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Moisture transport into the Ethiopian highlands

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ABSTRACT: The Ethiopian summer rains occur as air masses of various origins converge above the Ethiopian plateau. In this study, the relative importance of different moisture transport branches has been estimated using the Lagrangian trajectory model FLEXPART, and ERA-Interim reanalysis data, to backtrack air reaching the northern Ethiopian highlands in July–August 1998–2008. The Indian Ocean, the Congo Basin and the Red Sea were found to be important moisture source regions; for air from the Indian Ocean aided by a considerable moisture uptake along routes across the African continent. The following main transport branches were identified: (1) Flow from the Gulf of Guinea, (2) Flow from the Indian Ocean, and (3) Flow from the north; from the Mediterranean region across the Red Sea and the Arabian Peninsula. The largest contribution to the moisture transport into, and release of moisture within, the northern Ethiopian highlands, was associated with air traveling from the Indian Ocean and from the north. This was partly due to the relatively high mean specific humidity of this air, and partly because a large proportion of the air that reaches the highlands, follows these routes. As a total, the amount of moisture brought into the highlands from the north is 46% higher than from the south, whereas the contribution to moisture release within the highlands is about equal for air coming from the south and from the north. While previous studies have emphasized the importance of the Gulf of Guinea, we find that despite the high specific humidity of the low-level flow of air from the Gulf of Guinea, the amount of moisture carried into and released within the northern Ethiopian highlands through this branch, is much smaller than from the other branches – about 1/8 of that from the Indian Ocean. This is due to the fact that normally only a small proportion of the air reaching Ethiopia comes from the Gulf of Guinea. Copyright © 2011 Royal Meteorological Society

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

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1. Introduction

With annual rainfall amounts exceeding 2000 mm, the Ethiopian highlands represent a water tower in the drought-prone Horn of Africa (Griffiths, 1972). The northern hemisphere summer constitutes the main rainy season in most of Ethiopia, as air masses carrying moisture from various continental and oceanic sources, converge and ascend above the Ethiopian mountain plateau (Mohamed *et al*. 2005; Korecha and Barnston, 2007; Segele *et al*. 2009). In the Ethiopian highlands, rainfall during the months June–September accounts for 50–90% of the annual precipitation (Griffiths 1972; Korecha and Barnston, 2007). The intensity of the rains depends on the amount of moisture brought into or recycled in the region, and the extent to which ascent within the region leads to the formation of clouds and subsequent precipitation. This study will focus on the first of these factors – the transport of moisture into the northern Ethiopian highlands during the northern hemisphere summer.

Maps of the vertically integrated moisture flux (Figure 1) show two regions of strong inflow to 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, from the north and northeast, is associated with moisture convergence and rainfall in the Ethiopian highlands. Its direction is in accordance with Gimeno *et al*. (2010), who found that evaporation from the Mediterranean Sea, and especially from the Red Sea, are important contributors to Ethiopian summer precipitation.

Despite the northeasterly flux of moisture above Ethiopia, more attention has been given to the regions to the south. Several studies have commented on the effect of SST and pressure anomalies in the Gulf of Guinea and the Indian Ocean on the moisture flow toward Ethiopia (Korecha and Barnston, 2007; Segele *et al*., 2009; Diro *et al*., 2010). The moisture brought in from the south and southwest is recognized as having its origin both in the Atlantic and Indian Oceans as well as in Central Africa and the Congo Basin. Assumptions of Atlantic Ocean dominance seem to prevail, likely dating back to Flohn's (1987) map of southwesterly moisture transport across Africa in July–August. Similarly, Mohamed *et al*., (2005) refer to moisture fields and wind patterns at altitudes up to 700 hPa when concluding that 'moisture over the Ethiopian Plateau is largely originated from the Atlantic Ocean, and to a lesser extent from the Indian

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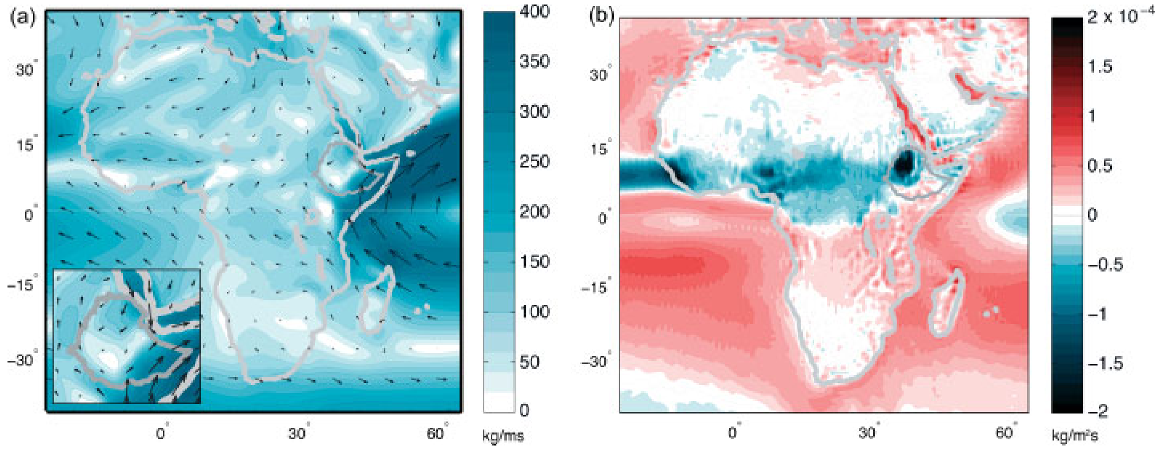

Figure 1. ERA-Interim vertically integrated (surface to top of atmosphere) moisture flux (a) and moisture flux divergence (b) in July–August 1989–2008. Ethiopia is outlined in grey.

Ocean'. Statistical correlations between Ethiopian summer precipitation, and pressure and SST anomalies in the Atlantic Ocean, as well as westerly low-level wind speed anomalies to the west of Ethiopia, may be interpreted as supporting this theory (Segele *et al*., 2009). However, moisture transport per se is not the subject of any of these studies, and the relative importance of the different branches of the flow in carrying humidity toward Ethiopia, has not been quantified.

A satisfactory explanation as to why the net moisture flux above the Ethiopian highlands would be northeasterly if most of the moisture was brought in from the south, is also missing. It has been suggested that the flux from the north may be mainly of southern origin; the result of moisture of Atlantic origin being lifted over or around the Ethiopian plateau, and then transported southwestward (Mohamed *et al*., 2005). As seen in Figure 1(a), the northern flux does have a component coming from continental Africa, passing northward to the west of Ethiopia, before turning southward. The possible role of weather systems propagating westward from the Rift Valley or the highlands of Yemen has also been highlighted (Segele and Lamb, 2005).

This study aims to describe and quantify the climatology of the moisture transport into the Ethiopian highlands in the summer rainy season, with emphasis on July and August, as these are the wettest months in all parts of the plateau (Gissila *et al*., 2004; Korecha and Barnston, 2007; Diro *et al*., 2009). The relative contribution from air entering Ethiopia from the north, across the Red Sea and the Arabian Peninsula, will be compared to the southern flow, of Atlantic and Indian Ocean origin.

As in Gimeno *et al*. (2010), the Lagrangian trajectory model FLEXPART (Stohl *et al*., 2005), is used. The greatest challenge when interpreting moisture transport from wind maps lies in determining the actual path taken by the air. Strong westerlies to the west of Ethiopia do not guarantee that this air will end up in Ethiopia. The Lagrangian approach allows air parcels reaching Ethiopia to be traced back in time, making it possible to determine their route, and to single out only those effects that have relevance for air entering the region. As a result, it is possible, not only to quantify the amount of moisture carried through different branches of the flow, but also to estimate the potential contribution from this moisture to precipitation in the region.

An overview of the region and the relevant circulation features is given in Section 2. Section 3 describes the general FLEXPART methodology and the data, whereas all further details of the analysis are presented together with the corresponding results in three sections: Section 4 contains an overview of the transport of mass and moisture into the northern Ethiopian highlands, with moisture source regions discussed in Section 5. A quantitative analysis of the different transport branches is presented in Section 6. A final summary is given in Section 7.

2. Background

2.1. The northern Ethiopian highlands

Ethiopia (Figure 2) is located within 3–15°N, 33–48°E and constitutes the northernmost part of the Rift Valley system. The elevation ranges from 135 m below sea level in the dry Denakil depression in the northeastern lowlands, to 4533 m above sea level (m.a.s.l.) on Ras Dashen in the northern highlands. The Ethiopian plateau is sharply delimited by pronounced escarpments, and divided by the Rift Valley, running southwest–northeast.

