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Intraseasonal precipitation variability on Kilimanjaro and the East African region and its relationship to the large-scale circulation

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With 9 Figures

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Summary

Atmospheric circulation anomalies, related to snowfall events on the Tanzanian volcano Kilimanjaro, were analyzed based on hourly snowfall data from an automated weather station (AWS), global precipitation and reanalysis products. Analysis of 5 years of data (2000–2005) shows that snowfall on Kilimanjaro is linked to large-scale circulation anomalies, which can be identified in global reanalysis products. During the *long rains* season (March–May) snowfall on Kilimanjaro is associated with a west to east propagating wave of convective activity, which over East Africa merges with a precipitation-band maintained by steady easterly moisture influx due to cyclonic activity over northern Madagascar. Snowfall events tend to be associated with low wind speed, favorable for the development of surface radiative heating, thereby destabilizing the atmospheric column and initiating upward motion and deep convection. High near-surface specific humidity provides the necessary water vapor so that convection becomes moist. The *short rains* season (October–December) is dominated by east to west moisture transport. This easterly flow extends vertically through much of the troposphere and horizontally from the western Indian Ocean westward across the African continent. An active center of vertical motion and deep convection located over the western Indian Ocean near the East African coastline is responsible for easterly moisture transport and spill-over of precipitation into the East African domain. During positive phases of the Indian Ocean Zonal Mode (IOZM) strong trade winds prevail across the Indian Ocean, which, in combination with enhanced westerlies over the continental interior, tend to enhance low-level wind and moisture convergence near Kilimanjaro. During the negative IOZM phase on the other hand, the trade winds across the Indian Ocean and the westerly flow from the Atlantic Ocean are weaker, moisture convergence is reduced and conditions to initiate deep convection over Kilimanjaro are generally less favorable.

1. Introduction

The glaciers on Kilimanjaro (3°04′S, 37°21′E) retreated drastically throughout the 20th century and are likely to disappear early this century if current climate conditions persist. Complete loss of ice on the African continent would probably be unprecedented in the last 10,000 years (Thompson et al. 2002; Kaser et al. 2004; Cullen et al. 2006). If the ice disappears, the embedded historical archive would vanish and so will our chance to document past climate changes (Kaser et al. 2004). Tropical glaciers contain especially valuable proxy data as they are indicators of a particular sensitivity to a climate solely driven by the annual cycle of air humidity and related vari-

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ables instead of air temperature (Mölg et al. 2003; Kaser et al. 2004; Mölg and Hardy 2004). After the mid-19th century and throughout the 20th century, tropical glaciers all suffered major recession. Generally, air temperature changes are considered to be the most important factors influencing glacier retreat worldwide; however, direct field indications suggest otherwise for Kilimanjaro. Rather, a complex combination of changes in air humidity, precipitation, cloudiness, and incoming shortwave radiation might be the key components in determining tropical high-altitude climate. In the case of Kilimanjaro, glacier retreat is probably more directly due to reduced precipitation and increased shortwave radiation as a result of a decrease in cloudiness (Kaser et al. 2004). This change, while not directly due to increased temperature, could be the result of large-scale changes in atmospheric circulation in response to global warming. Therefore, it is important to understand how precipitation on the mountain is related to the large-and meso-scale atmospheric circulation, and how changes in this circulation may have altered precipitation, cloud cover, and humidity.

In 2000 an Automated Weather Station (AWS) was established on the summit of Kilimanjaro, accompanying the drilling of several ice cores (Thompson et al. 2002). This station provides hourly in situ climate data against which the proxy information from the ice cores can be calibrated (Hardy, D. R., The Climate of Kilimanjaro's Northern Icefield, manuscript in prep.), and AWS snowfall measurements have demonstrated the consequences of drought for glacier mass balance (Hardy 2003). Here we use hourly snowfall data from this AWS to investigate the intraseasonal precipitation variability on top of Kilimanjaro, in an attempt to identify the governing atmospheric circulation patterns leading to snowfall on the mountain. We intend to provide insights into atmospheric processes at high elevation in the tropics and to better characterize the regional climate. There is currently no adequate understanding of whether snowfall on the summit of Kilimanjaro is driven by perturbations of the large-scale circulation, or whether it is rather due to local-scale convective activity and orographic precipitation, which may not be discernible in global reanalysis data.

It is well known that precipitation variability in East Africa on all timescales typically results from complex interactions of forced and free atmospheric variations. Such interactions include synoptic-scale weather disturbances, sea surface temperature- (SST) forcing, large-scale atmospheric systems such as monsoon and trade winds, persistent mesoscale circulations, tropical cyclones, subtropical anticyclones, easterly/westerly wave perturbations, and extratropical weather systems (Mutai and Ward 2000). The local signals are further complicated by interactions of the near-surface flow with the complex topography in the East African region, and through modifications by large-scale teleconnections (Mutai and Ward 2000). While these aspects are quite well understood on seasonal and interannual timescales, this is much less the case for synoptic and intraseasonal variability.

East African rainfall is highly seasonal, as can be expected from its tropical location. Precipitation primarily occurs during boreal spring and autumn seasons as the solar-driven Intertropical Convergence Zone (ITCZ) crosses the equator from south to north, then north to south, respectively (Camberlin and Philippon 2002; Mutai and Ward 2000). The confluence of trade winds along the ITCZ causes gradual wind change from northeasterlies in January to easterlies in March, southeasterlies in July and again to easterlies in October (Gatebe et al. 1999). Therefore, the mean annual rainfall is divided into four periods: January–February, March–May (*long rains*), June–September, October–December (*short rains*), accounting for roughly 18, 42, 15, and 25% of the mean annual rainfall, respectively (Indeje et al. 2000). In general, precipitation events during the *long rains* season tend to be heavier and longer in duration, with less interannual variability, and are more likely associated with local factors. In contrast, precipitation events during the *short rains* season are less intense with shorter duration and stronger intraseasonal and interannual variability that mirrors large-scale phenomena such as El Niño-Southern Oscillation (ENSO) and the varying intensity of the zonal circulation cell along the equatorial Indian Ocean (Indeje et al. 2000; Mutai and Ward 2000; Camberlin and Philippon 2002; Hastenrath et al. 2004; Vuille et al. 2005).

In the tropics, ENSO is considered the dominant mode of interannual variability (Latif et al.

1999). Although ENSO is often to blame for rainfall anomalies in the East African region, other studies have presented contradictory results indicating the independence of ENSO and East African precipitation (e.g., Webster et al. 1999). Past studies have used numerical model simulations to show the relationship between East African precipitation and Indian Ocean SST, and the strong correlation suggests that the Indian Ocean may exert a greater influence over East African rainfall than ENSO-induced SST anomalies from the Pacific (Goddard and Graham 1999; Latif et al. 1999; Webster et al. 1999; Black et al. 2003; Vuille et al. 2005; Mölg et al. 2006). The Indian Ocean is believed to exhibit strong coupled ocean-atmosphere-land interactions that are self-maintaining, and are capable of producing an anomalous state in the Indian Ocean. One potential candidate for such rainfall variability is the Indian Ocean Zonal Mode (IOZM), explained by a quasi sea-saw east–west SST gradient reversal across the Indian Ocean. A positive IOZM indicates warmer and a negative IOZM indicates cooler than normal SST along equatorial East Africa, altering the large-scale wind fields, evaporation, and thus the moisture supply (Saji et al. 1999). While there is clear evidence that warm IOZM events tend to increase precipitation amounts in East Africa, in particular during the short rains, studies on the impact of the IOZM on the synoptic scale circulation are less abundant. In particular it is not clear whether the increase in precipitation during the positive phase of the IOZM is simply due to an intensification of the mean background state or whether it leads to a changed, anomalous circulation over and surrounding Kilimanjaro. Similarly the different precipitation response during warm and cold IOZM events may be due to an intensification/weakening of the 'mean state' climatology or it may be due to the establishment of very different, anomalous circulation regimes, which either favor or inhibit deep convective activity on synoptic timescales. The present study intends to shed some light on these questions.

