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The effect of moisture transport variability on Ethiopian summer precipitation

Ellen Viste[a]* and Asgeir Sorteberg[a,b]
[a] *Geophysical Institute, University of Bergen, Bergen, Norway*
[b] *Bjerknes Centre for Climate Research, University of Bergen, Bergen, Norway*

ABSTRACT: The main rainy season in Ethiopia occurs during the northern hemisphere summer, when air masses carrying moisture from the Indian Ocean, the Gulf of Guinea, the African continent, the Red Sea, and the Mediterranean Sea converge above the Ethiopian mountain plateau. In this study, the variability in different branches of this transport has been studied using the Lagrangian trajectory model FLEXPART and ERA-Interim reanalysis data of July–August 1998–2008. The largest relative fluctuations occur in the normally limited transport from the Gulf of Guinea, whereas smaller relative changes in the larger branches from the Indian Ocean and the regions to the north often have greater effects. Wet/dry summer months in the northern Ethiopian highlands were associated with increased/reduced transport of moisture from the south, with consequent changes in the release of moisture in the region. In dry months, the moisture transport from the south was reduced to 85% of its mean, and in wet months, it was increased to 107%. The increased transport in wet months could be attributed to low-level westerly anomalies above Central Africa – increasing moisture transport from the Gulf of Guinea and in most cases also from the Indian Ocean – and with enhanced southerlies along the coast of East Africa, increasing the transport from the Indian Ocean. The amount of moisture transported into the highlands from the north could not be consistently associated with wet and dry months, but in most cases, the release of moisture in air coming from the north contributed to the resulting precipitation anomaly. The release of moisture in the northern branch was reduced to 94% of its mean in dry months and increased to 111% in wet months. This may be an effect of altered convergence associated with changes in the transport from the south. Copyright © 2012 Royal Meteorological Society

KEY WORDS Ethiopia; Horn of Africa; precipitation; moisture transport

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1. Introduction

In the Ethiopian highlands, about 60 million people depend on mainly rain-fed agriculture (World Bank, 2005; CSA, 2010). June–September constitutes the main rainy season, providing 50–90% of the annual precipitation (Griffiths, 1972; Korecha and Barnston, 2007). In a study by Viste and Sorteberg (2011), it was shown that most of the moisture reaching the northern Ethiopian highlands in July and August is carried by air from the Indian Ocean or from the north, with a small share crossing Africa from the Gulf of Guinea. However, previous studies have indicated that Atlantic-related circulation anomalies influence Ethiopian summer precipitation more strongly than the Indian Ocean, stressing the moisture transport from the Gulf of Guinea (Korecha and Barnston, 2007; Segele *et al.* 2009a). In this study, the trajectory method used by Viste and Sorteberg (2011) has been extended to address the effect of moisture transport variability on precipitation. The results indicate that the transport from the Gulf of Guinea may appear more dominant than it is, because frequently occurring anomalies have a more consistent effect on this branch than on other transport branches. Wet and dry summer months are often associated with deviations in the flow from the Gulf of Guinea, but deviations in other branches play larger, although less consistent, roles. The real importance lies in the effect on the transport through and from Central Africa, regardless of the previous origin of the air.

The moisture flux above Africa in July–August is shown in Figure 1(a), integrated from the ground to the top of the atmosphere. As most of the moisture in the atmosphere is present at lower levels, similar patterns are seen in the wind field at 850 and 700 hPa (Figure 1(b,c)). Strong moisture fluxes are apparent in two regions of Ethiopia. The first, leading to divergence and dryness in the southeast, is a result of the strong, low-level Somali Jet (Findlater, 1969, 1977). The second, crossing the Rift Valley and entering the Ethiopian highlands from the north and northeast, is associated with moisture convergence and precipitation in the highlands. Its direction is in accordance with that of Gimeno *et al.* (2010), who found that evaporation from the Mediterranean Sea, and especially from the Red Sea, is important for the Ethiopian summer precipitation.

Even though the mean net moisture flux through the northern Ethiopian highlands is northeasterly, the real

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* Correspondence to: E. Viste, Geophysical Institute, University of Bergen, P.O. Box 7803, 5020 Bergen, Norway.
E-mail: ellen.viste@gfi.uib.no

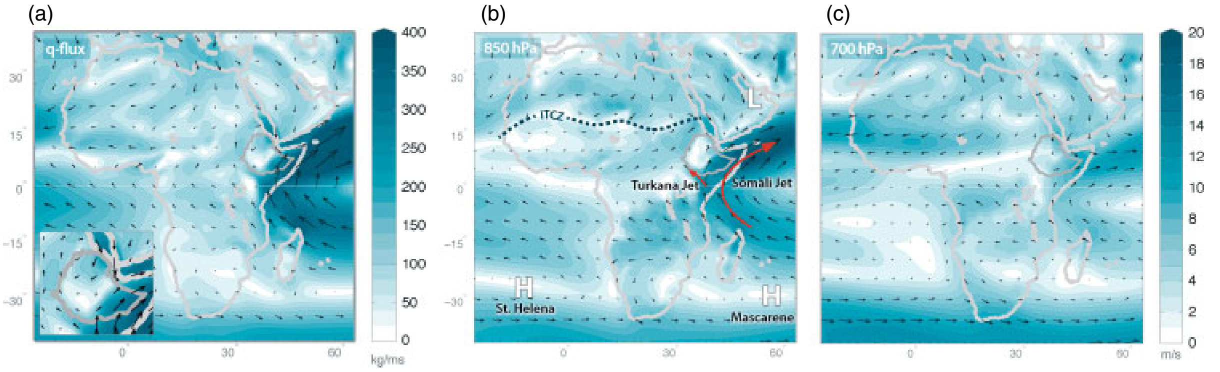


Figure 1. The atmospheric summer circulation over Africa. ERA-Interim vertically integrated moisture flux (a) in July–August, and wind at (b) 850 and (c) 700 hPa in July 1989–2008. Ethiopia is outlined in gray. The lower left, inset map in (a) is an enlargement of the flux above Ethiopia, with a higher arrow density. In (b), H/Ls indicate high/low pressure centers at sea level, ITCZ the Intertropical Convergence Zone at 1000 hPa, and the red arrows the jets through the Turkana Channel and along the Somalian coast. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

picture is complex. The summer rains occur as air masses carrying moisture from the Indian Ocean, the Gulf of Guinea, and the regions to the north of Ethiopia converge and ascend above the Ethiopian mountain plateau (Mohamed *et al*., 2005; Korecha and Barnston, 2007; Segele *et al*., 2009a; Viste and Sorteberg, 2011). In the study by Viste and Sorteberg (2011), the mean transport of moisture into the northern Ethiopian highlands was analyzed using the Lagrangian trajectory model FLEXPART (Stohl *et al*., 2005). Air parcels were backtracked from the northern Ethiopian highlands in July–August 1998–2008, and the following main moisture transport branches emerged: (1) the Gulf of Guinea, (2) the Indian Ocean, and (3) the northern region consisting of the Mediterranean Sea, the Arabian Peninsula, and the Red Sea. Several sub-branches were also analyzed.

The largest amount of moisture entering and being released in the northern Ethiopian highlands was carried by air having crossed the African continent from the Indian Ocean and by air coming from the north. This was partly due to the high specific humidity, and partly due to the large proportion, of air following these routes. The Indian Ocean, the Congo Basin, and the Red Sea were found to be important moisture source regions. Despite the high specific humidity of the low-level flow of air from the Gulf of Guinea, the net moisture contribution from this branch was found to be much smaller than that from the other branches. As indicated by the moisture flux (Figure 1(a)) and the wind field at 850 hPa (Figure 1(b)), there is a large amount of moisture flowing northeastward from the Gulf of Guinea. But, normally, only a small part of this air reaches as far east as the northern Ethiopian highlands, most of the air taking paths that pass farther west.

As air coming from the Gulf of Guinea normally provides a minor contribution to the moisture flux into Ethiopia (Viste and Sorteberg, 2011), this flow would have to increase substantially in order to be a main cause of precipitation increase in the Ethiopian highlands. Previous studies have suggested that anomalies in the summer circulation above Africa may facilitate such an increase. Anomalous summer precipitation in Ethiopia has been associated with anomalies in sea surface temperature (SST) and pressure in the Gulf of Guinea and the Indian Ocean (Korecha and Barnston, 2007; Segele *et al*., 2009a; Diro *et al*., 2010a, 2010b). Low SSTs in the South Atlantic Ocean/Gulf of Guinea and the Southern Indian Ocean are related to strengthening of the St. Helena and Mascarene high pressure regions, respectively. In both the cases, this should enhance the transport of moisture toward Ethiopia from the south. Both Korecha and Barnston (2007) and Segele *et al*. (2009a) documented a stronger link between the Ethiopian summer rains and SST anomalies in the Atlantic, as compared to the Indian Ocean.

Also supporting the hypothesis that transport from the Gulf of Guinea is a main driver, Segele *et al*. (2009a) found abundant summer precipitation in Ethiopia to be associated with enhanced low-level westerlies above western and central Africa, increasing the water vapor content in the atmosphere above the Horn of Africa. These wind anomalies are caused by the combination of increased MSLP above the Gulf of Guinea and a deepened monsoon trough above the Arabian Peninsula, creating a southwest-northeast pressure gradient anomaly across Africa (Segele *et al*., 2009a).

The connection between stronger westerlies above Central Africa and enhanced summer precipitation in Ethiopia may be due to enhanced transport or indirect causes such as changes in convection, related to the position and strength of the ITCZ (Intertropical Convergence Zone) (Diro *et al*., 2010a, 2010b). Enhanced westerlies to the southwest of Ethiopia affects the transport not only from the Gulf of Guinea but also from the Indian Ocean, as much of the air that reaches Ethiopia from the southwest, has crossed westward from the coast of Kenya and Tanzania, before turning north and northeast above the Great Lakes and Central Africa (Viste and Sorteberg, 2011). If the cause of wet summers is directly related to the inflow of moisture, it may be an increase in the flow from the Gulf of Guinea, the Indian Ocean, or both.

To assess connections between moisture transport and wet and dry summer months in the northern Ethiopian highlands, air parcels were backtracked from the region using the FLEXPART data set described by Viste and Sorteberg (2011). As in that study, the focus of this study has been on the transport, and not on treating variability in ascent, local moisture recycling, and the other factors that also influence the summer rains. The results suggest that circulation anomalies affecting the transport of moisture from the south, whether originating in the Indian Ocean, the Gulf of Guinea, or the African continent, have a more consistent effect and are easier to detect than those influencing the transport from the north. The largest relative variation occurs in the flow from the Gulf of Guinea, but as this transport is normally small, the consequences of anomalies in the flow from the Indian Ocean and the regions to the north of Ethiopia are greater.