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. This is a region covering 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 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. The borders were defined with the purpose of enclosing a region with a homogeneous climate regime, with respect both to

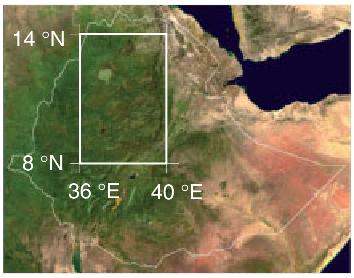

Figure 2. Satellite photo of the Horn of Africa, with Ethiopia outlined in white. The box marks the region 8–14°N, 36–40 °E. (Data source: NASA/www.maplibrary.org).

atmospheric circulation and to rainfall (Griffiths, 1972; Gissila *et al*., 2004; Korecha and Barnston, 2007), and at the same time not being too small compared to the resolution of the ERA-Interim data (Section 3.1).

2.2. The summer circulation around Ethiopia

The variations in Ethiopian climate during the year are largely associated with large-scale pressure changes and the monsoon flow related to these changes. The most important factors influencing Ethiopian summer rainfall are indicated in Figure 3, showing the mean atmospheric circulation in July. The surface level Intertropical Convergence Zone (ITCZ) is located north of Ethiopia throughout the summer, and convergence above the Ethiopian plateau occurs as humid air from the south meets air flowing in from the mainly dry regions to the north and northeast, as well as from the Red Sea (Figure 3(a)). Above this, the strength of the Tropical Easterly Jet (TEJ) at 200 hPa (Figure 3(c)) and higher, has been associated with enhanced precipitation in Ethiopia, linked to upper-level divergence promoting convection (Hastenrath, 2000; Grist and Nicholson, 2001; Nicholson and Grist, 2003; Segele *et al*., 2009).

The most prominent pressure features are the anticyclonic systems centred above St Helena and the Mascarene Islands, and the low-pressure trough overlying North Africa, and the Arabian Peninsula (Figure 3(a)). The Mascarene anticyclone is coupled to a weak, semi-permanent surface ridge, extending through the Mozambique Channel to the Ethiopian highlands. This ridge appears to limit the southern range of the ITCZ during the summer (Segele *et al*., 2009). The St Helena high is centred in the subtropical southern Atlantic Ocean, extending into the Gulf of Guinea. This anticyclone is responsible for the low-level flow through Central Africa, affecting the western part of Ethiopia and East Africa (McGregor and Nieuwolt, 1998; Sun *et al*., 1999).

The circulation over the Horn of Africa is linked to the Indian summer monsoon (McGregor and Nieuwolt 1998). Below 3 km, as seen in Figure 3(a) and (b) the strongest winds are found in the Somali Jet, also called the East African low-level jet. This is a system of low-level jets, extending from east of Madagascar, across the flat lands of eastern Kenya, Ethiopia and Somalia, across the Indian Ocean to India (Findlater, 1969, 1977). The jet induces considerable low-level divergence, resulting in dry summers and arid land in Somalia and eastern Ethiopia (Flohn, 1987).

At the same level as the Somali Jet, the Turkana Jet crosses westward through the dry Turkana Channel. The main forcing of this strong, easterly, all-year wind is orographic, as the air is led between the mountains of southern Ethiopia and northern Kenya (Kinuthia and Asnani, 1982; Kinuthia, 1992; Indeje *et al*., 2001). In the summer season, the Turkana Jet may be considered a branch of the Somali Jet, though a full documentation of the relationship between the two systems is still lacking (Vizy and Cook, 2003; Riddle and Cook, 2008).

Two distinct confluence zones may be identified near Ethiopia during the summer months. Over Eritrea and the northernmost part of Ethiopia, wind convergence is largely associated with the ITCZ, as its southernmost boundary reaches 15°N at the 1000 hPa level (Segele *et al*., 2009). Another zone is located further south, above the Rift Valley and Djibouti. At 1000 hPa, this confluence is mainly related to the trough above the Arabian Peninsula. At 850 hPa, the monsoon trough confluence dominates much of the northern two-thirds of Ethiopia (Segele *et al*., 2009). This confluence zone

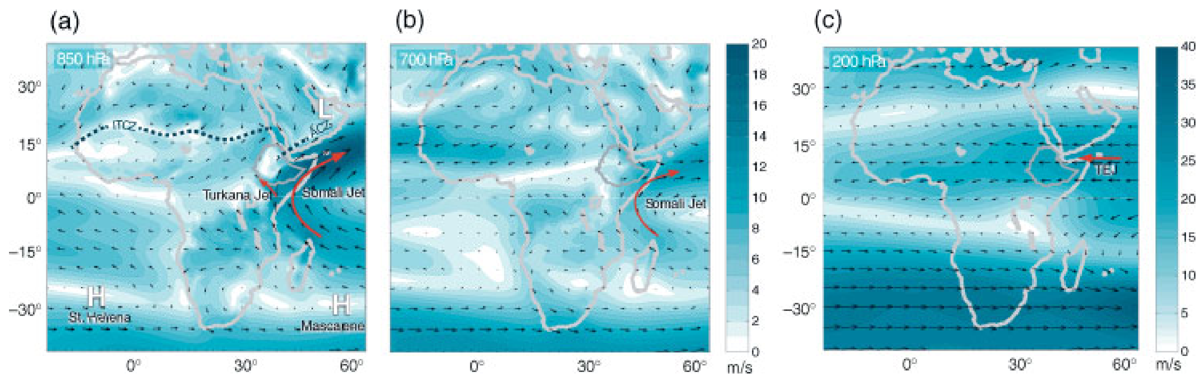

Figure 3. ERA-Interim mean wind in July 1989–2008 at (a) 850 hPa, (b) 700 hPa, and (c) 200 hPa. Ethiopia is outlined in grey. H/L indicates high/low pressure centre at sea level. In (a), ITCZ is the Intertropical Convergence Zone and ACZ the Afar Convergence Zone, both at 1000 hPa. TEJ (c) is the Tropical Easterly Jet. Owing to the high elevation of northwestern Ethiopia, 850 hPa winds are not representative of the low-level circulation there.

is part of the Afar Convergence Zone (ACZ), forming as moist northwesterlies converge with the monsoon southwesterlies over the southern Red Sea and the Gulf of Aden (Tucker and Pedgley, 1977). Reanalysis maps of vertical wind (not shown) show a general ascent at all levels up to above 200 hPa over the Ethiopian highlands.

Segele *et al*. (2009) found associations between positive summer rainfall anomalies in Ethiopia and most of the features that are dominant for the season, e.g. an increased north–south pressure gradient across the African continent, increasing the low-level cross-equatorial flow through Central Africa; a stronger Somali Jet, indicating a strengthened monsoon system, and an increase in the upper-level Tropical Easterly Jet. Also, correlations with concurrent SST anomalies in the Pacific, Indian and Atlantic Oceans have been documented (Korecha and Barnston, 2007; Segele *et al*., 2009; Diro *et al*., 2010).

3. Data and tracking methodology

The Lagrangian trajectory model FLEXPART (Stohl *et al*., 2005) was used to backtrack air parcels from a region in the northern Ethiopian highlands, using ERA-Interim (Berrisford *et al*., 2009) reanalysis data as input. The resulting trajectories were then analysed with the main purpose of studying the transport of moisture into the region, as well as the moisture uptake in the air along the routes taken. This section describes the input data and the methodology used for backtracking air parcels. The specific methods used for analysis of the various output parameters (mass, specific humidity and humidity uptake/release) are described in the relevant sections.

3.1. ERA-Interim

Wind, temperature and specific humidity data from the ERA-Interim reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used as input to FLEXPART. ERA-Interim is produced at a resolution of about 0.75° latitude and longitude, with 60 vertical levels, and a 4D variational assimilation system (Simmons *et al*., 2006; Uppala *et al*., 2008; Berrisford *et al*., 2009). In FLEXPART simulations, the number of air parcels used should not be lower than the number of grid cells in the input data (Stohl and James, 2004). In order to avoid the computational cost of increasing the number of parcels, the spatial resolution of the ERA-Interim data used with FLEXPART was reduced to 2° latitude and longitude.

The ERA-Interim vertically integrated moisture fluxes used in Figure 1, were calculated by the Climate Analysis Section at the National Center for Atmospheric Research (NCAR), using methods described in (Trenberth *et al*., 2002).