The datasets used in this study and the methods applied are explained in Sect. 2. Synoptic analyses are conducted to explain the evolution of significant snowfall events in Sect. 3. Section 4 ends with some conclusions and recommendations for future research.

2. Data and methods

In February 2000 an AWS was installed on the Northern Ice Field (NIF) of Kilimanjaro, located at 5794 m above sea level. The weather station has been operating autonomously and providing continuous data since then. The AWS records measurements such as aspirated air temperature, relative humidity, incoming shortwave radiation, wind speed and direction, barometric pressure, and ice/snow surface height change, as well as other meteorological variables needed to calculate the glacier energy balance (Mölg and Hardy 2004). In addition, an automated camera was mounted to capture diurnal weather patterns (Hardy, in prep).

Hourly surface height change data for the period February 2000 to May 2005 was the only dataset available for this study. Two sonic-ranging sensors were attached at equal height on either side of the AWS to increase the overall reliability rate. Each sensor measures the elapsed time between emission and return of an ultrasonic pulse as a means to determine snow depth, where a decrease of distance represents snow accumulation and increase of distance indicates ablation. The surface-height record was visually inspected to filter spurious values and a 25-hour running mean was applied to remove an artificial height cycle due to diurnal temperature fluctuations. Daily snow surface heights were determined from average daily change in the two smoothed records. There were two gaps in the surface-height record: the first one was from October 2000 to mid-February 2001 due to strong ablation that caused tilting of the AWS and the second minor gap occurred at the beginning of November 2003 as a result of measurement uncertainty. Although one of the longest high-elevation AWS records in existence, the measurement period is still relatively short, making it more difficult to put the regional climate into longer-term perspective. A similar analysis of snowfall variability on a volcano in Bolivia, however, yielded new insight into the seasonality of snowfall and its intraseasonal variations (Hardy et al. 1998, 2003), and was equally applied to study the relationship between snowfall and the large-scale circulation (Vuille et al. 1998). These studies have shown how valuable such in situ data are to understand snowfall-atmospheric circulation processes in remote mountain areas, even if the data set only covers a period of a few years.

A selection process was applied to identify significant snowfall events to be used in the synoptic analysis. The original dataset showed that snowfall events on Kilimanjaro tended to occur as multiple-day events rather than single-day events. In addition, it is likely that events of longer duration show a stronger coupling to the synoptic-scale circulation than snowfall events which last only a few hours. Therefore, a persistence criterion was set, to establish those times when a measurable snowfall amount was recorded during at least two days over a three-day window. This process began by calculating 3-day running totals, and all events that failed the persistence criterion were removed. Then for each event, the day with the highest magnitude was selected as the center day, and the neighboring values (±2 days) were removed to avoid double counting. As a result, 70 events were identified as significant snowfall events (from February 2000 to May 2005), and these significant snowfall events were subjected to a number of different spatial analyses (see below). The possibility of single-day snowfall events with large magnitude was also considered in this study. However, as none of these events exhibited more than 2 cm of snow accumulation, they were not analyzed separately in this study.

In order to link Kilimanjaro snowfall with the large-scale circulation it was necessary to compare the data with global precipitation products to assure their correct representation of Kilimanjaro snowfall or conversely, if the in situ data were capturing the regional-scale climate of East Africa. To do this, time series of various daily precipitation datasets were constructed and compared with Kilimanjaro snowfall data on annual and seasonal timescales. These data included National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) precipitation data (Kalnay et al. 1996), and data from the Global Precipitation Climatology Project (GPCP), which is a component of the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program (WCRP). The dataset is a merged analysis that incorporates over 6000 gauge observations with estimates derived from infrared and microwave satellites. Daily precipitation data are available on a $1^\circ \times 1^\circ$ latitude-longitude grid from 1997 to present (Huffman et al. 2001). In addition we also analyzed Outgoing Longwave Radiation (OLR) data, which provides a useful proxy for East African rainfall. In general, OLR measures the intensity of emitted infrared radiation, and thus indirectly the temperature of the highest emitter in the atmosphere. Low radiation/cold temperatures are indicative of high cloud cover (e.g., convective clouds in the tropics), and more intense radiation represents clear sky conditions that allow the warmer surface temperatures to dominate. The OLR-rainfall relationship is particularly strong during the *short rains* season, and weaker during the *long rains* (Mutai and Ward 2000). The dataset used is provided twice daily on a $2.5^\circ \times 2.5^\circ$ grid. The time span of this dataset is 1974–present (Liebmann and Smith 1996; Lucas et al. 2001). The advantage of using OLR as a proxy is that OLR data are purely observational, unlike reanalysis products that are model-dependent. However, OLR data are difficult to interpret, of lower spatial resolution, and it is especially difficult to separate regions of active convection from regions of thick cirrus clouds. In this study, using OLR data in conjunction with AWS and GPCP data, helped to identify the accuracy or consistency of the various datasets, leading to a greater certainty in our results.

Daily NCEP/NCAR reanalysis data were further used to analyze atmospheric circulation patterns associated with rainfall variability in East Africa. The NCEP/NCAR reanalysis consists of a comprehensive set of assimilated atmospheric variables (Kalnay et al. 1996), available for the period 1948-present on a $2.5^\circ \times 2.5^\circ$ grid. Among the available variables, we considered the zonal (u) and meridional (v) wind components at various vertical pressure levels to examine the circulation over Kilimanjaro and the East African coastal region, while vertical velocity (ω) and specific humidity (q) were used to identify the potential locations of deep convection. These reanalysis data were also used to calculate moisture flux and moisture convergence, in order to determine the location of moisture sources and transport pathways associated with the snowfall events.

Spatial maps of different meteorological variables such as wind, vertical velocity, specific humidity, moisture flux, precipitation, and OLR were analyzed by creating composites of the 70 significant snowfall events that fell during the *long rains* and the *short rains* season to determine the differences, if any, in circulation patterns. Composites were generated using the superposed epoch analysis method (Bradley et al. 1987). This approach attempts to identify commonalities between different events by averaging absolute or anomalous fields of individual events. While the common signal should remain in the average, random noise is expected to cancel, particularly for large composites. On the other hand mixing synoptic situations in an average circulation can be misleading if the circulation differs significantly from one event to the next. If the scatter between the individual events is too large, then an average of individual events may no longer represent the true synoptic conditions conducive to precipitation. We therefore first analyzed individual events separately to assess the event distribution within our population. It is clear from these separate analyses that the composite actually cancels out much of the noise and reinforces the dominant circulation features, which are also present in the individual precipitation events.

Synchronized around key dates that represented the center day of identified snowfall events on Kilimanjaro, the absolute and anomalous fields of interest (wind, temperature, humidity) were averaged across all events from 2000 to 2005 for a period of 2 days prior to 2 days after the key date. Such composites were created separately for the long rains (Sect. 3.2), the short rains (Sect. 3.3.) and also stratified into cold and warm phases, depending on the state of the IOZM (Sect. 3.4). Since no significant IOZM events occurred in the period of study, 2000–2005, a rather low threshold of ±0.5 standard deviation was chosen to stratify all snowfall events into warm, cold or neutral phases of the IOZM. Only the warm and cold phase events were analyzed further (see Sect. 3.4).

