Moisture Transport and Precipitation in Ethiopia

Ellen Viste

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Preface

Searching through job ads five years ago, the heading "Climate and health" caught my attention. To be honest, it was the health aspect that appealed the most to me; the effect of temperature and rain on something we all know as a part of us. The prospect of being able to use knowledge of the weather to predict a disease like malaria, with which this project has been associated, seemed instantly attractive. It took me half a year to realize that my deepest interest still lies in the atmosphere; in the swooshing winds, the splashing rain and the blasts of energy and motion that jumble the air around me. And sometimes – I must admit – far above my head.

My supervisor Asgeir Sorteberg deserves great thanks for helping me to draw these upper-level flows down to head level. In addition to being clearheaded, patient and socially conscious, he is always willing to share from his extensive collection of well-commented and readable Matlab scripts. I am also very grateful to my other supervisor, Nils Gunnar Kvamstø. What I have enjoyed most about this team is not the fact that they're of course highly qualified and professional, but that I have always felt free to knock on their doors.

There is no doubt that being part of the interdisciplinary and intercultural project the Ethiopian Malaria Prediction System (EMaPS) has made these last years all the more interesting. Bernt Lindtjørn has contributed greatly to this, both by leading the project, and by being our personal guide to Ethiopia. I would also like to mention the other EMaPS participants: Diriba Korecha, Dereje Mengistu, Abebe Animut, Adugna Woyessa, Eskindir Loha, Fekadu Massebo, and Torleif Lunde. Thanks to them, I've seen the rainbow in the Blue Nile Falls and the effect of rain on Ethiopian slopes, I've gained some insight into diseases I didn't know existed, and I've learned that a mosquito flies a distance of 500 meters a day. I'm especially grateful to Diriba, as well as to Seid Amedie and other colleagues at the National Meteorological Agency of Ethiopia, for informative discussions and critical comments, as well as for providing precipitation data. Torleif should also be mentioned specifically, as an extremely creative, technical wizard who is always willing to engage in enlightening thought experiments, whether concerned with the weather, or with anything else.

On the technical side, I wish to thank Andreas Stohl for providing the FLEXPART model, and Gunn Elisabeth Olsen Bjørkavåg for teaching me how to use it. On the social side, my office-mates Martin Flügge and Marius Jonassen have been a delightful company; during silent hours of concentrated work, through blackboard discussions of physical principles, and during take-offs and landings with Marius' office helicopter. The good social environment at the Geophysical Institute has also contributed to making these years enjoyable, as have other friends and family.

I still find the connection between climate and health appealing. The main challenge lies in quantifying relationships in a useful way, so as to separate the effect of weather or climate from those of infrastructure, politics and the human mind. Fortunately, while struggling to entangle intertwined curves, we can learn something about each other's fields. That might have as much value as common numbers.

Bergen, 15 February 2012
Ellen Viste

Abstract

With little irrigation and a diverse climate, Ethiopia is a country where the effects of too little precipitation are frequently seen. While the generation of precipitation also depends on local ascent and cooling of the air, the main focus of this thesis has been on the transport of moisture into the country. Three manuscripts are included. One provides an overview of drought episodes in all parts of Ethiopia during the last decades, while the other two discuss moisture transport as a component of the main rainy season in the northern Ethiopian highlands.

In the drought analysis (Paper III), gauge observations were used to construct monthly time series for 14 homogeneous rainfall zones, covering all of Ethiopia during 1971–2010/2011. The Standardized Precipitation Index (SPI) was then calculated for each zone on time scales of 3, 4, 6, 9, 12, 24 and 48 months. The results indicate that 2009 was one of the driest years in Ethiopia since 1971, and that there has been a cluster of dry spring seasons in most of the country during the last 10–15 years. Linear regression analysis confirmed a decline in precipitation in southern Ethiopia, both in the spring and in the summer. The trend analysis did not give us reason to draw any conclusions for central and northern Ethiopia, but the clustering of dry spring seasons during the last 10–15 years was apparent also in this part of the country.

For the moisture transport analysis documented in Paper I and Paper II, the Lagrangian trajectory model FLEXPART was used with ERA-Interim reanalysis data as input, to backtrack air parcels from the northern Ethiopian highlands (8–14 °N, 36–40 °E) during July and August 1998–2008. The resulting trajectories show that the transport of air into the region can be seen as the sum of a limited number of branches with distinct moisture characteristics.

Most of the moisture is transported into the highlands from the regions to the north, with moisture flowing from the Mediterranean region either above the Red Sea or above the Arabian Peninsula; and from the Indian Ocean, entering directly from the south, or crossing westward into Central Africa before turning northeastward and entering Ethiopia from the west. In addition, there is a distinct, but smaller branch crossing the continent from the Gulf of Guinea. The Indian Ocean and the Red Sea were found to be major sources of moisture, and there is also a considerable uptake of moisture along the routes above equatorial Africa.

Moisture entering a region can by no means be seen as a proxy for precipitation. If considering, not just the amount of moisture brought into the Ethiopian highlands, but also the amount of moisture released before the air leaves the region, there is a shift from the northern branch to the southern branches. The inflow of moisture from the north is about 30 % higher than from the south, but the contribution to the amount of moisture released, is roughly equal for air from the north and air from the south.

During 1998–2008 the variability in moisture transported by the southern branches, i.e. from the Indian Ocean, Central Africa and the Gulf of Guinea, was associated with precipitation variability of the same sign. During wet/dry summer months, the amount of moisture brought into the highlands from the south was increased/decreased, as was also the release of moisture in the region. Specifically, westerly anomalies in the low-level circulation anomalies above Central Africa were seen to increase the transport from the Gulf of Guinea, and in most cases also from the Indian Ocean. Southerly anomalies along the coast of East Africa were also associated with increasing moisture transport from the Indian Ocean. The amount of moisture brought into the highlands from the north could not be consistently related to changes in precipitation.

Contents

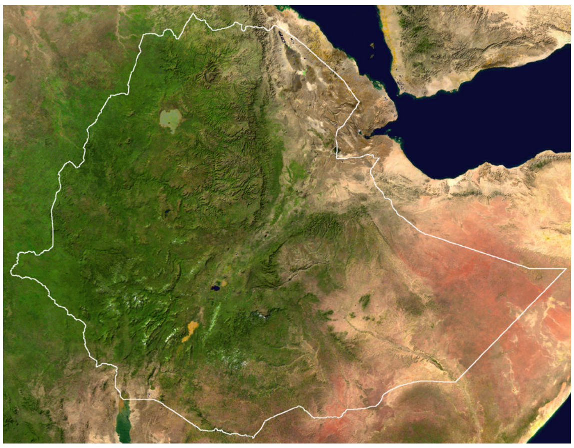
1 Introduction

1.1 Background

With irrigation covering only 1 % of the soil that feeds 84 million people, the link between rainfall and social welfare cannot be much closer than in Ethiopia (WorldBank 2005; CSA 2011; CSA 2012). There is no one-to-one correspondence between precipitation and socio-economic conditions, but unmitigated deviations in precipitation are likely to have a high impact (Conway and Schipper 2011). Throughout history, droughts have been part of the collective memory, both in and of, Ethiopia (Keller 1992; Webb, Braun et al. 1992).

Looking at the vegetation map in Figure 1-1, this may appear as a paradox. In parts of the green Ethiopian highlands, the mean annual precipitation exceeds 2000 mm; among the wettest regions in Africa outside of the equatorial belt. But in the other end of the scale, arid and semi-arid regions in the lowlands receive less than 400 mm per year (Griffiths 1972). In addition to the effect of orography, this large geographical variation reflects the strong seasonal character of precipitation in Ethiopia. The seasonal cycle varies in different parts of the country, mainly in relation to the movement of the tropical rain belt, but modified by topography and regional circulation features. Whereas the southern regions receive rain mainly during the Northern Hemisphere spring and fall, June–September is the main rainy season in the highlands (Griffiths 1972; Korecha and Barnston 2007).

Figure 1-1 Vegetation map of Ethiopia
Satellite photo from NASA/www.maplibrary.org.



Taking population density into account, there are two types of regions where water availability is limited: The semi-arid regions in the east and north; and wet, densely populated regions in the southern highlands and the Rift Valley (Funk, Senay et al. 2005). The difference between the weight of social and natural conditions in creating the water-stressed situation in these regions is just one example of how difficult it may be to establish clear links between the lack of precipitation and water scarcity. Common for both types of regions, is that the dependency on stable rainfall from year to year is high.

In this thesis, the inter-annual variability of precipitation in Ethiopia is discussed from two perspectives. One of them is an analysis of the meteorological contribution to well-known droughts in different zones of the country since 1971, together with a general overview of precipitation in these zones. Concerns have been raised about declining precipitation in the spring season during the last decades (Seleshi and Zanke 2004; Seleshi and Camberlin 2006; Williams and Funk 2011), and this issue is also discussed. Ethiopian famines have occurred in a climate of political crises, dislocation, epidemics, erosion, over-grazing and locust attacks – in addition to the underlying lack of precipitation (Kiros 1991; Keller 1992; Webb, Braun et al. 1992; Webb and Braun 1994; Bariagaber 1997; Comenetz and Caviedes 2002). To quote Webb and Braun (1994), "Neither drought nor food supply in themselves determine whether a famine will occur". As a result, records of famine cannot be used as a proxy for precipitation. Conversely, it is also impossible to assess the role of the socio-economic factor in aggravating the effect of drought, unless the magnitude of precipitation deficits at different times is known.

The other part concerns the mechanisms influencing the summer precipitation in the northern Ethiopian highlands. Most of the agricultural activity – responsible for 45 % of the Ethiopian national income and 85 % of the employment – takes place in the highlands (World Bank 2005; World Bank 2007). As the main rainy season in the highlands, the Northern Hemisphere summer is thus considered the season with the strongest influence on society. This has resulted in a number of studies analyzing trends and associations between summer precipitation and the regional atmospheric circulation, as well as tele-connections (Seleshi and Demaree 1995; Segele and Lamb 2005; Seleshi and Camberlin 2006; Korecha and Barnston 2007; Segele, Lamb et al. 2009; Diro, Grimes et al. 2010).

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 2011). This opens for the possibility of predicting precipitation, provided that these larger-scale phenomena are also predictable, or occur prior to the summer. Warning of a dry summer season, the Ethiopian National Meteorological Agency (NMA) issued the first seasonal weather outlook as early as in 1987 (Bekele 1997; Korecha and Barnston 2007). Since then, several statistical models for the Ethiopian summer rains have been shown to have skill, compared to climatological forecasts (Gissila, Black et al. 2004; Block and Rajagopalan 2007; Korecha and Barnston 2007; Diro, Grimes et al. 2010).

Despite the documented associations between anomalies in Ethiopian summer precipitation and the atmospheric circulation over Africa, a full understanding of the mechanisms involved, is still lacking – both for the inter-annual variability and the climatology. Two of the papers in this thesis treat one of the possible links: The transport of moisture into the Ethiopian highlands.

The moisture entering Ethiopia from the south and southwest during summer is recognized as coming from the both the Atlantic and Indian Oceans, as well as Central Africa and the Congo Basin. Assumptions of Atlantic Ocean dominance have seemed to prevail, mostly based on low-level wind maps (Flohn 1987; Mohamed, Hurk et al. 2005). Associations 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, Lamb et al. 2009). However, the moisture flow itself has not been the main subject of any previous studies, and no quantitative estimates of the contribution from the various sources have been published.

1.2 Aims

The overall aim of this thesis has been to contribute to the understanding of some of the mechanisms influencing Ethiopian precipitation. The amount of precipitation in any region depends on how much moisture that is available in the air, and the extent to which this moisture condensates to form cloud and rain drops. The first factor depends on the transport of moisture into the region, as well as recycling within the region. The second factor usually depends on ascent cooling the air, whether the rising motion is generated locally or as part of a larger weather system. In most of Ethiopia, the main rainy season occurs as moisture from various sources converges above the Ethiopian plateau during the northern hemisphere summer. In this thesis, the main focus has been on the transport of moisture into the northern Ethiopian highlands during summer, concentrating on the following questions:

- Where are the major moisture transport routes?

- How much does the transport along each route contribute to the inflow of moisture?

- How much does the inflow from each route contribute to precipitation?

- Can specific moisture source regions be identified?

- How do common atmospheric circulation anomalies influence the transport?

- To what extent can precipitation anomalies be explained by anomalies in the moisture transport?

With a broader perspective, another aim has been to give an updated overview of precipitation and drought conditions in all parts of Ethiopia during the last decades. Specific objectives have been:

- To provide a national and regional overview of the meteorological contribution to droughts of various lengths since 1970.

- To provide an updated analysis of precipitation trends in different regions of Ethiopia in those seasons that are most relevant for the agricultural activity in each region.

1.3 Outline

This thesis consists of three papers preceded by a synthesis. The main purpose of the synthesis is to provide additional background information, both scientifically and about the context of the papers, as well as their mutual/combined relevance. To provide background for the discussion in the synthesis, an overview of the papers is given in Chapter 2. Data used in the synthesis are presented in Chapter 3. Two background chapters follow. Chapter 4 describes the climate of Ethiopia, and the related atmospheric circulation. Special attention is given to the northern hemisphere summer, as this is the main rainy season in most of Ethiopia, and has been the topic of two of the papers. Chapter 5 gives an overview of how the trajectory model FLEXPART was used to analyze the transport of moisture into Ethiopia. Some benefits and caveats of the trajectory tool are also discussed, before concluding remarks are presented in Chapter 6. The second part of the thesis contains the three papers, referenced as Paper I, Paper II and Paper III.

2 Overview and summary of papers

The aim of this study has been two-fold: First to provide an overview of Ethiopian precipitation and drought periods, and second, to examine some of the mechanisms behind precipitation and inter-annual variability in precipitation during the main rainy season in the Ethiopian highlands. The results have been presented in three papers, placed chronologically in the order they were written.

The first and the second paper contain analyses of the moisture transport into the northern Ethiopian highlands during the main rainy season in July–August 1998–2008. Paper I describes the climatological transport and sources of moisture, defining branches through which most of the moisture is brought toward the highlands. Paper II treats the inter-annual variability in these branches, comparing the moisture reaching the region, and released within it, to gauge observations of precipitation. The third paper contains an analysis of the meteorological conditions during historic drought episodes in Ethiopia, including the most recent episode, using data through May 2011.

2.1 Paper I: An 11-year moisture transport climatology

Viste E., Sorteberg A., 2012: Moisture transport into the Ethiopian highlands. Published online in the *International Journal of Climatology*, DOI: 10.1002/joc.3409.

Air parcels were backtracked from the northern Ethiopian highlands (8–14 °N, 36–40 °E), using the Langrangian trajectory model FLEXPART (Stohl and James 2005) and ERA-Interim reanalysis data (Berrisford, Dee et al. 2009) in July–August 1998–2008. The resulting trajectories show that the transport of air into the region can be seen as the sum of a limited number of branches with distinct moisture characteristics.

Most of the moisture is transported into the highlands from the regions to the north, with moisture flowing from the Mediterranean region either above the Red sea or above the Arabian Peninsula; and from the Indian Ocean, entering directly from the south, or crossing westward into Central Africa before turning northeastward and entering Ethiopia from the west. In addition, there is a distinct, but smaller branch crossing the continent from the Gulf of Guinea. The Indian Ocean and the Red Sea were found to be major sources of moisture, and there is also a considerable uptake of moisture along the routes.

If considering, not just the amount of moisture brought into the Ethiopian highlands, but also the amount of moisture released before the air leaves the region, there is a shift from the northern branch to the southern branches. The moisture release in a region may be seen as a potential contribution to precipitation. The inflow of moisture through the northern branch is about 30 % higher than from the south, but the contribution to the amount of moisture released is roughly equal for air from the north and air from the south.

This study outlines some regions of influence, when it comes to the moisture brought into Ethiopia. Previous studies have pointed to the possible influence of SSTs in the Gulf of Guinea on Ethiopian summer precipitation (Segele, Lamb et al. 2009; Segele, Lamb et al. 2009). Our results show that, climatologically, the moisture contribution from this side of the continent is small compared to that from the Indian Ocean and the Red Sea region. This indicates that the documented associations between anomalies in the Gulf of Guinea and precipitation in Ethiopia should be due to other factors than the transport of moisture from the Gulf. However, the climatological results obtained do not prove that this might not be different in dry or wet summers. Paper II, treating relationships between moisture transport anomalies and precipitation, follows up on this question.

The results may also be seen in the context of the effect of remote changes on Ethiopian precipitation. Eg., a drying of Central Africa, whether related to climate change or to changes in land-use could lead to less moisture reaching Ethiopia.

2.2 Paper II: Inter-annual variability in moisture transport

Viste E., Sorteberg A., 2012: The effect of moisture transport variability on Ethiopian summer precipitation. Under revision for resubmission to the *International Journal of Climatology*.

In Paper I, the climatology of the moisture transport into the northern Ethiopian highlands during the main rainy season was outlined. Different branches of the transport were considered important or less important depending on their relative contribution to the total amount of moisture flowing into, and being released within, the region. In this study, the methodology was extended to assess the importance of transport variability for summer precipitation.

The results show that during 1998–2008 the variability in moisture transported by the southern branches, i.e., from the Indian Ocean, Central Africa and the Gulf of Guinea, was associated with precipitation variability of the same sign. During wet/dry summer months, the amount of moisture brought into the highlands from the south was increased/decreased, as was also the release of moisture in the region. Specifically, westerly anomalies in the low-level circulation anomalies above Central Africa were seen to increase the transport from the Gulf of Guinea, and in most cases also from the Indian Ocean. Southerly anomalies along the coast of East Africa were also associated with increasing transport from the Indian Ocean.

The amount of moisture brought into the highlands from the north could not be consistently related to changes in precipitation. But in most cases of anomalous precipitation, a substantial part of the associated reduction or increase in moisture occurred in air parcels belonging to the northern branch. A possible explanation for this is that, as reduced or increased inflow of moisture from the south alters the degree of convergence above the highlands, processes in the air coming from the north are also affected. Starting in the other end, the reduced convection/ascent could be the cause of the reduced flow of moisture into the region, and for unknown reasons affecting the southern branches more than the northern.

The results of this study build up under previous studies pointing to low-level circulation anomalies above Central Africa as the main driver of anomalies in the summer precipitation in Ethiopia (Conway 2000; Mohamed, Hurk et al. 2005; Segele, Lamb et al. 2009). But, as shown by Jury (2011) the worst short-time flood episodes in a decade took place during increased moisture transport from the north, and our results support the idea that anomalies in the northern transport may play a significant role in some cases. The net flux above Ethiopia during the summer is northerly/northeasterly (Figure 4-9 on page 29), and the large number of air parcels reaching Ethiopia this way means that relatively small shifts in this flow may have a large impact. Unfortunately, the branching/clustering methodology applied did not allow for a complete investigation of the characteristics of the northern branch, and a full understanding of the role of the atmospheric circulation to the north of Ethiopia is still missing.