3.2. FLEXPART

The Lagrangian trajectory model, FLEXPART (Stohl *et al*., 2005), is a tool for tracing air based on gridded data from weather forecasting 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 was originally developed for calculating the dispersion of air pollution (Stohl *et al*., 2005), but has been used in several studies of moisture transport worldwide, both for the investigation of single events and climatologically (James *et al*., 2004; Stohl and James, 2005; Stohl, 2006; Nieto *et al*., 2007; Drumond *et al*., 2008; Nieto *et al*., 2008; Stohl *et al*., 2008; Gimeno *et al*., 2010).

FLEXPART may be run with a limited number of particles, or air parcels, released within a limited geographical boundary, or with the global atmosphere divided into a specified number of parcels, filling the atmosphere completely. The parcels are then allowed to move with the input dataset 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 taken from the gridded input data and interpolated to the parcel positions.

To account for updrafts in convective clouds, FLEXPART uses a version of the convective parameterisation scheme by Emanuel and Živković-Rothman (Emanuel and Zivkovic-Rothman, 1999). The implementation of the scheme is described by Forster *et al*. (2007), finding the convection scheme in FLEXPART to reduce 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 result is interpreted as positive. For the Ethiopian highlands, their results indicate a slightly higher upward convective mass flux in the ECMWF convection scheme than in the FLEXPART convection scheme. As their test was performed in October, which is mostly dry in the northern Ethiopian highlands, there is limited information about the performance of the convection scheme during heavy precipitation in this region, as may occur during summer.

In this study, FLEXPART was run globally with 1 000 000 air parcels for the continuous period 1998–2008 using winds, temperature, specific humidity, and various surface and topographic parameters from the ERA-Interim reanalysis. This period was chosen so as to include the most recent 11 years of the reanalysis, limited mainly by computational resources. Data for every 3 h were used as input, and output data saved for every 6 h. All parcels present in the northern Ethiopian highlands at any time were then backtracked 80 time steps (20 days), neglecting air parcels above the tropopause. Segments of 15 or 20 days were used in different parts of the analysis, as discussed in the relevant sections.

In all plots of gridded data, each grid cell represents the mean daily value of parcels present in this air column 1–15 days before reaching the boxed *target* region in the northern Ethiopian highlands. The maps thus represent

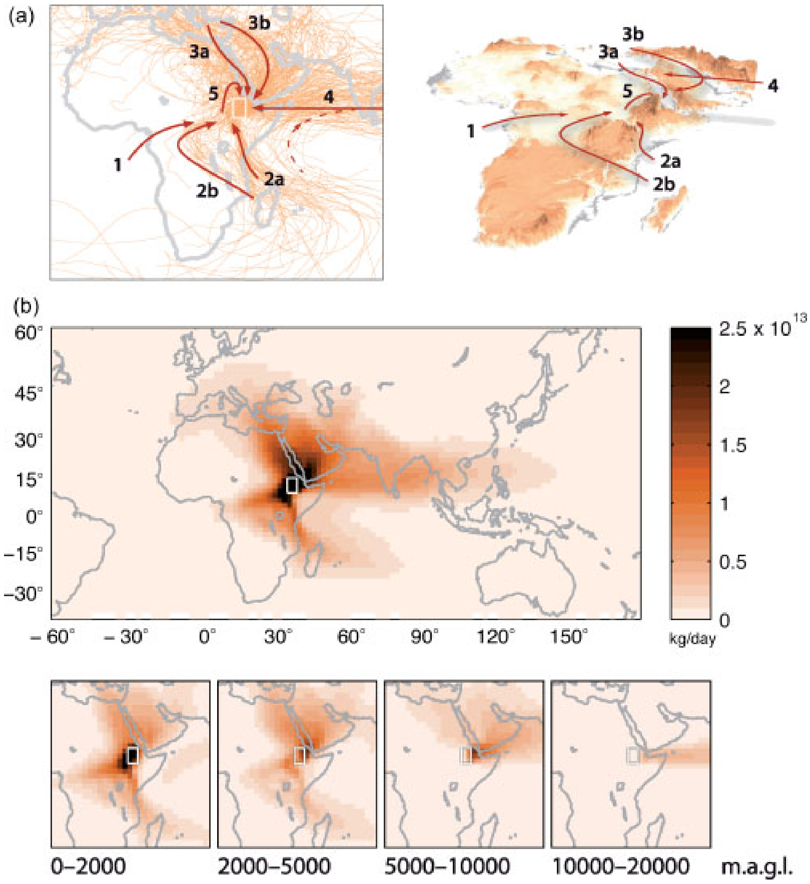

Figure 4. Air reaching 8–14°N, 36–40 °E (white box) in July–August 1998–2008. a) Random subset of 300 (≈0.3‰) trajectories of air parcels backtracked 15 days, with arrows marking branches referred to in the text. The map to the right shows the same branches relative to topography (Elevation data: GTOPO30, http://eros.usgs.gov). b) Mean daily mass (kg) 1–15 days before the air enters the region. Large map: All levels. Small maps: Same data classified by height (m.a.g.l.). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

the potential contribution of air, with its properties, to the target region from other geographical regions. The term *target-bound* will be used to describe air parcels that travel to the target region.

4. Transport of air and moisture

Air transport into the northern Ethiopian highlands in July–August 1998–2008 is shown in Figure 4. To illustrate the movement of air, Figure 4(a) contains a random subset of 300 trajectories of air parcels, backtracked 15 days from the boxed target region. The main branches of the flow reflect the general regional circulation (Figure 3), with upper-level easterlies, mid-level northerlies and northeasterlies, and low-level inflow from the south.

The main branches analysed are (labelled as in Figure 4): (1) The flow from the Gulf of Guinea, (2) The flow from the Indian Ocean, (3) The flow from the north and northeast above the Red Sea and the Arabian Peninsula, and (4) The upper-level flow from the east. The branch coming from the Indian Ocean is further divided into the sub-branches 2a flowing directly toward Ethiopia above the Great Lakes or through the Turkana Channel, and 2b crossing Central Africa westward before turning northeast and reaching the highlands from the southwest. Arrow 5 represents southern-origin air that continues around the highlands before entering the target region from the north.

The density of parcels/trajectories is a measure of the mass contribution to the air entering the target region, as the mass of individual parcels is similar. For 90% of the parcels used in the global simulation, the mass of the individual parcels differed by less than 1.5%, and for 99% of the parcels by less than 4.4%. Figure 4(b) shows the daily mean mass of target-bound air during the last 1–15 days before the air enters the target. It is thus a quantification of the flow pattern and the branches indicated by the trajectories (Figure 4(a)).

Two factors may lead to a large amount of moisture being transported into a region. Either the air must be humid, or the flow must be strong, carrying a larger, and possibly drier, mass of air. The moisture content of the target-bound air is shown in Figure 5. This is the product of the mass (Figure 4(b)) and the specific humidity (Figure 6). The moisture content represents the potential moisture contribution to the target region from the air in other regions. Whether this is representative of the actual inflow of moisture into the highlands will be discussed in the next section. The main contribution to the

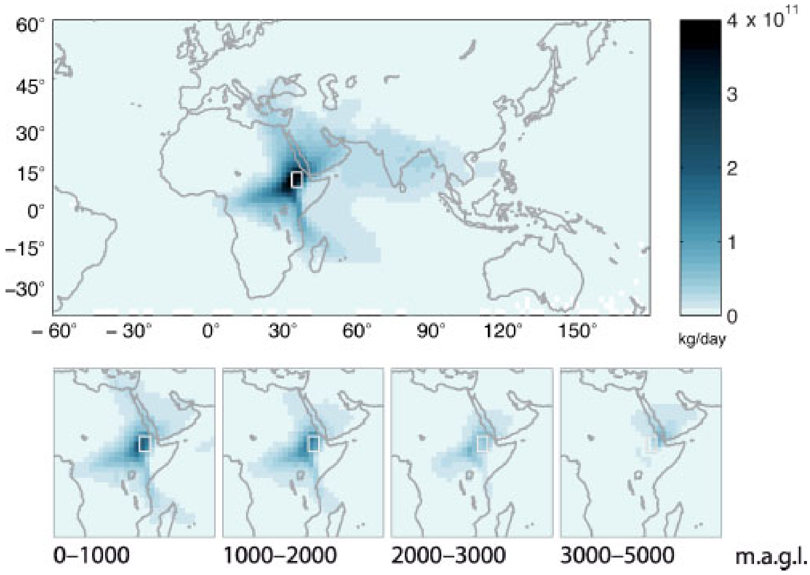

Figure 5. Mean daily moisture content (kg) of air 1–15 days before reaching 8–14°N, 36–40 °E (white box) in July–August 1998–2008. Large map: All levels. Small maps: Same data classified by height (m.a.g.l). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