2. Data and methodology

The Lagrangian trajectory model FLEXPART (Stohl *et al*., 2005) was used to backtrack air parcels reaching a region in the northern Ethiopian highlands, using ERA-Interim (Berrisford *et al*., 2009) reanalysis data as input (Viste and Sorteberg, 2011). For each July and August month during 1998–2008, the resulting trajectories were classified into branches and the moisture transport through each branch quantified. The amount of moisture brought into the region was compared with ground observations of precipitation. Composites of the ERA-Interim moisture flux and low-level winds were made for cases of wet-minus-dry summer months and for strong-minus-weak occurrences of each of the transport branches.

All anomalies used in the analysis were calculated as percentages of the 1998–2008 July or August mean. Percentage anomalies were used instead of, e.g. standardized anomalies or other statistical measures due to the relatively short record.

2.1. The northern Ethiopian highlands

Ethiopia is located at the Horn of Africa, within 3–15°N, 33–48 °E. The northernmost part of the Rift Valley cuts southwest–northeast through the country, with pronounced escarpments around the highlands of the Ethiopian plateau. In the dry Denakil depression in the northeastern lowlands, the terrain reaches 135 m below sea level, climbing to 4533 metres above sea level (m.a.s.l.) on Ras Dashen in the northern highlands.

When the *northern Ethiopian highlands* or *target region* is used in this study, it refers to the boxed region within 8–14°N and 36–40 °E, as shown in Figure 2. The selection was based on two criteria: the region should have a homogeneous climate regime with respect to both atmospheric circulation and rainfall (Griffiths, 1972; Gissila *et al*., 2004; Korecha and Barnston, 2007), without being too small compared to the resolution of the ERA-Interim data (Section 2.3). The selected region has an area of 290,000 km^2 and covers the northern part of the Ethiopian plateau, with the northernmost part of the Rift Valley to the east, the sloping sides toward the drier lowlands of Sudan to the west, Eritrea and the slopes toward the Red Sea to the north, and the southern Ethiopian highlands and the southern parts of the Rift Valley to the south. Most of the region lies above 2000 m.a.s.l., and there are several peaks above 4000 m.a.s.l.

2.2. Precipitation

Regional mean values of monthly precipitation for the northern Ethiopian highlands for 1998–2008 were calculated using ground observations, as outlined in Figure 2. Monthly precipitation data for 108 weather stations in the northern Ethiopian highlands were obtained from the National Meteorological Agency of Ethiopia. Requiring that the stations had data for at least 80% of each calendar month during 1998–2008, left 47 stations for the analysis. The regional mean was calculated by taking the mean of the monthly precipitation at stations in six 2° × 2° sub-regions within 8–14°N, 36–40 °E, then taking the mean of these sub-regional means. The number of stations within each sub-region (Figure 2) varied from 2 in the northwest to 18 in the southeast.

2.3. ERA-Interim

ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used as input to FLEXPART. ERA-Interim has a 4D variational assimilation system, and output is produced at a resolution of about 0.75° latitude and longitude, with 60 vertical levels (Simmons *et al*., 2006; Uppala *et al*., 2008; Berrisford *et al*., 2009). In FLEXPART simulations, the number of air parcels should not be too low compared to the resolution of the input data (Stohl and James, 2004). To reduce computational costs, the spatial resolution of the ERA-Interim data used with FLEXPART was reduced to 2° latitude and longitude.

The ERA-Interim vertically integrated moisture flux was calculated by the Climate Analysis Section at the National Center for Atmospheric Research (NCAR), using methods described by Trenberth *et al.* (2002).

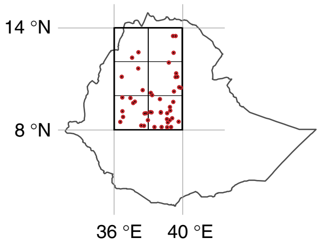


Figure 2. Ethiopia, with the study region (8–14°N, 36–40 °E) in the northern highlands, and the sub-regions used for calculating regional mean precipitation. The dots represent the precipitation gauges used in the calculations. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Anomalies of ERA-Interim vertically integrated moisture transport, and wind at 700 and 850 hPa, were calculated for each month. Maps of individual months were examined, but will not be shown.

2.4. Backtracking air using FLEXPART

Originally developed for calculating the dispersion of air pollution, the Lagrangian trajectory model FLEXPART has been used in several studies of moisture transport (James *et al*., 2004; Stohl and James, 2005; Stohl, 2006; Nieto *et al*., 2007, 2008; Drumond *et al*., 2008; Stohl *et al*., 2008; Gimeno *et al*., 2010). In FLEXPART, particles are traced based on gridded input data from weather forecast or reanalysis models, such as the products from the European Centre for Medium-Range Weather Forecasts (ECMWF), the Weather Research and Forecasting (WRF) Model, and the Global Forecast System (GFS).

FLEXPART may be used to calculate the dispersion of a limited number of particles released locally, or – as in this study – with the total mass of the atmosphere divided into a specified number of particles. As the set of mass particles in this case represents the complete atmosphere, we refer to them as air parcels. The parcels are allowed to move with the input data set winds interpolated to the parcel positions, as well as random motions to account for turbulence. The mass of each parcel remains constant, and values of specific humidity and temperature are interpolated from the gridded input data to the parcel positions at each time step.

In this study, FLEXPART was run globally for the years 1998–2008, with one million air parcels, using ERA-Interim input data. The period was limited to the most recent 11 years, mainly due to computational resources. Data for every 3 h were used as input, and output data saved for every 6 h. Then, all air parcels present above the northern Ethiopian highlands at any time step in July or August were backtracked 80 time steps (20 d). Only parcels above the tropopause were neglected.

As described by Forster *et al*. (2007), FLEXPART uses a version of the Emanuel and Živković-Rothman (1999) convective parameterization scheme to account for convective updrafts. The convection scheme reduced vertical mass fluxes and precipitation rates by about 25% compared to the ECMWF ERA-40 reanalysis. As precipitation is generally overestimated in ERA-40, this was interpreted as a positive adjustment.

2.5. Quantifying moisture contributions from FLEXPART data

As documented in the study by Viste and Sorteberg (2011), the transport of air into the northern Ethiopian highlands may be considered as the sum of a few distinct branches or pathways: (1) air coming from the Gulf of Guinea, (2) air coming from the Indian Ocean, (3) air coming from the north, and (4) air coming from the east. In addition to branches 1–4, a separate analysis of the flow coming from the African continent, whether from the Gulf of Guinea or the Indian Ocean, and then continuing around the Ethiopian highlands, finally reaching the target region from the north or east (5), was performed. Also, the combined effect of all branches entering via the continent to the south of Ethiopia was studied (6).

The branches were determined visually from trajectory maps, and then, clustering was performed by selecting air parcels on the condition that they must have crossed two lines from specific directions. The coordinates of these lines are given in table I. Requiring that parcels had crossed the ‘start’ line, ensure that they came from a certain region (e.g. the Gulf of Guinea or the Indian Ocean). Stray parcels, moving far away from the branch path, were then eliminated by including only parcels that also crossed a ‘transit’ line. Ideally, the lines should identify the highest possible number of trajectories belonging to the branch while including as few others as possible. Several alternative lines were tested, and those considered the best compromise were used.

How much the transport in each of these branches contributes to rainfall depends on both the amount of moisture in the air and how much of this moisture that is released in the region. Decreasing moisture in one air parcel does not necessarily represent precipitation, as it may be balanced by increases in other parcels in the same air column. Still, a decrease in the moisture content of an individual parcel represents a negative contribution to the net moisture content in the column, and thus a potential contribution to precipitation.

Incoming moisture was calculated as

$$mq_{in} = \sum_{i=1}^{n} m_i q_{\mathrm{border},i}$$

where m is mass and q specific humidity, n is the number of parcels, i denotes each parcel, and border refers to the last time step before the parcel entered the target region. In order to assess the potential contribution to precipitation, moisture release within the target region was calculated as the difference between incoming and outgoing moisture:

$$\Delta(mq) = \sum_{i=1}^{n} m_i [q_{\mathrm{end},i} - q_{\mathrm{border},i}]$$

Table I. Transport branches, numbered as listed in the text. To be included in a branch, air parcels must first cross the Start line and then the Transit line.

ID	Start line	Transit line
1	15°N,0°E–15°S, 15°E	0°N, 25°E–15°N, 25°E
2	20°S,35°E–0°N, 43°E	8°N, 0°E–8°N, 40°E
2a	20°S,35°E–0°N, 43°E	8°N, 36°E–8°N, 40°E
2b	20°S,35°E–0°N, 43°E	8°N, 0°E–8°N, 36°E
3	30°N,15°E–20°N, 65°E	20°N, 15°E–10°N, 65°E
4	0°N, 65°E–20°N, 65°E	0°N, 55°E–20°N, 55°E
5	8°N,0°E–8°N, 36°E	14°N, 36°E–24°N, 36°E
6	8°N, 0°E–8°N, 40°E	8°N, 0°E–8°N, 40°E

where end refers to the last time step before the parcel left the target region.

Both quantities were calculated for each branch as well as for the complete set of air parcels. The total $\Delta(mq)$ for all air parcels traveling through the region was compared to the gauge-based regional mean precipitation.

2.6. Classifying wet/dry months and strong/weak branch cases

Months were classified as wet, dry, or normal based on the gauge-based regional precipitation. Months having 95–105% of the 1998–2008 July or August mean precipitation were classified as normal, those having more than 105% as wet, and less than 95% as dry. The resulting groups were of mainly equal size, meaning that months classified as wet or dry were not necessarily climatologically extreme.

The precipitation categories were compared to the corresponding anomalies of FLEXPART moisture release within the region ($\Delta(mq)$). Months with too large discrepancy between anomalies of precipitation and moisture release were considered unsuitable for further analysis. Both anomalies were required to have the same sign. Discrepancies between precipitation and the amount of released moisture as given by FLEXPART may be a result of errors in the ERA-Interim data, errors produced by FLEXPART, or the lack of representativeness of the regional precipitation, which was calculated from a scatter of ground observations. In any one of the cases, there is little sense in discussing the conditions producing a moisture budget that is not in accordance with the observed precipitation. Some of the figures shown in Section 3 include the results for such months, but they have not been used in any of the calculations, except in the mean reference values of precipitation and FLEXPART incoming and released moisture. Removing these months before recalculating the mean values would only change the anomalies by 0–2% and not alter the distribution between the branches notably.