2.3 Paper III: Drought in Ethiopia – an overview of precipitation

Viste E., Korecha D., Sorteberg A., 2012: Recent drought and precipitation tendencies in Ethiopia.

Submitted to *Theoretical and Applied Climatology*.

This study had a non-scientific as well as a scientific motivation. After a number of times – whenever telling people that I worked on precipitation in Ethiopia – having struggled to answer the question "But isn't there a drought there?", I was curious to see how the recent situation compares with the globally broadcasted crises of the 1980s. A quick search through the Internet caused increasing confusion. In the news media, the words famine and drought are used almost interchangeably (McCann 1990), and it is impossible to deduce anything about the scale of one of the phenomena from reports of the other. Also, in Ethiopia it is always possible to find a dry spot for a press photo, and the picture may not say much about the unusualness of the motive. With an area of 1,104,300 km^2 (CIA 2011), Ethiopia is a large country with great geographical variation; when it comes to the total amount of precipitation, to the annual cycle of precipitation and to inter-annual anomalies in precipitation. From the wealth of drought reports, one may get the impression that it never rains – in a country where some regions receive more than 2000 mm of precipitation per year (Griffiths 1972).

The scientific motivation became clear when we got access to an updated set of gauge observations, covering all parts of Ethiopia. One aim was to provide a quantitative overview of the meteorological component of historic and recent drought episodes. The famines that have in many cases been seen as the end result of precipitation deficits, are as much social as natural disasters (Torry 1986; Webb, Braun et al. 1992; Broad and Agrawala 2000; Conway and Schipper 2011). In most cases the scientific literature on drought-related famine in Ethiopia recognizes this, but there are only a few cases where meteorological data are included for comparison (Degefu 1987; Webb, Braun et al. 1992; Webb and Braun 1994; Comenetz and Caviedes 2002). Neither of these provides a full, geographical overview of the precipitation deficits during Ethiopian droughts.

Our analysis indicates that 2009 was one of the driest years in Ethiopia since 1971, and that there has been a cluster of dry spring seasons in most of the country during the last 10–15 years. A natural question then arises whether there has been a general tendency of drying over the last decades. In a recent study, Williams and Funk (2011) suggested that large-scale shifts in the circulation above the Indian Ocean were responsible for a general, decadal-scale, reduction in the February–May precipitation in East Africa and the Horn of Africa. Previous studies have also reported precipitation declines, though mainly in southern Ethiopia, with no confirmed trends in central and northern Ethiopia (Seleshi and Zanke 2004; Seleshi and Camberlin 2006; Bewket and Conway 2007).

Building on these results, the second task of this study was to conduct an updated trend analysis for all of Ethiopia for both the spring and the summer season, using data from a higher number of stations than in most of the previous studies. Linear regression analysis indicated a decline in precipitation in Southern Ethiopia during 1971–2010, both in the spring and in the summer. No conclusion could be drawn for Central and Northern Ethiopia. However, the clustering of dry spring seasons during the last 10–15 years was apparent in this part of the country, as well as in the south. This suggests that – whether producing an identifiable linear trend or not – our spring data support the decadal, national drying documented by Williams and Funk (2011).

Even when considering meteorological drought only, quantifying drought is not a clearly outlined procedure. Among many possible indicators (eg., Heim 2002; Mishra and Singh 2010), we chose to use the Standardized Precipitation Index (SPI) (McKee, Doesken et al. 1993), mainly because this index makes it possible to compare drought across geographical regions and on different timescales. Also, it requires only monthly precipitation as input, which makes it useful in data-scarce regions. Thus, we limited our definition of drought to a lack of precipitation compared to the normal situation.

With this simplified concept of drought, a number of questions still arise when attempting to present an overview through time and space. In addition to technical assumptions such as the statistical distribution of precipitation, described in the paper, the selection of the presented data should reflect assumptions of the social relevance of the drought measure. In this context, the choice of timescale is vital. SPIs may be calculated for any timescale of accumulated precipitation, and the possible impact of the observed drought will be according to this time period. A drought of, e.g., 3 months may severely damage the crops in one season, but will normally not influence ground water conditions notably. Edwards and McKee (1997) suggested using 3 months of accumulated precipitation in the SPI for a short-term or seasonal drought index, a 12-month SPI for an intermediate-term index, and 48 months for a long-term index, signifying a multi-year drought. We used the 4-month accumulations in May and September to assess seasonal droughts, while defining intermediate and long-term droughts by SPIs of 12, 24 and 48 months.

With access to monthly precipitation data only, we were not able to infer anything about abnormalities on shorter time-scales. We truly acknowledge that the value of precipitation is not just a question of the total amount accumulated over a period of time, but also of the temporal distribution within this period – whether a month or a season.

3 Data

This section describes the data sets used in the illustrations in the synthesis, i.e., mainly in Chapter 4. Data used in each individual paper are described in that paper.

3.1 Gauge-based regional precipitation

Data for 238 gauge stations were obtained from the National Meteorological Agency of Ethiopia (NMA). These data were used to calculate mean monthly precipitation in the 14 homogeneous zones identified by Korecha and Sorteberg (2012). Figure 4-12 on page 39 contains maps of monthly standardized anomalies during 1971–2010, while the same data set was used for drought evaluation in Paper III.

For each of the 14 zones (Figure 3-1) a time series of monthly precipitation for 1970 – May 2011 was made. First, the monthly climatology of each station was calculated, and averaged over the stations in the zone to produce the zone climatology. Similarly, station anomalies were calculated for each month in the record, as the fraction of the climatological values at each station. The station anomalies were then averaged to produce a time series of zone anomalies. As the last step, this anomaly series was multiplied by the zone's climatology to obtain a time series of monthly precipitation in the zone.

The temporal coverage of the 238 stations varied, and only stations with a minimum number of months were used when calculating the monthly zone values. To avoid distorting the seasonal cycle, each calendar month was considered separately. I.e., to be included in the zone climatology, stations were required to have data for at least 50 % of all January months during the reference period 1971–2000, and for 50 % of all February months etc., through December. For stations to be used in the subsequent anomaly calculations, the corresponding requirement was set to 70 %. As a result, 174 stations were used in the climatology, and 132 stations in the time series. Due to the geographical spread in the observations (Figure 3-1), the number of stations differed from zone to

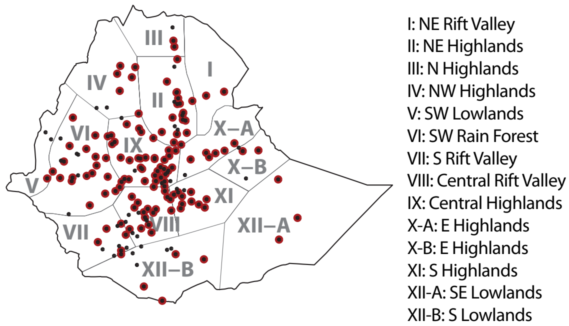


Figure 3-1 Ethiopian rainfall zones
Zones and stations used for calculating zone precipitation. Black markers are stations used in the climatology, whereas red markers are stations used both in the climatology and in the monthly time series. Zone names are listed to the right.

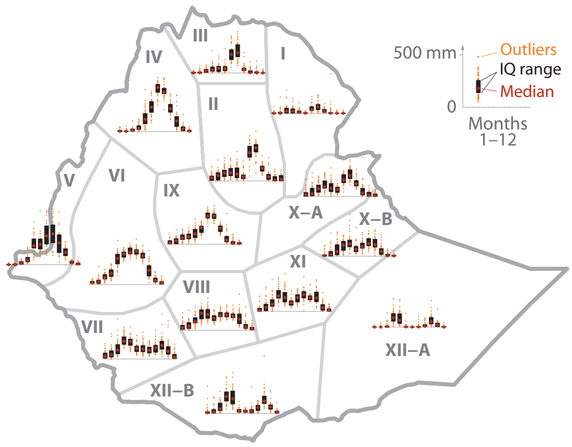


Figure 3-2 Monthly zone precipitation
Boxplots of monthly zone precipitation for 1970–2010, with median (red dot), interquartile range (black bar) and outliers (orange dots). The months January–December run along the horizontal axis, while the vertical scale (shown only in the legend to the right) represents monthly precipitation from 0 to 500 mm.

zone and month to month, ranging from 1 in the Southwestern Lowlands (zone V) to a maximum of 40 in the Central Highlands (zone IX). The boxplots in Figure 3-2 shows the seasonal cycle and inter-annual variation in each of the zones.

3.2 GPCP

The Global Precipitation Climatology Project (GPCP) includes monthly, pentadly and daily precipitation data, on grids varying from 1 ° (daily) to 2.5 ° (pentadly and monthly) latitude and longitude. The monthly and pentadly data are available from January 1979 to the present, and the daily data from October 1996. Version 1 of the monthly data set is described by Huffman et al. (1997) and version 2 by Adler, et al. (2003). The pentad and daily sets are described by Xie et al. (2003) and Huffman et al. (2001), respectively. A GPCP Version 2.1 monthly precipitation was released in 2009, and is described and compared to Version 2 in Huffman et al. (2009). Version 2.2 of the monthly data was released in July 2011 and is available at http://precip.gsfc.nasa.gov (Huffman and Bolvin 2011). Version 2.1 and 2.2 have been used in figures in Chapter 4.

The monthly precipitation analysis is a merged analysis that incorporates precipitation estimates from low-orbit satellite microwave data, geosynchronous-orbit satellite infrared data, and surface rain gauge observations. In the merging approach, the low-orbit microwave observations – with a higher accuracy – are used to calibrate, or adjust, the more frequent geosynchronous infrared observations. In the end, the combined satellite-based product is adjusted by the rain gauge analysis (Adler, Huffman et al. 2003).

The rain gauge data used in the GPCP products are constructed by the Global Precipitation Climatology Centre (GPCC; Rudolf and Schneider 2005; Rudolf, Becker et al. 2010), operated by the German Weather Service. These data have been implemented in the GPCP for the period after 1986. For 1979–1985, the rain gauge analysis used is a combination of gauge data from the Global Historical Climate Network (GHCN), produced by NOAA/National Climate Data Center, and Climate assessment and Monitoring System (CAMS), produced by the CPC, NCEP and NOAA. The procedures used for combining these sets are described in Xie et al. (1996).

3.3 TRMM

A joint project between NASA and the Japan Aerospace Exploration, the purpose of the Tropical Rainfall Measuring Mission (TRMM) is to monitor and study tropical rainfall. Running from 1998 till the present, the TRMM data sets have a spatial resolution of 0.25°x0.25° and cover a global band extending from 50 °S to 50 °N (until February 2002, the coverage was 40 °S to 40 °N) (Huffman, Adler et al. 2007). Monthly TRMM data have been used to illustrate mean precipitation patterns over Africa in some figures in this thesis, but due to obvious problems over Ethiopia in at least one summer, we restrained from using TRMM in the precipitation analysis in any of the included papers.

There are two main methods for satellite estimation of precipitation (Arkin and Ardanuy 1989). The first is based on the detection of clouds in visible or infrared data. The basis of this indirect method is the fact that rainfall is associated with clouds, and that higher and/or thicker clouds are associated with heavier or more frequent precipitation. The second method is based on observations of the radiative effects of hydrometeors in the microwave region of the spectrum. This more physically direct method uses the presence of ice layers, easily detectable due to scattering, to map precipitation, as low temperatures are known to coincide with heavy convective rainfall. The TRMM-based precipitation products 3B42 (3-hourly) and 3B43 (monthly) combine microwave and infrared precipitation estimates, scaled to the monthly accumulated Climate Assessment and Monitoring System (CAMS) or the Global Climatology Centre (GPCC) rain gauge analysis (Huffman, Adler et al. 2007). The TRMM illustrations used in this thesis are based on monthly accumulations of 3B42 data.

Both the TRMM 3B42 and TRMM 3B43 products have been evaluated over the Ethiopian highlands (Dinku, Ceccato et al. 2007; Dinku, Chidzambwa et al. 2008; Dinku, Connor et al. 2008; Dinku, Connor et al. 2010). Comparing 3B43 with other monthly gridded data sets (GPCP and CMAP) in 1999–2004, Dinku et al. (2007) found 3B43 values to correspond better with gauge data than the other data sets did. All products showed some underestimation at high rainfall accumulations.

Despite the preferable reviews, caution should be taken when using TRMM data for Ethiopia and the Horn of Africa. As noted by Paeth et al. (2011), TRMM rainfall estimates for June–September 2007 differed substantially from GPCP and GPCC in Sudan and Ethiopia. As seen in Figure 3-3 TRMM estimates were extremely low in July 2007, while there was a curious, sharply outlined maximum over Sudan, present in both July and August. A rough calculation of the TRMM precipitation in the boxed region 4–14 °N, 34–40 °E, covering the western half of Ethiopia, gave only about 1/3 of the corresponding GPCP V2.1 value for this month. Other sources support the picture of a wet season. According to the Dartmouth Flood Observatory, flooding was reported both around Lake Tana in the Ethiopian highlands, and in the Rift Valley during July–October 2007 (Brakenridge 2012). This is also in accordance with the flood belt across Sub-Saharan African documented by Paeth et al. (2011).

Dinku et al. (2008) describe some of the challenges involved in using infrared (IR) and passive microwave (PM) sensors to detect precipitation over the Ethiopian topography. Orographic lifting may cause cloud development and precipitation while the cloud top is still relatively warm. IR algorithms use cloud-top temperature thresholds that are too cold for the orographic clouds, leading to an underestimation of orographic precipitation. The rainfall signal for over-land PM rainfall retrieval is based mainly on scattering by ice aloft. As orographic clouds may produce heavy rainfall without much ice aloft, surface rainfall may be underestimated. On the other hand, very cold surface and ice over mountain-tops may be misidentified as raining clouds. Whether this may have influenced the data differently in the summer of 2007 than in other years, is unknown.

The discrepancy between TRMM and other precipitation data sets in the summer of 2007 led us to avoid TRMM in our analyses of

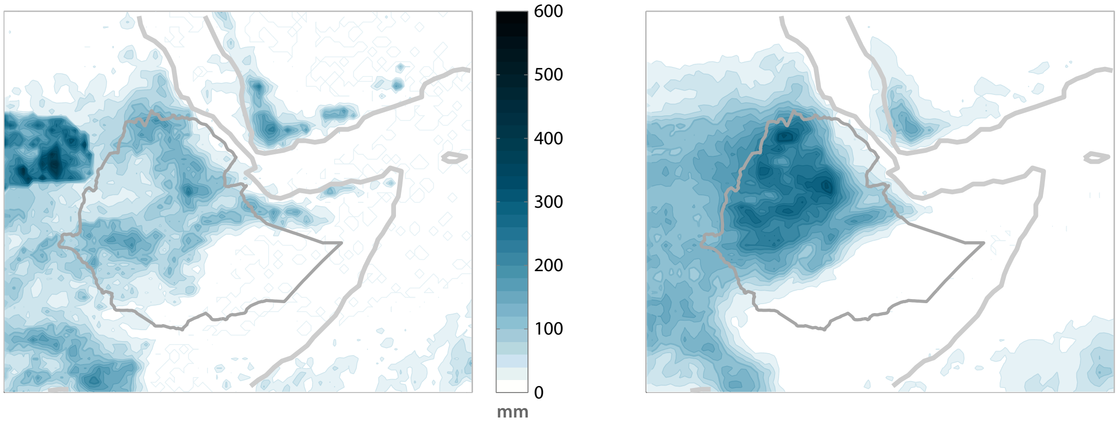


Figure 3-3 TRMM-based precipitation in July 2007
TRMM data showed unrealistically low precipitation amounts in the Ethiopian highlands in July 2007 (left) compared to the 1998–2007 mean (right). Data: TRMM 3B42.

Ethiopian precipitation. Still, as the data have previously been found to correspond reasonably well with ground observations in different climatic regions of Africa (Adeyewa and Nakamura 2003; Nicholson, Some et al. 2003; Dinku, Ceccato et al. 2007), we considered them to be sufficiently good for illustrating mean precipitation patterns, as done in Chapter 4.

3.4 ERA-Interim

ERA-Interim is a reanalysis product from the European Centre for Medium-Range Weather Forecasts (ECMWF). The data set is produced at a resolution of T255, about 0.75 degrees latitude and longitude, with 60 vertical levels. It has a 4-dimensional variational assimiliation system (Simmons, Uppala et al. 2006; Uppala, Dee et al. 2008).

ERA-Interim data have been used in all illustrations of atmospheric circulation parameters, as well as for input to the Lagrangian trajectory model FLEXPART (Stohl, Forster et al. 2005), used for tracking moisture in Paper I and II.

Figure 4-5 on page 23 and Figure 4-9 on page 29 include vertically integrated moisture fluxes, and corresponding divergence, from ERA-Interim. These fluxes were calculated by the Climate Analysis Section at the National Center for Atmospheric Research (NCAR), using methods described in Trenberth et al. (2002).

The moisture budget in ERA-Interim has been assessed and compared with other data sets by Trenberth et al. (2011). Although there are still important differences with observations, the quality of the ERA-Interim was characterized as high, and much higher than in older reanalyses. A jump in 1997 was documented over the ocean regions, with a modest decrease in precipitation and an increase in evaporation. Land values were found to be overall more stable.

4 The seasons and climate of Ethiopia

Located in the inner part of the Horn of Africa, Ethiopia constitutes the northernmost part of the African rain belt. The region is also under influence of the Indian monsoon system, governing or modifying the atmospheric circulation above the Indian Ocean and the surrounding land areas. The variations in climate during the year occur largely because of large-scale pressure changes and the monsoon flow related to these changes. On top of this, the rugged terrain causes great local variation.

With an area of 1,104,300 km², Ethiopia is the 26th largest country in the world (CIA 2011). The topography may be seen as a mountain plateau divided by the geologically active Rift Valley, which runs from the northeast to the southwest of the country (Figure 1-1 on page 9). The green region in the northwestern half of the map constitutes the largest part of the highlands, with a mean elevation of 2000–2200 meters above sea level (m.a.s.l.). This plateau is sharply divided from the valley to the east along the 40 ° longitude line. The lowest point – in the dry Denakil depression, at about 135 meters below sea level, in the northeastern lowlands – and the highest, Ras Dashen (also spelled Ras Dejen) at 4550 m.a.s.l., in the northern highlands – are located within one latitudinal degree. The green region on the eastern side of the Rift Valley is the Bale mountains, with peaks above 4000 m.a.s.l.