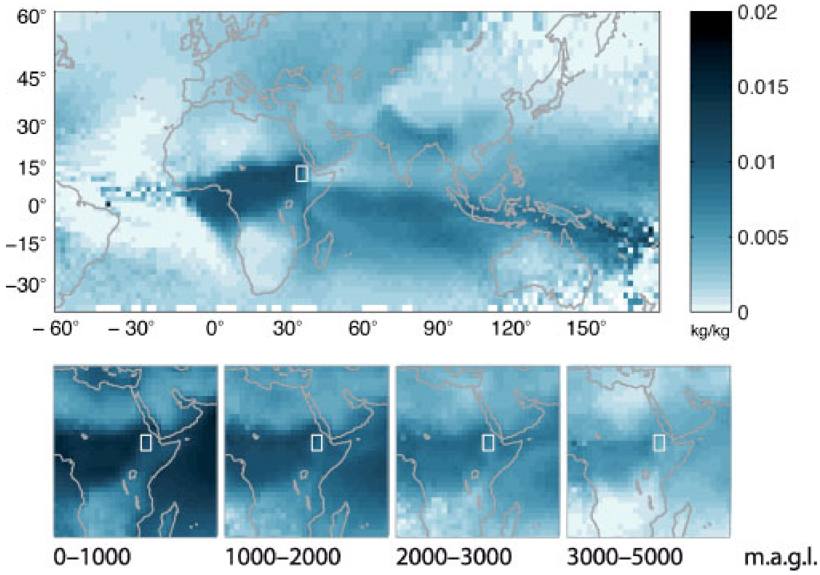

Figure 6. Mean specific humidity (kg/kg) of air 1–15 days before reaching 8–14°N, 36–40 °E (white box) in July–August 1998–2008. Large map: All levels. Small maps: Same data classified by height (m.a.g.l). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

total amount of moisture (Figure 5) flowing toward the northern Ethiopian highlands comes from the continent to the south, with a moderate transport of very humid air at low altitudes; and from the north and northeast, with a large transport of air at various levels of altitude and humidity.

As seen in the trajectory map (Figure 4(a)), most of the air entering the northern Ethiopian highlands via the African continent to the south comes from the Indian Ocean, despite its southwesterly entry direction suggesting an Atlantic origin of the air. The flow through the Turkana Channel, between the Ethiopian highlands and the mountains in northern Kenya and Uganda, may be seen as a clearly defined branch (arrow 2a in Figure 4(a)). Some air parcels enter the highlands directly from the south, releasing moisture during the ascent, whereas most of the air will follow the flow around the mountain plateau. The remaining southern trajectories are more dispersed, some air parcels travelling all the way to the Atlantic side of the continent before turning northeastward (arrow 2b). There is also a small contribution to this flow from the Gulf of Guinea (arrow 1). As the target-bound air above the Gulf of Guinea and Central Africa is concentrated at lower levels of the atmosphere (Figure 4, lower panels), the specific humidity (Figure 6) of air from this region is higher than for any other air mass reaching the northern Ethiopian highlands. The sharp edge between regions of high and low specific humidity (Figure 6) in the Gulf of Guinea, marks the maximum travel length of low-level air during the 15 days that the air parcels were backtracked. The much drier regions farther out in the South Atlantic Ocean are associated with higher-level air continuing eastward across the southern tip of Africa, later reaching Ethiopia from the Indian Ocean, as seen in the trajectory map (Figure 4(a)).

The moisture transport into the Ethiopian highlands from the north has three main components: Air coming from the Red Sea (arrow 3a, Figure 4(a)), the Arabian Peninsula (arrow 3b), and air coming from the south (arrow 5). As shown in Figure 4(b) the flow above the Red Sea and the Arabian Peninsula occurs at all levels below 10 000 m above ground level (m.a.g.l.), with increasing dominance of the regions to the northeast with increasing altitude. The specific humidity (Figure 6) of the air above the Arabian Peninsula is low, but as the mass transport (Figure 4(b)) is high, there is a notable amount of moisture (Figure 5) brought into the highlands this way. As opposed to transport from most other regions, the reduction of the specific humidity (Figure 6, lower panels) with height up to 5000 m.a.g.l. is low, and transport at any altitude carries roughly the same amount of moisture.

Owing to the large range in altitude (Figure 4(b), lower panels) of air parcels coming from the north, low-level, very humid air rising from the Red Sea toward the northern Ethiopian highlands is masked by drier air at higher levels. Globally, the Red Sea is the ocean basin with the highest net evaporation, of more than 1300 mm/year (Stohl and James 2005), and the specific humidity of air parcels 1–1000 m.a.g.l. above the southern Red Sea is close to the same level as above the most humid parts of the African continent.

As seen in the 850 hPa wind field (Figure 3(a)) and in the trajectory map (Figure 4(a), arrow 5) there is a strong low-level flow from the south around the northwestern part of the Ethiopian mountain plateau. As this air meets the predominant northerly flow north of the ITCZ, it curves around the plateau. Ascent will also contribute to this turning; as seen in Figure 3(b), the 700 hPa winds are northerly both above and to the west of the northern Ethiopian highlands. The vertically integrated moisture flux (Figure 1(a)) indicates that this contributes to the northerly transport of moisture into the northern Ethiopian highlands. An estimate of the relative size of this contribution will be given in Section 6.

Upper-level air entering Ethiopia from the east is very dry (Figure 6), contributing only negligibly to the transport of moisture into the highlands (Figure 5) despite the large amount of air following this path (Figure 4). Air that is originally part of the low-level Somali Jet, in some cases rises with the convection over the Arabian Sea or India, and then follows the upper-level, easterly flow toward Ethiopia (arrow 4, Figure 4(a)).

All results shown are from July and August. In June and September (not shown) the transport of air from Central Africa, whether of Atlantic or Indian Ocean origin, is drastically reduced. Moisture transport from the Indian Ocean occurs mainly in a narrow branch through the Turkana Channel, partly continuing around the mountain plateau and entering from the western side.

5. Moisture uptake and source regions

5.1. Calculating moisture uptake from FLEXPART data

For a specific region to be a source of moisture for another region, three criteria must be satisfied: moisture must be picked up over the source region; this needs to travel to the target region without being released en route; then discharge its load within the target region. A method for calculating FLEXPART moisture transport between regions is outlined in (Stohl and James, 2004) and (Stohl and James, 2005). In assuming that water that precipitates over any region has spent a specific period of time in the atmosphere after evaporating from the ground, it is possible to estimate its origin by back-tracking the air for periods of this length.

FLEXPART output includes the specific humidity, q, for each air parcel for each time step. Following a single-parcel trajectory, this may be used to calculate the change in moisture content with time

$$e - p = m\frac{dq}{dt} \tag{1}$$

where m is the mass of the parcel, and e and p are the rates of moisture increase and decrease, respectively.

Integrating $e - p$ over all particles N residing over an area A, gives

$$E - P \approx \frac{\sum_{i=1}^{N}(e-p)_i}{A} \tag{2}$$

where $E - P$ represents the total moisture flux of parcels in the air column above A: The difference between evaporation into the air and precipitation from the air, is calculated as the change in specific humidity from one time step to the next.

This method does not diagnose E and P individually, but by assuming instantaneous rates of evaporation $E_i = E - P$ when $E - P > 0$ and precipitation $P_i = E - P$ when $E - P < 0$, this can be estimated. The justification for doing so is that evaporation and precipitation can be assumed not to coexist at the same time in the same place. Precipitation occurs on 6% of the globe at any given time (Trenberth *et al.*, 2003), whereas, evaporation will, to some extent, occur everywhere all the time. However, during rainfall, the amount of water falling clearly exceeds that which evaporates. Thus, it is meaningful to consider only one of them as occurring at any given time. Stohl and James (2005) recommends limiting this procedure to strong precipitation events. As precipitation estimates were not used for comparison in this study, separation of E and P was not needed; only the net change in specific humidity of the air, represented by the difference $E - P$.