Due to the rather small number of events that fell into each category and because our analysis only covers a short time span (2000–2005), we refrained from applying a Students' t-test to assess the significance of the difference between short and long rain composites or between warm and cold IOZM phases. So while our discussion of the results remains largely qualitative, we believe that is provides for new and interesting insight into the large-scale dynamics and controls of Kilimanjaro snowfall. As more data from the AWS become available, a more stringent statistical analysis will become possible.

3. Results and discussions

3.1 Kilimanjaro snowfall events

The 2000–2005 Kilimanjaro snowfall data shown in Fig. 1 reasonably portrays the annual precipitation cycle, showing the *long rains* and *short rains* seasons separated by two intermediate dry seasons. The *long rains* and *short rains* seasons accounted for ∼40% and ∼26% of the annual snowfall totals, respectively. The Kilimanjaro snowfall data were compared to GPCP, NCEP/NCAR reanalysis precipitation and OLR data, by extracting the data point closest to Kilimanjaro. All datasets produce similar annual cycles, although the intensity of precipitation differs significantly. The NCEP/NCAR reanalysis data shows almost continuous rainfall, and indeed, snowfall events of low magnitude (e.g., <1 cm) do occur frequently on the mountain. In general, these data show similar activity during corresponding days of snowfall on Kilimanjaro. Because of the potential for an overemphasis of local effects, the global analysis data were further sampled by averaging over a 5° (5° S–0, 35° E–40° E) and 15° grid (10° S–5° N, 30° E–45° E), centered over Kilimanjaro. Such a sampling method takes into account the large differences in spatial coverage between Kilimanjaro station data and the global analysis products. The spatial expansion somewhat improved the agreement between the three datasets, though some clear differences remained (not shown). The OLR data provides an additional means of validating the Kilimanjaro snowfall record. A similar annual cycle was found in the OLR data, with seasonal peaks during the austral summer (January–March), which corresponds to the onset of the *long rains* season. In addition, there was a strong agreement between OLR and GPCP data, which is not surprising, since GPCP data incorporates OLR observations as one component of the satellite observations. Overall, daily variability in Kilimanjaro snowfall is reflected with enough temporal agreement in the analysis products that

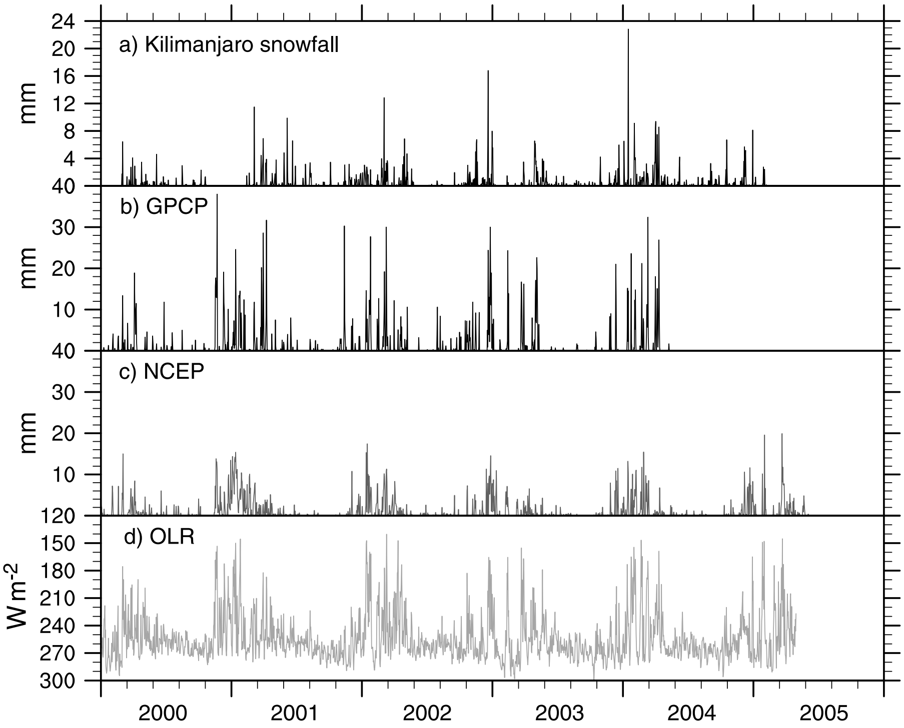

Fig. 1. Precipitation time series of **a**) Kilimanjaro, **b**) GPCP, **c**) NCEP, and **d**) OLR (with inverted y-axis) for 2000–2005. Data in **b–d** were extracted over the grid point closest to Kilimanjaro (3° S, 37° E). Note that **b** and **c** show mm of precipitation, while **a** shows mm of snowfall. No GPCP data was available for 2005

it can be used for identification of regional precipitation events.

The method discussed in Sect. 2.1 identified 70 significant snowfall events that passed the persistence criterion, in which measurable snowfall amount was recorded for at least two days over a three-day window. These events represent $\sim$73% of the total snowfall from 2000 to 2005. The top 10 snowfall events (greater than 10 cm of snowfall accumulation) explain $\sim$30% of the total snowfall recorded on Kilimanjaro from 2000 to 2005. The seasonal distribution of the 70 significant snowfall events include: 32 events in the *long rains* season (MAM), 18 events in the *short rains* season (OND), and 20 during the two intermediate dry seasons [JF (14) and JJAS (6)]. The high number of snowfall events in January–February is somewhat a surprise and shows that the JF dry season is not nearly as pronounced on Kilimanjaro as generally portrayed for East Africa (see also Hardy, in prep.).

3.2 Long rains

Over the *long rains* season the ITCZ is generally moving from the southern into the northern hemisphere. East Africa is influenced by the continental centers of convection, as well as by the strengthening trade winds from the Indian Ocean. Using a composite of all 3-day events registered on Kilimanjaro, the GPCP data clearly show the two primary locations of precipitation in the western Indian Ocean and over the continental interior (Fig. 2). In the 5-day composite from 2 days prior to 2 days after the event, a west to east propagating wave-like structure is observed over the African continent that appears to be related to precipitation on Kilimanjaro. At the same time, a precipitation band from the Indian Ocean moves eastward and merges with the continental moisture along the East African coastline. In addition, the GPCP precipitation and OLR anomalies (Fig. 3b and d) exhibit positive and negative anomalies concentrated over the Kilimanjaro region, respectively, indicating the presence of enhanced moisture and convective clouds. Figure 3a shows the 850 hPa wind field (vectors) and 500 hPa vertical motion (color scale). The most prominent feature is cyclonic activity associated with strong rising motion at 500 hPa over the western Indian Ocean and northern tip of Madagascar. The western side of the cyclonic flow creates southeasterly airflow that advects moisture from the Indian Ocean toward the East African coast. While the absolute winds show an easterly component, they are weaker than average for this season, indicating a clear slow-down of the moisture propagation (Fig. 3c). This behavior is evident in the anomalous wind field (not shown).