The general climate of Ethiopia has been described by Griffiths (1972). Ethiopia is situated within the tropical belt, but due to the high altitude, the temperature is moderate in large parts of the country. The traditional Ethiopian classification, based on elevation, identifies at least three climatic zones. Kolla is the lowland zone, below 1800 m.a.s.l., with mean annual temperatures of 20–28 °C. Woina Dega is the zone between 1800 and 2400 m.a.s.l., with mean annual temperatures of 16–20 °C. The Dega zone denotes regions above 2400 m.a.s.l., with mean annual temperatures of 6–16 °C (Griffiths 1972; Conway 2000).

Annual precipitation amounts range between 4–500 mm in the arid lowland regions to more than 2000 mm in the highlands (Griffiths 1972, and Figure 4-1). Topography influences Ethiopian rainfall patterns, but the relationship is not straightforward (Gamachu 1977; Dinku, Chidzambwa et al. 2008; Dinku, Connor et al. 2008). In most parts of the country, precipitation increases with elevation. However, there are also regions where the annual amount of precipitation decreases with height, most importantly in the northern and southern mountainous regions (Dinku, Chidzambwa et al. 2008). Precipitation increases up to about 2000 m.a.s.l., then decrases with elevation (Dinku, Connor et al. 2008). Dinku et al. (2008) suggest that the main cause of decreasing precipitation with height is moisture depletion, as most of the moisture is released as rain before reaching the top of the mountains.

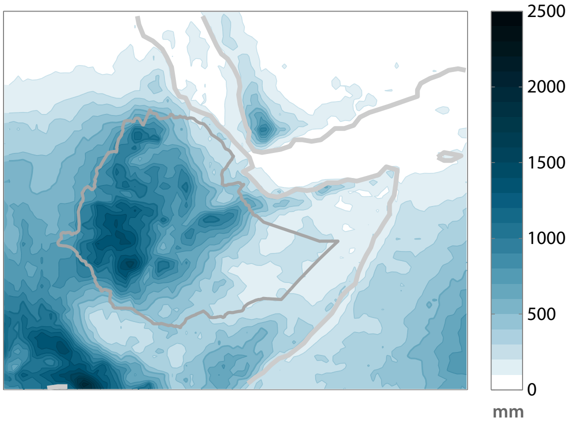


Figure 4-1 Annual precipitation in Ethiopia
Mean annual precipitation for 1998–2007 over the Horn of Africa. Data: TRMM 3B42.

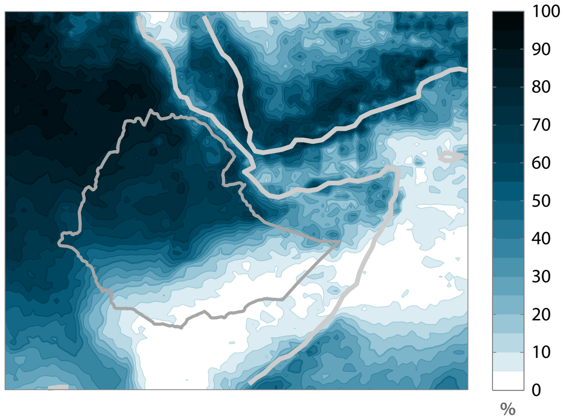


Figure 4-2 Dominance of summer precipitation
June–September precipitation as % of annual over the Horn of Africa. Data: TRMM 3B42.

Ethiopia has three climatological seasons: The main rainy season of June–September (*Kiremt*), the dry season of October–January (*Bega*) and the short rainy season of February/March–May (*Belg*). It should be noted that this is seen from a highland perspective. As shown in Figure 4-2, the southern regions do not receive much precipitation during June–September, considered the main rainy season in the highlands.

Figure 4-3 shows the seasonal cycle of precipitation over the Horn of Africa. The southern part of Ethiopia has a bimodal rainfall regime, with most of the precipitation falling during the Northern Hemisphere spring and fall. Farther north, in the highlands, the spring and summer seasons overlap, producing a monomodal regime. As is also seen in Figure 4-1, the southwestern part of the highlands is the wettest region, receiving rain from the start of the Belg season in March, throughout the main rainy season, and in some years also in October–November. The northernmost part of the highlands receive rain only at the peak of the Kiremt season, in August–September, when the ITCZ is located at its northernmost position, above Eritrea.

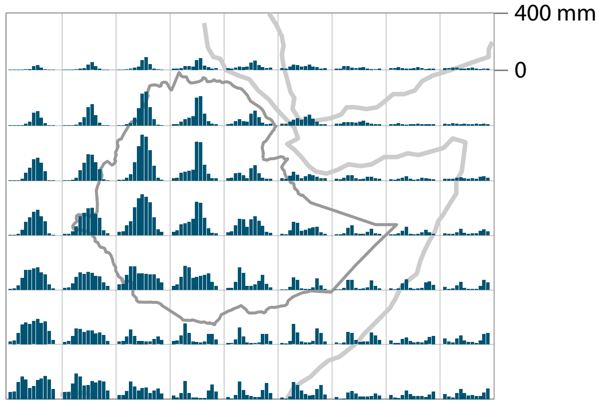


Figure 4-3 Seasonal precipitation cycle
Monthly mean GPCP V2.1 precipitation in 2.5° grid cells over the Horn of Africa. The 12 bars in each cell represent January–December precipitation, from left to right, on a scale from 0 (bottom of cell) to 400 mm (top of cell).

This chapter starts with an overview of the atmospheric circulation causing the seasonal cycle of precipitation in Ethiopia. Then each season is described, with the strongest emphasis on the summer precipitation. Geographical names used in the text are shown in Figure 4-4.

4.1 Atmospheric circulation

The variations in Ethiopian climate during the year are largely a result of pressure changes and the monsoon flow related to these changes. Located at a latitude between 3 and 15 °N, Ethiopia has a seasonal distribution of precipitation that is highly influenced by the movement of the tropical rainbelt, following the position of the sun. As demonstrated in Figure 4-2 and Figure 4-3, large parts of the country receives most of the annual precipitation during the northern hemisphere summer. But interacting with this dominant driver, are other large-scale features, such as the development of the Indian summer and winter monsoons, and the intrusion of extra-tropical weather systems, as well as small-scale systems that cause notable local variation. In this section, an overview of the large-scale circulation will be given first, and then a more detailed description of each season. The emphasis will be on precipitation and moisture transport.

Figure 4-4 Physical map of Africa
Background map: Shaded relief with elevation colors based on climate. Lowlands in humid areas are green and arid regions are brown (naturalearthdata.com).

The following figures, illustrating the seasonal cycle with the climatology for January (winter), April (spring), July (summer) and October (fall), will be used as references throughout this section:

Figure 4-5: Precipitation, Mean Sea Level Pressure (MSLP), vertically integrated moisture flux and vertically integrated moisture flux divergence.

Figure 4-6: The horizontal circulation: Wind at 200, 700 and 850 hPa.

Figure 4-7: The vertical circulation: Omega at 200, 500 and 700 hPa.

In addition, Figure 4-9 gives an overview of the month-by-month development of the vertically integrated moisture flux above Africa. This will be used when describing the different seasons.

When the terms winter, spring, summer and fall are used without further specifications, they refer to the northern hemisphere seasons.

4.1.1 Pressure zones

As shown in Figure 4-5, the most prominent pressure features in the region are the semi-permanent high pressure zones near St. Helena in the South Atlantic Ocean and the Mascarene islands in the Southern Indian Ocean, and the low pressure trough overlying North Africa and the Arabian Peninsula.

During the year, there is a slight variation in the latitudinal position of the anticyclonic systems around 30 °S. For the Mascarene anticyclone there is also a much larger longitudinal variation, from 85 °E in December–February to 55 °E in June–August (Slingo, Spencer et al. 2005). The high pressure zone in the northern hemisphere exhibits a larger seasonal variation, extending above the Saharan desert in January, retreating to the north and giving way to the low pressure zone associated with the Intertropical Convergence Zone (ITCZ) during the northern hemisphere summer.

Throughout most of the year, the Mascarene anticyclone is coupled to a weak, semi-permanent surface ridge, extending through the Mozambique Channel to the Ethiopian highlands. For Ethiopia, the zone of high pressure is mainly restricted to the level below 850 hPa. According to Segele et al. (2009), this ridge appears to limit the southern range of the ITCZ during summer. In the lowest levels, the ITCZ-/monsoon-related trough has a southern boundary at about 15 °N, over Eritrea. At 850 hPa, the trough reaches 10 °N, over northeastern Eritrea during the summer (Leroux 2001; Segele, Lamb et al. 2009). From the high in the southern Indian Ocean, a flow is set up through eastern Africa, reaching Ethiopia from the southwest, as indicated in the 850 hPa wind field in Figure 4-6.

4.1.2 The Intertropical Convergence Zone

Tracing a sinusoidal curve between 23.5 degrees south and north, the sun's seasonally shifting position in the sky causes the tropical rain belt to move northward during the Northern Hemisphere summer and southward during the Southern Hemisphere summer. As the sun moves, so do the zones of maximum low pressure, maximum temperature, maximum convergence, and maximum cloudiness and rainfall – as a seasonally migrating meteorological equator. This is the main driver of the seasonal cycle throughout the tropics, and is most often referred to as the Intertropical Convergence Zone (ITCZ). On top of this basic clockwork, regional and temporal variations add to the final climate and weather.

Figure 4-5 Atmospheric characteristics over Africa
Next page: Precipitation, mean sea level pressure (MSLP), vertically integrated moisture flux and vertically integrated moisture flux divergence, in January, April, July and October. All data are ERA-Interim 1981–2010 monthly averages, except precipitation, which is the 1979 – 2008 GPCP V2.1 average.

Figure 4-6 Atmospheric circulation over Africa
Second next page: Wind field at 200, 700 and 850 hPa in January, April, July and October. The red arrows (unscaled) mark the main flow. H/L in the 850 hPa maps mark the surface location of some of the main high and low pressure centers. All data are ERA-Interim 1981–2010 monthly averages.

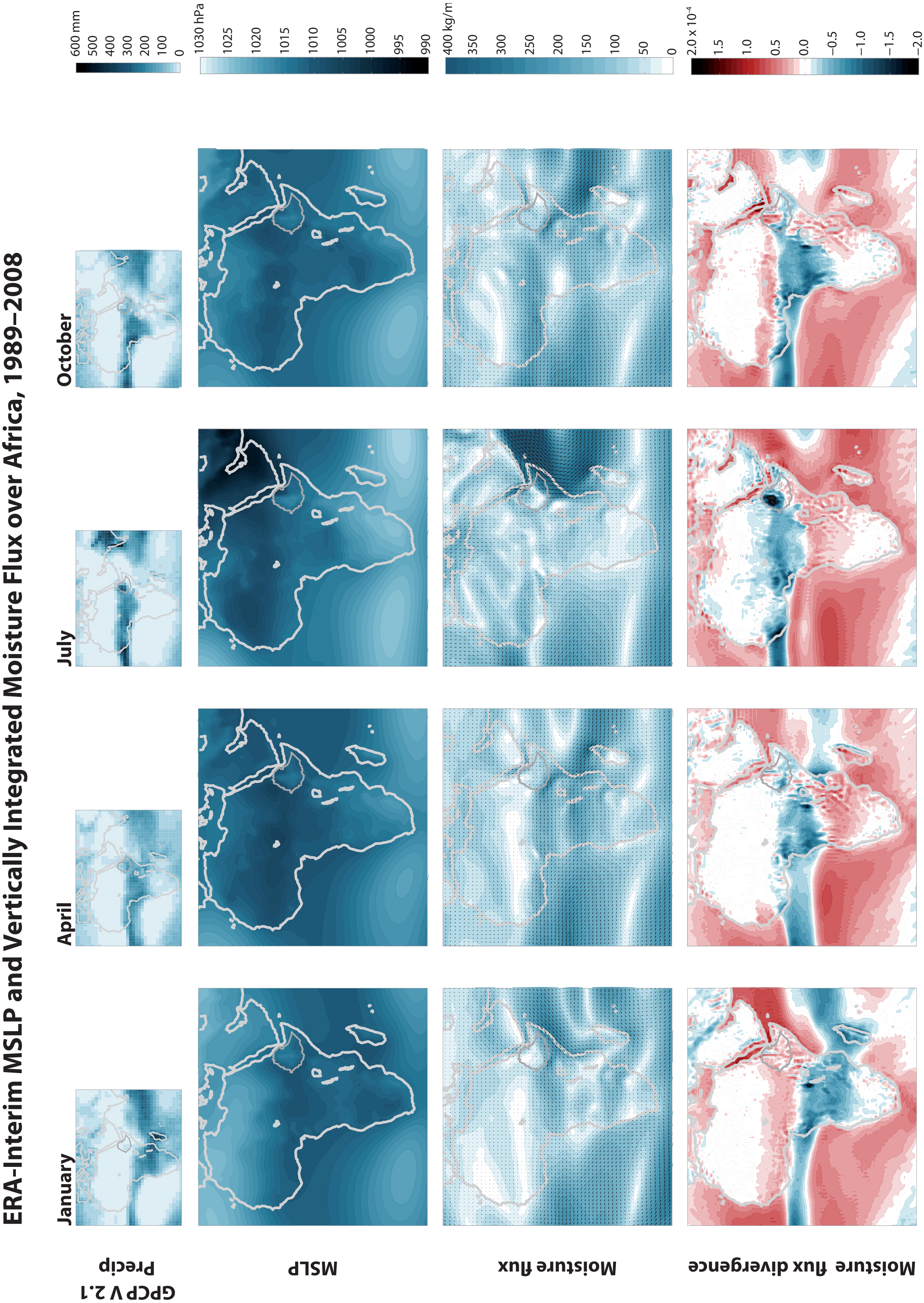

ERA-Interim MSLP and Vertically Integrated Moisture Flux over Africa, 1989–2008
January
April
July
October
GPCP V 2.1 Precip
MSLP
Moisture flux
Moisture flux divergence
600 mm
500
400
300
200
100
0
1030 hPa
1025
1020
1015
1010
1005
1000
995
990
400 kg/m
350
300
250
200
150
100
50
0
2.0 x 10^{-4}
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0

Figure 4-5

The Atmospheric Circulation over Africa, with Emphasis on Ethiopia

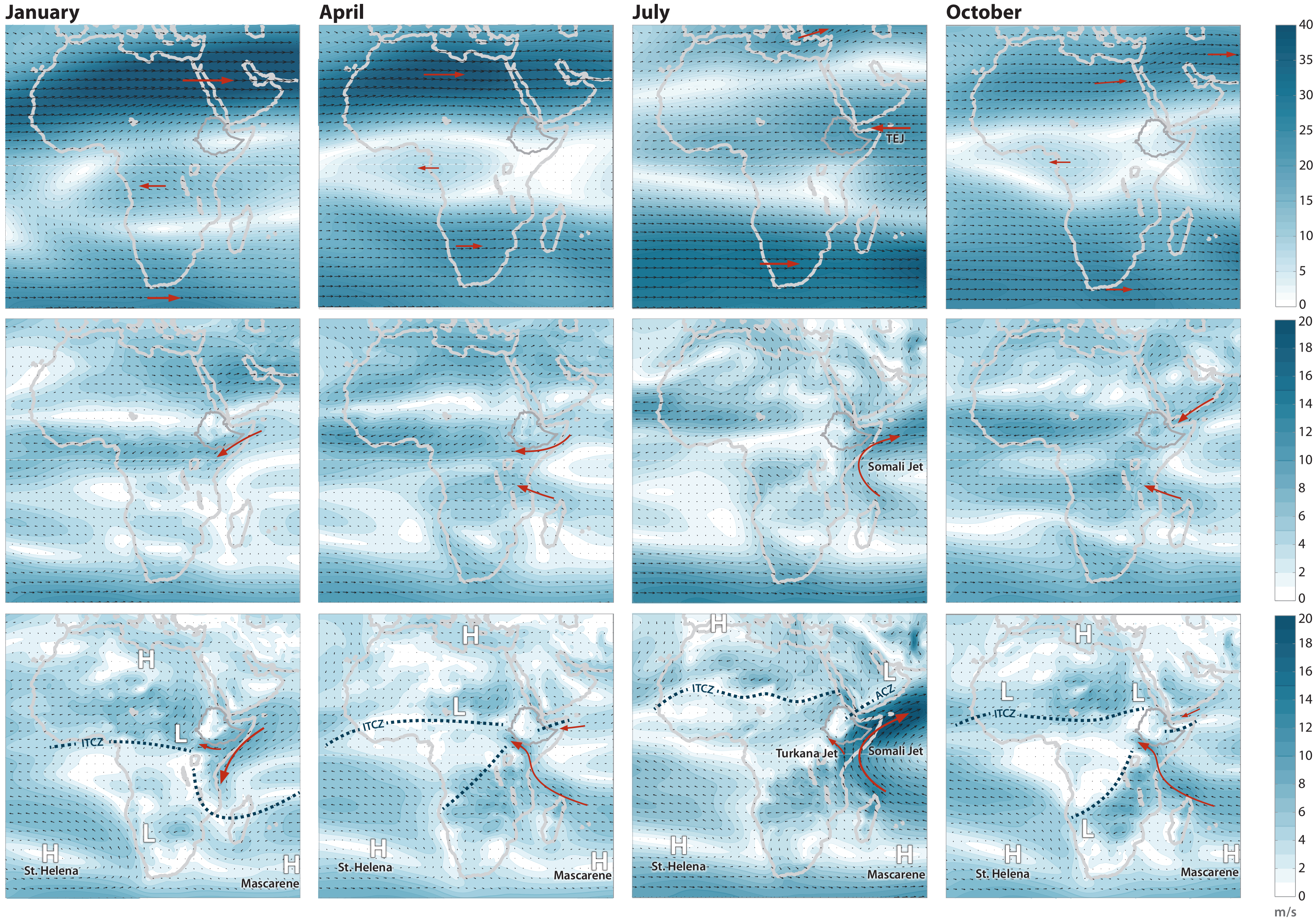
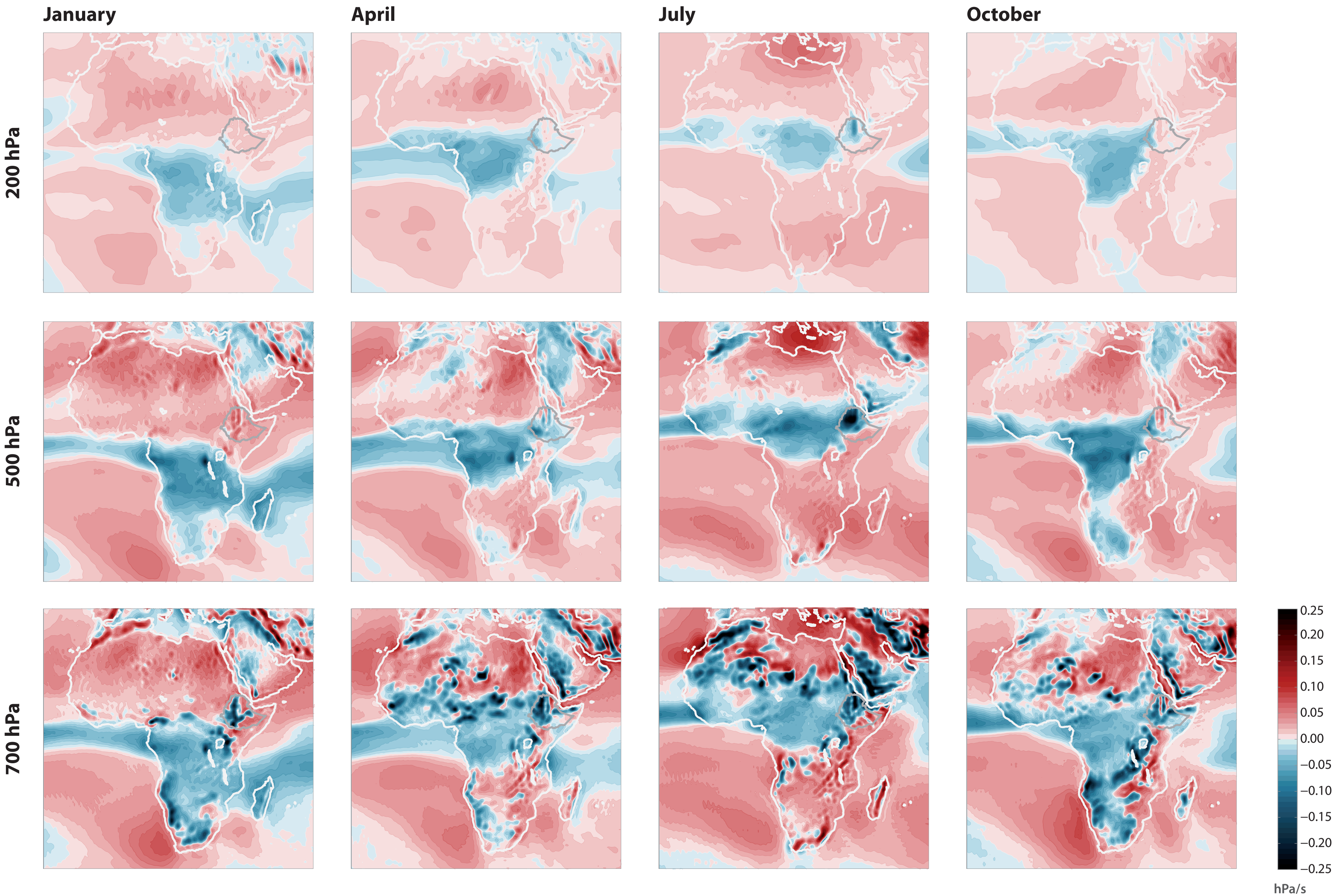