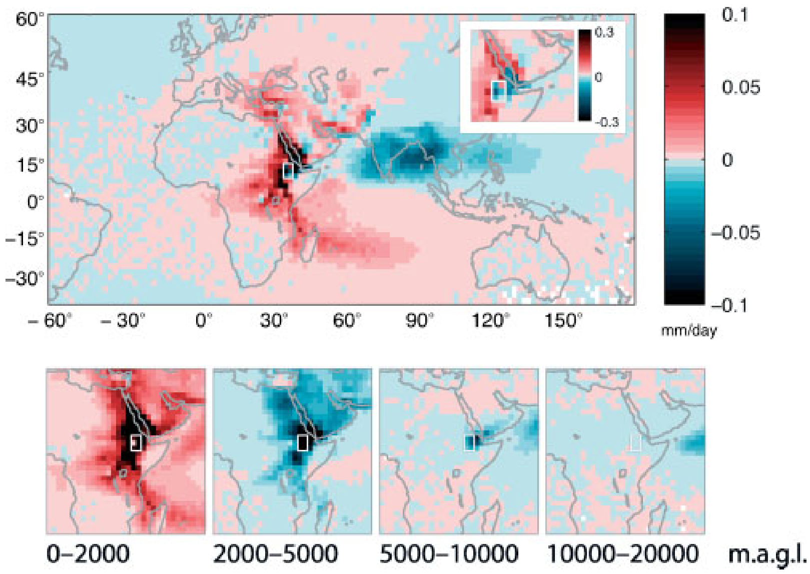

Figure 7. Mean daily $E - P$ of air 1–15 days before reaching 8–14°N, 36–40°E (white box) in July–August 1998–2008. Red (positive) indicates uptake of moisture, blue (negative) release of moisture. The large map shows the total for all heights. The inset figure shows the same data plotted with a tripled colour scale, to facilitate interpretation of the pattern around Ethiopia and the Red Sea. In the small maps the same data have been classified according to height (m.a.g.l.). When a parcel changes height class from one time step to the next, its $E - P$ contribution is attributed to its final height class.

Stohl and James (2004) point to certain problems with this procedure, mainly related to the fact that liquid water and ice have been neglected. This implies that all condensed water is considered to precipitate out immediately, so that phase changes in clouds are not included in the estimates of $e - p$. There are two cases where this may produce errors. The most important is an overestimation of both P and E if the two are separated. This is not relevant for this study, as no separation was performed. If cloud water or ice is transported across grid-column boundaries before evaporating, the estimates of instantaneous evaporation and precipitation as well as $E - P$ for the individual columns will be affected. Stohl and James (2004) classifies this as a relatively minor problem. Another problem mentioned is interpolation or trajectory errors leading to a high bias for $e - p$ values. Among the many parcels in each air column, this will be averaged out.

5.2. Moisture uptake in target-bound air

Daily mean $E - P$ of air entering the boxed target region in July–August 1998–2008 is shown in Figure 7 for a backtracking period of 15 days. Red color represents a net increase in the specific humidity of the air, whereas blue represents a net decrease. This may be interpreted as regions of net moisture uptake (red) and drying (blue) in air that later enters the northern Ethiopian highlands. As the parcels present above each grid cell do not represent the full column, positive or negative values do not necessarily indicate net evaporation or precipitation in this cell. Red color merely indicates that the target-bound air increases its moisture content at this point, whereas blue color indicates moisture loss.

The most notable feature in the $E - P$ map is the continuous uptake of moisture along the routes leading to the northern Ethiopian highlands from the African continent and the region around the Red Sea. Whether the air travels from the Gulf of Guinea, the Indian Ocean, or the Mediterranean Sea, its moisture content will continue to increase as the air approaches Ethiopia.

It is important to note that whether regions with positive (negative) $E - P$ may be interpreted as true moisture sources (sinks) depends on whether the air undergoes subsequent changes before reaching the highlands. As the map represents all $E - P$ changes during the 15 days before the air enters the target region, air taking up or releasing moisture in one region may later experience changes that reduce, or even reverse, this effect. An alternative approach which takes into account these changes is described in Sodemann *et al.* (2008). In both approaches, an increase in an air parcel's $e - p$, and thus the column's $E - P$, may occur either because the specific humidity in a region increases from one time step to the next, or because an air parcel moves – horizontally or vertically – from a drier region into a region where the specific humidity is higher. A change in the specific humidity of parcels traveling at high altitudes is mainly a result of ascent or descent. To be able to pinpoint true ground moisture source regions, $E - P$ maps must be considered together with altitude changes (Figure 8) and ground evapotranspiration, represented by the surface flux of latent heat in Figure 9.

That the African continent south of the equator is an important source region for Ethiopian summer rainfall, is supported by the findings of Gimeno *et al.* (2010). Maps of altitude change/vertical velocity (Figure 8) indicate that, while there is a contribution from descent of air above eastern Africa, the positive $E - P$ (Figure 7) along the paths crossing the African continent, whether from the Indian Ocean or the Gulf of Guinea, is due to evaporation

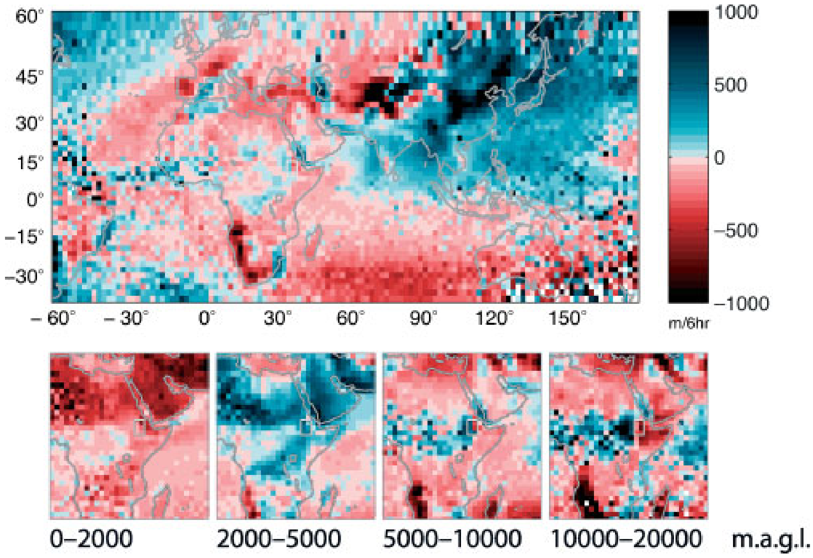

Figure 8. Mean 6-h altitude change of air 1–15 days before reaching 8–14°N, 36–40 °E (white box) in July–August 1998–2008. The scale corresponds to a vertical velocity range of +/− 0.046 m/s. Large map: All levels. Small maps: Same data classified by height (m.a.g.l.).

from the ground. Above Central Africa, where the continental evaporation (Figure 9) is the highest, there is only a minor effect of vertical displacement on E−P. Thus, the Indian Ocean, the Gulf of Guinea, and Central Africa may be considered to be true sources of moisture for the northern Ethiopian highlands. As seen from the map of specific humidity (Figure 6), the air flowing westward from the Indian Ocean, and crossing the continent before continuing northeastward, increases its moisture content substantially above Central Africa, more so than the already very humid air from the Gulf of Guinea. When entering the border of the target region in the Ethiopian highlands, the specific humidity of these air masses is the same, whether of Indian or Atlantic origin.

To the north, the Red Sea is characterized by sinking air (Figure 8) in the northern half, and rising air in the southern part, in association with the ITCZ (Figure 3(a)). The sinking in the north brings mid-level air from the Mediterranean down into the planetary boundary level, where it picks up moisture before reaching Ethiopia. In the southernmost part of the Red Sea, and to the east of the target region (small inset map in Figure 7) the air loses moisture as it ascends in association with the ITCZ and the Afar Convergence Zone, as well as upon reaching the mountains of Eritrea and Ethiopia. There is also a net decrease in specific humidity in the target region itself, representative of the summer rains.

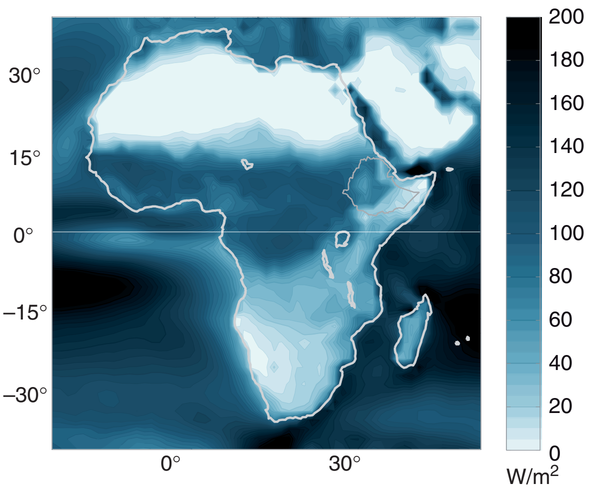

Figure 9. ERA-Interim surface latent heat flux (W/m^2) for July–August 1989–2009.