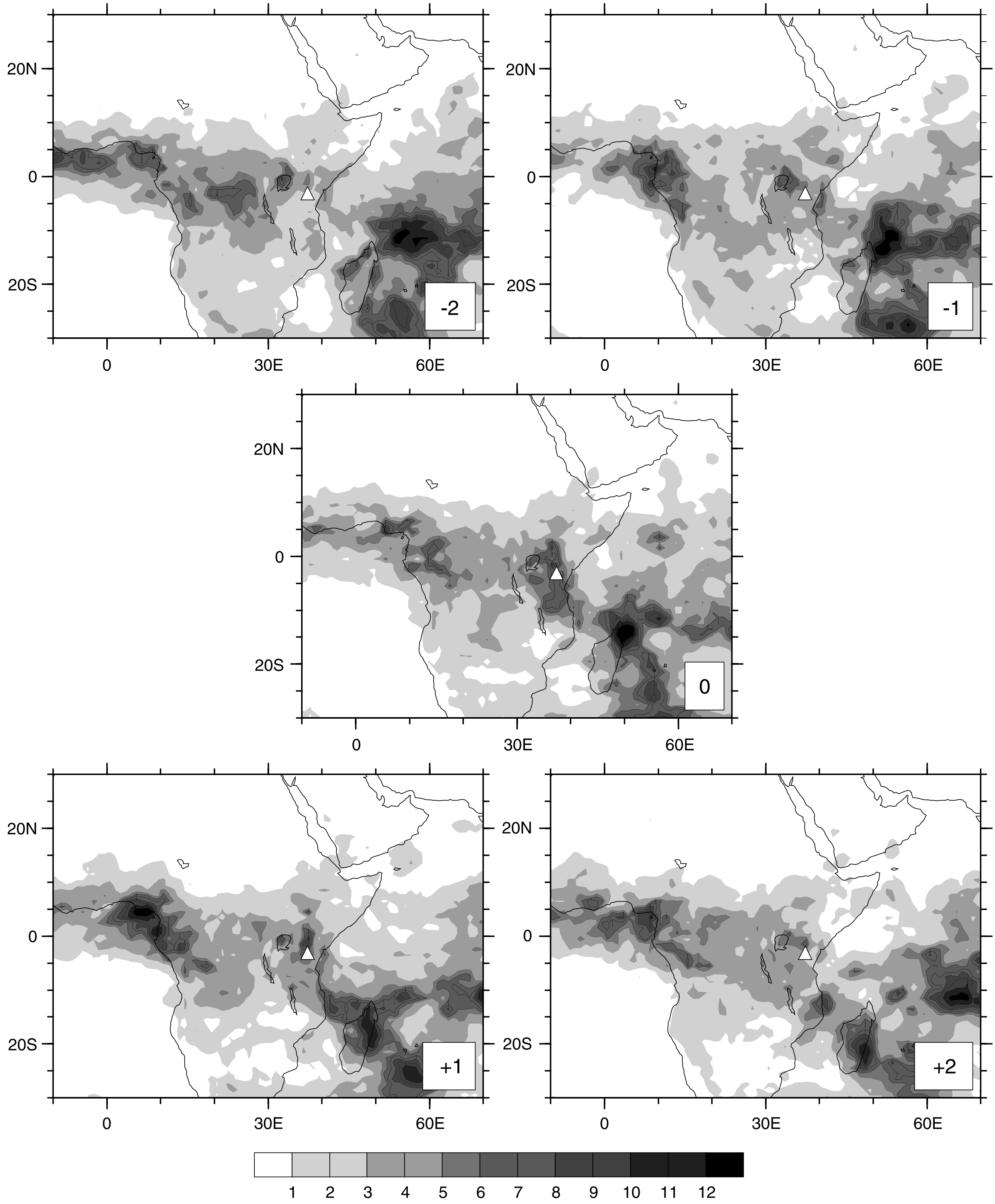

Fig. 2. A 5-day panel showing composites of all *long rains* snowfall events 2000–2005. The gray shading is a measure of precipitation intensity (in mm) from GPCP. White triangle represents location of Kilimanjaro

The zonal and meridional winds during the *long rains* season are dominated by easterlies from generally southerly directions, respectively. However, near Kilimanjaro, both the zonal and meridional wind components in the reanalysis data are close to zero for the largest snowfall

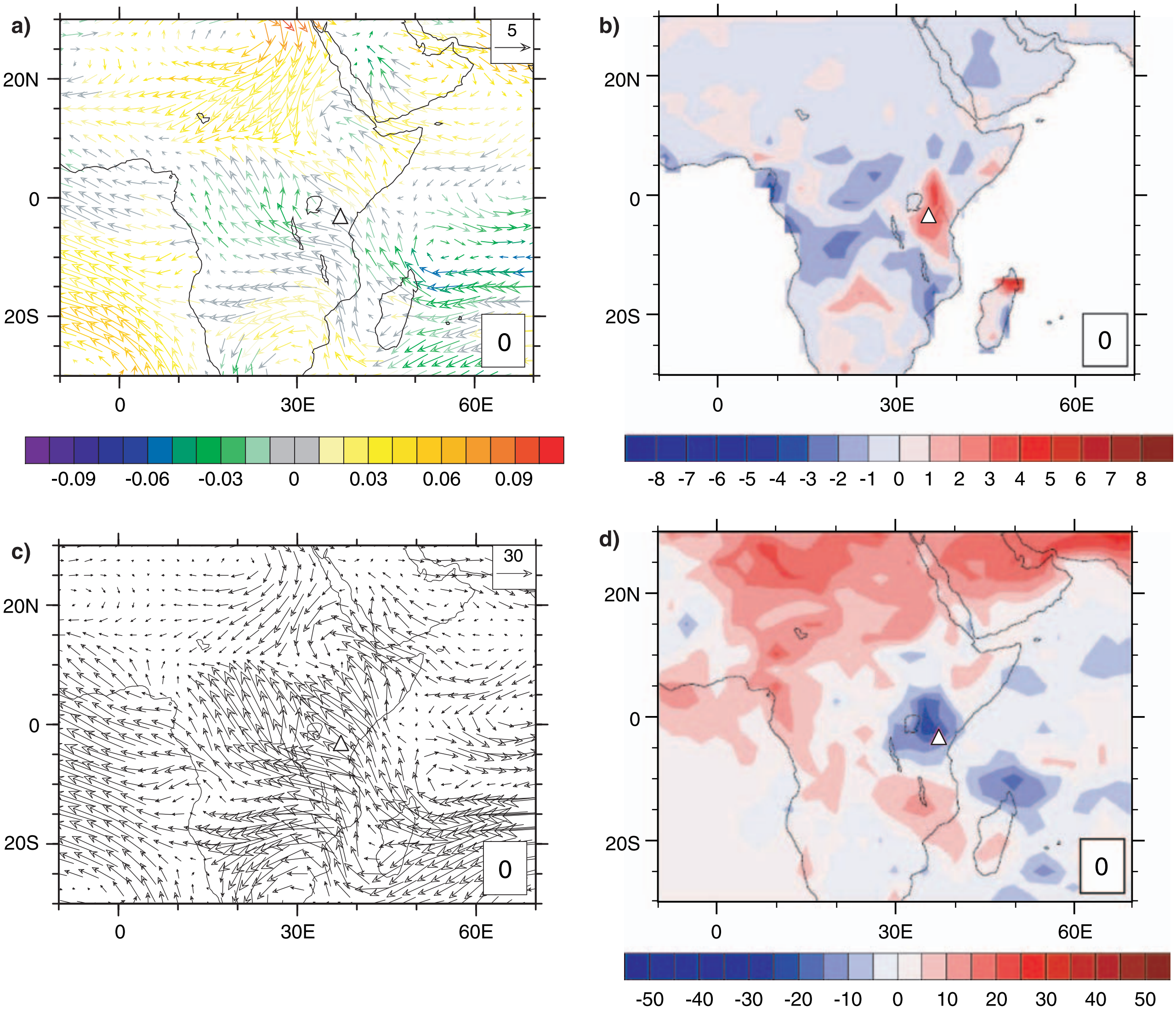

Fig. 3. Composite of all *long rains* snowfall events on day 0 for **a**) 850 hPa wind speed (in m s^{-1}) and direction and 500 hPa vertical motion (in Pa s^{-1}), **b**) GPCP precipitation anomaly (in mm), **c**) 850 hPa moisture flux (in g s^{-1} m^{-2}) **d**) OLR anomaly (in W m^{-2}). Scale for wind speed and moisture flux in **a** and **c** is shown in upper right corner. The color scale in **a** is a measure of vertical motion (omega) at 500 hPa with cool colors (negative values) representing upward motion and warm colors (positive values) indicating subsidence. White triangle indicates location of Kilimanjaro

events (not shown). The calculated total wind speed also suggests an association between low reanalysis wind speed and large snowfall events at 850 hPa. Furthermore, when comparing zonal wind component and specific humidity, there is an association of strong winds (both easterlies and westerlies) with low specific humidity, and weak winds (peak still in the easterly part) with high specific humidity (not shown). The near-surface specific humidity is of course of great importance for large snowfall events, as it is a necessary ingredient to initiate deep convection. Hence it seems as if the vertical expansion of humidity and the onset of moist convection are related to diminishing wind speed, as enhanced vertical mixing could occur during low wind speed conditions.