Figure 4-6

ERA-Interim Omega over Africa, 1981–2010



4.1.2.1 Defining and locating the ITCZ

The terms Intertropical Convergence Zone (ITCZ), equatorial trough and meteorological equator are used to describe the seasonally shifting zone associated with the tropical rain belt. The classical picture is that of converging trade winds and convection as the ground is heated. But as described by McGregor and Nieuwolt (1998), with reference to Hastenrath and Lamb (1977), and also demonstrated by Leroux (2001), the reality is much more complex. The zone of low pressure, maximum surface temperatures and surface wind confluence is located farther north than the zone of maximum cloudiness, precipitation and convergence. Over the African continent the distance between them may reach 1000 km. In West Africa, Nicholson (2009) found that the ITCZ defined as the trade wind convergence was directly linked to rainfall only in the southern Sahara and the northernmost Sahel, and only in abnormally wet years.

The difference between the zones is easily demonstrated by comparing climatological maps of precipitation with the maps of the atmospheric circulation. In the 850 hPa wind field over Africa in January, April, July and October in Figure 4-6, the label *ITCZ* is set at the curve marking the position of the surface confluence. As seen in the precipitation maps for the same months in Figure 4-5, this position is more representative of the northernmost extension of the rain belt than of the zone of maximum precipitation. The geographical distribution of precipitation in each month resembles the zone of moisture convergence shown in the lower panel in Figure 4-5, as well as the 500 hPa omega in Figure 4-7. The surface confluence zone drawn in the 850 hPa wind field map (Figure 4-6), has a branch that stays north of the equator throughout the year. As for the zone of maximum low pressure (Figure 4-5), this can be seen as a broad belt, with a maximum in the north in July, and maxima both north of the equator and above southern Africa in January.

As the term ITCZ is used differently in different studies, and sometimes used interchangeably with equatorial trough and meteorological equator, comparing statements made about the zone may often be difficult. Defining the ITCZ as the zone of maximum cloudiness has become common, as this parameter may be detected in satellite data (McGregor and Nieuwolt 1998).

Figure 4-7 Vertical winds over Africa
Previous page: Omega at 200, 500 and 850 hPa in January, April, July and October. All data are ERA-Interim 1981–2010 monthly averages.

4.1.2.2 The global ITCZ

Waliser and Gautier (1993), using satellite images showing the occurrence of large-scale convective cloud systems, found the ITCZ – or strictly, the zone of maximum cloudiness – to be made up of a number of distinctly different zones showing different characteristics, both in terms of structure and behavior. The classical narrow, well-defined cloud band, was found over the Atlantic and eastern Pacific Oceans, covering nearly half of the globe's circumference.

Its migration lagging slightly behind the land ITCZ, the ITCZ over extended ocean regions reaches its southernmost position further into the northern spring, and its northernmost position into the northern fall. This has to do with the differential heating due to the larger heat capacity of the oceans, as well as with surface currents in the equatorial oceans From the western Pacific through the Indian Ocean, strong monsoon flows and large ocean warm pools wash out the narrow banded structure, creating an ITCZ with a broader latitudinal range and more spatial variation (Waliser and Gautier 1993).

4.1.2.3 The ITCZ over Africa

Over Africa – the only region in the world – the cloud-based ITCZ has a nearly sinusoidal migration curve between 10 degrees north and south and appears to be in near-perfect phase with the solar cycle of surface heating. The northern migration appears to be inhibited by the Saharan desert, which also suppresses ITCZ activity slightly while the ITCZ is in the northern hemisphere (Waliser and Gautier 1993).

The location of the ITCZ above the Western Indian Ocean is highly influenced by the SST pattern created by the Indian monsoon. The landmasses respond rapidly to solar forcing, whereas the ocean

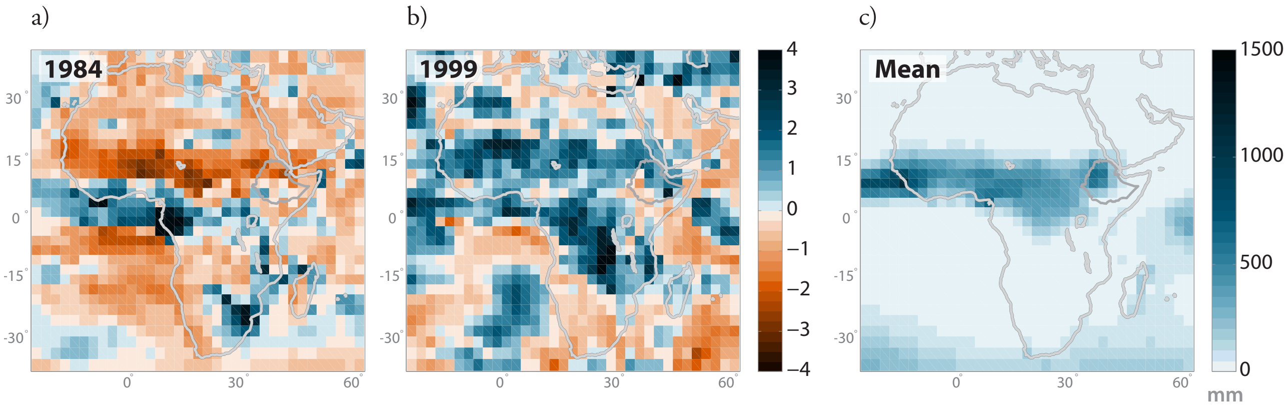


Figure 4-8 Strengthening/weakening of the ITCZ
Standardized precipitation anomalies in July–August 1984 (a) and 1999 (b), compared to the 1979–2010 mean (c). Data: GPCP Version 2.2.

surface temperatures show a close relationship with the low-level circulation (Slingo, Spencer et al. 2005). As seen in Figure 4-5, the rain belt outside of the coast of East Africa is distorted during most of the year – and in the summer broken – as are the belts in the moisture convergence (Figure 4-5, lower panel) and rising air (omega 500, Figure 4-7). Coastal upwelling related to the strong low-level wind (Figure 4-6, lower panel) in this region, cools the surface waters and suppresses convection. In the boreal winter, the upwelling off the coast of East Africa is reduced, and the convergence zones over Africa and the Indian Ocean are well connected (Waliser and Gautier 1993).

The ITCZ is sometimes pictured as located far to the north of Ethiopia in the northern hemisphere summer (Segele, Lamb et al. 2009; Laing and Evans 2011), but following the argument in Section 4.1.2.1, this is only correct if the ITCZ is defined as the zone of surface confluence. Two distinct confluence zones may be identified near Ethiopia during the summer months (marked in the 850 hPa map in Figure 4-6). Over Eritrea and the northernmost part of Ethiopia, wind convergence is largely associated with the large-scale, ITCZ-related confluence zone across Africa, as the southernmost border of the equatorial trough reaches 15 °N at the 1000 hPa level (Segele, Lamb et al. 2009). Another zone is located further south, above the Rift Valley and Djibouti. This zone is mainly related to the trough above the Arabian Peninsula. At 850 hPa, the Arabian trough confluence dominates much of the northern two-thirds of Ethiopia (Segele, Lamb et al. 2009). This confluence zone is part of the Afar Convergence Zone, forming as moist northwesterlies converge with the Indian summer monsoon's southwesterlies over the southern Red Sea and the Gulf of Aden (Tucker and Pedgley 1977).

4.1.2.4 Inter-annual variation in the ITCZ

Looking at the period 1971–1987, Waliser and Gautier (1993) found that most convection anomalies over Africa were associated with changes in the strength of the ITCZ in its mean position, rather than a change in the position. The strongest negative anomalies occurred in 1984 and 1987, which are well-known drought years across the continent from the Sahel to the Horn of Africa (Tucker, Dregne et al. 1991; Webb, Braun et al. 1992; Nicholson 1993; Dai, Lamb et al. 2004).

To illustrate the effect of possible ITCZ-related anomalies, Figure 4-8 shows July–August precipitation in Africa in 1984 and 1999, compared with the mean. In 1984 – one of the years with the weakest ITCZ in Waliser and Gautier's (1993) comparison – precipitation was reduced in the entire rain belt across Africa, except in the southern fringe near the Gulf of Guinea. Conversely, in 1999 July–August was wetter than normal in most of Africa between 15 °S and 15 °N, and the rain belt extended farther north than normal. Both examples exhibit latitudinal belts of equal-sign anomalies from one side of the continent to the other, suggesting that shifts in the large-scale circulation associated with the ITCZ played a role.

The position and strength of the ITCZ is commonly said to be a driver of the Ethiopian summer precipitation. Whether the ITCZ migrates sufficiently far north during the northern hemisphere summer is considered to be important, especially in the northern highlands, where (Figure 4-3) most of the annual precipitation falls in July and August (Griffiths 1972; Segele, Lamb et al. 2009; Diro, Grimes et al. 2010). Diro et al. (2010) found that high SSTs in the Gulf of Guinea were associated with increased ascent in northern Ethiopia, and reduced ascent in southern Ethiopia. This, together with positive correlations between Gulf of Guinea SSTs and summer precipitation in northern Ethiopia, led to the conclusion that high SSTs in the Gulf of Guinea strengthen the ITCZ in the north. Summer precipitation in the rest of Ethiopia has been shown to be negatively correlated with SST anomalies in the Gulf of Guinea (Segele, Lamb et al. 2009; Diro, Grimes et al. 2010).

4.1.2.5 The effect of the Indian monsoon on the circulation above Ethiopia

In addition to the seasonally changing position of the Sun, causing a north–south propagating global tropical rain belt, the differential heating of land and ocean surfaces causes latitudinal pressure gradients. The monsoon systems, and particularly the Indian monsoon, are the most pronounced large-scale effects of this asymmetry, with movements of pressure systems and seasonal reversal of wind regimes. As described by Gadgil et al. (2007), it is possible to view the development of the Indian monsoon both as part of the seasonal migration of the ITCZ and as a separate system pertaining to the monsoon region. When considering the effect on the circulation around Ethiopia, it is conceptually useful to consider the Indian winter and summer monsoons as an additional effect, or at least an adjustment to the features connected with the movement of the ITCZ.

For a general overview of the Indian monsoon, see McGregor and Nieuwolt (1998). During the northern hemisphere summer, the thermal contrast between land and ocean leads to the development of a heat low over northwestern India. The pressure gradient between this low and the Mascarene high in the Southern Indian Ocean sets up a cross-equatorial flow from the south to the north. Due to the Coriolis force, the air moves in a curved path, changing its direction from southeasterly to southwesterly after having crossed the equator.

North of the equator, along the coast of the Horn of Africa, the resulting intense, low-level flow is known as the East African Low-level Jet, or the Somali Jet (Figure 4-6, 850 hPa map for July). As indicated by a model study by Slingo et al. (2005), the mountains in East Africa and Ethiopia contribute to focusing the wind along the coast. The Somali Jet also causes strong upwelling along the coast, rapidly cooling the Northern Indian Ocean SSTs from June.

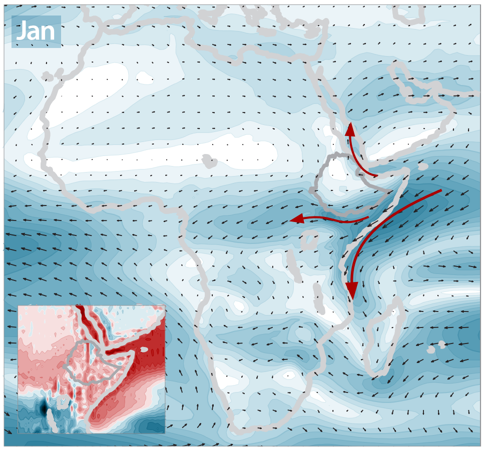
The Tibetan high is an upper-level anticyclone, located above the surface monsoon trough over northern India during the summer monsoon. Low-level convergence is matched by upper-level divergence. This gives rise to the upper-level (200 hPa and higher) Tropical Easterly Jet (TEJ), extending from India to Ethiopia (Figure 4-6, 200 hPa map for July).

During the northern hemisphere winter, a high pressure region develops over Siberia and Central Asia, setting up a clockwise circulation with air flowing out over the Indian Ocean. This is the Indian winter monsoon. As seen in the 850 hPa maps in Figure 4-6, the low-level flow in the Western Indian Ocean in January is reversed compared to in July; in the winter coming from the northeast. The strength of the flow is weaker than during summer, but there is still a distinct maximum near the coast of Somalia. During the transition seasons in April and October, the winds over the northern Indian Ocean are much lighter.

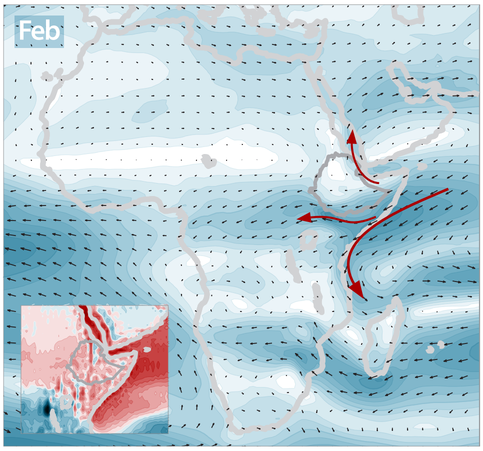
As described by Slingo et al. (2005), the seasonal cycle of the low-level winds modifies the movement of the ITCZ. In the northern hemisphere winter, the northeasterly monsoon flow along the coast of East Africa limits the northern extension of the tropical rain belt (Figure 4-5, upper panel for January). The warmest region in the western

Figure 4-9 Monthly moisture flux
Next two pages: Monthly 1989–2010 mean vertically integrated moisture flux and moisture flux divergence (small, inset maps). The red arrows (unscaled) mark some of the main features of importance for Ethiopia. Data: ERA-Interim.

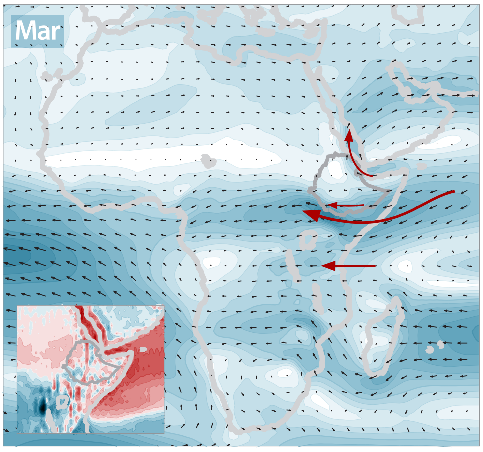
ERA-Interim monthly moisture flux and flux divergence



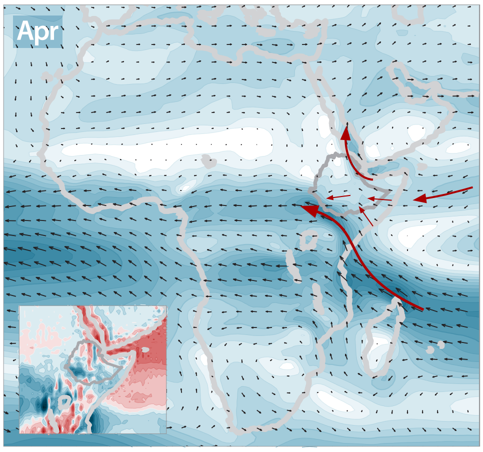
All transport from the north and east. Divergence above all of Ethiopia, except the northern Rift Valley and the southwestern border.



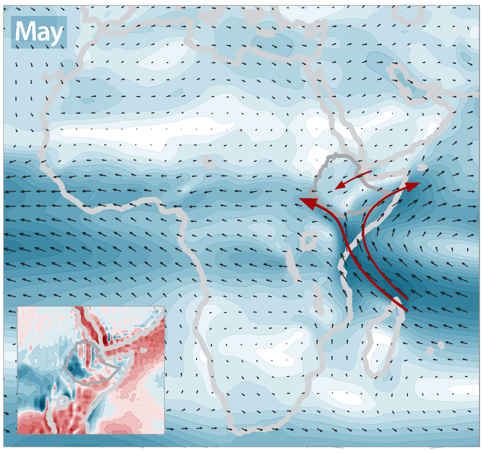
All transport from the north and east. Divergence above all of Ethiopia, except the northern Rift Valley and the southwestern border. Little change from January.