Above the Mediterranean Sea, descent at all levels (Figure 8) contributes to positive $E - P$ values (Figure 7), together with evaporation from the ocean into the low-level air (Figure 9). The positive $E - P$ values seen above the Arabian Peninsula are due only to descent below 2000 and above 5000 m.a.g.l (Figure 8, lower panels). As seen in Figure 9, ground evaporation is negligible except in the mountainous coastal regions, and the peninsula may not be considered a source region in the sense of bringing new moisture into the air. Above Turkey and the Balkans, both evaporation and sinking contribute to increasing the specific humidity of the parcels.

The most abrupt negative changes in the moisture content of air parcels occur as a result of convection, as is clearly indicated by the blue fields above southern Asia in Figures 7 and 8. The Indian and southeast Asian monsoon regions are the only main regions in which the air loses moisture before reaching the northern Ethiopian highlands. In these regions, the air rises and releases precipitation before continuing toward Ethiopia as part of the upper-level, dry, easterly flow (arrow 4 in Figure 4(a)). This flow includes low-level air that follows the Somali Jet northeastward from the ocean to the east of Somalia and Kenya, then ascends above the Arabian Sea or India, thereby releasing moisture. Despite the original moisture uptake, indicated by the red field, this part of the Indian Ocean may not be considered a moisture source region for the northern Ethiopian highlands.

Most previous studies have used tracking periods of 10 days (Stohl and James, 2005; Nieto *et al*., 2006; Gimeno *et al*., 2010), which is close to the mean residence time for water in the atmosphere (Trenberth, 1998, 1999; Numaguti, 1999). In this study, a period of 15 days was chosen for the gridded analysis. The main reason for extending the period was that – as demonstrated in Section 6.2.1 – the air in the southern branches may take more than 20 days to cross the African continent from the Atlantic or Indian Ocean. This low-level air contributes a substantial part of the moisture inflow to the Ethiopian highlands and travels partly through regions where there is very little precipitation during the northern hemisphere summer. It should be noted that beyond 10 days, trajectory calculation errors are known to increase (Stohl, 1998).

The only major difference from using a period of ten days is that each air parcel is back-tracked for five more days, extending its travel distance. This results in a small net increase in the uptake at the beginning of each branch; i.e. in the Gulf of Guinea, and in the first part of the Indian Ocean branch crossing the African continent (arrow 2b in Figure 4(a)), in a band starting in central parts of the Indian Ocean, and continuing to the western coast of Africa. There is also an increase in the eastern part of the Mediterranean Sea. For all these branches, there is a continuous net increase in moisture as the air approaches Ethiopia (Figure 7). The air coming from the Indian Ocean through the dry Turkana Channel (Figure 4(a), arrow 2a), south of the Ethiopian highlands, will also maintain its moisture content. In the belt south of the equator, rainfall is low in the Northern Hemisphere summer. Thus, it is reasonable to assume that most of the moisture that is picked up over the Indian Ocean remains in the air while crossing the continent westward. Meeting the branch from the Gulf of Guinea and crossing northeastward through the summer rain belt, more recycling of the moisture must be assumed. Ent and Savenije (2011) calculated an annual mean recycling period of 7 days in this region, with shorter time-scales during the Northern Hemisphere summer, but the heavy recycling in this region will influence the results similarly whether the tracking period is 10 or 15 days.

6. Quantifying branch-specific moisture contributions

As seen in the trajectory and mass transport maps (Figure 4), the transport of air into the northern Ethiopian highlands may be considered the sum of a few separate branches. The relative contribution from each branch to the total rainfall, depends both on the amount of moisture brought into the region, and on how much of this moisture is released in the region.

In order to quantify the relative contribution from each branch, air parcels were grouped according to their travel paths. The labels were kept as in Sections 4 and 5, i.e.: (1) the Gulf of Guinea, (2) the Indian Ocean, (3) the north, and (4) the east. A separate analysis was performed on the flow crossing the African continent, either 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). Also, the combined effect of all branches entering via the continent to the south of Ethiopia was studied (6).

6.1. Classifying air parcels into branches

Air parcels belonging to each branch were selected on the condition that they must have crossed two geographical lines from specific directions. The first line was chosen to ensure that the parcels came from a certain region (e.g. the Gulf of Guinea or the Indian Ocean), and the second used to eliminate stray parcels taking, often upper-level, paths outside of the branch in question. The purpose of the lines was merely to allow the identification of parcels following each of the previously observed paths, the exact position of the lines being otherwise irrelevant. Several alternative lines were tested, and those lines identifying the highest number of trajectories following the selected paths, while including as few misplaced parcels as possible, were chosen.

In order to assess the potential contribution to precipitation for each branch, the relative difference between their moisture content at the last time step in the target region and their moisture content at the last time step before entering, relative to the corresponding moisture change for all parcels passing through the target, was calculated. The percentage of released moisture that can be attributed to the parcels in each branch is given by

$$\Delta(mq)_{b,target} = 100 \times \frac{\sum_{i=1}^{n_b} m_i[(q_{b,border})_i - (q_{b,end})_i]}{\sum_{j=1}^{n_{total}} m_j[(q_{border})_j - (q_{end})_j]} = 100 \times \frac{\Delta(mq)_b}{\Delta(mq)_{total}} \quad (3)$$

where b denotes parcels belonging to the branch, n is the number of parcels, *border* refers to the last time step before entering the target region, and *end* refers to the last time step before leaving the target region.

For the purpose of identifying the ocean origin of parcels reaching Ethiopia, the tracking period of 15 days used in the analysis of the gridded maps of mass and moisture was too short. Air parcels from the Gulf of Guinea, and those taking the cross-continental route from the Indian Ocean, may use more than 20 days to reach the northern Ethiopian highlands. In order to include as much of the air coming from each basin as possible, a period of 20 days was chosen. The tracking time does not influence the number of air parcels entering the region, but it does influence the distribution of parcels into branches. As the parcels in each branch must have crossed the start line during this period, using too short tracks eliminates some of the most slow-moving parcels, which – due to their low altitude – are likely to have the highest moisture content.

6.2. Characteristics of the identified branches

An overview of the transport contribution by the specified branches is shown in Figure 10, based on details from Figure 11 and Table I. Owing to the summer rains, there is a general reduction in the moisture content of the air as it passes through the northern Ethiopian highlands. A decrease of moisture in one air parcel may not necessarily lead to rainfall if it is balanced by a corresponding increase in the moisture content of other parcels in the same air column. Still, this individual parcel's decrease represents a contribution to the net moisture release in the air, and thus, a potential contribution to rainfall. 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%.

6.2.1. Transport from the south

The southerly flow (branch 6, Figure 11(b)) constitutes 12% of the air parcels, carrying 38% of the moisture that reaches the northern Ethiopian highlands, contributing to 47% of the moisture release in the region. This is low-level air that to a large extent maintains its low altitude until reaching the border of the target region, then rising and releasing moisture efficiently above the plateau. The main contribution to this flow is found in the branches from the Gulf of Guinea (1) and the Indian Ocean (2). Air from the Indian Ocean (Figure 11(c)), whether having travelled across Central Africa or through the Turkana Channel, accounts for 7% of the air parcels, 25% of the moisture inflow, and 32% of the moisture released in the northern Ethiopian highlands. The air coming from the Gulf of Guinea (Figure 11(d)) is very humid (Figure 6), but as it constitutes less than 1% of the total mass of

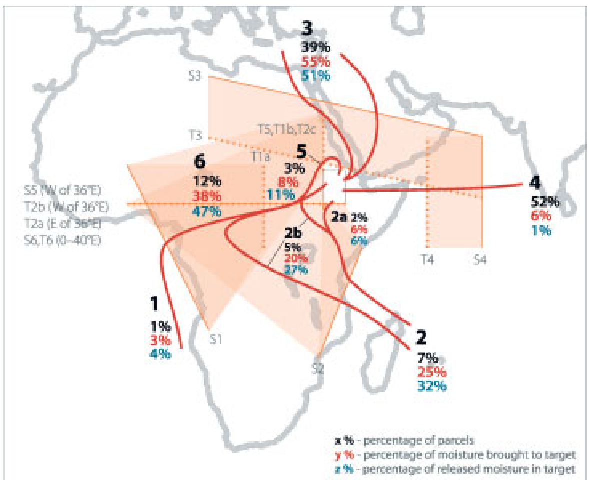

Figure 10. Main branches (red) of the transport into 8–14°N, 36–40 °E (white box) in July–August 1998–2008. Orange sectors mark the lines (S – start, T – transit) used to cluster the trajectories, marked with the branch number. The percentages represent each branch's relative contribution to the inflow of air (black) and moisture (red) to, and the release of moisture within (blue), the boxed region.

air entering the target region, only 4% of the moisture release may be attributed to this branch.