The mean difference between wet and dry (wet-minus-dry) months was calculated for the ERA-Interim vertically integrated moisture flux and for winds at 700 and 850 hPa. Similarly, for each branch, months were classified as strong or weak, with a strong branch defined as above 105% of its monthly mean, and a weak branch as below 95%. The difference between strong and weak (strong-minus-weak) months for each branch was then calculated for the same parameters as in the wet-minus-dry case.

3. Results

An overview of the 1998–2008 monthly mean transport is presented, followed by an analysis of the role of the different branches in wet and dry July and August months. Then, a different approach is taken, with an analysis of the characteristics of strong and weak occurrences of each branch, without regard to precipitation anomalies. Two quantities are used to characterize each branch: the amount of moisture carried by air in this branch when entering the region (mq) and the net amount of moisture released within the region ($\Delta(mq)$), representing the branch's potential contribution to precipitation.

The branches documented by Viste and Sorteberg (2011) are illustrated in Figure 3. Figure 3(a) shows a random subset of trajectories of air parcels reaching the target region in July–August 1998–2008. The red arrows mark the main branches identified: (1) flow from the Gulf of Guinea; (2) flow from the Indian Ocean; (3) flow from the Mediterranean, crossing the Red Sea or the Arabian Peninsula; and (4) dry, upper-level flow from the east. The flow from the Indian Ocean may be seen as the sum of two sub-branches. The first, 2a, enters through the southern border of the target region, either directly from the south or after having traveled through the Turkana Channel and then turned northeast. The other, 2b, consists of air that crosses westward into the African continent, passing the East African Great Lakes or the Congo Basin, before turning northeastward and reaching Ethiopia from the west. Owing to the method used to classify the air parcels, air entering through the Turkana Channel and continuing along the western side of the highlands before entering is also included in this branch. The topographic map in Figure 3(b) indicates that the highlands of East

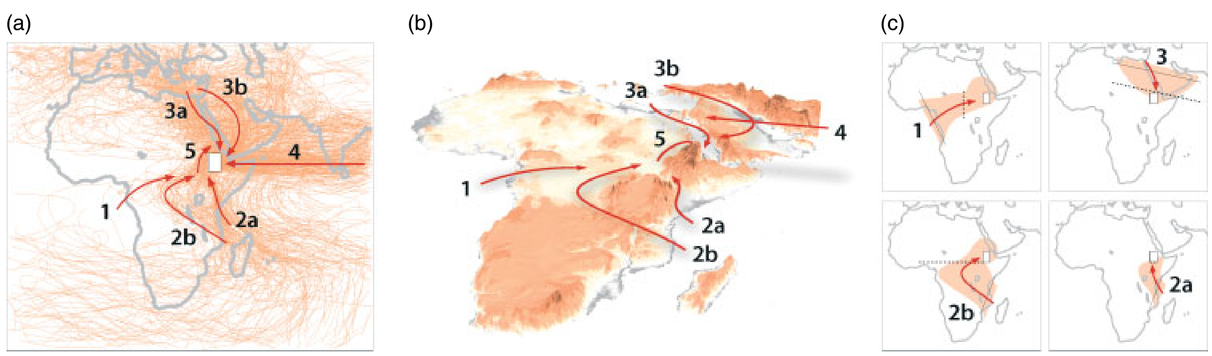


Figure 3. Main flow paths into the northern Ethiopian highlands. Air parcels entering 8–14°N, 36–40°E (boxed region) in July–August 1998–2008. (a) A subset of trajectories, with branches (arrows) as defined in table I. (b) Topographic map of Africa with branches as in (a). (c) Main range of tracks for selected branches, with start (–) and transit lines (– –) as listed in table I. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Africa have a steering effect on the flow from the Indian Ocean. As seen from the westernmost trajectories in this branch (Figure 3(a)), some air parcels cross all the way to the Atlantic side of the continent and merge with the flow from the Gulf of Guinea (1). Some of the air to the west of Ethiopia does not enter the highlands directly but continues northward, before re-curving and reaching Ethiopia from the north. This sub-branch is labeled 5, its air parcels also belonging to either of the other southern branches (1 or 2).

The total contribution from air coming from the south is labeled 6 in Table I (not shown in Figure 3). This represents all moisture entering Ethiopia from the continent after crossing the 8° latitude line extending westward from the southern border of the target region. Thus, it includes branches 1, 2a, and 2b, as well as air parcels that have spent more than 20 d above Africa and as a result, have not been counted in the ocean-origin branches.

As demonstrated by the trajectories in Figure 3(a), each branch arrow represents a wider sector of paths. The sectors covered by those branches that bring most of the moisture into Ethiopia are marked in Figure 3(c), together with the start and transit lines used to define each branch (based on Figure 11 of Viste and Sorteberg (2011) and Table I). This illustrates the geographical region that directly influences each branch.

3.1. An 11 year moisture transport climatology

This section summarizes the relative importance of moisture transport from different regions in July–August, outlined by Viste and Sorteberg (2011). We have also extended the analysis with results for each of the 2 months.

All results in this section refer to Figure 4, which compares the relative moisture contribution by the different branches in July and August. As described in Section 2.5, two quantities are of interest: the amount of moisture brought into the target region (mq) and the amount of moisture released within the target region ($\Delta(mq)$). For each branch, these values are given as the percentage of the total for all air parcels entering the region. Incoming moisture is represented by the color and width of each branch, and the moisture release in the target by the marker and number. The markers in the lower right corner of each map summarize contributions to incoming and released moisture from the north (branch 3) and the south (branch 6). Note that the branches were drawn so as to allow presenting all branches in one map; for a more realistic representation of the travel paths, refer to Figure 3. As there is some overlap between the branches, and because some parcels enter and re-enter the target region several times, the numbers do not add up to 100%.

The moisture inflow associated with the northern branch (3) is seen to be the largest, accounting for more than half of the total amount of incoming moisture – 55% as a total for July and August. The corresponding southern contribution is 38%. The contribution to the moisture release in the target region is roughly the same for air coming from the north and the south: 51 and 47%, respectively.

Among the southern branches, the flow from the Indian Ocean across the continent, entering Ethiopia from the west (2b), dominates. In July, 31% of the moisture released in the northern Ethiopian highlands is associated with air following this route and 35% with the Indian Ocean branches as a total (2). In August, these branches contribute with 23 and 28%, respectively. The corresponding contribution from the Gulf of Guinea branch (1) is only 2% in July.

Even though the main features of the atmospheric circulation in July and August are similar (Griffiths, 1972), there are some differences worth noting in the transport. Almost three times as many air parcels cross from the Gulf of Guinea to the northern Ethiopian highlands in August as in July, tripling this branch's relative contribution to the moisture release in August compared to July. The relative contribution from the north compared to the south is also higher in August

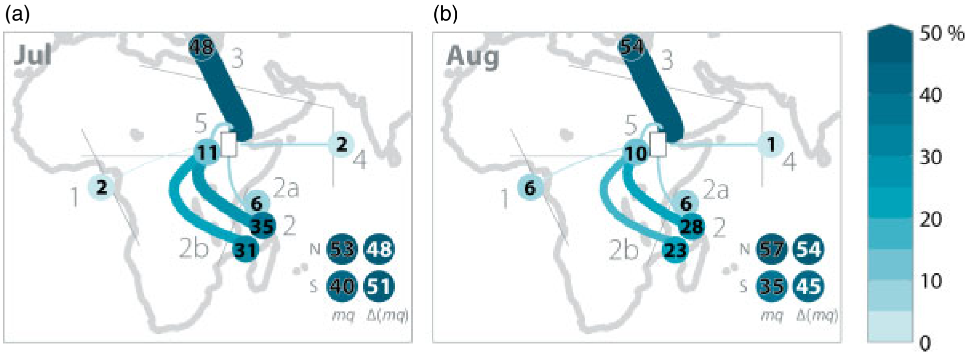


Figure 4. Moisture transport into the northern Ethiopian highlands (8–14°N, 36–40 °E) in July–August 1998–2008. The gray numbers refer to the branches shown in Figure 3 and described in Table I, with line segments representing the start line used to identify each branch. Quantities displayed are the relative contribution from each branch, as the percentage of the total for all air parcels entering the region. Incoming moisture (the amount entering the region) is represented by the color and width of each branch, and moisture release in the region by the marker at the beginning of each branch. The four markers in the lower right corner compare incoming (mq) and released ($\Delta(mq)$) moisture by the northern branch (N, branch 3) and the collective southern branches (S, branch 6, defined in Table I, but not included in the map). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

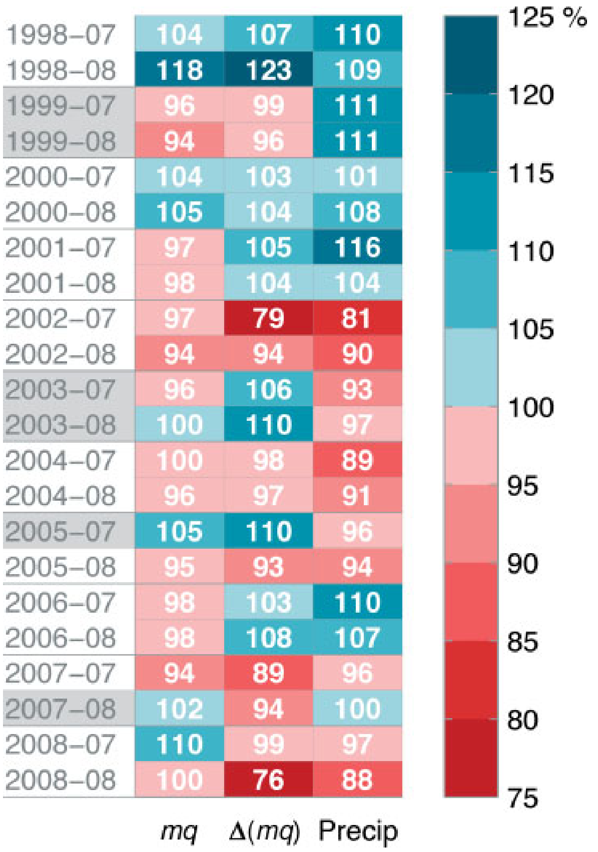
than that in July. This is reflected in the reduction of the relative importance of the moisture flow from the Indian Ocean (2) in August.

Most of the air entering the northern highlands from the east (4) travels at high altitudes and do not normally contribute much to the moisture entering or being released in the region (Viste and Sorteberg, 2011).