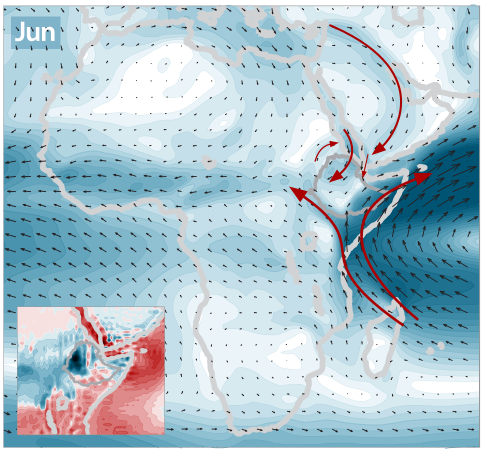
Easterlies from the Indian Ocean. Small convergence zone in the southwest, as air blowing through the Turkana Channel curves slightly to the north.



Moisture from the east and southeast converges above the southern half of Ethiopia.



Somali Jet latitudinal branch developed, causing divergence in the southeast. Flux from the northeast develops, increasing highland convergence.



Increased Somali Jet increases divergence in the south. Flow from Red Sea and Arabian Peninsula establishes, creating convergence in the northern highlands.

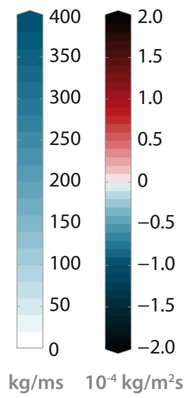
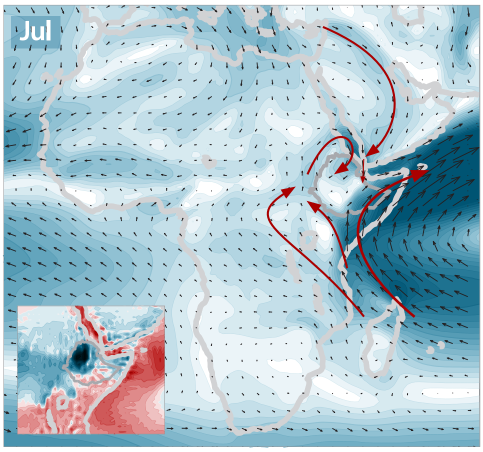
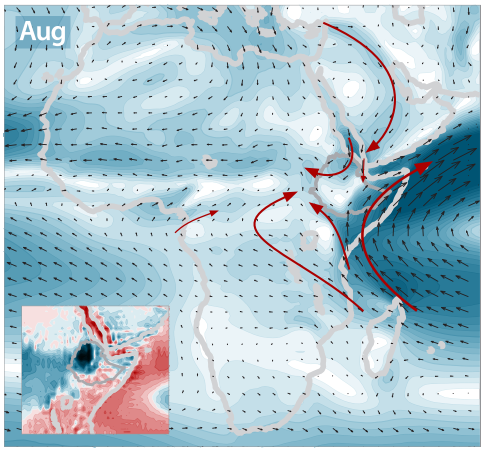


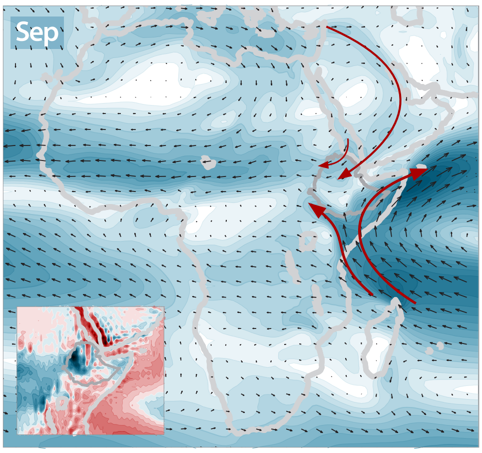
Figure 4-9



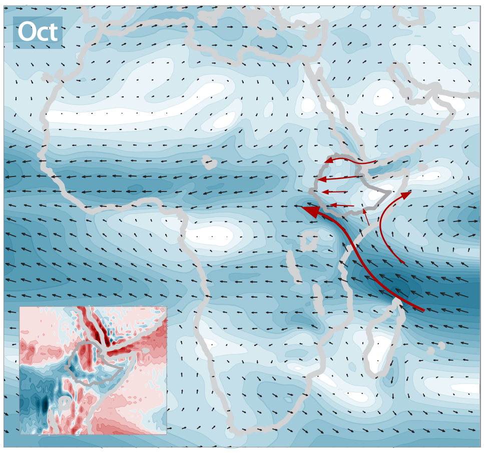
Indian Ocean cross-continental transport and south-north flow around plateau established. Maximum convergence above the highlands.



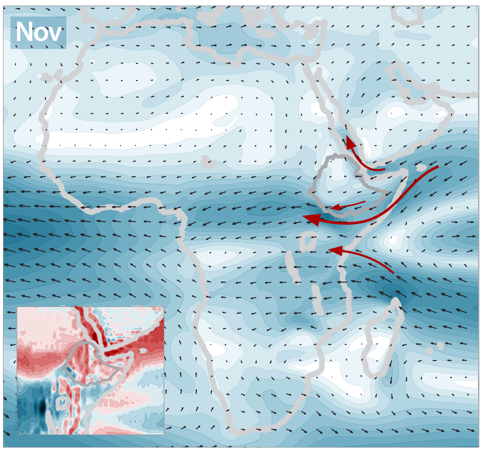
Flow around northern plateau cut. Indian Ocean cross-continental transport farther west. Cross-coastal flow from the Gulf of Guinea farther south, allowing it to reach Ethiopia.



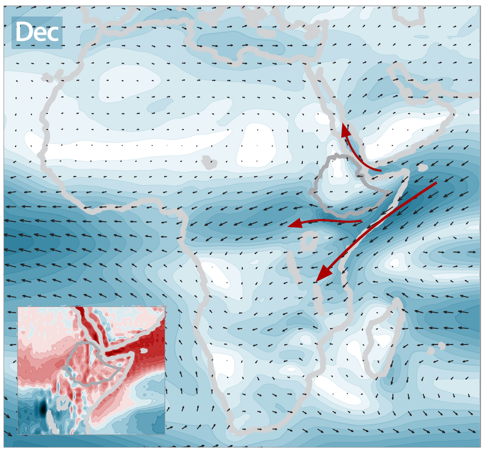
Weakened fluxes lead to less convergence. Direct transport from Red Sea only in the north. “Unbroken” flux from the Arabian Peninsula. No transport from the west.



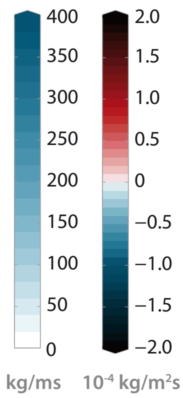
Easterly transport around the northern plateau causes divergence in most of the highlands. Convergence with Turkana flow in the south. Cross-coastal inflow in the southeast.



November resembles March. Moisture flux from the Northern Indian Ocean through Turkana, convergence in the southwest. Otherwise divergence.



All transport from the north and east, as in Jan–Feb. Divergence above all of Ethiopia, except the northern Rift Valley and the southwestern border region.



Indian Ocean lies near Madagascar, largely due to the surface cooling associated with the strong northeasterlies farther north. In the Western Indian Ocean, the ITCZ lies much farther south than on the Atlantic side of the African continent, where southeasterly winds connected with the St. Helena high push the ITCZ northward. The result is a marked southern boundary in both precipitation and moisture flux convergence on the Atlantic side, throughout the year (Figure 4-5, upper and lower panels).

Camberlin et al. (2010) hypothesized that the onset of the Indian summer monsoon is associated with a large-scale rearrangement in convective activity and atmospheric circulation over several parts of Africa, including East Africa and southern Ethiopia. For example, an early cessation of the March–May rains in East Africa tends to be followed by an early monsoon onset over India. On average, the monsoon onset occurs on 1 June. Prior to, and at the time of, the onset of the monsoon, there is a strengthening of the Somali Jet to the east of the East African highlands. This strengthening increases the low-level wind divergence above East Africa, effectively ending the spring rains.

The Ethiopian summer rains have on the other hand been shown to correlate positively with the Indian summer monsoon, on inter-annual and to some extent also on intra-seasonal basis (Camberlin 1997). The mechanism is believed to work through an increase in the southwest–northeast pressure gradient across Africa toward India, as a result of a pressure decrease in India during strong monsoon seasons. A stronger pressure gradient is associated with increased low-level westerlies above Africa, bringing more moisture to the highlands of East Africa and Ethiopia (Camberlin 1997; Segele and Lamb 2005; Segele, Lamb et al. 2009).

4.2 Winter precipitation: December–January/February

December and January are dry months in all of Ethiopia. Occasionally, low pressure centers that move eastward through the Mediterranean, cause convergence and rain in Eritrea and the Ethiopian highlands (Griffiths 1972). Still, no part of the country receives more than 5–6 % of the annual precipitation during any of these months; in some parts as little as 1 % (Paper III, and Figure 4-3).

The monthly climatology of the vertically integrated moisture flux and its convergence/divergence is shown in Figure 4-9. As seen in the maps for December, January and February, there is a strong flux of moisture across the southern part of Ethiopia. But with minor exceptions, the country is in a zone of divergence, with the ITCZ-related moisture convergence belt located to the south of Lake Victoria.

As the winter is a dry season in all of Ethiopia, its direct influence on crop production is limited. However, whatever little rain that falls during these months is important for maintaining the fields for grazing cattle. The absence of such rainfall in the winter of 1983–1984 marked the beginning of the catastrophic 1984 drought (Degefu 1987).

4.3 Spring precipitation: February/March–May

February/March–May is the period of the small rains, *Belg*. The Arabian high weakens and moves toward the Indian Ocean, and warm, moist air reaches southern Ethiopia from the south. Combined with upper-level cold westerlies, this promotes thunderstorms (Griffiths 1972). As shown in the precipitation map for April in Figure 4-5, the spring rains cover most of Ethiopia, bringing the continuous precipitation zone to higher latitudes than anywhere else in Africa at this time of the year. This occurs as the tropical rainbelt approaches from the south, and the low-level winds along the coast of East Africa and the Horn of Africa are in transition between their northeasterly, winter direction and the fully developed summer Somali Jet (Figure 4-6, 850 hPa).

Through model simulations, Riddle and Cook (2008) examined how the ITCZ and the related zone of maximum rainfall performs a 20-degree monsoon jump from 10 °S to 10 °N between late March and the end of May. They found that the development of the Ethiopian spring rains coincides with different stages in the development of the Somali Jet. The transition occurs in two stages. A meridional branch of the Somali Jet forms in March, almost a month before the zonal branch. In April the precipitation maximum in East Africa is brought from south of the equator to the northern equatorial region. At the same time, a southerly flow organizes along the equatorial coast, forming the meridional, cross-equatorial branch of the Somali jet (Riddle and Cook 2008). As seen in the 850 hPa wind field for April (Figure 4-6), there is already a low-level flow toward southern Ethiopia from the Southern Indian Ocean, as opposed to the northerly and northeasterly direction of the flow in this region in January. Farther north along the Horn, the flow is still northeasterly, and there is yet no sign of the strong southwesterlies that are characteristic of the approaching summer. The southerly flow leads moisture towards the southern slopes of the Ethiopian plateau from the south, resulting in moisture convergence over most of Ethiopia (Figure 4-9). The zonal part of the Somali Jet develops later, in May. This component diverts moisture eastward from southern Ethiopia, ending the spring rains.

As summarized by Camberlin and Philippon (2002), various studies report contradictory results regarding any relationships between the spring precipitation in Eastern Africa and ENSO indices, and no strong conclusions may be drawn. Instead, a signal was found in the northern hemisphere extratropics and subtropics, with wave activity setting up an upper- and mid-tropospheric ridge–trough anomaly extending from western Europe to the Arabian peninsula (Camberlin and Philippon 2002). Over the region between Northeastern Africa and Southwestern Asia, such a pattern corresponds to a southwards shift of the subtropical jet represented in the 200 hPa April wind field in Figure 4-6. Divergence ahead of the Arabian trough likely induces upward motion. In addition, an anomalous surface high over the Arabian Sea enhances the northeasterlies bringing moisture to Ethiopia (Camberlin and Philippon 2002).

Shanko and Camberlin (1998) saw a relationship between spring precipitation anomalies in the Ethiopian highlands and tropical cyclones in the southwestern Indian Ocean. Years with many strong cyclones coincide with drought years, and years with abnormally few cyclones were associated with heavy precipitation. The relationship was also found to hold on a daily basis. A suggested explanation was that during years with many cyclones, the cross-equatorial flow from the northern hemisphere to the southern hemisphere is stronger, bringing more moisture towards the center of the cyclones. The low pressure system causes a marked diffluence off East Africa, and less flow of moisture from the central Indian Ocean. Near Ethiopia, the flow from the southeast or east is weakened, or even replaced by cool, dry northeasterlies. Also, the upper-level easterlies are stronger than usual, and the subtropical westerly jet does not move as far south as usual. This leads to less convection above Ethiopia (Shanko and Camberlin 1998).

4.4 Summer precipitation: June–September

The northern hemisphere summer is the main rainy season in most of Ethiopia, *Kiremt*, with June–September accounting for 50–90 % of the annual rainfall in the northwestern highlands (Griffiths 1972; Korecha and Barnston 2007; and Figure 4-2). During this season, air masses carrying moisture from the Indian and Atlantic Oceans, as well as the Red Sea, converge and ascend above the Ethiopian mountain plateau (Mohamed, Hurk et al. 2005; Korecha and Barnston 2007; Segele, Lamb et al. 2009; Viste and Sorteberg 2012). The convective instability of the air is enhanced due to heating of the plateau (Griffiths 1972), but on a larger scale, the summer rains may be seen as a product of the northward movement of the ITCZ, and the Indian summer monsoon system, adjusted by the dominant topography of the Ethiopian highlands.

During the northern hemisphere summer, the tropical rain belt is at its northernmost position, reaching Eritrea and the northern Ethiopian highlands. As seen in the precipitation map in Figure 4-5, in July Ethiopia constitutes the easternmost part of the belt. The summer rains start in the west in June, gradually spreading northeastward. July and August are the wettest months in all parts of the plateau. The greatest rainfall during the June–September season, as well as annually, occurs in the western highlands (Figure 4-1 and Figure 4-3). Convective activity typically develops over the highlands, while the southern and southeastern lowlands receive little rain (Korecha and Barnston 2007). In July the strongest moisture convergence (Figure 4-5) and the strongest 500 hPa ascent (Figure 4-7) in Africa occur over the Ethiopian highlands. Ascent is seen at all levels up to above 200 hPa (Figure 4-7).

As identified by Segele et al. (2009), the convergence observed above Ethiopia during the summer is related to two distinct confluence zones. The ITCZ-related zone of maximum low-level wind convergence is located north of Ethiopia throughout the summer (Figure 4-6, as marked for July in the lower panel). Over Eritrea and the northernmost part of Ethiopia, wind convergence is largely associated with the ITCZ. 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, this monsoon trough confluence dominates much of the northern two-thirds of Ethiopia (Segele, Lamb et al. 2009). This confluence zone is part of the Afar Convergence Zone (ACZ; Figure 4-6, lower panel), forming as moist northwesterlies converge with the monsoon southwesterlies over the southern Red Sea and the Gulf of Aden (Tucker and Pedgley 1977).

Other monsoon features have also been related to Ethiopian summer precipitation, namely the Somali Jet and the Tropical Easterly Jet.

4.4.1 Low-level circulation: The Somali and Turkana Jets

For centuries, sailors have been aware of the strong surface winds between the northern part of the east coast of Somalia, and India, during the northern hemisphere summer. Coined the Somali Jet, or the East African Low-Level Jet, these winds constitute only a small part of a major cross-equatorial current in the lowest 3 km of the atmosphere, extending from the regions east of Madagascar, over the flat lands of eastern Kenya, Ethiopia and Somalia, and across the Indian Ocean to India (Findlater 1969; Findlater 1977). The jet is clearly seen in the 700 and 850 wind fields in Figure 4-6. A system of low-level jet streams make up the flow in the jet, with speeds of 25–50 m/s 1 km above the ocean surface (Flohn 1987).

As shown in Figure 4-9, the Somali Jet transports an extremely large amount of moisture across southeastern Ethiopia. Paradoxically, this flow is the cause of a longitudinal break in the tropical rain belt in this region, above southern and eastern Ethiopia, and Somalia and the Arabian Sea (Figure 4-5). The jet induces considerable low-level wind divergence, reflected in the moisture flux divergence seen in Figure 4-9. The result is dry summers and arid land in Somalia and eastern Ethiopia (Flohn 1987). In summer, the northern part of the Somali Jet brings a lot of moisture through, but not to, Ethiopia. The role of the Somali Jet in supplying moisture for the spring rains was discussed in Section 4.3.

The southern part of the Somali Jet brings moisture to Ethiopia during summer, with the topographic corridor between Kenya and Ethiopia as one of the main pathways (Viste and Sorteberg 2012). At the same level as the Somali Jet, the Turkana Jet (Kinuthia and Asnani 1982) crosses westward through the dry Turkana Channel (Figure 4-6, as marked in the 850 hPa panel). Moisture divergence (Figure 4-9) in the Turkana Channel and the southern Ethiopian highlands delimits the southern extension of the summer ITCZ above Ethiopia, but the Turkana Jet brings moisture to the Ethiopian highland farther north, as the flow continues around the mountain plateau (Viste and Sorteberg 2012). The main forcing of the strong, easterly, all-year wind through Turkana is orographic, as the air is led between the mountains of

Southern Ethiopia and Northern Kenya (Kinuthia and Asnani 1982; Kinuthia 1992; Indeje, Semazzi 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).

4.4.2 Upper-level circulation: The Tropical Easterly Jet

Also a component of the Indian monsoon, the Tropical Easterly Jet (TEJ) is an upper-level jet blowing across the Indian Ocean during summer. Centered on 15 °N, 50–80 °E and extending from Southeast Asia to Africa at 100–200 hPa, the TEJ (labeled in the 200 hPa wind field for July in Figure 4-6) is an upper tropospheric easterly wind that lasts from June to September. The jet strength reaches a maximum of 40–50 m/s over the Arabian Sea, west of the southern tip of India (Krishnamurti and Bhalme 1976). This jet can be described as a thermal wind, as it is formed as a result of differential heating of the subtropical Asian land masses compared to the relatively cool equatorial ocean (McGregor and Nieuwolt 1998).