The Gulf of Guinea and Indian Ocean branches add up to only 67% of the air parcels, and 75% of the released moisture in the southerly flow (branch 6, Figure 11(b)). As shown in Figure 12, a substantial number of air parcels were concentrated in a belt above the African continent south of the equator 20 days before reaching the target region. As these parcels took more than 20 days to cross the continent – their location suggesting from the Indian Ocean – they were not accounted for in the branches from the Atlantic or Indian Ocean. Subtracting the partial contribution of the other southern branches (1, 2) from the total (6) indicates that about 4% of the air reaching the northern Ethiopian highlands – associated with 13% of the moisture inflow and 11% of the released moisture – has spent at least 20 days above the African continent to the south of the region before arriving.

If the target region is extended 2° to the south, encompassing 6–14°N, 36–40 °E, instead of 8–14°N, 36–40 °E, thus including the southern Ethiopian highlands, the relative importance of branch 2a doubles, and the relative importance of both Indian Ocean branches increases, on behalf of both the branch from the Gulf of Guinea and of the air from the north.

6.2.2. Transport from the north

As seen in Figure 1(a), the largest moisture flux into the northern Ethiopian highlands comes from the northeast. This is the combined result of branches 3 (Figure 11(f)) and 5 (Figure 11(e)). Branch 3 – crossing southward from the Mediterranean Sea and the Middle East – constitutes 39% of the the flow and 55% of the moisture transport into, and 51% of the moisture release within, the target region. This flow occurs at various altitudes. As seen in ERA-Interim maps of vertical velocity (not shown), there is a general ascent at all levels above the Ethiopian highlands, and below 500 hPa also above the southern Red Sea. Histograms (not shown) of the specific humidity and altitude of air parcels in the northern branch at different stages, indicate that the main ascent and moisture release occurs below 2500 m.a.g.l. Also, the moisture content of this air is higher at the border of the target region than it was at the start line. This suggests that low-level air ascending from the southern Red Sea provides a major contribution to the release of moisture in the northern Ethiopian highlands.

The Mediterranean Sea contributes to the fluxes above both the Red Sea and the Arabian Peninsula. Some of the air crossing Saudi Arabia also picks up moisture from the Persian Gulf. However, as the area of the Gulf is small, and the mass of air moving at low levels through this easternmost part of the Saudi Arabian sub-branch is small (Figure 4(b), lower panels), the moisture contribution from the Gulf is also small.

It can be said that 33% of the air parcels that reach the northern Ethiopian highlands from Central Africa and Southern Sudan enter from the north or east. This

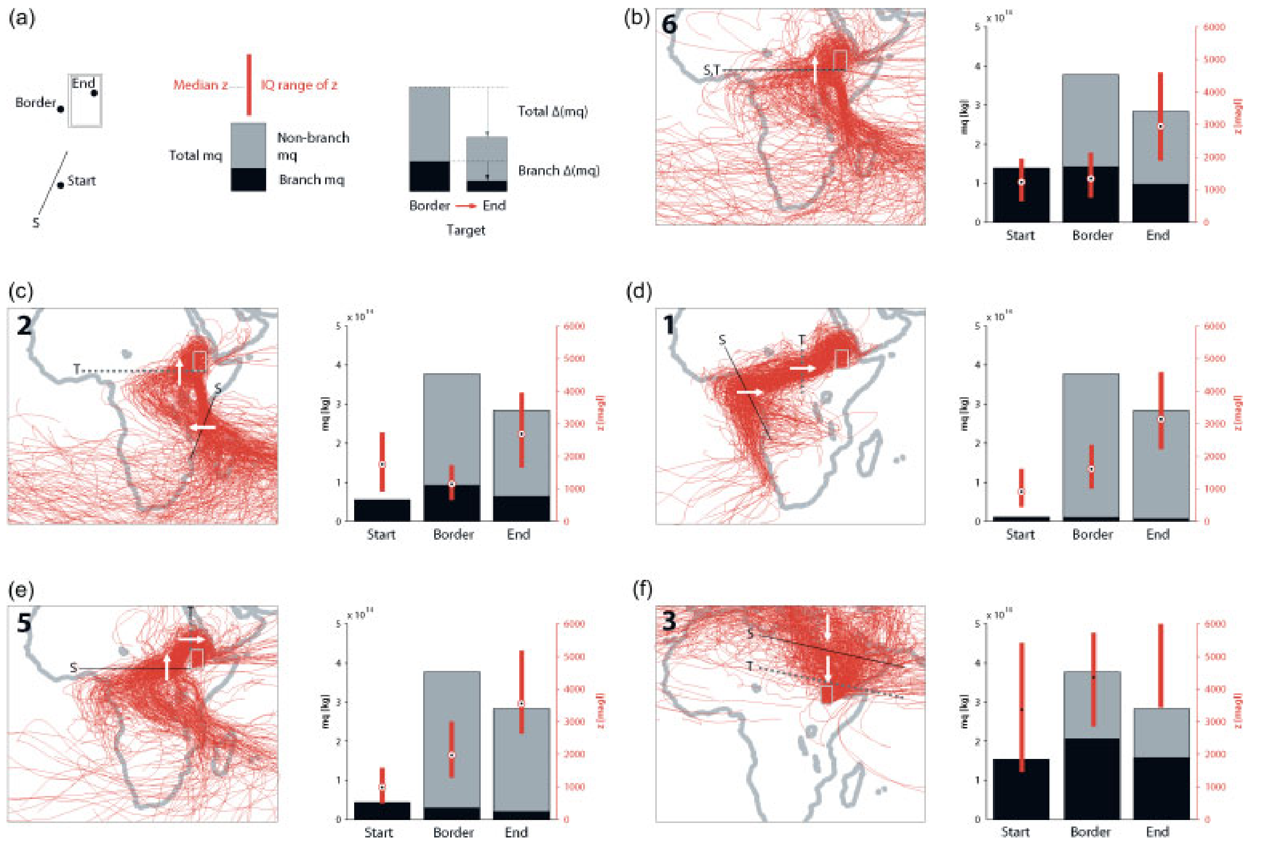

Figure 11. Main branches of transport into 8–14°N, 36–40 °E in July–August 1998–2008. (a) Overview of graph components. (b)–(f) Branches as described in the text and Table I. *Trajectory maps*: Subset of 150 trajectories for backtracks of 20 days belonging to each branch; i.e. passing the solid (S–) line and dashed (T–) line from specific directions (white arrows). *Graphs*: Values are shown at the stages indicated in (a), i. *Start* refers to the last time step before crossing the start line, *Border* to the last time step before entering the target region, and *End* to the last time step before leaving the target region. Total moisture content (*mq*) is shown in black (branch parcels)/grey (all parcels), and the median and inter-quartile range of the altitude of branch parcels in red ((a), ii). The moisture contribution to the target region is the difference between values at End and Border ((a), iii).

Table I. Transport branches, numbered as listed in the text and displayed in Figures 10 and 11. *n* refers to the number of parcels, *mq* to the amount of moisture brought into the target region, and Δ (*mq*) to moisture released within the target region, all as percentages of the total for all parcels. The values refer to the last time step before entering the target region. For parcels that enter, leave and re-enter the target region during the period considered, the sum of the contributions was used.

Id	Start line	Transit line	*n* [%]	*mq* [%]	Δ (*mq*) [%]
1	15°N,0 °E – 15 °S,15 °E	0°N, 25 °E – 15°N, 25 °E	0.9	3.0	3.9
2	20 °S,35 °E – 0°N,43 °E	8°N, 0 °E – 8°N, 40 °E	7.0	24.7	31.5
2a	20 °S,35 °E – 0°N,43 °E	8°N, 36 °E – 8°N, 40 °E	2.0	6.4	6.3
2b	20 °S,35 °E – 0°N,43 °E	8°N, 0 °E – 8°N, 36 °E	5.4	20.0	27.3
3	30°N,15 °E – 20°N,65 °E	20°N, 15 °E – 10°N, 65 °E	38.5	54.9	51.4
4	0°N, 65 °E – 20°N, 65 °E	0°N, 55 °E – 20°N, 55 °E	52.4	6.2	1.2
5	8°N,0 °E – 8°N,36 °E	14°N, 36 °E – 24°N, 36 °E	3.0	7.9	10.9
6	8°N, 0 °E – 8°N, 40 °E	8°N, 0 °E – 8°N, 40 °E	11.5	37.6	47.4

air flows to the west of the highlands, follows the mountain plateau and bends eastward and southward as it meets the northerly flow in the ITCZ region around the Red Sea. As a total, 11% of the moisture release is attributed to the 3% of air parcels following this path. Among parcels coming from the Gulf of Guinea, 47% of the air takes this route. Assuming that the effect of air coming from the north is greatest in the northernmost part of the highlands, this suggests that the direct moisture-transport-related influence of the Gulf of Guinea on Ethiopian rainfall is relatively higher in the north. Maps of the vertically integrated moisture flux in individual months (not shown) indicate that this effect begins in June, is greatest in July, and tapers off in August.