3.3 Short rains

The GPCP data composite of the *short rains* events indicates precipitation located primarily over the western Indian Ocean and just north of the Gulf of Guinea, shifting westward and eastward, respectively, toward Kilimanjaro as time progresses from day −2 to day 0 (not shown).

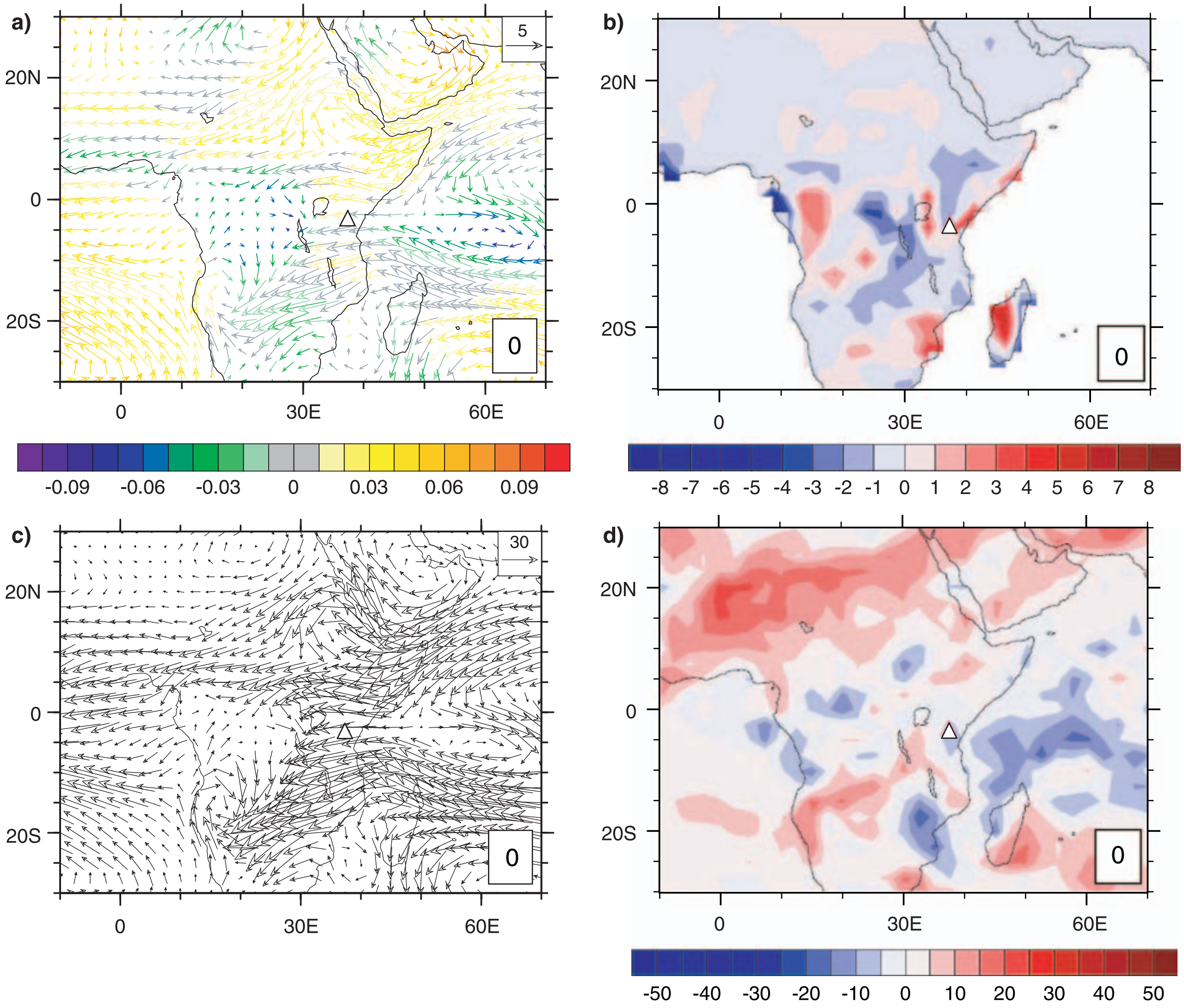

Fig. 4. As in Fig. 3, but for *short rains* season

In the vicinity of East Africa, precipitation seems to be concentrated along the coastal region and enhanced over time as verified by the absolute and anomalous fields of GPCP and OLR data (Fig. 4b and d), due to the cyclonic flow in the western Indian Ocean (Fig. 4a). Such cyclonic patterns located east of Kilimanjaro, allow the southeasterly flow from the western side of the cyclone to advect moisture directly from the Indian Ocean to Kilimanjaro (Fig. 4c). This pattern is consistent with the observed negative OLR anomalies over Kilimanjaro and its vicinity (Fig. 4d). The strong trades observed across the Indian Ocean (Fig. 4a) suggest that the *short rains* are dominated by a general continent-wide east to west transport. This points toward the Indian Ocean as the primary moisture source during the *short rains* season.

The east–west pressure-longitude transect of Fig. 5 exhibits strong easterlies throughout the vertical profile with two primary regions of rising motion over the Indian Ocean and the continent, corresponding with areas of negative OLR anomalies. This is consistent with the notion of east to west moisture transport from the Indian Ocean to East Africa. The strong easterly wind acts to enhance low-level moisture transport toward East Africa. Furthermore, low-level wind and moisture convergence is evident just west of Kilimanjaro with easterly flow coming from the Indian Ocean and the westerlies from the continental interior converging (Fig. 4c). While the zonal wind com-