3.2. The relationship between moisture transport and precipitation

The intensity of the summer rains depends on the amount of moisture that is available in the region and how effectively this water vapor is condensed to form clouds and subsequent precipitation. Figure 5 compares the total moisture entering (*mq*) and released ($\Delta(mq)$) within the target region and the gauge-based regional precipitation.

For FLEXPART to be a good representation of the system, the amount of moisture released should correspond to the observed precipitation at the ground, here represented by the gauge-based regional precipitation. As described in Section 2.5, excessive discrepancies between moisture release and precipitation anomalies led us to discard the 6 months that have been shaded in Figures 5–7.



	mq	Δ(*mq*)	Precip
1998–07	104	107	110
1998–08	118	123	109
1999–07	96	99	111
1999–08	94	96	111
2000–07	104	103	101
2000–08	105	104	108
2001–07	97	105	116
2001–08	98	104	104
2002–07	97	79	81
2002–08	94	94	90
2003–07	96	106	93
2003–08	100	110	97
2004–07	100	98	89
2004–08	96	97	91
2005–07	105	110	96
2005–08	95	93	94
2006–07	98	103	110
2006–08	98	108	107
2007–07	94	89	96
2007–08	102	94	100
2008–07	110	99	97
2008–08	100	76	88

Figure 5. Anomalies of moisture and precipitation in the northern Ethiopian highlands (8–14°N, 36–40 °E) in July–August 1998–2008, as percentage of the monthly mean for 1998–2008. For each month, the anomalies in FLEXPART incoming (*mq*) and released ($\Delta(mq)$) moisture and gauge-based regional mean precipitation (Precip) are displayed. As described in Section 2.6, the months marked with gray shading have not been used in the analysis.

These months were excluded from the subsequent analysis. In the remaining months, the agreement between released moisture and precipitation was considered to be good enough to allow FLEXPART and the underlying ERA-Interim data to be used for describing the atmospheric conditions associated with the observed precipitation anomalies.

3.3. Moisture transport in wet *versus* dry summer months

Segele *et al.* (2009a) found abundant summer precipitation in Ethiopia to be associated with enhanced low-level westerlies over western and central Africa, increasing the water vapor content in the atmosphere over the Horn of Africa. Our results for July and August 1998–2008 support these findings. Figure 6 shows the difference in moisture flux, and 850 and 700 hPa winds, between wet and dry months, defined as outside of the 95–105% range of the regional mean monthly precipitation. The moisture flux difference (Figure 6(a)) is westerly in a latitudinal belt ranging from the equator to the Ethiopian highlands, starting at 10 °E, and continuing into the Indian Ocean. This westerly anomaly is also visible in the wind fields at 850 and 700 hPa (Figure 6(b,c)). Compared to dry months, wet months were also associated with a southerly 850 hPa wind anomaly along the coast of East Africa and a strengthening of the southeasterly flow above the Congo Basin south of the equator.

To show how these flow anomalies are reflected in the transport of moisture into the northern Ethiopian highlands, Figure 7 summarizes the mean anomalies of incoming and released moisture associated with the sets of wet and dry months. Figure 8 provides details for the individual months categorized as wet, dry, and normal, and Figure 9 compares these anomalies in air coming from the south (branch 6) and the north (branch 3).

3.3.1. Dry months

Figure 7(a) indicates that reduced moisture transport from the south causes dry summer months in the northern Ethiopian highlands, the highest relative decrease occurring in air coming from the Gulf of Guinea (branch 1). The moisture release was reduced in all main branches, the deviation being about equal in air coming from the Indian Ocean (2) and the Gulf of Guinea (1) but more than 50% higher in air from the north (3). Analysis of individual dry months (the middle panels in Figures 8 and 9) reveals notable differences from one month to another. Reductions in the branch from the Gulf of Guinea were consistent but too small to be the only cause of dry months; the Indian Ocean branch (2) contributed in half of the dry cases; and the northern branch tended to play a larger role in the reduced release of moisture than in the transport of moisture into the region.

As shown in the middle panel in Figure 9, all months in the dry set are characterized by reduced moisture transport from the south, e.g. as a total for air entering the northern Ethiopian highlands from the Gulf of Guinea,

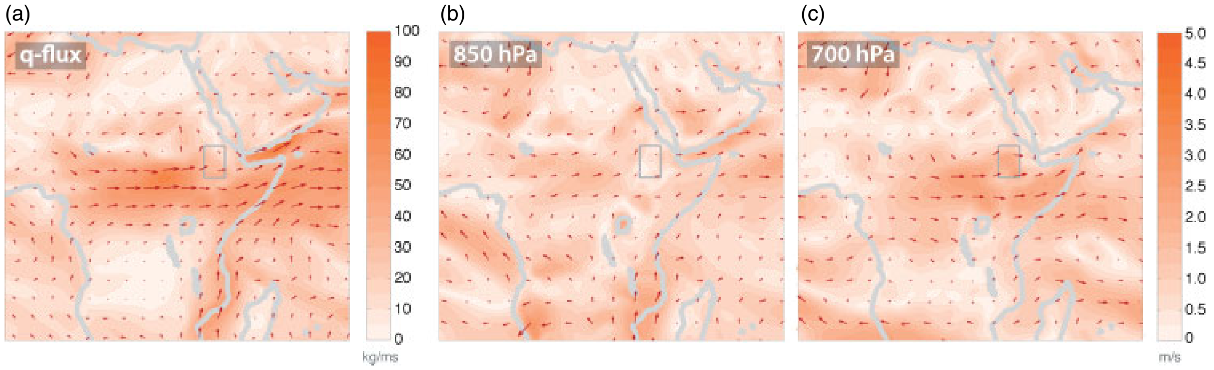


Figure 6. Wet-minus-dry composite. Difference between wet and dry July and August months in 8–14°N, 36–40 °E (boxed region) in ERA-Interim vertically integrated moisture flux (a), and wind at 850 (b) and 700 (c) hPa.

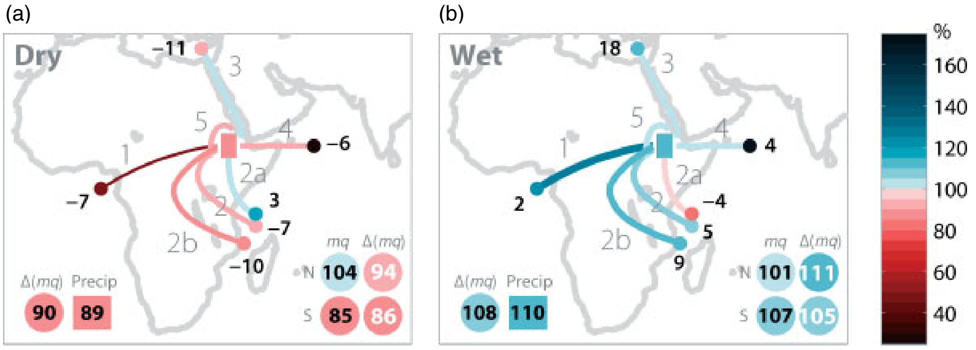


Figure 7. Mean characteristics of wet and dry summer months. Anomalies in moisture transport into the northern Ethiopian highlands (8–14°N, 36–40 °E) in dry (a) and wet (b) July and August months during 1998–2008. The gray numbers refer to the branches shown in Figure 3 and described in Table I. The width and color of each branch represent the anomaly in moisture transport into the region, while the marker at the beginning of each branch represents the anomaly in moisture release within the region. All quantities are percentage of anomalies relative to the 1998–2008 monthly means, except for the number at the beginning of each branch, which is the absolute deviation from the branch's mean moisture release, in units of millimetre per month over the area of the target region. The color of the region (box) represents the gauge-based regional precipitation anomaly used for categorizing the months: 95–105% normal, >105% wet, and <95% dry. This value is repeated in the rectangle-shaped marker in the lower left corner, for comparison with the total moisture release anomaly in the target region, given by the round marker to the left of the rectangle. The four markers in the lower right corner compare transport and release of moisture associated with air from the north (branch 3) and south (branch 6).

the Indian Ocean, and continental Africa to the south of the target region. With the exception of August 2002, the moisture release in air from the south was also lower than normal.

The most consistent component in the southern deficits was the transport from the Gulf of Guinea (branch 1), which was reduced in all months, except August 2005 (Figure 8, middle panel). As documented by Segele *et al.* (2009a), dry summers in Ethiopia are generally associated with easterly anomalies in the low-level wind west of Ethiopia. The wet-minus-dry difference maps in Figure 6 show that this was also the case in the months used in this study. Representing a reduction in the low-level southwesterly flow (Figure 1(b)) in this region, an obvious effect of an easterly anomaly is to reduce the amount of air reaching Ethiopia from the Gulf of Guinea. In July 2004 (Figure 8, middle panel), the amount of moisture carried into the northern Ethiopian highlands by air coming from the Gulf of Guinea was only 9% of the 1998–2008 mean for this branch.

As the Gulf of Guinea branch is normally small, there is a limit to the effect of such large relative reductions. In July (Figure 4(a)), air in this branch contributes 1.6% of the moisture entering the northern Ethiopian highlands and 2.0% (0.7 mm) of the released moisture. Thus, the direct effect of a complete cut-off of this branch may not be larger than these values. In August (Figure 4(b)), the numbers are higher: 4.2% of the incoming moisture and 5.9% (1.9 mm) of the released moisture. This means that the effect of relative reductions in the transport of moisture from the Gulf of Guinea is greater in August than in July but that reduced flow through this branch may never be the primary cause of a dry summer. In all dry months, the transport in at least one of the other branches was also reduced, and only in August 2004 (Figure 8, middle panel) could most of the reduction of released moisture in the target region be attributed to air coming from the Gulf of Guinea.