The method used for clustering the air parcels into branches does neither ensure that all parcels are accounted for, nor that each one is classified only once. The total

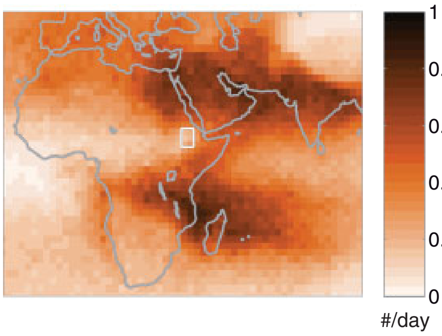

Figure 12. Mean density of air parcels 20 days before reaching 8–14°N, 36–40 °E (white box) in July–August 1998–2008. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

effect of such errors on the relative distribution between the most important moisture-transporting branches is considered to be small. The largest overlap found – 4% of all trajectories – occurs between the branches from the north (3) and the east (4). Some of the parcels from the north continue southeastward, ascend above the Arabian Sea and enter Ethiopia from the east. Ideally, these parcels should only have been counted in the eastern branch (4). Similarly, some parcels from the east pass north of the target region, following the flow indicated by the 200 hPa wind field (Figure 3(c)), descend above the Sahara and then enter Ethiopia with the branch from the north (3). As the moisture release in the air in the eastern branch is small, the overlap between the northern and eastern branches is considered to be of little importance for the moisture analysis.

Very few of the air parcels coming from the south are counted in more than one branch. The overlap between the branches from the Gulf of Guinea (1) and the Indian Ocean (2), amounts to only 0.3% of the Indian Ocean branch and 2.4% of the Gulf of Guinea branch – 0.02% of the total set of trajectories. Overlap between the branches from the north (3) and from the Indian Ocean (2) is negligible (0.01% of all trajectories).

Comparing the branches from the south (6), north (3) and east (4), leaves 4% of the air parcels unaccounted for. The majority of these parcels follow the Somali Jet northeastward through the Indian Ocean, ascend above the Arabian Sea and enter Ethiopia with the upper level flow from the east. These parcels belong to the dry, upper-level branch (4), but ascend farther west than the start line used to define this branch. Most of the remaining parcels in this group have spent more than 20 days in the air above the Red Sea and the Arabian Peninsula, as indicated in Figure 12. Ideally, they should have been included in the northern (3) branch.

6.2.3. Potential effects of the relative distribution between branches

The amount of moisture brought into the northern Ethiopian highlands from the north (branch 3) is 46% higher than from the south (branch 6). This reflects the vertically integrated moisture flux shown in Figure 1. The partial contribution to the amount of moisture released within the target region is roughly the same, 47% of the total for air coming from the south and 51% for air coming from the north. This shows that there is a greater relative moisture release in the low-level southern air than in the northern air, which occurs at various levels. The low-level humid air is, to a greater extent, affected by convection. Any factor increasing the inflow of low-level air from the south or from the Red Sea has the potential to increase the moisture available for precipitation in the northern Ethiopian highlands.

Wet summers in Ethiopia have previously been associated with a general strengthening of the summer circulation, and vice versa. A strengthening includes enhanced north-south pressure gradients across the African continent, increased ITCZ strength, increased low-level westerlies west and southwest of Ethiopia, increased Somali Jet strength, and an increased upper-level Tropical Easterly Jet (Segele *et al.*, 2009; Diro *et al.*, 2010). Several studies have documented associations between summer rainfall in Ethiopia and SST anomalies in the South Atlantic Ocean/Gulf of Guinea and the Southern Indian Ocean. Low SSTs in these regions are related to a strengthening of the St Helena and Mascarene highs, increasing the moisture transport toward Ethiopia. Stronger correlations have been found for the Atlantic than for the Indian Ocean (Korecha and Barnston, 2007; Segele *et al.*, 2009; Diro *et al.*, 2010).

A strengthening of the low-level westerlies above Central Africa and western equatorial Africa may have the direct effect of increasing the flow from the Gulf of Guinea toward Ethiopia. As this branch normally provides a minor contribution to the moisture flux into the northern Ethiopian highlands, the transport from the Gulf of Guinea would have to increase substantially in order to be the main cause of the associated precipitation increase. However, enhanced westerlies to the southwest of Ethiopia increase the transport of humid air from the continent, whether of Indian Ocean or Gulf of Guinea origin.

Whether moisture transport variability is the main cause of variability in the Ethiopian summer rains is a different question. As shown by Kucharski *et al.* (Kucharski *et al.*, 2007, 2008; Kucharski *et al.* 2009), positive SST anomalies in the south equatorial Atlantic excite a wave which weakens the Indian monsoon circulation. In addition to reduced moisture convergence above the Horn of Africa, they point to a thermodynamic effect as the atmosphere is stabilized due to a temperature increase. For northern Ethiopia, Diro *et al.* (2010) find that positive SST anomalies in the Gulf of Guinea, reducing the flow through Central Africa, are associated with higher-than-normal precipitation. The increase is attributed to an enhancement of the ITCZ.

7. Summary and conclusion

Rainfall in a region depends on the amount of moisture brought into the region, the amount of moisture recycled within the region, and the extent to which the available moisture condensates to form rain-generating clouds. This study has focused mainly on the first factor, but the release of moisture has also been addressed. Reanalysis moisture flux maps (Figure 1) show a northerly flux into the northern Ethiopian highlands. This is in contrast with the focus most previous studies have given to atmospheric conditions to the south of Ethiopia, as well as with the general dryness of the region to the north. By backtracking air from the northern Ethiopian highlands using ERA-Interim reanalysis data for July–August 1998–2008, it has been shown that the dominant flux of moisture from the north is due largely to evaporation in the Red Sea region, as well as to the large proportion of the air reaching Ethiopia this way.

The inflow of moisture through the northern branch is almost 50% higher than from the south, whereas the two branches contribute roughly equally (47% south/51% north) to the amount of moisture released in the region. The main contribution to the dominant, northerly flux of moisture into the highlands is due to air coming from the Mediterranean region, partly travelling above the Arabian Peninsula and partly above the Red Sea. Some of this air sinks and picks up moisture from the Red Sea, and to some extent also from the coastal mountain chain on the eastern side of the Red Sea, before ascending across Eritrea and into the Ethiopian highlands.

The flow from the south is dominated by air originating in the Indian Ocean, with a much smaller component (<1% of the total mass of air) coming from the Gulf of Guinea. The air from the Indian Ocean enters the northern highlands directly through Kenya and southern Ethiopia, or crosses farther inland through Central Africa. The air flow from the Gulf of Guinea occurs at low levels and has, in general, a higher specific humidity when entering the African continent than air from the Indian Ocean. However, due to the limited amount of air coming from the Gulf of Guinea, this branch provides only 3% of the moisture entering the northern Ethiopian highlands, compared to 25% for air from the Indian Ocean. Also, the increase in specific humidity as the air crosses the continent is higher for air coming from the Indian Ocean, partly due to subsidence and partly to moisture uptake from the ground. About 30% of the air reaching the northern highlands from Central Africa flows around the Ethiopian plateau before entering from the north. This air carries 8% of the moisture entering the region, contributing to 11% of the released moisture. As a result, about 13% of the moisture flux from the north is of southern origin.

These climatological findings do not rule out the role of other branches when it comes to influencing interannual variability in summer precipitation in the northern Ethiopian highlands. Variability in the moisture transport may be a result of a general strengthening or weakening of the mean circulation, or of variation in the relative contribution from the different transport branches. The degree to which the amount of incoming moisture affects precipitation also depends on mechanisms within the region. This has not been the topic of this study, and neither has the amount of released moisture in the reanalysis data been compared to the actual precipitation in the region. These questions will be addressed in a later study.

On the basis of the ERA-Interim data from 1998–2008 it is still possible to conclude that most of the moisture that enters the northern Ethiopian highlands in July–August is carried by air travelling from the Mediterranean Sea and the Indian Ocean, picking up moisture from the Red Sea and Central Africa along the respective routes.

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