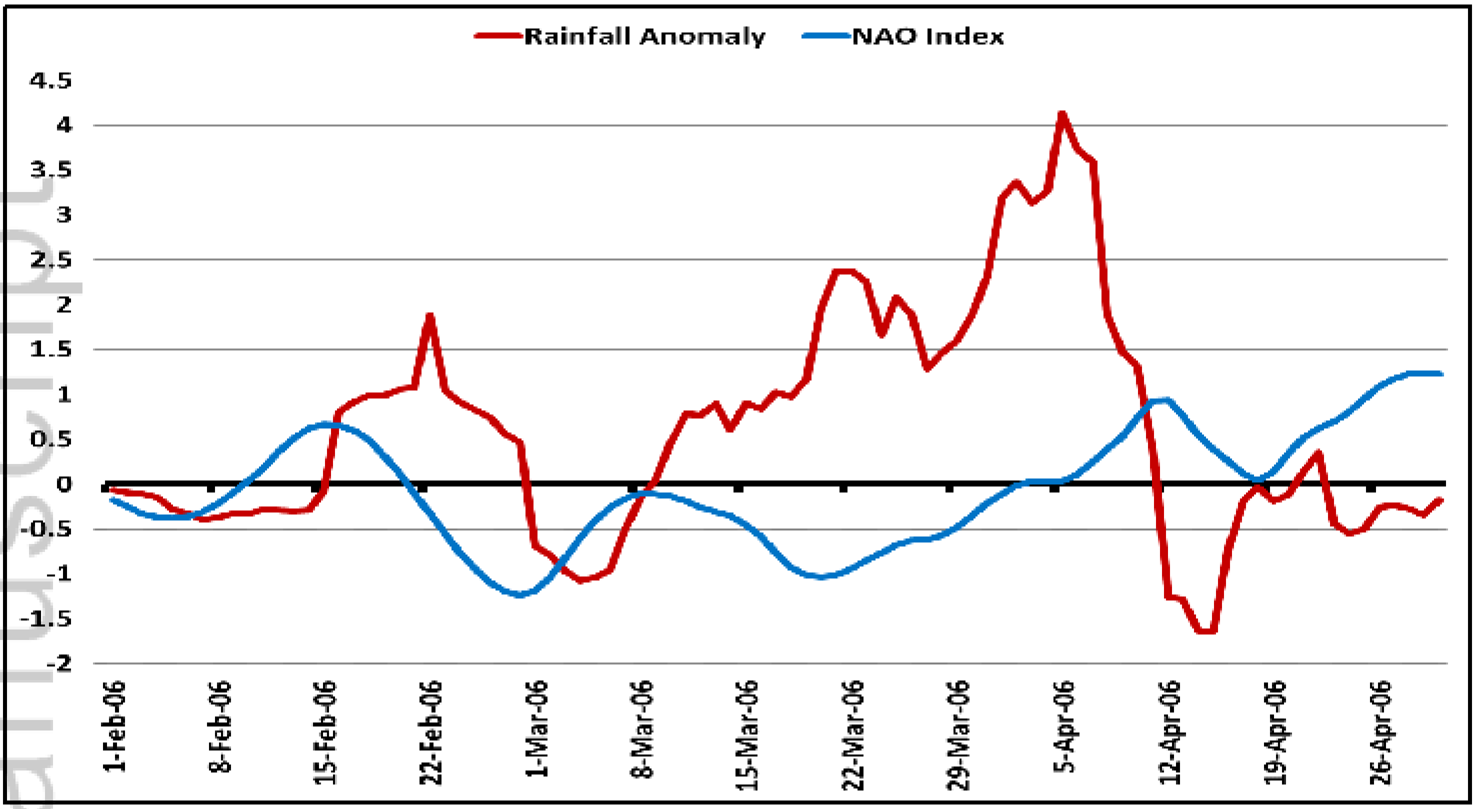


figure_10.tif

a)2006



b)2015

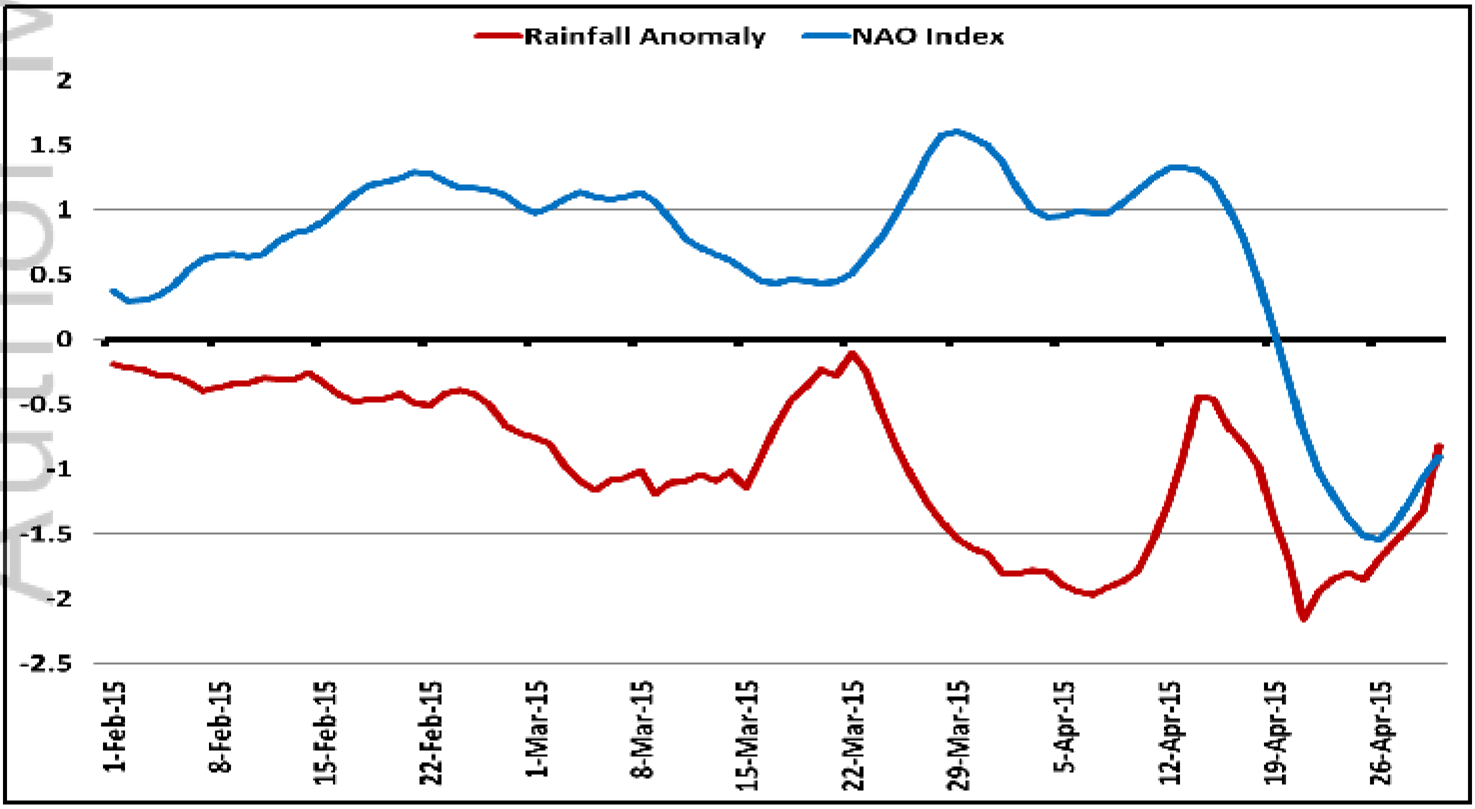


figure_11.tif

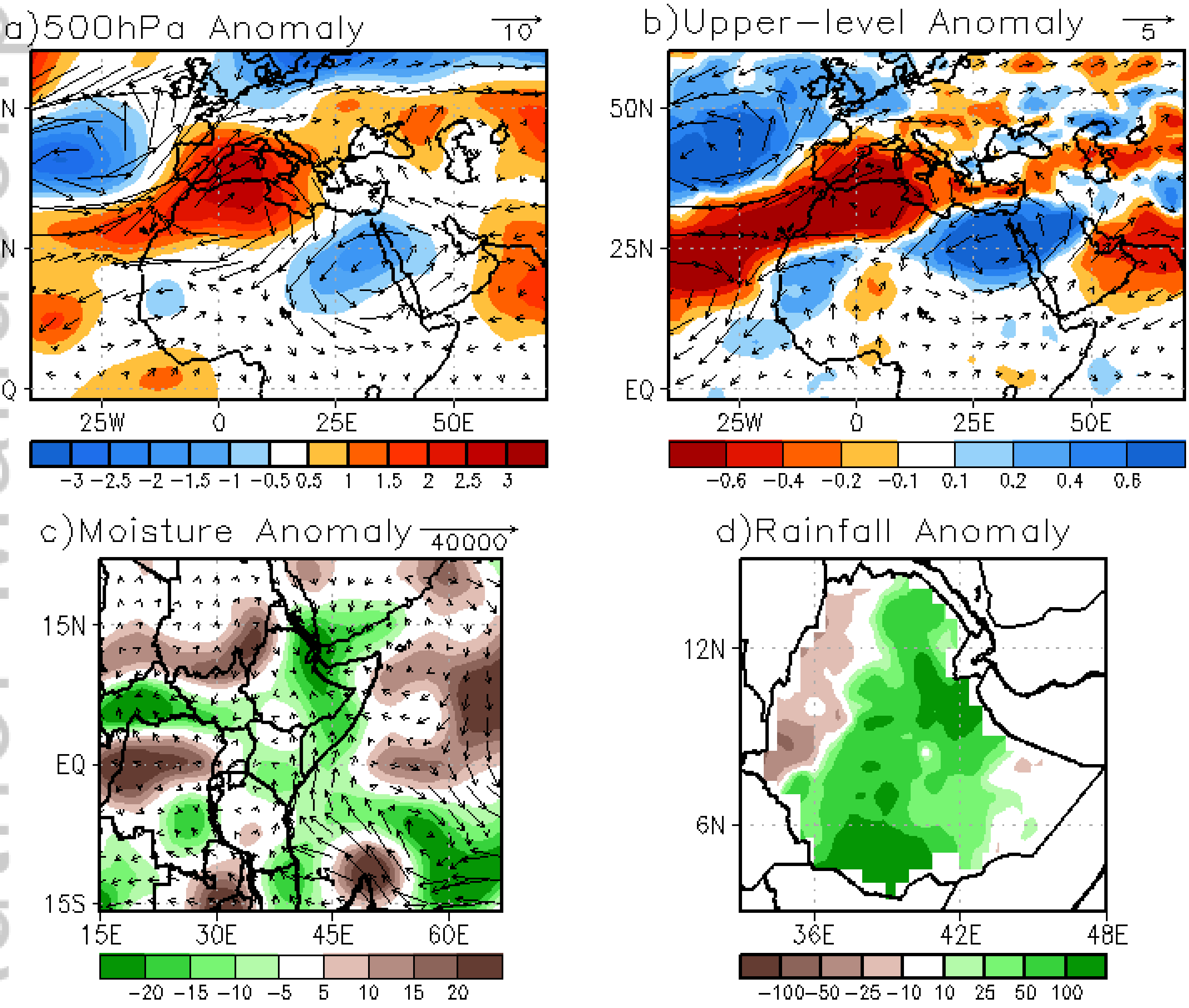


figure_12.tif

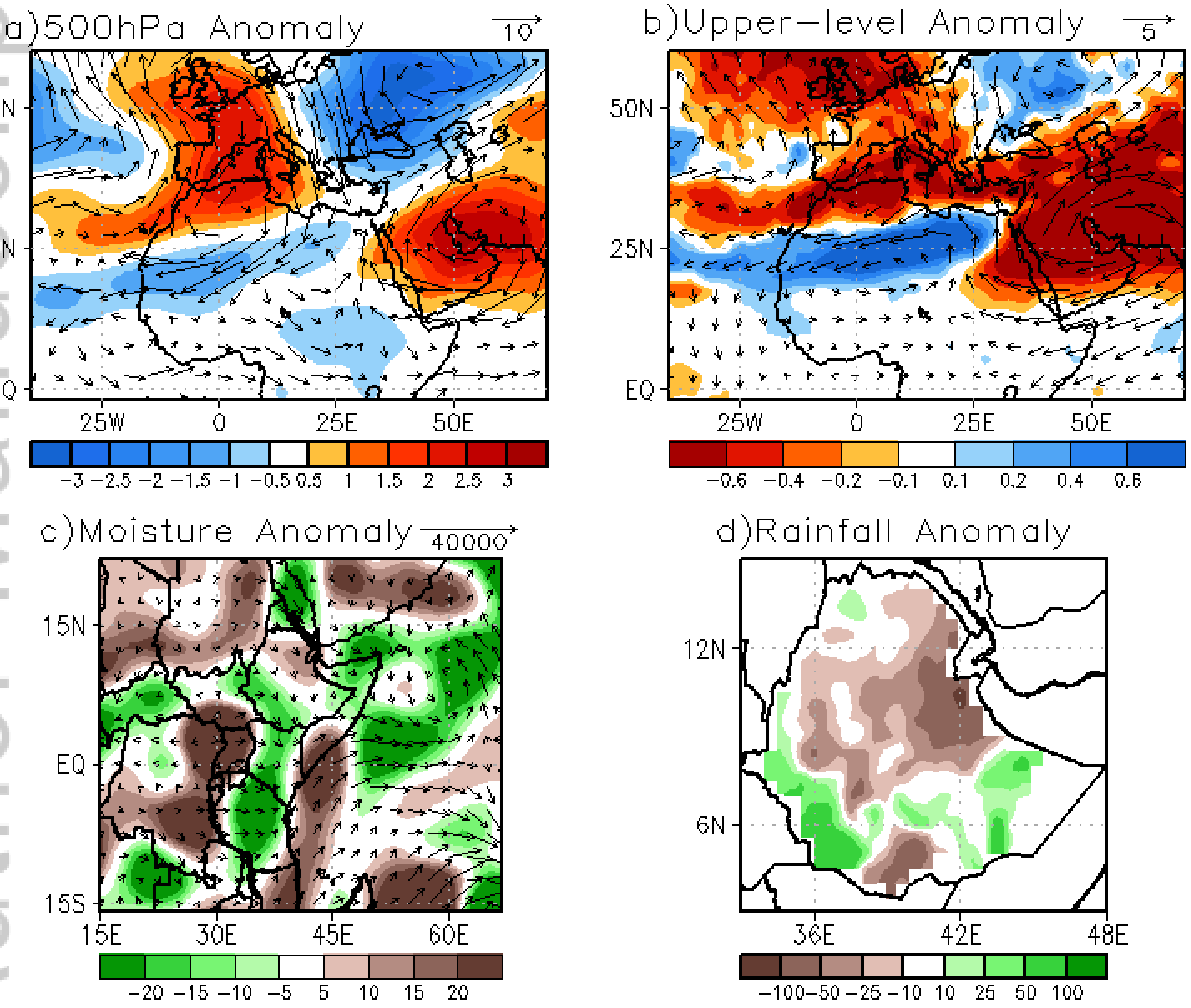