In the driest month, July 2002, the reduction in released moisture attributed to air from the Indian Ocean was more than five times as high as that from the Gulf of Guinea. The total transport of moisture from the Indian Ocean was reduced to 84% of the 1998–2008 July mean, mainly associated with the western sub-branch, crossing Central

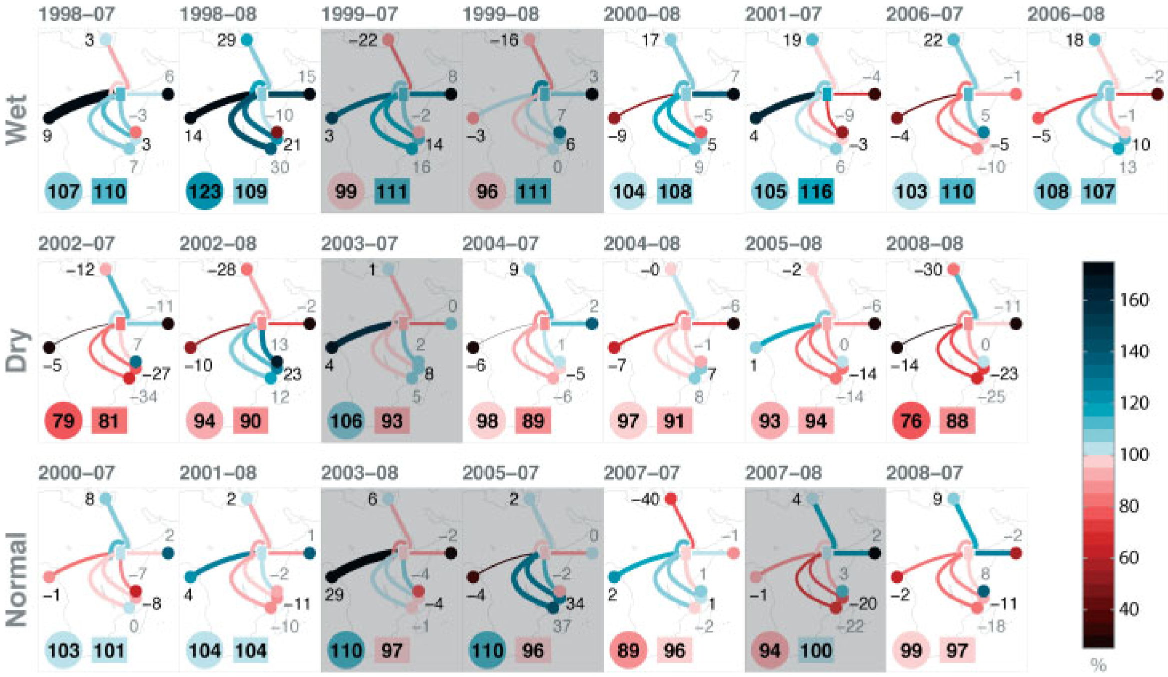


Figure 8. Moisture anomalies in dry, wet, and normal July and August months – as in Figure 7, but for individual months. The color of the boxed, target region at 8–14°N, 36–40 °E represents regional precipitation, also shown in the lower rectangle. Branches represent anomalies in moisture transport (width and color) to, and moisture release within (marker) the target. The lower left marker is the total moisture release anomaly. All quantities are percentage of anomalies relative to the 1998–2008 means for July and August except for the number at each branch, which is the absolute deviation from the mean moisture release, in units of millimetre per month over the area of the region. Months that have not been used in the analysis are shaded.

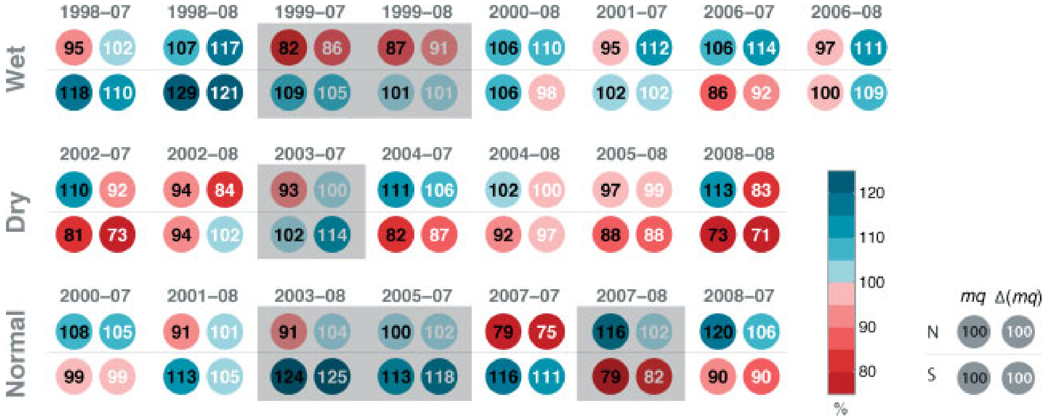


Figure 9. Moisture transport from the north and south in wet, dry, and normal summer months. Anomalies (%) of incoming (mq) and released ($\Delta(mq)$) moisture in air entering 8–14°N, 36–40 °E from the north (N, branch 3) and south (S, branch 6), as in the lower right corners in Figure 7, but for individual July and August months during 1998–2008. Months that have not been used in the analysis are shaded.

Africa (2b: 81%). As a total, about 50% of the moisture release reduction in this month took place in air from the Indian Ocean, 10% in air from the Gulf of Guinea, 20% from the east, and 20% from the north.

On the basis of the available data, it is not possible to draw any general conclusions about the role of the northern branch (3) during dry months in the northern Ethiopian highlands. Only in August 2002 may the transport of moisture from the north be said to have been below normal, at 94% (Figures 8 and 9). This was associated with a moisture release of only 84% of the normal, making the northern branch the major contributor to the precipitation deficit. But the moisture release was lower than normal also in July 2002 and August 2008–months during which the inflow of moisture from the north was as high as 110 and 113% of the 1998–2008 mean. In August 2008, this was the result of a strong negative moisture divergence anomaly (not shown) over the northern Ethiopian highlands.

August 2008 serves as an example of the effect of the size of some branches compared to others, as well as the importance of other factors than moisture transport. The transport from the south was reduced to 73% of the normal (Figure 9), but the transport from the north was high enough to balance this, so that the total transport of moisture into the northern highlands was close to normal (Figure 5). But as a result of reduced moisture convergence above the highlands (not shown), the moisture release was reduced in all branches, except the eastern Indian Ocean sub-branch (2a). As the northern branch is normally one of the largest contributors (Figure 4), a relative decrease in this branch leads to a large absolute decrease in the amount of moisture released. A similar effect was seen in July 2002.

3.3.2. Wet summer months

In Section 3.3.1, it was shown that reduced flow from the Gulf of Guinea may never be the main cause of dry summers in the northern Ethiopian highlands, simply because the contribution is normally small. Theoretically, increased moisture transport through this branch could still be the main cause of wet months. This was the case in one of the months in this study period, whereas in the remaining cases, increases in the branches from the Indian Ocean and/or the north were the main drivers.

As shown in Figure 9 (upper panel), there are some features common to wet months, but the pattern is less clear than for the dry cases. The northern branch may be seen as more influential than in the set of dry months, especially when considering moisture release anomalies. In five of the six wet months, the increase in moisture release associated with air coming from the north, was relatively higher than or about equal to the increase associated with air coming from the south. But only in July 2006 was the relative increase in incoming moisture indisputably higher in air from the north than from the south. Half of the wet cases were associated with increased transport of moisture from the south.

Increased flow from the Gulf of Guinea contributed to the total increase, both in incoming and released moisture, in three of the six wet months (Figure 8). In the remaining months, this branch was reduced. The total transport from the Indian Ocean contributed in four of the months, with one of the two sub-branches (2a and 2b) contributing in each of the two remaining months. The moisture release associated with air entering the highlands from the north was higher than its mean value in all the wet months. In three of these months, this was coupled with higher than normal moisture transport from the north, whereas in the remaining cases, the increased release occurred despite reductions in incoming moisture through this branch.

The largest positive anomalies in incoming and released moisture occurred in August 1998. In this, and only this month, all the branches were stronger than normal (Figure 8, upper panel). Except from the eastern branch from the Indian Ocean (2a), all branches also contributed to the higher than normal release of moisture. The largest deviation in released moisture occurred in the northern branch, with 29 mm, about 1.5 times as much as in air coming from the Indian Ocean and twice that from the Gulf of Guinea. In the previous month, July 1998, the situation was relatively similar but with smaller anomalies in all branches. In addition, less moisture than normal was transported through the northern branch. In this month, the only time, the branch from the Gulf of Guinea contributed most to the total increase in released moisture −38% of the total.

In four of the six wet months, the moisture transport anomalies in the eastern (2a) and western (2b) sub-branches from the Indian Ocean have opposite signs (Figure 8, upper panel). The sign of the moisture release anomalies for these branches are opposite in all wet months, as well as in most dry and normal months. As the western branch is the largest (Figure 4), deviations in this branch will in most cases dominate the total result (branch 2). But in July 2001, the reduction in the eastern branch was larger than the increase in the western branch, leading to a net negative contribution from air from the Indian Ocean. Anomaly maps of the ERA-Interim vertically integrated moisture flux for this month (not shown) show that this was the result of a weakening of the Somali Jet, together with easterly anomalies in the Turkana Channel. The moisture transport inland from the Indian Ocean was reduced, but for air taking the inland route (2b), westerly anomalies to the west and south of Ethiopia balanced this reduction, resulting in a small net increase in this branch. For the eastern branch (2a), the westerly anomaly was purely a negative factor.

The flow from the east (branch 4) consists mainly of upper-level air with very low specific humidity (Viste and Sorteberg, 2011). The mean height when crossing the start line is 11 900 metres above ground level (m.a.g.l.). As a result, the moisture carried into, and released within, the region by this branch is normally negligible. However, as seen in Figure 8, in some months, the anomalies associated with this branch are sizeable to the other branches and may not be neglected. Closer inspection of trajectory maps reveals that some air parcels in this branch follow a curved path to the north, crossing the southernmost part of the Arabian Peninsula and the Gulf of Aden before entering the northern Ethiopian highlands. This requires travel at mid-level and lower level, in accordance with the 500 hPa (not shown) and 700 hPa (Figure 1(c)) flow in this region. A look at several parameters (not shown) for August 1998, the month with the highest contribution from the eastern branch, indicates that an increased contribution from this sub-branch may have played a role. First, the moisture content in the eastern branch was almost twice as high as normal at the start line in the Arabian Sea, and altitude histograms show that more air parcels were present at lower levels than normal. This indicates that lower-level and mid-level air was involved from the start. Second, FLEXPART transport maps show a higher than normal number of air parcels, with a higher than normal moisture content, coming from Oman and the northern Arabian Sea. Third, southeasterly and easterly anomalies in the 500 and 700 hPa wind fields support this explanation, as such anomalies may bring more of the parcels above the Arabian Sea into paths leading to the northern Ethiopian highlands. Whether increased flow at mid-levels above the northern Arabian Sea was the main cause of the anomalous contribution by the eastern branch in August