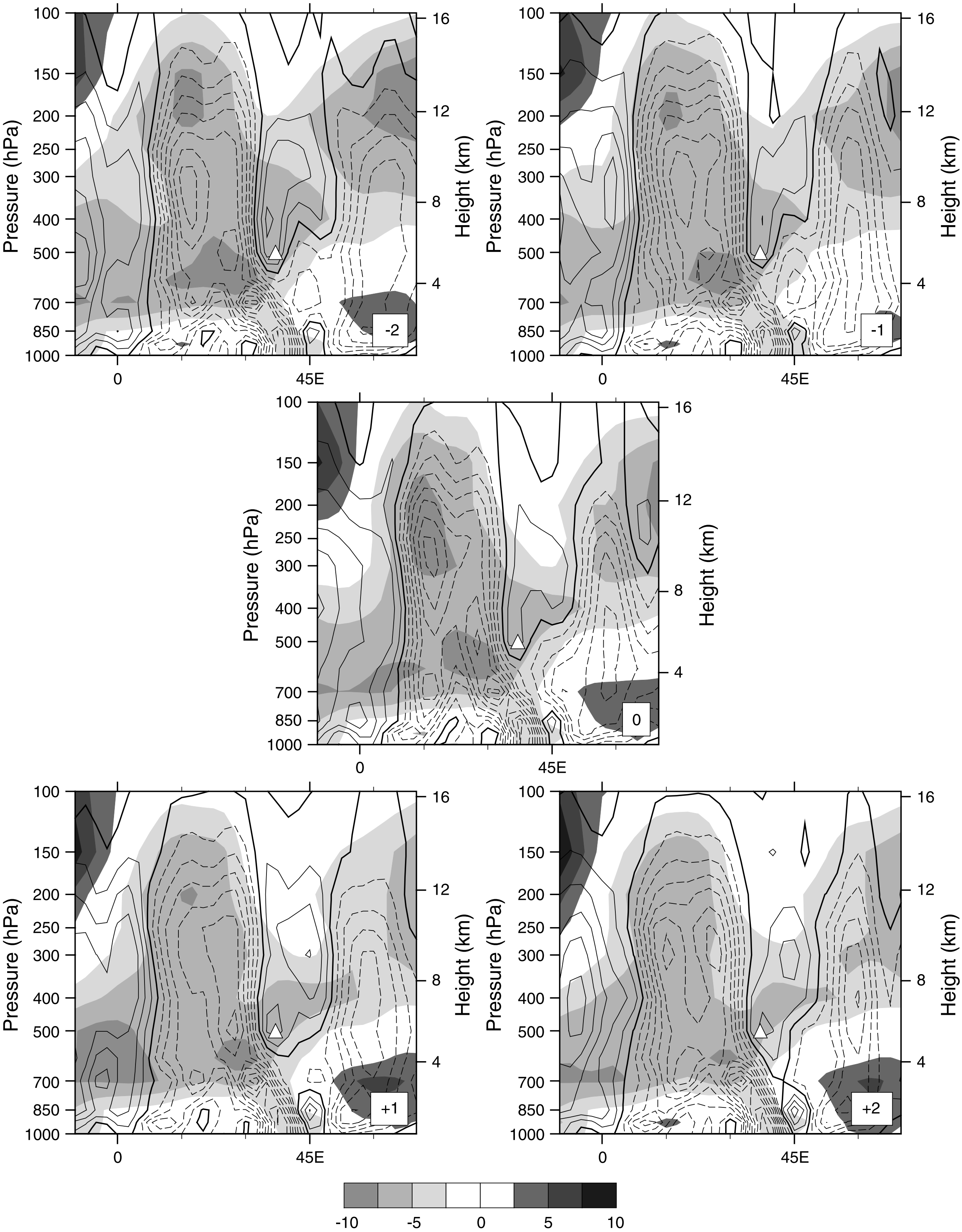

Fig. 5. Composite of east–west transect for *short rains* season at latitude of Kilimanjaro (3° S). Gray shading represents zonal (u) wind (in $\mathrm{m\,s^{-1}}$) component. Vertical motion (omega) is shown in contours, indicating regions of rising motion (dashed) and subsidence (solid). Contour interval is $0.01\,\mathrm{Pa\,s^{-1}}$. White triangle represents the longitude and altitude of the summit of Kilimanjaro

ponent is dominated by easterlies, the meridional wind component has little impact on snowfall variability. A comparison of wind speed with snowfall totals further indicates that wind speed, while relevant during the *long rains* season, plays much less of a role in determining snowfall amounts during the *short rains* (not shown). Nevertheless, an indication exists that large snowfall events during the *short rains* season appear to be associated with generally lower wind speed.

3.4 Kilimanjaro snowfall and its relationship with the IOZM

The relationship between Kilimanjaro snowfall and the IOZM was analyzed separately for the positive and negative IOZM phases of both the *long rains* and *short rains* seasons. Our results indicate that – for at least the 2000–2005 period – the anomalous IOZM phase appears to have little effect on the *long rains* season. This is not surprising given the phase-locking to the seasonal cycle of the IOZM, with its peak phase during ON. Hence we only discuss the results for the *short rains* season below.

Due to the small SSTA fluctuations that occurred in the Indian Ocean from 2000 to 2005, we could only attribute a small number of snowfall events (4 warm and 3 cold cases) to anomalous IOZM phases. Therefore, our results give a qualitative description only and more events analyzed over a longer time period will