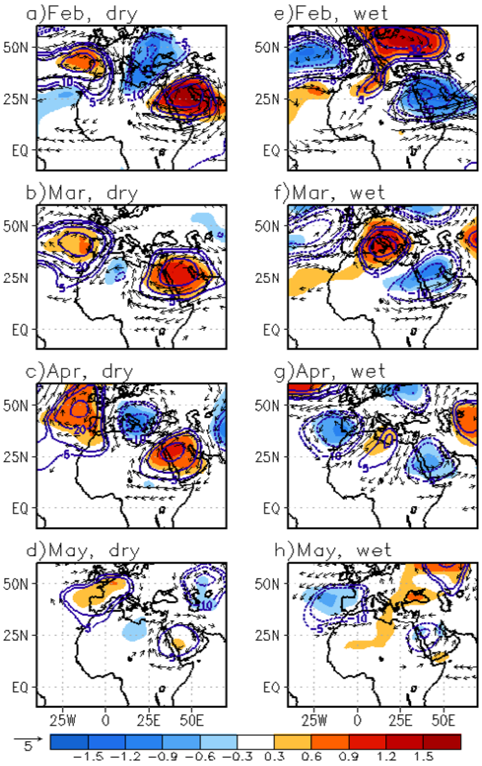


figure_13.tif

Subseasonal Variability of the Belg Rains in Ethiopia

*Endalkachew Bekele-Biratu, Wassila M. Thiaw and Diriba Korecha



Composites of circulation anomalies at 500-hPa (above) shows a tripole circulation pattern in the form of anticyclone-cyclone-anticyclone (ACA) for dry Belg (a –d), and cyclone-anticyclone-cyclone (CAC) for wet Belg (e - h). The ACA and CAC patterns indicate influence of tropical/extratropical interactions in modulating the Ethiopian Belg rainfall. NAO related anomalies in the North Atlantic are also linked to anomalies in the Red Sea region through the tripole pattern.