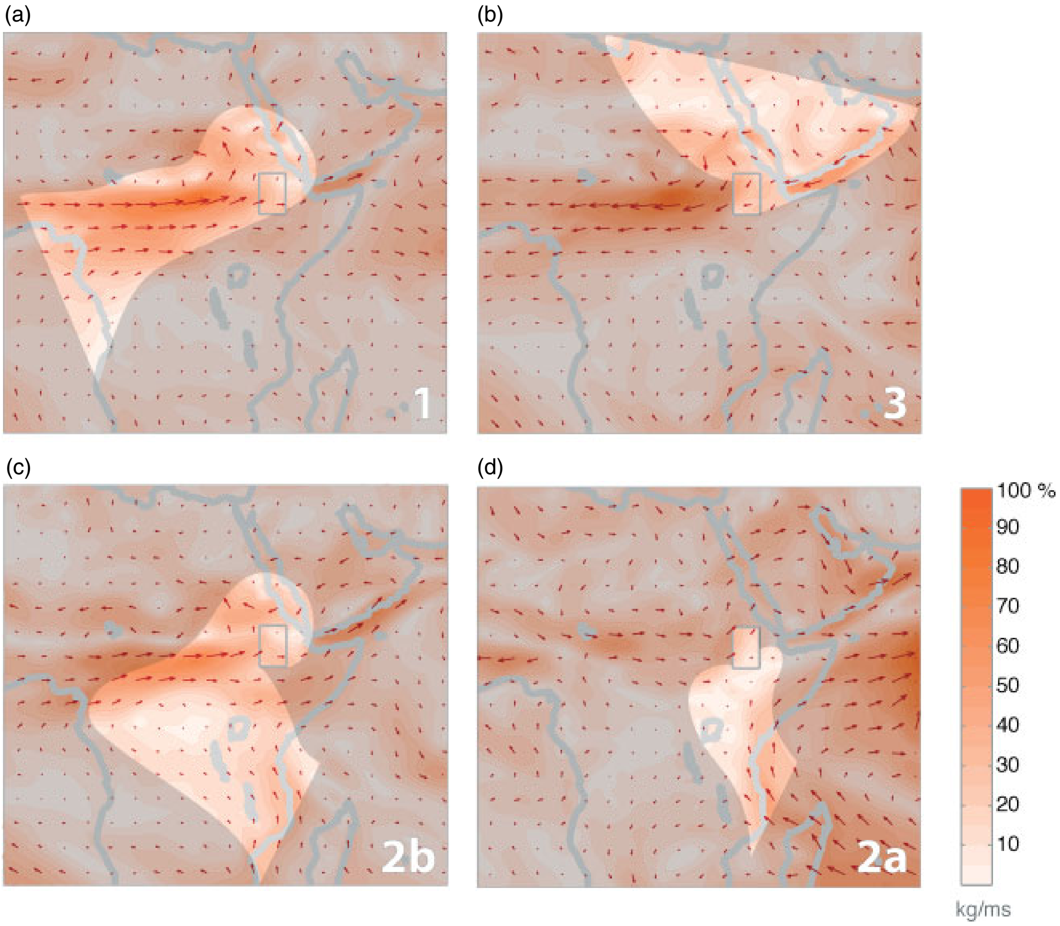


Figure 10. Strong-minus-weak composites. ERA-Interim vertically integrated moisture flux difference between months with strong and weak moisture inflow through the following branches: (a) Gulf of Guinea; (b) The north (Red Sea and Arabian Peninsula); (c) Indian Ocean, crossing west; and (d) Indian Ocean, entering the target region from the south. The white number in the lower right corner of each map is the branch identification number (Figure 3 and Table I). Regions outside of the branch's normal travel path (Figure 3(c)) have been shaded (darker), as they do not directly influence the transport. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

1998 may not be induced from this analysis, but it is likely to have been a contributing factor.

3.4. Circulation anomalies related to weak and strong moisture transport

One of the main benefits of using a Lagrangian model instead of Eulerian data is that it is possible to separate out only those air parcels that are of interest for the region studied. In Section 3.3, the branch contributions to wet and dry months were analyzed. Only in August 1998, was higher than the normal precipitation in the northern Ethiopian highlands associated with moisture increase in all the branches analyzed. In all other months, the anomalies of different branches were of opposite signs, some contributing to the precipitation anomaly, others opposing it. Thus, it is important to understand how different circulation anomalies in an Eulerian framework strengthen or weaken each of the transport branches.

Analogous to the wet-minus-dry difference map in Figure 6(a), Figure 10 shows the difference between the vertically integrated moisture flux in months with strong and weak moisture inflow to the northern Ethiopian highlands. Strong-minus-weak differences for four different branches are shown: the Gulf of Guinea (1), the north (3), and the eastern (2a) and western (2b) sub-branches from the Indian Ocean. A strengthening of a branch may be the result of either one or both of two causes: either the transport through the ordinary branch path is higher than normal, because of stronger winds or higher specific humidity in the air, or more air is deflected into the branch, so that air that would not under normal conditions end up in the northern Ethiopian highlands, does so.

In order to bring focus to anomalies directly influencing the transport, regions that are outside of the normal travel paths associated with each branch have been shaded. The influence regions shown in Figure 3(c), based on the results of Viste and Sorteberg (2011), have been used as masks, expanded slightly to make it easier to analyze deflections in and out of the path. The shaded regions may give important indications of the general atmospheric circulation connected with the situation, but do not have any direct influence on the transport through each branch. Masking regions considered non-influential, takes the attention away from irrelevant anomalies, but does not guarantee that all unmasked anomalies affect the net transport. This is discussed in each case.

3.4.1. *The Gulf of Guinea*

The most important anomalies affecting flow from the Gulf of Guinea occur to the west and southwest of Ethiopia. Westerly, low-level anomalies in this region increase the flow; easterly anomalies reduce it. This is seen in both the vertically integrated moisture flux (Figure 10(a)) and the 850- and 700 hPa wind field (not shown). Maps for individual months (not shown) confirm this for 5 of the 6 months with strong moisture inflow from the Gulf of Guinea, and six of the eight weak cases. As shown in Figure 10(a), there are two main reasons why such anomalies affect the amount of moisture transported into the northern Ethiopian highlands. First, the transport through the main part of the branch, above Central Africa, is higher in the strong cases than in the weak cases. Also, westerly anomalies to the west of the northern highlands push more of the air into the flow entering the highlands, instead of continuing north- or westward.

In 10 of the 16 months in the study, strong/weak transport from the Gulf of Guinea is accompanied by anomalies of the same sign in branch 5 (Figure 8). As illustrated in Figure 3(a,b), this branch brings air from the south around the western side of the Ethiopian plateau, before entering the northern highlands from the north. In the remaining months, the signs of the anomalies differ, and the strong-minus-weak pattern in this region in Figure 10(a) indicates why. Months with strong inflow from the Gulf of Guinea are associated with southerly and southeasterly anomalies in the moisture transport northwest of Ethiopia. This is an example of a counteracting anomaly. It is likely that the observed southeasterlies reduce rather than increase the amount of moisture entering Ethiopia from the Gulf of Guinea. Westerly anomalies to the northwest and northerly anomalies to the north of Ethiopia would theoretically increase the flow around the highlands. But this effect seems to be overshadowed by variations in the amount of air entering the branch from the south. Months with strong/weak inflow through branch 5 (not shown) are more often associated with high/low moisture transport from the south, than with low-level circulation anomalies steering the air around the northwestern corner. This indicates that this branch is affected more strongly by the amount of moisture flowing into it from the south than by how much of this air is turned southward again once it reaches the northern side of the highlands. When the transport from the south is high, this branch is large, even when atmospheric conditions to the northwest and north of the highlands counteract this effect. In August 1998, the transport through this branch was 118% of its August mean, the highest during the studied period. But compared to the total transport from the south (branch 6), which was 129% of its mean, this was low. A strong easterly anomaly north of Ethiopia worked against the increased flow from the south, reducing the relative effect of the flow around the highlands.

3.4.2. *The Indian Ocean*

Anomalies associated with strong and weak inflow from the Indian Ocean are more complex than for flow from the Gulf of Guinea. Two features still stand out as dominant. The first is a common benefit with the Gulf of Guinea branch of westerly anomalies above Central Africa. The other is related to the inflow of moisture along the coast of East Africa. The two identified sub-branches, 2a and 2b, as well as different parts of these branches, are affected differently by frequently occurring circulation anomalies. To get a clear picture of relevant anomalies in each case, strong-minus-weak differences were calculated for each sub-branch (Figure 10(c,d)).

The western sub-branch (2b) consists of air parcels that cross westward into the continent and curve northeastward above the Congo Basin, before reaching Ethiopia from the southwest. In the last part of the path, the air meets the flow from the Gulf of Guinea, and both branches benefit from the same anomalies. Increased westerlies increases the transport of moisture from the continent toward Ethiopia and also leads more of the air entering the continent through the Turkana Channel, into the flow toward the northern highlands. But while the strong-minus-weak moisture flux difference map for the Gulf of Guinea branch (Figure 10(a)) resembles the wet-minus-dry map (Figure 6(a)), the southern extension of the westerly anomalies in the strong-minus-weak map for the Indian Ocean branch (Figure 10(c)) is limited. Westerlies further south do not facilitate the flow from the Indian Ocean, as it hinders the northwestward transport of moisture in the southern part of the branch paths. Instead, southeasterly anomalies over the southern Congo enhance the flow in the southern part of the Indian Ocean branch.

Southeasterly strong-minus-weak differences are also seen along the coast of Kenya, Tanzania, and Mozambique, where moisture is brought inland from the Indian ocean, affecting both the Indian Ocean sub-branches (Figure 10(c,d)). This represents a strengthening of the climatological mean flow and increases the moisture transport to the continent. The transport anomaly is associated with increased winds in both 700 and 850 hPa (not shown), for the southernmost part mostly at 850 hPa. The case of the wet August 2000 (Figure 8, upper panel) illustrates the importance of the southeastern region. Strong southerly anomalies along the coast of Tanzania and Mozambique, then southwesterlies farther north above Lake Victoria, led to increased transport through the western Indian Ocean sub-branch (2b). At the same time, northeasterly anomalies farther west hampered the transport from the Gulf of Guinea.

The westerly anomalies generally associated with increased moisture transport into Ethiopia, may also act to reduce transport. This may occur not only if the anomaly belt extends too far to the south, as described for branch 2b, but also if it extends too far to the east. The wet-minus-dry difference maps in Figure 6 show a band of westerlies across the continent, a feature that may also be seen in some of the maps for individual months (not shown). The strong-minus-weak difference map for the western Indian Ocean sub-branch (branch 2b; Figure 10(c)) indicates that stronger inflow from the

Indian Ocean is associated with westerly anomalies in the Turkana Channel, to the south of Ethiopia. As westerlies in this region work against the transport direction in both the Indian Ocean branches (2a and 2b), this relationship is not causal but rather a factor that diminishes the increase in the transport from the west: Moisture brought from the continent outweighs the effect of reduced inflow from the Indian Ocean at Turkana. Once the air has reached the western side of Ethiopia, westerly anomalies facilitate the flow toward the northern highlands.