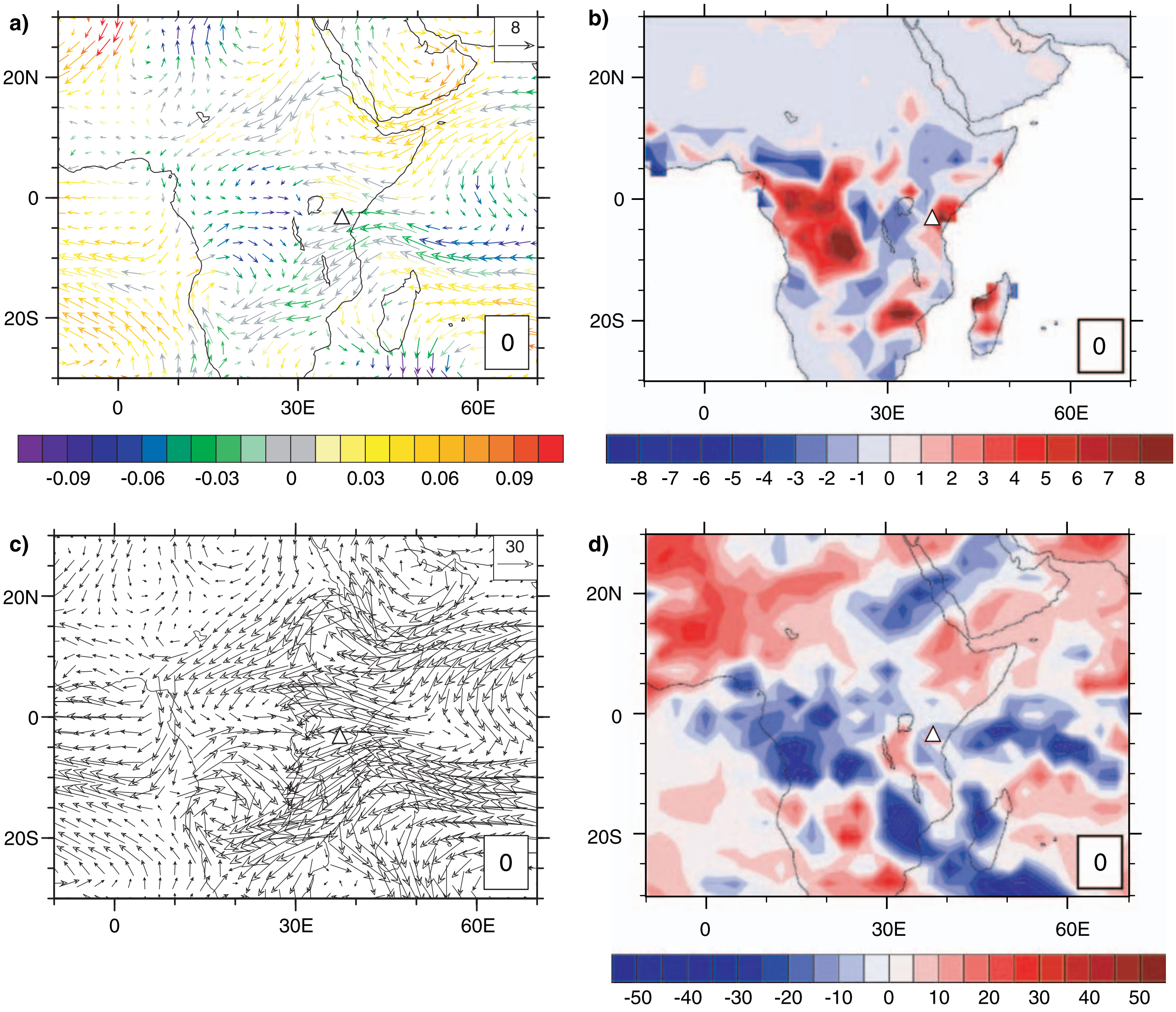

Fig. 6. As in Fig. 3, but for positive IOZM *short rains* snowfall events

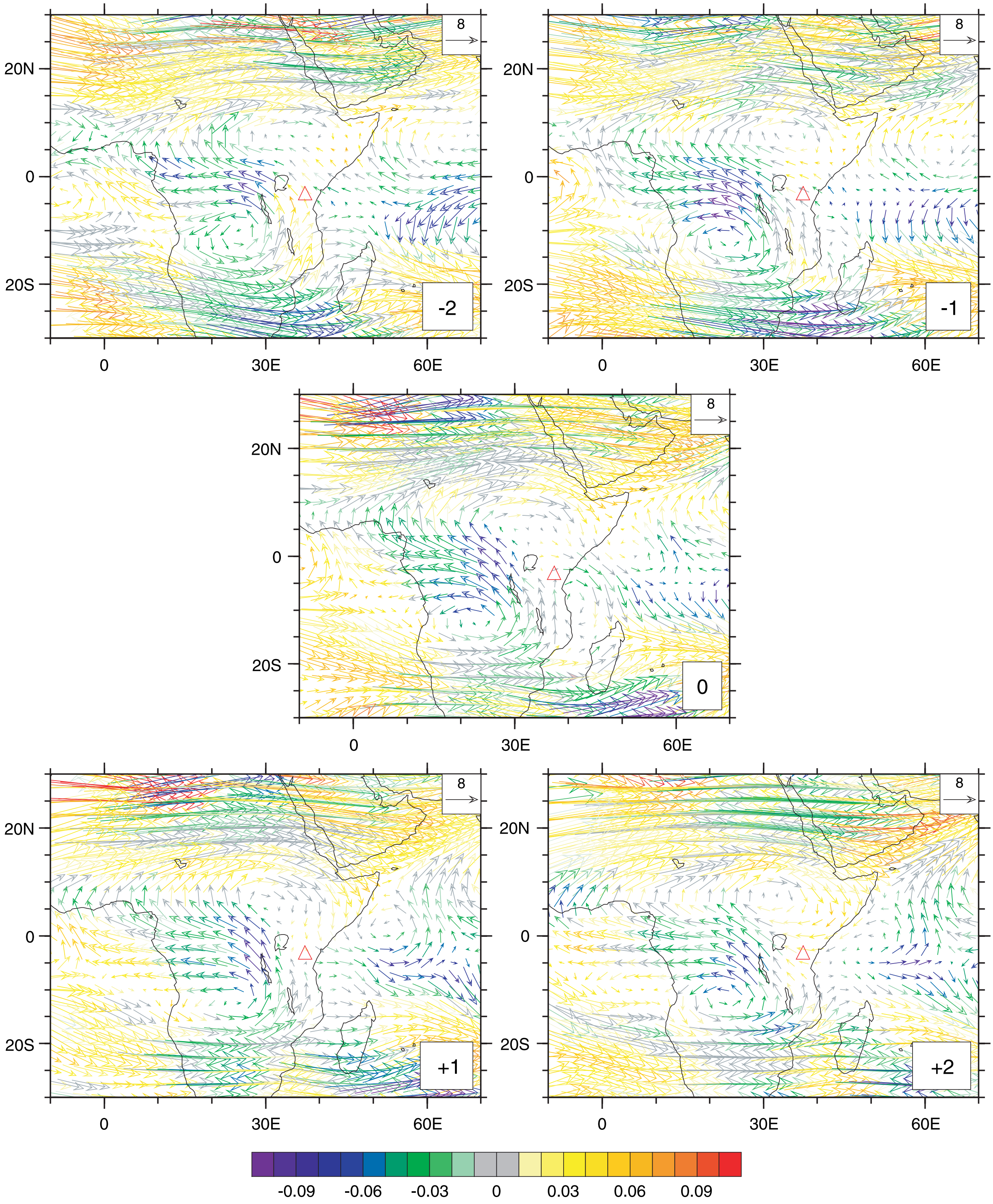

Fig. 7. Superposed epoch analysis of the absolute fields for positive IOZM *short rains* events 2000–2005. Arrows are wind speeds (in m s^{-1}) and direction at 200 hPa. Scale for wind vector is shown in upper right corner. The color is a measure of vertical motion (omega) at 500 hPa with cool colors (negative values) representing upward motion and warm colors (positive values) indicating subsidence. Red triangle indicates location of Kilimanjaro

be needed for more robust and quantitative conclusions.

During positive IOZM, enhanced precipitation is evident in the GPCP precipitation composite with a precipitation band along the East African coastline that is tied to the western Indian Ocean. Meanwhile, a second precipitation center is located over West Africa (not shown). The GPCP precipitation anomaly field also shows positive precipitation anomalies in these two locations, consistent with the negative OLR anomalies, indicating the presence of low-level moisture and convection (Fig. 6b and d). Strong easterly trade winds over the western Indian Ocean and westerlies over the continent at 850 hPa, apparent in both the absolute (Fig. 6a) and anomalous fields (not shown), lead to enhanced wind and moisture convergence just west of Kilimanjaro. The low-level convergence is compensated by divergence aloft at 200 hPa (Fig. 7), which helps maintain anomalous convective activity over the region. The anomalously strong low-level easterlies over the western Indian Ocean and the direction and magnitude of the moisture flux suggest that the Indian Ocean is the primary moisture source, with the continental interior acting as a secondary moisture supplier (Fig. 6c).

During the negative IOZM the large-scale situation is generally considered unfavorable for precipitation over East Africa. Nonetheless three snowfall events were recorded with intense precipitation centers concentrated in the western Indian Ocean and the continental interior (Fig. 8d). The boundary between these two centers is located farther out in the Indian Ocean than during the positive IOZM phase. The GPCP