TEJ strength has been positively linked to rainfall in West Africa (Hastenrath 2000; Grist and Nicholson 2001; Nicholson and Grist 2001), in India (Chen and van Loon 1987; Raju, Mohanty et al. 2002) and in Sudan (Hulme and Tosdevin 1989). Ethiopian summer precipitation has also been associated with the TEJ. A strong TEJ has been seen to coincide with abundant summer precipitation in Ethiopia (Hastenrath 2000; Grist and Nicholson 2001; Nicholson and Grist 2003; Segele, Lamb et al. 2009). However, a thorough investigation into the role of the jet has not been performed, and a formal quantification of the effect is still missing (Shanko and Camberlin 1998; Segele and Lamb 2005; Korecha and Barnston 2007; Segele, Lamb et al. 2009).

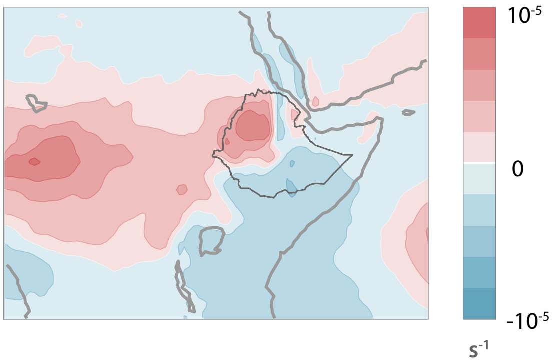


Figure 4-10 TEJ divergence in July
Mean July 1981–2010 200 hPa wind divergence over the Horn of Africa, with Ethiopia outlined in gray. Data: ERA-Interim.

The link between TEJ strength and rainfall in Ethiopia has been suggested to be the effect of upper-tropospheric divergence on convection. In general, maximum TEJ divergence occurs at the Indian entrance and African exit regions of the jet (Chen and van Loon 1987). Figure 4-10 shows the wind divergence at 200 hPa as a belt stretching westward from the Ethiopian highlands. This zone is part of the TEJ exit divergence, although the maximum in this region occurs at higher levels. Even though the maximum TEJ strength over Ethiopia is found at 150 hPa (Segele and Lamb 2005), the main divergence occurs at 100 hPa. At 15 °N, representative of the Ethiopian highlands, the exit zone is found at this level (Segele, Lamb et al. 2009). Stronger divergence as a result of stronger winds, is believed to favor a more intense ascent at lower levels, thus enhancing the generation of precipitation (Grist and Nicholson 2001; Segele, Lamb et al. 2009). Hulme and Tosdevin (1989) also pointed to a decline in wave propagation in years with weak TEJ strength.

4.4.3 Inter-annual variability in the summer precipitation

The inter-annual variability of precipitation in Ethiopia is relatively low (Conway 2000). Comparing seasons, the variability in the northern hemisphere summer rains is lower than in the spring rains (Cheung, Senay et al. 2008), and the intra-seasonal variability of summer precipitation is greater than the inter-annual variability (Segele, Lamb et al. 2009; Segele, Lamb et al. 2009b). But as the northern hemisphere summer is the main rainy season in most of Ethiopia, the inter-annual variability in the summer precipitation has a high impact on the national agricultural yield (World Bank 2005). As a result, the characteristics of dry and wet summers have been the subject of many studies, often with the attempt to connect precipitation with large-scale phenomena such as ENSO. Whether related to local, regional or global-scale phenomena, the direct cause of variations in the summer precipitation must be variations in the amount of moisture available and/or variations in the processes by which this moisture is converted into precipitation.

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 2011). In general, wet summers in Ethiopia have been associated with a general strengthening of the summer circulation, and vice versa. Segele et al. (2009) found associations between positive June–September precipitation anomalies in Ethiopia and most of the dominant characteristics of the summer season. Among these is a strengthening of the north–south pressure gradient across Africa, increasing the low-level cross-equatorial flow through Central Africa, and the low-level westerlies to the west and southwest of Ethiopia. A stronger Somali Jet and an increase in the upper-level Tropical Easterly Jet (TEJ) have been seen as indicators of an enhanced monsoon system during wet summers (Segele, Lamb et al. 2009; Diro, Grimes et al. 2010).

As early as in 1987, the Ethiopian National Meteorological Agency (NMA) issued its first seasonal weather predictions (Bekele 1997; Korecha and Barnston 2007). Since then, several statistical models for the Ethiopian summer rains have been shown to have skill, compared to climatological forecasts (Gissila, Black et al. 2004; Block and Rajagopalan 2007; Korecha and Barnston 2007; Diro, Grimes et al. 2010). The main basis of these models is correlations between Ethiopian precipitation and SST anomalies, although the NMA approach involves a second step of finding analog years with comparable circulation characteristics (Bekele 1997; Korecha and Barnston 2007).

The relationship between Ethiopian summer precipitation and SST anomalies has been the topic of many studies, all pointing to the concurrent ENSO as the dominating influence, with various degree 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, Lamb et al. 2009; Diro, Grimes et al. 2010). 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, Lamb et al. 2009; Segele, Lamb et al. 2009b).

In order to affect Ethiopian precipitation, faraway phenomena such as ENSO have to influence the atmospheric circulation over Africa. Letting increased SST in the Equatorial Pacific represent El Niño in a general circulation model, 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, as well as reductions in the Somali Jet and the low-level westerlies to the southwest of Ethiopia. These features are all characteristic of dry summers in Ethiopia (Segele, Lamb et al. 2009).

More weakly than the Pacific SSTs, SST anomalies in the South Atlantic Ocean and the Southern Indian Ocean have also been associated with dry and wet summers in Ethiopia (Korecha and Barnston 2007; Segele, Lamb et al. 2009; Diro, Grimes et al. 2010). 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 the Horn of Africa from the south (Korecha and Barnston 2007; Segele, Lamb et al. 2009; Diro, Grimes et al. 2010). Stronger correlations have been found for the Atlantic than for the Indian Ocean (Korecha and Barnston 2007; Segele, Lamb et al. 2009; Diro, Grimes et al. 2010), although intensification of the Mascarene high has also been seen as one of the main links between El Niño and Ethiopian rainfall (Segele, Lamb et al. 2009). Segele et al. (2009) suggested that the relationship with the Southern Indian Ocean may be reduced because of the ridge related to the Mascarene high, passing the Mozambique Channel toward Ethiopia. If positive pressure anomalies reach Ethiopia, this may reduce convection in the Ethiopian highlands.

The connection between dry summers in Ethiopia and warm water in the Gulf of Guinea may lie both in reduced moisture availability and in reduced local ascent. As shown by Kucharski et al. (Kucharski, Bracco et al. 2007; Kucharski, Bracco et al. 2008; Kucharski, Bracco 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, these studies point to a thermodynamic effect as the atmosphere is stabilized due to a temperature increase.

The geographical variation in Ethiopian precipitation anomalies should be noted. For northern Ethiopia, Diro et al. (2010) found that positive SST anomalies in the Gulf of Guinea, reducing the flow through Central Africa, were associated with higher than normal precipitation. The increase was attributed to an enhancement of the ITCZ, balancing reductions in the low-level circulation and the TEJ. Also believed to reflect ITCZ distortions, Korecha and Barnston (2007), found a weak association between Ethiopian summer precipitation and SST anomalies off the coast of West Africa near the Cape Verde islands. The flow of moisture toward the warm ocean pool during years with positive SST anomalies in this region, may disturb the northward migration of the ITCZ.

Although several statistical prediction models have been developed, with documented skills (Gissila, Black et al. 2004; Block and Rajagopalan 2007; Korecha and Barnston 2007; Diro, Grimes et al. 2010), there are factors that limit the possibility of predicting the Ethiopian summer rains. Despite correlations of up to -0.75 between Ethiopian July precipitation and Pacific SST anomalies, the devastating drought summer of 1984 occurred in an ENSO-neutral year (Korecha and Barnston 2007). Another drawback is that the strongest associations have been found between precipitation and concurrent ENSO conditions, implying that predictions of Ethiopian summer precipitation depends critically on the ability to predict ENSO (Korecha and Barnston 2007). Also, as will be discussed in Section 4.5, El Niños are often followed by a warming in the Indian Ocean, increasing precipitation in Ethiopia and East Africa in the fall season (Indeje, Semazzi et al. 2000; Schreck and Semazzi 2004; Bowden and Semazzi 2007; Camberlin 2009). During strong El Niño episodes, this warming may come early enough to increase the precipitation in all of Ethiopia in September, at the end of the summer season (Korecha and Barnston 2007).

4.5 Fall precipitation: October–November/December

October–December is the season of the *short rains* in Kenya and Tanzania, and as seen in Figure 4-3, also important in southern Ethiopia. In October the rain belt moves quickly southward, leaving most of northern Ethiopia practically free from rain (Griffiths 1972). As seen in Figure 4-9, there is a marked change from moisture convergence above the Ethiopian highlands in September to divergence in October. In Southern Ethiopia, the shift is opposite – from divergence to convergence. This is related to the weakening of the northern part of the Somali Jet, as seen both in the moisture flux in the same figure, and in the 850 and 700 hPa wind field for October in Figure 4-6.

In some years, most of Ethiopia experiences anomalously wet conditions in the fall. As seen in Figure 4-12 October–November 1977, 1982 and 1997 are strong examples of this. In Southern Ethiopia, the 1997 anomaly is seen to continue through

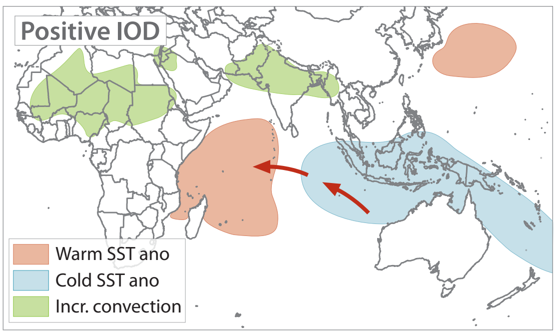


Figure 4-11 Positive IOD event
The main characteristics of a positive IOD event, with positive SST anomalies (red) in the Western Indian Ocean, negative SST anomalies (blue) in the Eastern Indian Ocean, and easterly wind anomalies above the Equatorial Indian Ocean. Increased convection is seen in the green regions, as well as in the Western Indian Ocean. Based on figure from www.jamstec.go.jp/frsgc/research/d1/iod.

January 1998. These years were El Niño years, and as summarized by Camberlin (2009), the negative correlation between ENSO and Ethiopian / East African precipitation during summer switches to positive in October–December (Indeje, Semazzi et al. 2000; Schreck and Semazzi 2004; Bowden and Semazzi 2007; Camberlin 2009).

The years 1977, 1982 and 1997 were also years with positive events of the Indian Ocean Dipole (IOD), a concept first introduced by Saji et al. (1999), as a pattern of quasi-biennial internal variability in the Indian Ocean. The main characteristics of a positive IOD event are outlined in Figure 4-11, with anomalously low sea surface temperatures off Sumatra and high sea surface temperatures in the western Indian Ocean. In relation to this change in the sea surface temperature gradient, there is increased convection and precipitation in the western Indian Ocean and easterly low-level anomalies in the Central Equatorial Indian Ocean (Saji, Goswami et al. 1999).

As seen in the easternmost parts of the 700 and 850 hPa wind fields in Figure 4-6, there is belt of strong westerlies in the Equatorial Indian Ocean in October. These low-level westerlies are the surface manifestations of a zonal (Walker) circulation cell (Hastenrath and Lamb 2004; Hastenrath and Polzin 2004; Hastenrath 2007). The easterly anomalies associated with positive IOD events represent a reduction of this circulation above the Indian Ocean (Saji, Goswami et al. 1999).

It has been suggested that ENSO may trigger IOD (Xie, Annamalai et al. 2002). Oppositely, it has also been argued that the El Niño signal in the fall precipitation in Eastern Africa may reflect concurrent positive IOD events. The fall precipitation in Eastern Africa correlates more strongly with the zonal SST gradient in the Indian Ocean than with ENSO (Behera, Luo et al. 2005). The correlation between time series of ENSO and IOD indices is relatively low, e.g., less than 0.35 as found by Saji et al. (1999). On the other hand, positive IOD events have only rarely occurred at the same time as a La Niña in the Pacific (Behera, Luo et al. 2008).

4.6 Trends and tendencies in Ethiopian precipitation

Farmers in Northern Ethiopia claim to have shifted to more drought-resistant crops due to declining rainfall during the last couple of generations (Meze-Hausken 2004). However, there is little evidence for precipitation trends in this part of the country (Conway 2000; Meze-Hausken 2004; Seleshi and Zanke 2004; Seleshi and Camberlin 2006; Bewket and Conway 2007). However, several studies have reported declining precipitation in Southern and Eastern Ethiopia, especially during the spring season (Seleshi and Zanke 2004; Seleshi and Camberlin 2006; Williams and Funk 2011).

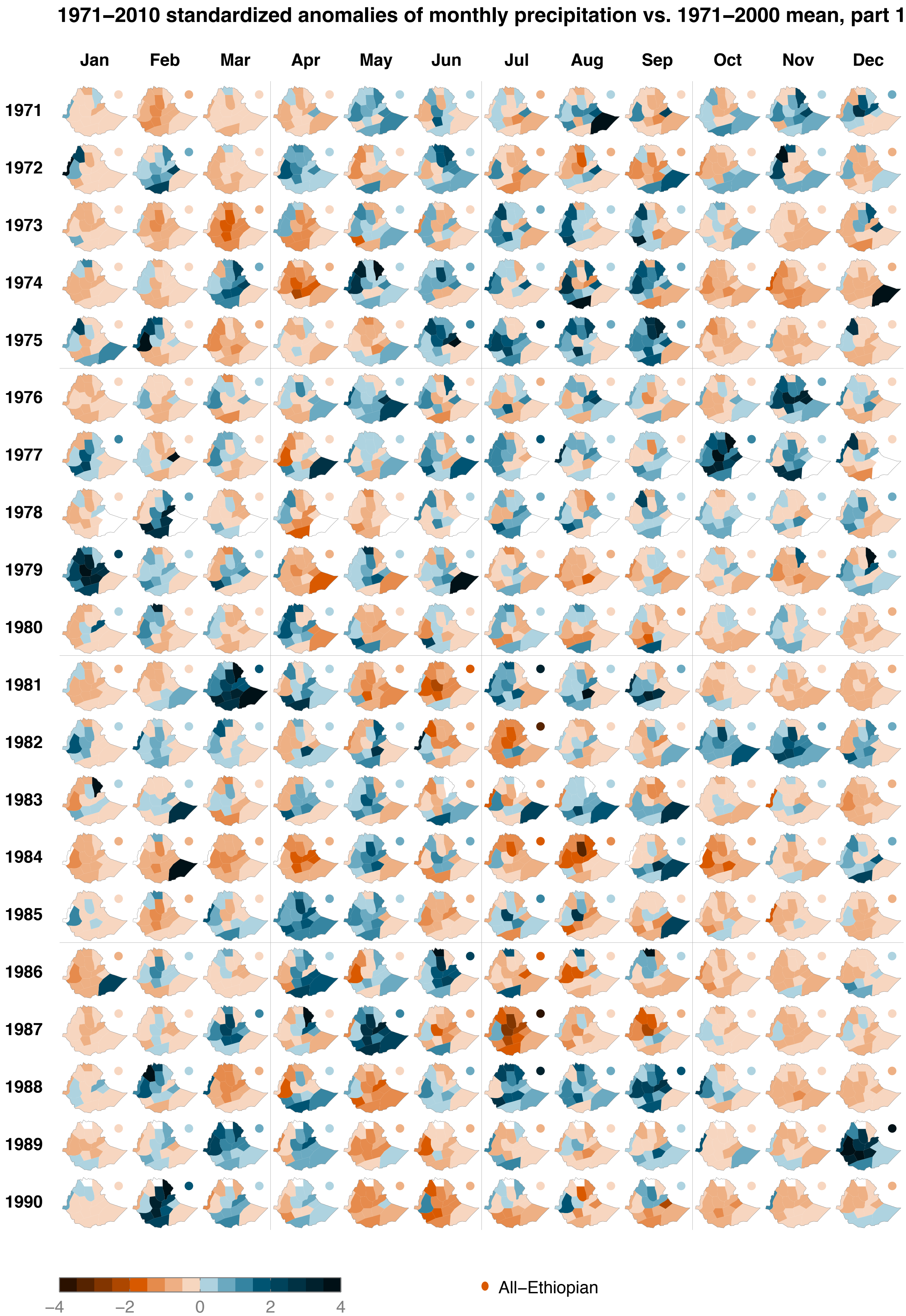
Precipitation trends in Ethiopia have been the subject of several studies; sometimes with contrasting conclusions (Conway 2000; Funk, Asfaw et al. 2003; Seleshi and Zanke 2004; Bewket and Conway 2007; Shang, Yan et al. 2011). In Central and Northern Ethiopia, most studies have found little evidence for precipitation trends, neither in seasonal precipitation amounts, nor in the frequency and intensity of extreme events (Conway 2000; Meze-Hausken 2004; Seleshi and Zanke 2004; Seleshi and Camberlin 2006; Bewket and Conway 2007).

Seemingly in contrast to the lack of trends in other studies, Conway (2000) found that the rainfall over the Upper Blue Nile Basin in the Ethiopian highlands had decreased markedly from the mid-1960s to the late 1980s. As pointed out by Bewket and Conway (2007), the use of different time periods in the analyses is most likely the main reason for discrepancies between trend studies in the central and northern highlands. Variations on decadal scales have been documented, and the dry 1980s were followed by recovering rainfall in the 1990s (Seleshi, Demarée et al. 1994; Jury 2010). Thus, it is more likely that a negative trend will be detected in a time series ending in the late 1980s or early 1990s, than in the late 1990s. Over the more than hundred years from 1898 to 2002, Conway and Bewket (2004) found no trend in precipitation in Addis Ababa, though also noted that the lack of spatial correlation means that the Addis Ababa record may not be used to infer anything about other parts of the Ethiopian highlands.

In Southern and Eastern Ethiopia, precipitation declines have been documented, most strongly for the spring season (Seleshi and Zanke 2004; Seleshi and Camberlin 2006; Funk, Dettinger et al. 2008; Williams and Funk 2011). A decline in precipitation has been documented for individual gauge stations in Southern, Southwestern and Southeastern Ethiopia during 1965–2002, but mainly during June–September from 1982 (Seleshi and Zanke 2004). Investigating extreme rainfall events in the same data, Seleshi and Camberlin (2006) reported decreasing trends in the extreme rainfall intensity during both February–May and June–September at the same stations.