How the eastern Indian Ocean sub-branch (2a) is influenced by westerly/easterly anomalies to the south of Ethiopia is less obvious. Strong-minus-weak difference maps for this branch (Figure 10(d)) do not indicate any preference in the Turkana Channel, except for a weak southeasterly sign in the 850 hPa winds (not shown). Compared to the other southern sub-branches, the percentage of anomalies in incoming moisture associated with air in this sub-branch are small, leading to only 3 months categorized as strong and 3 as weak. Maps for individual months (not shown) include cases with easterly and westerly anomalies in both groups, causing them to balance out in the strong-minus-weak difference maps. In the month with the strongest inflow, August 2002, there was a southeasterly anomaly in and around Turkana, obviously bringing more moisture from the south into the northern highlands. Oppositely, a northwesterly anomaly in July 2001, the month with the weakest contribution, signified a general reduction in the inflow. On the basis of the observed cases, it is not possible to relate neither strong nor weak flow in the eastern Indian Ocean sub-branch with reduced or increased flow through the Turkana Channel. This does not mean that anomalies in this region do not influence the moisture transport but that other effects may be more important. The anomaly maps for the individual months are very different, and there may be various causes of variation in this branch.

As for the branch from the Gulf of Guinea (Section 3.4.1), it is difficult to see why the easterly anomalies to the north and northwest of Ethiopia should strengthen the western Indian Ocean sub-branch (Figure 10(c)). As such anomalies deflect air parcels away from tracks ending up in the northern Ethiopian highlands, it is more likely that they represent phenomena that occur simultaneously with the westerly anomalies farther south.

3.4.3. The North

The northern branch is complex, in reality being the sum of many different sub-branches (e.g. 3a and 3b in Figure 3). Anomaly maps for individual months (not shown) suggest that a suite of atmospheric conditions may enhance or reduce the transport of moisture into the northern Ethiopian highlands from the north. As a result, no clear patterns may be detected in the map showing moisture flux differences between months with strong and weak transport from the north (Figure 10(b)). Some characteristics are still worth mentioning, mainly the easterly anomalies above the Arabian Peninsula and the northerly anomalies above the Red Sea.

The mean vertically integrated moisture flux in Figure 1(a) may give the impression that the river-like moisture flow from the Mediterranean region above the Arabian Peninsula does not reach Ethiopia, instead turning east through the Gulf of Aden. The trajectories of air parcels reaching Ethiopia shown in Figure 3 demonstrate how misleading this is. While the flux map shows the vertical integration of movement at the monthly scale, the Lagrangian analysis tracks air at 3 h time steps in three dimensions, thus accounting for vertical movements that may alter parcel tracks. A large proportion of the moisture that reaches the northern Ethiopian highlands has passed above the Arabian Peninsula (Viste and Sorteberg, 2011). Anomalies that steer more air into tracks leading to Ethiopia may increase the moisture inflow from the north. In the weak-minus-strong difference map (Figure 10(d)), such steering is represented by the easterly anomalies above the southern Arabian Peninsula and the Gulf of Aden.

Above the Red Sea, the anomalies for individual months (not shown) vary so much that no conclusions may be drawn. It is still worth noting that in the month when the moisture inflow from the north was the strongest, July 2008 (Figure 9, lower panel), there was a northerly anomaly in the southernmost part of the Red Sea. As described for the Indian Ocean (Section 3.4.2), circulation anomalies may have counteracting effects on the transport in different sub-branches, as well as at different stages of each sub-branch. A northerly anomaly in the southern Red Sea may increase the direct transport from the Red Sea into the Ethiopian highlands, but it may also increase the flow from the Red Sea to the Gulf of Aden. As a total, this may increase the moisture inflow from the Red Sea (branch 3a, Figure 3(a,b)) but at the same time, may reduce the flow from the Arabian Peninsula (branch 3b). At 850 hPa (not shown), the strong-minus-weak wind difference is northerly above the Central Red Sea and southeasterly above large parts of the Arabian Peninsula.

4. Discussion

The Ethiopian National Meteorological Agency (NMA) issued its first seasonal weather outlook in 1987, timely warning the nation of a dry summer season (Bekele, 1997; Korecha and Barnston, 2007). Since then, several statistical forecast models for the Ethiopian summer rains have been shown to have skill, compared to climatological forecasts (Gissila *et al*., 2004; Block and Rajagopalan, 2007; Korecha and Barnston, 2007; Diro *et al*., 2010a, 2010b). Still, Jury (2011a, 2011b) concludes that more than half of the variance in the flow in the Nile River, coming from the Ethiopian highlands, is random, in the sense that it cannot be attributed to large-scale atmospheric and oceanic patterns.

The results in this study are based on 22 summer months categorized as wet, dry, or normal, depending on whether precipitation was above, below, or within

95–105% of the monthly mean. Wet and dry months are thus not necessarily extreme, but the suite of cases illustrates some important relationships between circulation anomalies and moisture transport. Improved understanding of the flow pattern allows for a closer interpretation of the results of atmospheric circulation anomalies in other summers. The results described in Section 3 thus provide details of some of the mechanisms that make seasonal forecasting possible and also show examples of the variety of atmospheric conditions that may influence the Ethiopian summer rains. As moisture is brought into the Ethiopian highlands from various directions, atmospheric circulation anomalies that enhance the contribution from one of the transport branches often reduce the flow in other branches. This balance poses a theoretical challenge to the development of seasonal forecasts.

The relationship between Ethiopian summer precipitation and SST anomalies has been the topic of many studies, all pointing to the concurrent El Niño Southern Oscillation (ENSO) as the dominating influence, with various degrees of association found with SST patterns in the Southern Indian Ocean, the Gulf of Guinea, and the Southern and Equatorial Atlantic Ocean (Seleshi and Demaree, 1995; Korecha and Barnston, 2007; Segele *et al*., 2009a; Diro *et al*., 2010a, 2010b). The connection between such anomalies and transport of moisture to the Ethiopian highlands is discussed in Section 4.1. While the 11 year record in this study is too short for a quantitative analysis of ENSO effects, we consider the association between circulation anomalies and transport anomalies to be a useful indicator. In order to make full use of the established relationships between SST anomalies and precipitation, there is a need for more knowledge about the circulation above and around Ethiopia, both climatologically and as a response to anomalies in the large-scale climatic patterns. Section 4.2 addresses some questions related to transport anomalies that may be less predictable than those typically associated with tele-connections. Some brief comments on the magnitude of the variability in Ethiopian precipitation, as well as the use of Ethiopian precipitation data, are given in Section 4.3.

4.1. Connections between common large-scale circulation anomalies and moisture transport to the Ethiopian highlands

Relationships between Ethiopian summer precipitation and precipitation in India and the Sahel suggest that variations in Ethiopian precipitation are related to global or other large-scale regional phenomena (Flohn, 1987; Camberlin, 1997; Jury, 2011a, 2011b). The amount and intensity of precipitation in a region depends on the amount of moisture that is available and the extent to which ascent within the region leads to the formation of clouds and precipitation. Tele-connections must work through one of or both these parts of the chain. The clearest connection between far-away SST anomalies and moisture inflow to the Ethiopian highlands lies in the low-level circulation above Central Africa.

ENSO has been on the list of predictors since the first seasonal precipitation forecast was issued by the NMA. Coupled with regional synoptic patterns, ENSO indicators are used to find analog years, and observed precipitation from these years used to predict wet, dry, or normal conditions for the coming season (Bekele, 1997; Korecha and Barnston, 2007). The relationship between ENSO and Ethiopian summer precipitation is well documented. El Niño episodes are associated with dry summers in the Ethiopian highlands, and La Niñas with wet summers (Seleshi and Demaree, 1995; Eltahir, 1996; Conway, 2000; Segele and Lamb, 2005; Korecha and Barnston, 2007; Segele *et al*., 2009a, 2009b). The strongest associations have been found between precipitation and concurrent ENSO conditions, implying that prediction of the Ethiopian summer rains depend critically on the ability to predict ENSO (Korecha and Barnston, 2007).

The mechanisms through which ENSO may influence precipitation in Ethiopia have been less studied than the association itself. Using a general circulation model with increased SST in the Equatorial Pacific to represent El Niño, Diro *et al*. (2010) found a subsidence anomaly over northeastern Africa, a weakening of the monsoon trough over the Arabian Sea, a weakened Tibetan high- and upper-level TEJ (tropical easterly jet), as well as reductions in both the Somali Jet and the low-level westerlies to the southwest of Ethiopia – all features associated with dry summers in Ethiopia (Segele *et al*., 2009a). Atmospheric Rossby and Kelvin waves were suggested to transfer the signal from the Pacific to Africa (Diro *et al*., 2010a, 2010b).

Changes in the low-level circulation above Africa have also been associated with SST anomalies in the South Atlantic Ocean and the Southern Indian Ocean, although more weakly than with the Pacific SSTs (Korecha and Barnston, 2007; Segele *et al*., 2009a; Diro *et al*., 2010a, 2010b). Low SSTs in these regions are related to a strengthening of the high pressure regions near St. Helena in the Atlantic and the Mascarene Islands in the Indian Ocean, increasing the north–south pressure gradient across Africa and thus the moisture transport toward Ethiopia (Korecha and Barnston, 2007; Segele *et al*., 2009a; Diro *et al*., 2010a, 2010b). Korecha and Barnston (2007) also found that a weak association between Ethiopian summer precipitation and SSTs off the coast of West Africa near Cape Verde may reflect the effect of SST on the northward migration of the ITCZ, as moisture is drawn toward the warm pool.

The clearest link between large-scale phenomena and the moisture transport to the Ethiopian highlands goes through the low-level circulation to the west. The El Niño-related decrease in the low-level westerlies above Central Africa reduces the transport of moisture to the northern Ethiopian highlands, regardless of the previous origin of the air. La Niñas have the opposite effect (Segele *et al*., 2009a; Diro *et al*., 2010a, 2010b). As described in Section 3.4, this effect is close to consistent, with enhanced/reduced westerlies causing a net increase/decrease in the moisture availability in the highlands. This is the most important contributor to strong transport branches both from the Gulf of Guinea and from the Indian Ocean.

The effect of the low-level anomalies is more uniform for air coming from the Gulf of Guinea than for the more complex branch coming from the Indian Ocean. While westerly anomalies always act with the flow from the Gulf of Guinea, they may reduce the transport from the Indian Ocean, if the anomaly belt reaches far enough south or east. The effect on the branches from the Indian Ocean is more diverse, but in most cases, the net result is positive and contributes more to the total moisture deviation than air from the Gulf of Guinea. The net effect of westerly low-level anomalies on the transport of moisture from the continent is positive, but the degree may be altered depending on the exact location of the anomalies. Overall, the effect of westerly anomalies is to bring more moisture from Central Africa, regardless of previous origin. Any possible negative effects should be looked for in the eastward extension of the anomaly belt, as westerly anomalies above Southern Ethiopia and East Africa may reduce the inflow of moisture in the eastern Indian Ocean sub-branch.

The strength of the Somali Jet similarly influences the inflow of moisture from the Indian Ocean to the continent, as described in Section 3.4.2. However, the net effect depends on whether the anomaly represents a pure strengthening/weakening of the existing winds, or whether there are deflections away from or toward the shore. Whether changes take place in all parts or just the northern or southern part of the low-level circulation outside of East Africa also matters, as the southern part of the jet carries moisture toward Ethiopia, and the northern part away from Ethiopia.

Effects such as the El Niño-related subsidence anomaly over northeastern Africa and the reduced upper-level TEJ, most likely work through hampering convection in the region (Diro *et al.*, 2010a, 2010b). This effect may not be attributed to specific moisture transport branches, only to the total amount of incoming and outgoing moisture, as well as the degree to which incoming moisture is released as precipitation. The position and strength of the ITCZ may affect the relationship between the branches, but this influence is difficult to separate from other factors.

4.2. Contributions from other processes

Jury (2011a, 2010b) documented that two major Ethiopian flood events in July 2006 and July 2007 – the two wettest 6 d periods during 1997–2007 – occurred without any increase in the inflow from the southwest. Instead, the inflow from the north was increased due to a cyclonic mid-level circulation anomaly to the east and north of Ethiopia. Pulses of northerly wind were found to correspond with increased convection, and meridional convergence in the lower levels played a significant role. Little discussed elsewhere in the literature, this illustrates the possible consequences of atmospheric anomaly patterns that are very different from the low-level anomalies acting on the moisture transport from Central Africa. Seasonal forecasting is made more difficult by the fact that small relative changes in the large moisture transport branches cause larger deviations than large relative changes in small branches and by processes within the region.

Moisture transport from the Gulf of Guinea has the largest relative variability and may be more than doubled, as in July 1998, or almost eliminated, as in July 2002. But, as shown in Section 3.3.1, a complete cut-off of this branch cannot lead to more than a 2% (July) to 6% (August) reduction in the moisture release in the northern Ethiopian highlands. More than half of the moisture release occurs in air carried through the northern branch, and comparatively small relative changes in this branch may have much larger consequences. Even though most of the wet/dry summers months discussed in Section 3.3 occurred in connection with enhancement/reduction of moisture inflow through the southern branches, there were exceptions.

The importance of deviations in the moisture contribution from the northern branch is most prominent, not in the incoming moisture but in the subsequent moisture release within the region. When a specific amount of moisture is available in a region, the amount of precipitation depends on the efficiency with which this moisture is converted into falling water. Despite the reduced inflow from the north in half of the wet months, the moisture release in this air is higher than normal, contributing to the precipitation increase. Some dry summer months similarly show reductions in the release, but not in incoming moisture. In four of the six wet months, the branch from the north contributed more to the total increase in moisture release than air coming from the south.

This illustrates the effect of processes within the region modulating the release of moisture, such as static stability and convergence. A clear relationship between reduced precipitation in the northern Ethiopian highlands and anomalous moisture transport from the north may not be deduced from the available data. But when the moisture convergence in the highlands is decreased due to less moisture entering from the south, this may also reduce the moisture release in air coming from the north.

Previously, more attention has been given to the regions to the southwest than to the north. The presence of humid, low-level southwesterlies, together with statistical associations between Ethiopian summer precipitation and low-level circulation wind anomalies above Central Africa and to the west of Ethiopia, has made this a natural focus region (Flohn, 1987; Mohamed *et al.*, 2005; Segele *et al.*, 2009a). Westerly anomalies above Central Africa are easily documented, partly because they are related to frequently occurring global phenomena and act mainly in one direction: to increase the transport of moisture and the resulting precipitation. This does not necessarily mean that other, less systematic anomalies may not have consequences of the same magnitude. They may simply be more difficult to detect.

4.3. Precipitation variability and representativity

Despite correlations of up to −0.75 between Ethiopian July precipitation and Pacific SSTs, the devastating drought summer in 1984 occurred in an ENSO-neutral year (Korecha and Barnston, 2007). Enhanced westerlies above Central Africa, some years associated with La Niñas, bring more moisture and precipitation in Ethiopia, but the worst short-time flood episodes in a decade took place during increased moisture transport from the north (Jury, 2011a, 2010b). It is hardly surprising that not all local weather events can be attributed to large-scale, climatic patterns. The suite of wet and dry summer months described in Section 3.3 illustrates how various atmospheric conditions may affect the strength and distribution of branches transporting moisture into Ethiopia. Another reason why statistical measures may fail to capture variability is the rarity of large deviations in the amount of precipitation falling over Ethiopia during summer. Only small shifts in the circulation are required to produce comparatively large precipitation anomalies.

Inter-annual variability of precipitation in Ethiopia is relatively low (Conway, 2000). Conway and Schipper (2011) found the annual national precipitation to be within 74–119% of the mean. Comparing seasons, the variability in the spring rains, in March–May, is higher than in the summer rains, especially in the north and northeast (Cheung *et al.*, 2008). For the regional mean for the northern Ethiopian highlands used in this study, all July and August months were within 81–116% of the 1998–2008 mean (Figure 5). Extending the period to 1965–2009, using 1971–2000 as a reference, increases the range to 61–132%. The variation between different stages of the June–September summer season is much higher than the inter-annual variation (Segele *et al.*, 2009a).

The inter-annual variability at individual observation stations, and the difference between stations in the same region, may be much higher than that of regional or national averages. The rugged terrain and convective nature of the summer rains cause considerable local differences. The choice of stations does matter and different studies display different lists of wet and dry summers (Gissila *et al.*, 2004; Seleshi and Zanke, 2004; Segele and Lamb, 2005; Korecha and Barnston, 2007; Cheung *et al.*, 2008; Diro *et al.*, 2010a, 2010b; Jury, 2010). The low variability of precipitation on a regional scale, combined with large local variations, means that regional mean values will be highly dependent on the set of observations used. This adds to the challenges involved in coupling large-scale climatic patterns to Ethiopian precipitation.

5. Summary and conclusions

The Ethiopian summer rains occur as air masses carrying moisture from the Indian Ocean, the Gulf of Guinea, and the region to the north of Ethiopia converge above the Ethiopian highlands (Mohamed *et al.*, 2005; Korecha and Barnston, 2007; Segele *et al.*, 2009a; Viste and Sorteberg, 2011). Despite the net northeasterly moisture flux above the highlands (Figure 1(a)), more attention has previously been given to the transport from Central Africa (Flohn, 1987; Mohamed *et al.*, 2005; Segele *et al.*, 2009a). This study confirms the importance of moisture transport from the continent and also shows that anomalies in other transport branches may have large consequences. The atmospheric conditions affecting the transport from the north are less well understood but may be as relevant as those in the southwest.

Backtracking air parcels from the northern Ethiopian highlands in July–August 1998–2008, using the trajectory model FLEXPART, has revealed some patterns associated with wet and dry months. Wet summer months are associated with westerly anomalies in the low-level circulation above Central Africa – increasing the moisture transport from the Gulf of Guinea and in most cases also from the Indian Ocean – and with enhanced southerlies along the coast of East Africa, increasing the transport from the Indian Ocean. The contribution from the south is increased, both incoming and released moisture, in wet months and decreased in dry months. As a mean during the period studied, incoming and released moisture in air from the south was 85 and 86%, respectively, of the mean in the dry months, and 107 and 105%, respectively, in the wet months.

For the flow from the north, above the Red Sea and the Arabian Peninsula, the picture is more complex. Whether the moisture entering the highlands through this branch is higher or lower than normal varies in both wet and dry months. This is reflected in the mean moisture transport associated with this branch: 101% in the wet months and 104% in the dry months. But in most cases, the moisture release associated with air in this branch is a major contributor to the resulting precipitation anomaly, with mean values of 94% in dry months and 111% in wet months. Anomalies in convergence and ascent above the northern Ethiopian highlands affect the contribution from all branches and the large branches more than the small.

The most consistent circulation anomaly affecting the moisture transport into the northern Ethiopian highlands is westerly/easterly anomalies to the west and southwest of Ethiopia. Such anomalies influence the transport of moisture from the Congo Basin, whether the air above the basin comes from the Gulf of Guinea or from the Indian Ocean. Air coming from the Gulf of Guinea is affected uniformly by such anomalies. Westerly anomalies above Central Africa increase the amount of moisture entering Ethiopia with air coming from the Gulf of Guinea, while easterly anomalies reduce this contribution. This is the branch with the highest relative variation. In some July and August months, the amount of moisture brought into the northern Ethiopian highlands this way may be more than doubled compared to the mean, and in other months almost cut-off. But as the branch is normally small, the effect is limited. Reductions associated with this branch may not reduce the total moisture release by more than

2% (July) or 6% (August). The transport from the Gulf of Guinea was strengthened in most of the wet summer months, and similarly reduced in dry months, but only once was this the largest contributor to reductions or increases in the total inflow of moisture to the northern highlands. Deviations in other, larger transport branches played a larger role.

In most cases, westerly/easterly anomalies above Central Africa also increase/reduce the moisture transport from the Indian Ocean, but due to the more diverse paths taken by air parcels in this branch, the effect is not as uniform as for the transport from the Gulf of Guinea. Once the air is present in the region to the southwest of Ethiopia, enhanced westerlies enhance the transport into the highlands, but if the belt of westerlies extends too far south, they may impede some of the flow northwestward from the Indian Ocean across the Congo Basin. Also, if westerly anomalies are present in the Turkana Channel and along the coast of East Africa, they act against the flow of moisture from the Indian Ocean into the African continent.

Shifts in the low-level westerlies that bring moisture from Central Africa into Ethiopia have a more consistent, and thus more predictable, effect than, e.g. anomalies above the Red Sea region to the north. This does not necessarily mean that circulation anomalies in this region have smaller effects. For a complete understanding of the variability in the Ethiopian summer rains, more research is needed on the atmospheric circulation to the north and east of Ethiopia.

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