Recently, Funk et al. (2008) and Williams and Funk (2011) have concluded that established relationships between large-scale climate variability and spring precipitation in eastern Africa are being altered. While the March–June precipitation in Eastern Africa has decreased during 1979–2009, compared to 1950–1979, there has been a corresponding trend toward increased convection and precipitation over the tropical Indian Ocean. These studies suggest that, as the tropical warm pool has extended westward into the Indian Ocean, the western, ascending branch of the Walker circulation has been extended westward. Diabatic heating anomalies related to increased cloud formation in the Indian Ocean may drive upper-level easterly anomalies toward the coast of Africa, while lower-level westerly anomalies reduce the inflow of moisture from the Indian Ocean (Shanko and Camberlin 1998; Funk, Dettinger et al. 2008; Williams and Funk 2011). Following this reasoning, a shift in the Walker circulation has suppressed convection over eastern Africa, decreasing precipitation in the northern hemisphere spring.

Figure 4-12 Regional precipitation anomalies
Next two pages: Monthly standardized anomalies of Ethiopian precipitation for 1971–2010, compared to the 1971–2000 reference period. Data: Regional monthly precipitation, as described in section 3.1. All-Ethiopian precipitation is a national, but highland-dominated, average based on Korecha and Barnston (2007) and personal communication with Diriba Korecha. Zones/months with missing data have been colored white.


1971–2010 standardized anomalies of monthly precipitation vs. 1971–2000 mean, part 1
Jan
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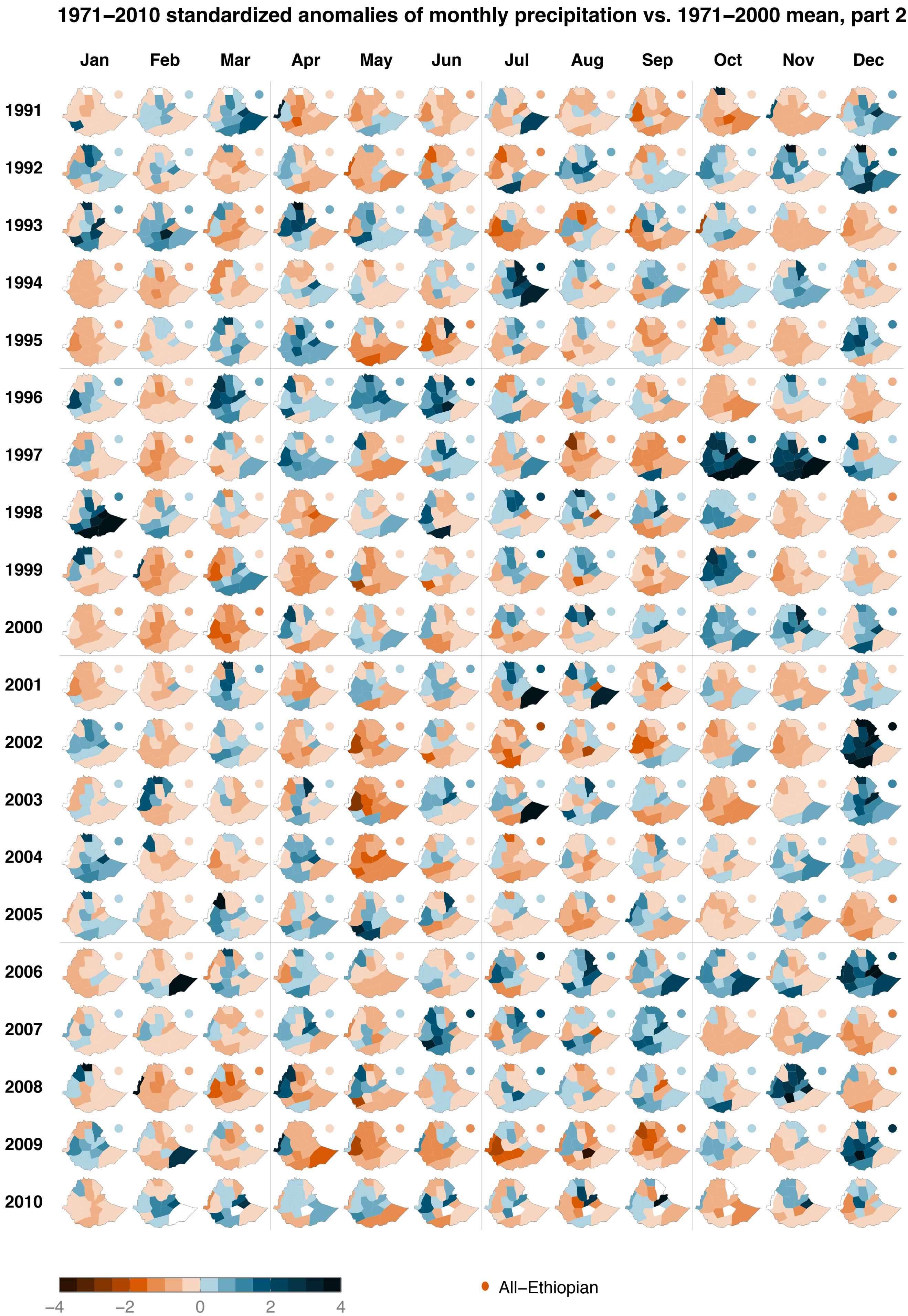
All–Ethiopian

Figure 4-12


1971–2010 standardized anomalies of monthly precipitation vs. 1971–2000 mean, part 2
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All−Ethiopian

5 Moisture tracking using FLEXPART

Among the more curious applications of atmospheric trajectory models, marihuana pollen found in Spain was traced to illegal plantations in Northern Morocco (Cabezudo, Recio et al. 1997). More commonly, trajectories are used to indicate the dispersion of air pollution, and the model used in this study, FLEXPART, was also originally developed for that purpose (Stohl, Forster et al. 2005). However, in the recent years these models have become a common tool for investigating moisture transport (James, Stohl et al. 2004; Stohl and James 2005; Stohl 2006; Nieto, Gimeno et al. 2007; Drumond, Nieto et al. 2008; Nieto, Gallego et al. 2008; Stohl, Forster et al. 2008; Gimeno, Drumond et al. 2010). In addition to the position of individual air parcels through time, the output from FLEXPART contains the mass and specific humidity of the parcels. This opens for calculations both of moisture content and of changes in moisture content along the route that the air takes.

In this study, FLEXPART was used as a Lagrangian tool for investigating the transport of moisture into the Ethiopian highlands. Some of the general features characterizing the flow of moisture through the region were discussed in Chapter 4. The strong convergence zone above Ethiopia in the northern hemisphere summer (Figure 4-9), represents the meeting of air masses carrying moisture from various continental and oceanic sources (Mohamed, Hurk et al. 2005; Korecha and Barnston 2007; Segele, Lamb et al. 2009; Viste and Sorteberg 2012). Air enters at different levels, and with different speed at different times, so the dominant sources and pathways of the air may not be easily identified from climatological, Eulerian maps. As shown in Figure 4-9, the vertically integrated moisture flux above the northern half of Ethiopia is northeasterly in all months from May to September. Comparing with the July wind field in Figure 4-6, the moisture flux field seems to be well represented by the 700 hPa wind field. The 850 hPa winds (not valid above the Ethiopian highlands, due to the high terrain) are generally southwesterly in a belt from the Gulf of Guinea to northern Ethiopia.

Previously, the direction of these low-level winds has been used to conclude that most of the moisture climbing the Ethiopian plateau during the northern hemisphere summer must be of Atlantic origin, with a smaller contribution from the Indian Ocean (Flohn 1987; Mohamed, Hurk et al. 2005). Even though the distinct southwesterly belt in the 850 hPa wind field is also partly represented in the moisture flux field (Figure 4-9), it is not obvious from these maps that this air and moisture enters Ethiopia. Quite the opposite, streamline maps based on the climatological 850 and 1000 hPa winds (Korecha and Barnston 2007) suggest that most of the air coming from the Gulf of Guinea passes to the west of Ethiopia, and that most of the air that enters Ethiopia comes from the Indian Ocean.

The Eulerian maps may give an impression of the importance of different regions for the flow, but they cannot be used directly to infer the magnitude of the transport from one region to another. With the aim of quantifying the amount of moisture brought into Ethiopia from various sources, we used the Lagrangian trajectory model FLEXPART (Stohl, Forster et al. 2005). The Lagrangian method was chosen in order to be able to perform a quantitative analysis of the contribution of moisture transport from different branches of air flowing into the Ethiopian highlands. FLEXPART was run globally from 1998 to 2008, using ERA-Interim reanalysis data as input. The region 8–14 °N, 36–40 °E in the northern Ethiopian highlands was defined as the target for incoming moisture. All air parcels passing through the atmosphere above this region in July and August were backtracked for 20 days.

The results are presented in two papers, as outlined in Section 2.1 and 2.2. Paper I focuses on the climatology of the moisture transport, while Paper II treats the inter-annual variability. This section provides some background underlying the interpretation of the results. For specific details of the methodology, see Paper I and II.

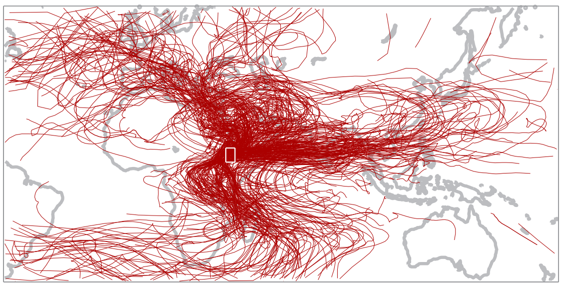


Figure 5-1 Trajectories of air reaching Ethiopia
Trajectories (red) for a random subset (0.6 %) of air parcels reaching the boxed target region (8–14 N°, 36–40 °E) in the northern Ethiopian highlands in July 1999. Trajectories are shown for the last 20 days before the parcels reach the target.

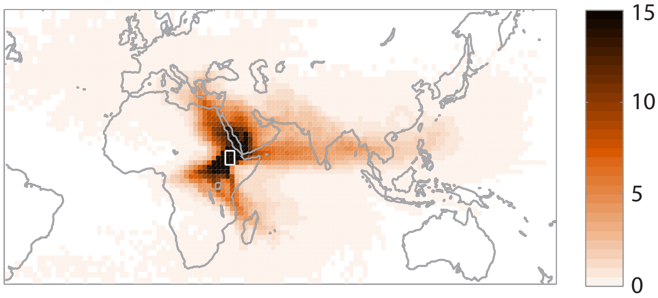


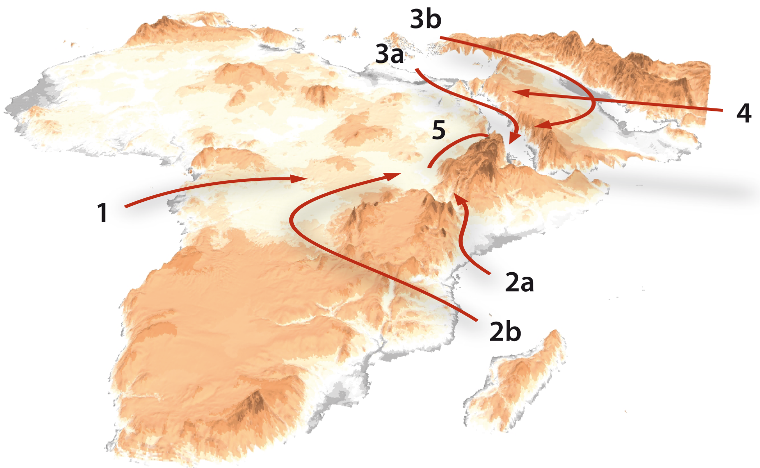
Figure 5-2 Air parcels reaching Ethiopia
Mean daily number of air parcels reaching the boxed target region (8–14 N°, 36–40 °E) in the northern Ethiopian highlands in July 1999. Values shown are the number of air parcels per grid cell over the last 1–10 days before the parcels reached the target.

5.1 Tracing the air: Transport of air and moisture

How does the air move? Whether the answer should be seen as a result or as part of the methodology, this question was the first to consider. The map in Figure 5-1 shows a subset of trajectories entering the target region (8–14 °N, 36–40 °E) in the northern Ethiopian highlands in July 1999. Similar plots were also made at different height levels to show how the incoming air was distributed vertically. Based on these maps, a picture of distinct branches transporting air into the zone of convergence above the Ethiopian highlands developed. These branches, described in Paper I and illustrated in Figure 5-3, became the main framework of the analysis.

Trajectory maps are useful tools for getting an impression of how the air moves, but in this case they had limited value when it came to the quantitative analysis. With more than 50 000 trajectories per month, eleven years and two months per year, a plot of all the data would have to contain well above one million indistinguishable trajectories. To solve this problem, the data were gridded into 2° latitude x 2 ° longitude cells. Figure 5-2 is a gridded version of the trajectory map (Figure 5-1), made by counting the number of air parcels above each grid cell, as a daily average over the 1–10 days before the parcels entered the northern Ethiopian highlands. Figure 5-4 describes the principle of this procedure. At each time step t_{end} representing the end of a backtrack, the air column above a grid cell in the target region is complete from the ground to the top of the atmosphere (Figure 5-4c). Tracing the parcels back one or more time steps, this column has

Figure 5-3 Transport branches
Transport of air into the northern Ethiopian highlands (8–14 °N, 36–40 °E) in July–August 1998–2008, relative to the topography (elevation data: GTOPO30, http://eros.usgs.gov). The red arrows represent the transport branches identified in Paper I.



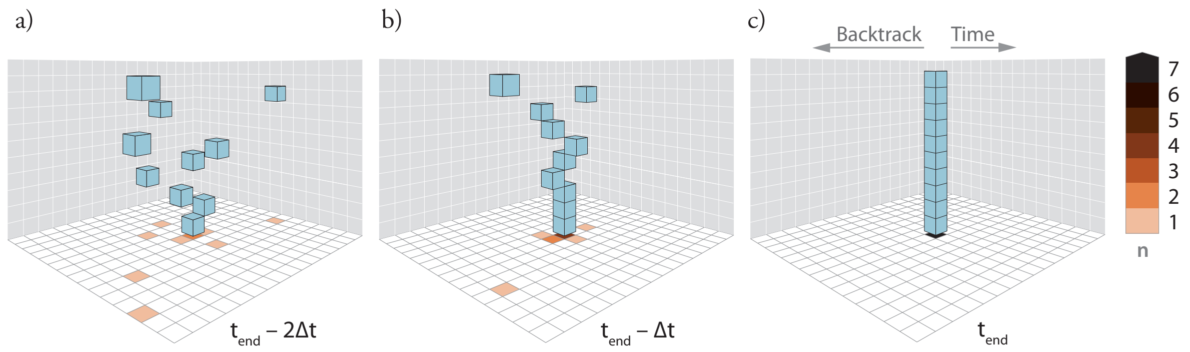


Figure 5-4 Gridding trajectory data
The main principle behind the gridded FLEXPART maps. Three consecutive time steps are shown, ending (c) with the last time step, t_{end}, for a set of trajectories. At this time step, the air parcels (blue cubes) that constitute the column of air between the ground and the tropopause above a grid cell in the target region, are identified, and then backtracked. In a) and b), the same air parcels are shown at the two preceding time steps, $t_{end} - \Delta t$ (b) and $t_{end} - 2\Delta t$ (a). As the parcels have entered from different directions and travel with different velocities, the air column is only complete at the last time step. The color of the horizontal grid cells represents the number, n, of target-bound parcels above each cell, analogous to the map in Figure 5-2, but for single time steps instead of the mean over a period.

spread out (Figure 5-4a,b), as the parcels have entered the target from different directions. Only horizontal displacements are shown in Figure 5-4, but the parcels may of course also have moved vertically. The horizontal, colored squares at each time step represent the "foot print" of the air parcels at that time step; the number of target-bound air parcels above each grid cell. Averaging over all time steps during the 10 days before the parcels reached the target region, as in Figure 5-2, produces a quantitative pattern complementing the trajectories in Figure 5-1.

Most of the air parcels have similar mass. Thus, if calculating the total mass of target-bound air parcels above each grid cell instead of the number of parcels (as in Figure 5-2), the patterns will appear identical. A different picture develops when calculating the amount of target-bound moisture in the atmosphere above each grid cell, using the same procedure (Figure 5-5). While the trajectory, number and mass maps are indications of the movement of air in general, the moisture content map may be used to suggest which transport branches that are most important when it comes to bringing moisture into the region. The interpretation should be performed with caution, though. In the gridded map, the value in each grid cell represents the amount of moisture that the air which later entered the Ethiopian highlands, had at the time when it was positioned above the grid cell. This moisture may or may not condensate out before the air reaches the highlands.

To allow calculations of the amount of moisture brought into the highlands, the air parcels were first clustered into branches, based on their trajectories. The amount of moisture contained in each parcel at the time when it entered the target region was then calculated, and the results summed up over all parcels. In order to say something about the possible contribution to precipitation, the difference between the moisture content in these parcels when entering, and later leaving, the region was also calculated. This quantity is a measure of the amount of moisture that was released in the region. These steps were carried out in both Paper I and Paper II, and in Paper II the released moisture was compared with precipitation.

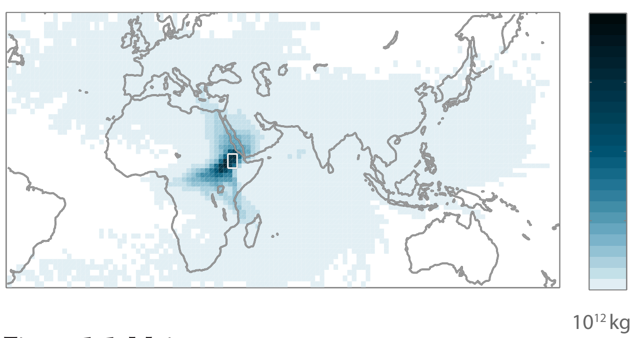


Figure 5-5 Moisture content
Mean moisture content [kg] in air parcels reaching the boxed target region (8–14 N°, 36–40 °E) in the northern Ethiopian highlands in July 1999. Values shown are the mean daily amount of moisture in the atmosphere above each grid cell over the last 1–10 days before the parcels reached the target.

5.2 Tracing changes in the air: Moisture uptake and release

Stohl and James (2004) described a method for calculating the transport of moisture from one region to another, and the approach has been used in several later studies (Stohl and James 2005; Nieto, Gimeno et al. 2006; Nieto, Gallego et al. 2008; Gimeno, Drumond et al. 2010). Provided no other changes take place, evaporation from the ground increases the moisture content of the air above, whereas precipitation reduces the moisture content. The net change in the amount of moisture in an air column from one time step to the next may thus be interpreted as the result of evaporation minus precipitation ($E - P$).

For a single air parcel, the change in moisture content from one time step to the next can be described as

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

where e and p are the rates of moisture increase and decrease, respectively, m the mass, q the specific humidity, and t time. Integrating $e - p$ over all particles N located above an area A, gives

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

where $E - P$ represents the total change in moisture in the air column above A. This is the difference between evaporation into the air and precipitation out of the air.

If either evaporation or precipitation is zero, this method may be used to estimate the other parameter. Precipitation occurs on 6 % of the globe at any given time (Trenberth, Dai et al. 2003), whereas evaporation always occurs to some extent. When it rains, however, the amount of water exceeds that which evaporates, and Stohl and James (2005) concluded that it was meaningful to consider only either evaporation or precipitation as occurring at any given time.

Maps of $E - P$ may be used to identify sources and sinks of moisture in the air before it enters the region. In Figure 5-6, the $E - P$ map for July 1999 shows how air that crosses Africa toward Ethiopia increases its moisture content on the way, whereas air that comes from the region of the Indian monsoon rains, loses moisture before reaching Ethiopia.

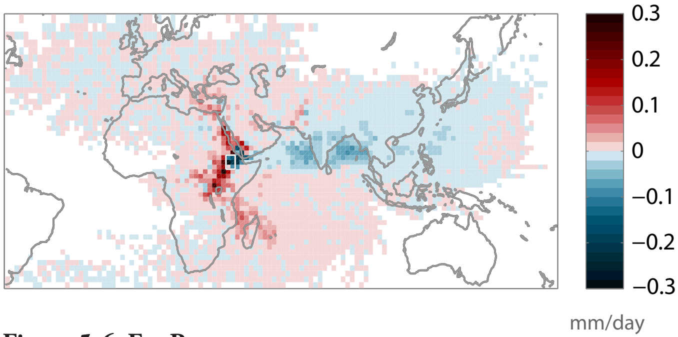


Figure 5-6 E – P
$E - P$ [mm/day] in air parcels reaching the boxed target region (8–14 N°, 36–40 °E) in the northern Ethiopian highlands in July 1999. Values shown are the mean daily $E - P$ in the column above each grid cell over the last 1–10 days before the parcels reached the target.

To state that regions with negative $E - P$ are sinks and regions with positive $E - P$ are sources of moisture to the northern Ethiopian highlights, may still not be correct. A main assumption in this method is that water spends a specific period of time in the atmosphere, from the time when it evaporates from the earth to the time when it falls back down as precipitation. The parcels are then tracked for a period of this length, and the average $E - P$ over the period used to locate possible source/sink regions. Most studies have used tracking periods of 10 days (Stohl and James 2005; Nieto, Gimeno et al. 2006; Gimeno, Drumond et al. 2010), which is close to the mean residence time for water in the atmosphere (Trenberth 1998; Numaguti 1999; Trenberth 1999).

In certain regions, the global mean residence time may not be a good representation of the actual time between evaporation and precipitiation. For example, Ent and Savenije (2011) calculated an annual mean recycling period of 7 days in the Congo basin, with shorter time-scales during summer. For a specific region to be a source of moisture for another region, moisture must be taken up over the source region, travel to the target region without being released, and then fall out within the target region. A positive $E - P$ value does not prove that the water that is taken up by the air in this region is the same that falls down in the target region. However, $E - P$ is a useful indicator of regions that are important for shaping the characteristics of the air traveling toward the target.

5.3 Tracing the effect: Moisture release and precipitation

Knowing how much moisture that enters a region may have a scientific value, as it improves our understanding of the processes in the atmosphere. However, unless the water vapor condenses to cloud drops and falls out as rain before leaving the region, the practical value is low. The outer part of the Horn of Africa – Somalia and eastern Ethiopia – is a good example. As shown in Figure 4-9 on page 29, this region has the strongest moisture flux in East Africa. Plotting a similar global map (not shown) demonstrates that, in July, it is also one of the land regions in the world where the flux is the strongest. But, as seen by the moisture flux divergence (small, inset map in Figure 4-9), the strong influx is more than balanced by the amount of moisture leaving the region. As a result, there is hardly any rainfall in this region during the Northern Hemisphere summer. In the Ethiopian highlands, the influx of moisture is smaller, but there is a strong zone of convergence. This convergence is one of the main characteristics of the Ethiopian summer rains (Mohamed, Hurk et al. 2005; Korecha and Barnston 2007; Segele, Lamb et al. 2009). In the Lagrangian framework, net precipitation may be derived from changes in the moisture content of the air parcels.

As described in Section 5.2 the difference between evaporation and precipitation, $E - P$, may be calculated by adding the changes in the humidity content of all air parcels constituting an air column, and then dividing by the cross-sectional area of the column. This may be used to calculate the precipitation in the target region, under the assumption that the evaporation is zero a time steps when there is net precipitation ($E - P < 0$) in the column (Stohl and James 2005). Note that this procedure may not be used similarly outside of the target region, as the air column is only complete at the last time step of each trajectory, used as a starting point for the backtracking (Figure 5-4).

Stohl and James (2005) recommended using the $E - P$ method to calculate precipitation only during strong rainfall events. In order to do so, we could have used ERA-Interim precipitation data, a choice that would be consistent, but not optimal, considering the problems identified in similar reanalysis precipitation data in Ethiopia (Diro, Grimes et al. 2009). As an alternative, we backtracked all parcels passing through the region, and used the net difference between incoming and outgoing moisture as a proxy for the monthly precipitation. Due to the summer rains, there is a general reduction in the moisture content of the air as it passes through the northern Ethiopian highlands. In general, the FLEXPART precipitation proxy scaled well with ground observations of precipitation in the region. When comparing these quantities in Paper II, we still chose to use percentage anomalies instead of absolute values.

A downside of using the difference between incoming and outgoing moisture as a measure of precipitation, is that recycling of moisture within the region, with water evaporating and re-precipitating before the air parcels leave the region, will not be accounted for. On the other hand, the procedure also allowed us to identify the potential contribution from different branches of the air flow (Figure 5-3). A decrease of moisture in an individual air parcel does not necessarily mean that the same amount of water falls to the ground as rain. It may be balanced by a corresponding increase in the moisture content of another parcel. Still, the decrease in the first parcel represents a contribution to the net moisture change in the air, and may thus be seen as a potential contribution to rainfall. As a total, over time, the difference between moisture brought into the region and moisture leaving the region, must rain out – unless the condensed water leaves the region as droplets. It is difficult to see that this should be the general case.

In Paper I, the moisture release within the northern Ethiopian highlands is used in to assess the relevance of each transport branch for precipitation in the region. The efficiency of the moisture release in different branches gives an indication of their role in the generation of precipitation. The inflow of moisture from the north (branch 3a and 3b in Figure 5-3) was found to be about 30 % higher than from the south, while the two air masses contributed equally to the amount of moisture released in the highlands. The release in the southern air (branch 1, 2a, 2b and 5) may thus be seen as more efficient, in the sense that a higher proportion of the moisture content in this air is released while passing through the highlands. The difference in release efficiency may be related to the fact that the air entering from the south is more homogeneous, in general traveling at lower levels of the atmosphere. The large amount of moisture coming from the north, partly reflects the large number of air parcels constituting this branch, as well as their diverse origin; some low-lying and some at mid-level, some having traveled over the dry Arabian Peninsula, and some over the Red Sea.

5.4 Tracing causes: What can be inferred from trajectories?

FLEXPART proved to be an adequate tool for answering most of the main questions underlying this study. The Ethiopian summer atmosphere is also a good case for using trajectories, as the inflow of air in the convergence zone is a combination of relatively clearly defined branches coming from different directions (Figure 5-3). This mix of air masses makes it easy to misinterpret the information that lies in Eulerian maps at different levels – as well as the sum represented by the vertically integrated moisture flux (Figure 4-9 on page 29). Trajectories showing the actual movement of air parcels can provide a clearer picture, allowing us to separate different effects. Does this perspective bring us nearer causality than the Eulerian approach? Yes and no.

One of the main benefits of the Lagrangian approach, is that air parcels may be followed from a region believed to be influential (eg. through associations between precipitation and SST anomalies) to the target region, with the possibility of analyzing changes in the characteristics of the air on the way. Unfortunately, with a large number of air parcels (more than one million in the case of the 11-year July–August climatology), simplifications have to be made, and the results must be grouped in one way or the other. In this study this was done by gridding the data, as explained in Section 5.1, and by clustering trajectories based on which regions they traveled through. This way, some of the Lagrangian data characteristics were inevitably lost, but trajectory maps showing the mean paths of the air, aided in interpreting the gridded data.

In Paper I, maps of $E - P$ (as Figure 5-6) are shown as averages during a period before air parcels enter the target region in the northern Ethiopian highlands. As in several other studies, these maps are used to identify moisture sources and sinks for the target region (Stohl and James 2005; Nieto, Gimeno et al. 2006; Gimeno, Drumond et al. 2010). This is based on the assumption that the residence time of moisture in the atmosphere is relatively constant through time and space. In reality, the length of this period varies greatly from place to place (Ent and Savenije 2011). To state that water that rains out in the target region has its origin east of Madagascar, simply because the maps show that moisture is being picked up there and transported toward Ethiopia, is not possible.

However, it is possible to conclude that moisture enters Ethiopia in air that is carried from this ocean region. This air flow is an important contributor to the Ethiopian summer rains, and whether the air parcels contain the same water molecules when reaching Ethiopia, is not necessarily relevant. Knowledge of the pathways demonstrated by the trajectories of the air can tell us whether this is a true source region, or whether the moisture is released before reaching Ethiopia. The red field in the ocean to the east of the Somalian coast in Figure 5-6, is an example of a non-realistic source region. This can be seen by looking at the trajectory map in Figure 5-1. Moisture is evaporated into the air from the ocean to the east of Somalia, but as illustrated in the enlarged sub-section of Figure 5-6 in Figure 5-7, the air parcels that reach Ethiopia from this region first travel northeastward into the

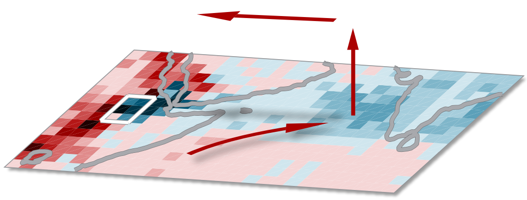


Figure 5-7 Transport with the northern Somali Jet
Section of the map in Figure 5-6, showing $E - P$ above the Indian Ocean and the Arabian Sea. The arrows illustrate how moist, low-level air in the northern part of the Somali Jet reaches Ethiopia as part of the dry, upper-level flow from the east, after ascending above the Arabian Sea.

Arabian Sea toward India, where they ascend due to the strong convection related to the Indian summer monsoon, release most of their moisture content, and enter Ethiopia with the dry, upper-level easterly flow.

The second approach used in Paper I and Paper II, was to cluster the air parcels into branches, determined by which regions they had passed through before reaching Ethiopia. The inflow of moisture from the north (branch 3a and 3b in Figure 5-3) was found to be about 30 % higher than from the south (branch 1, 2a, 2b and 5), and the two air masses contributed equally to the amount of moisture released in the highlands. The large inflow from the north may seem to contradict the fact that region to the north of Ethiopia consists of the dry lands of the Arabian Peninsula and Egypt. Northeasterly winds are generally considered as dry in Ethiopia. Judging from the moisture flux maps for July and August in Figure 4-9, the results are still consistent. As seen in the map, there is a relative strong transport of moisture across the Arabian Peninsula. The specific humidity of this air (shown in Paper I) is not high, and comparison with the 850 and 700 hPa wind field (Figure 4-6) shows that the wind is the dominant factor in the resulting flux. However, the strong flux is consistent with the high number of air parcels reaching Ethiopia this way, each contributing to the total amount of moisture. In addition, a notable proportion of the water that evaporates from the Red Sea, ends up in the Ethiopian highlands (Gimeno, Drumond et al. 2010). Detailed trajectory maps (not shown) show how air parcels that leave the Mediterranean region through northern Egypt, are channeled through the southern Red Sea before entering Ethiopia. As mentioned in Section 5.3, the release of moisture in air from the north was lower than in air from the south; not surprising considering the high proportion of mid-level, dry parcels in this branch. However, as the northern air contributes with half of the total moisture release within the highlands, there must be sub-branches of this branch that have an important effect on Ethiopian summer precipitation, at least climatologically.

In Paper II, dry summers are seen to be associated with reduced inflow of moisture from the south. It is tempting to conclude that the reduced inflow of moisture leads to reduced precipitation, even more strongly so than if the relationship was a purely statistical association between precipitation and westerly winds above Central Africa, as has previously been documented (Segele, Lamb et al. 2009). After all, the trajectory analysis shows that fewer humid Central African air parcels reach Ethiopia in dry years than in wet years. A similar reduction is not seen in the inflow of moisture from the north. In several of the dry cases, though, the reduction in the moisture release in air coming from the north is as high, or higher, than in the southern air. The reduction in precipitation may be as much the direct result of reduced moisture release in the northern air as in the southern – or both.

The reduction in moisture release represents reduced convergence, affecting both branches. The convergence is related to air rising above the Ethiopian plateau, but it is not clear whether the ascent is a cause or a result of the convergence. Nor is it obvious whether the reduction in moisture release is a result or a cause of the reduced inflow from the south. In Paper II, it is hypothesized that the reduction in moisture inflow from the south may lead to a general reduction in the convergence above the plateau, thus affecting the moisture release in all branches. If this is the case, low-level easterly wind anomalies above Central Africa, reducing the inflow of moisture from this region, is the indirect and fundamental cause of reduced precipitation in the northern Ethiopian highlands. The direct cause would still be the reduced ascent following the reduced convergence, resulting in reduced moisture release.

The limited period 1998–2008 used in this study is not a full climatological period, and the monthly scale does not resolve short-time, extreme episodes. However, as examples of circulation features associated with specific anomalies, the findings may be useful also when analyzing situations outside of this time frame. Knowledge of how the air normally moves, increases the possibility of interpreting the real effect and relevance of near and distant variations in the atmosphere.

6 Concluding remarks and perspectives

This study had two main objectives. The first was to give a general overview of precipitation deficits in Ethiopia during the last decades, the second to explore one of the mechanisms affecting the main rainy season in the most populous part of the country. On different scales, both relate to the importance of precipitation for Ethiopian society.

The main part of the study relates to the role of moisture availability as one of the mechanisms affecting the summer rains in the Ethiopian highlands. Whereas previous studies have made assumptions concerning the role of the flow from different sides of the continent, the results in Paper I and Paper II provide quantitative values. There are some caveats to these results. Obviously, as ERA-Interim reanalysis data have been used as input to the trajectory model, the results depend on the quality of this data set. Also, it may be argued that the 11-year period is too short to constitute a full climatological period. This limited the possibility of using statistics, and in Paper II the summer months classified as wet and dry must be considered a collection of case studies.

Some of the results may still be generalized. In many of the summer months examined, the low-level circulation anomalies corresponded well with well-known anomalies known to occur relatively frequently, and previously documented to be associated with wet or dry summers in Ethiopia (Segele, Lamb et al. 2009; Diro, Grimes et al. 2010). Provided that the ERA-Interim reanalysis data represent the circulation above Africa well, the FLEXPART analysis presented in Paper II shows the effect of such anomaly patterns on the transport of moisture toward Ethiopia.

Another question is the interpretation of the moisture transport field. As shown in Figure 4-9 on page 29, the vertically integrated moisture flux above Ethiopia is northeasterly during the northern hemisphere summer. The pattern is similar to the 700 hPa wind field, whereas most of the moisture in the air is contained in the lower layers, where the winds are weaker. Consistent with the moisture flux map, in Paper I the air from the north was shown to provide more of the moisture inflow than the southern branches, while air from the north and air from the south contributed about equally to the release of moisture within the highlands. The fact that more of the moisture entering from the south is released before the air leaves the highlands, indicates that this air, residing at lower levels, may play a more active role in the generation of precipitation. This view was also supported by the results of Paper II, where wet/dry summer months were associated with increased/reduced transport of moisture from the south.

The amount of moisture entering the highlands from the north could not be similarly associated with wet and dry months, although in most cases the release of moisture in air coming from the north contributed to the resulting precipitation anomaly. There may be two reasons for the lack of documented contribution by these air masses. Either, the northern air is not important when considering precipitation anomalies in the Ethiopian highlands, or the methods applied in this study were not sufficient in respect to answering this question. The answer may involve both reasons.

Most previous studies point to the regions to the south as most important for bringing moisture into the highlands (Flohn 1987; Mohamed, Hurk et al. 2005; Segele, Lamb et al. 2009). This is in line with frequently occurring westerly anomalies in the low-level circulation above Central Africa. However, the role of transport from the Red Sea has also been recognized (Mohamed, Hurk et al. 2005; Gimeno, Drumond et al. 2010), and cases of extreme precipitation related to anomalies to the north of Ethiopia have been documented (Jury 2011). Occurring less frequently, and with more diverse patterns, it is possible that deviations in the northern field are missed out when statistical analyses are used to search for circulation anomalies affecting Ethiopian precipitation. Considering the large inflow of moisture from the north, it may be speculated that anomalies in this region can have a large impact. Whether this is the case, and under which conditions, may not be inferred without further analysis of the flow on the northern side of the Ethiopian highlands – both the component coming from the Mediterranean and the component originally coming from the south, rounding the northern side of the plateau before climbing the highlands from the north.

The aim of Paper III was to quantify the meteorological component of Ethiopian droughts, as precipitation deficits constitute the first, fundamental step on the drought ladder. A possible extension of this work would be to widen the approach to include the subsequent steps through agriculture and society. As an example of such an investigation, Conway and Schipper (2011) compared rainfall variability and fluctuations in GDP growth rates in Ethiopia. Disputing a previous report (World Bank 2005), the authors concluded that only the most severe droughts had a clear impact on the economy, while the relationship was weak in other years.

From a natural scientist's point of view, the consequences of weather and climate anomalies on society may seem to be more obvious and strongly determined than they actually are. Asking natural scientists and economists to give their expert opinion on the total damage that could be caused by climate change, Nordhaus (1994) found that the natural scientists' estimates were much higher than the economists'. It was suggested that "economists know little about the intricate web of natural ecosystems, whereas scientists know equally little about the incredible adaptability of human economies."

This reflects the main reason for this part of the study: That the situation experienced on the ground is the combined result of both natural and socio-economic factors. Only by obtaining sufficient knowledge of the underlying national and regional precipitation deficits, is it possible to assess the importance of other components — and only by increasing the understanding of the mechanisms influencing precipitation, is it possible to improve seasonal predictions and early warning systems.

7 References

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