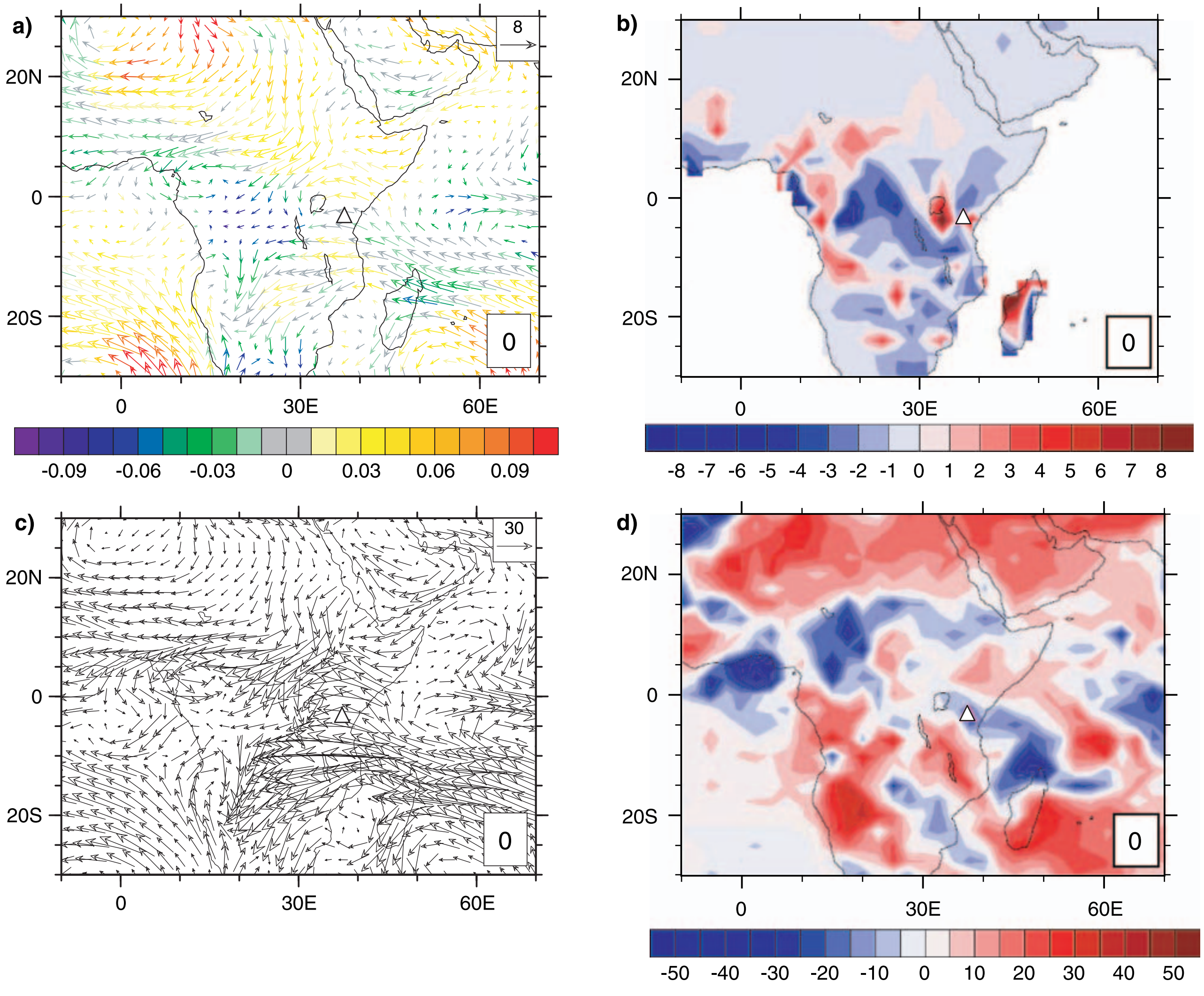

Fig. 8. As in Fig. 3 but for negative IOZM *short rains* snowfall events

anomaly field suggests that precipitation is only locally enhanced over Kilimanjaro and Lake Victoria (Fig. 8b). The 850 hPa wind field again shows a cyclonic pattern in the Indian Ocean, but it is relatively weak and farther east over the Indian Ocean than during the positive IOZM

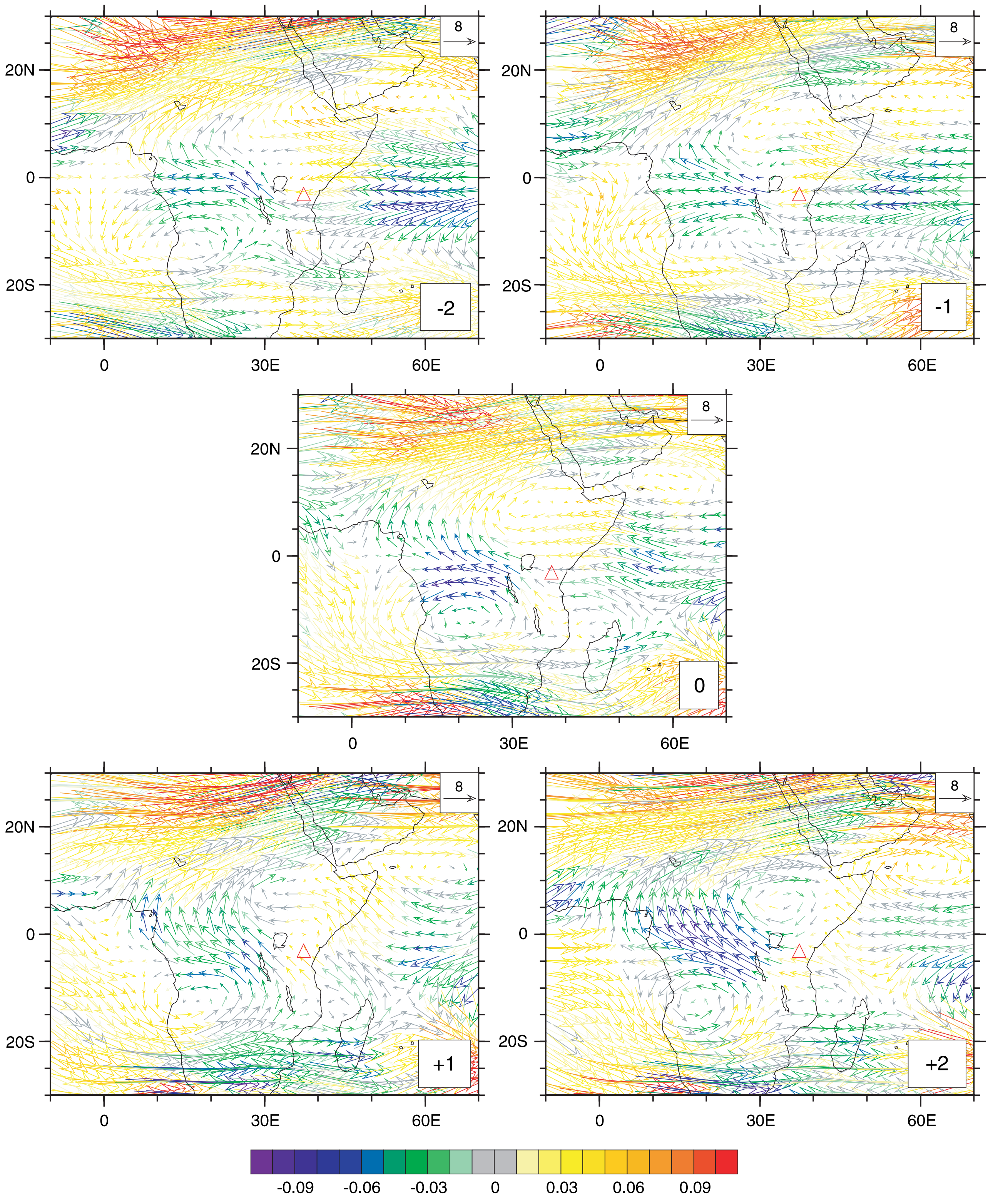

Fig. 9. As in Fig. 7 but for negative IOZM *short rains* snowfall events

phase. Only weak low-level moisture convergence is found near the mountain, and there is no distinctive convergence band like the one observed during positive IOZM state. Nonetheless moisture flux is appears to be from the east, pointing toward the Indian Ocean as the main moisture source (Fig. 8a and c). The flow from the Atlantic Ocean is relatively weak, moisture convergence is reduced and less moisture is available to initiate deep convection over the continental interior and over Kilimanjaro. The strong easterlies found at 200 hPa (Fig. 9) are the opposite of what is seen during the positive IOZM phase and suggests a reversal of the zonally overturning circulation, and conditions generally not conducive for convective activity in the region.

4. Summary and conclusions

Kilimanjaro glaciers have been retreating drastically in the past century and triggered much attention worldwide. A permanent disappearance of ice is projected to occur in the near future, which would wipe out all of the embedded climate signals and make it impossible to further document past climate changes from glaciological proxies. In an effort to accurately analyze the proxy records already retrieved from the mountain and to improve our current understanding of the climatic conditions on Kilimanjaro, an AWS was installed on the summit of Kilimanjaro to provide high resolution in situ data. By using this dataset and other global analysis products, East African precipitation variability and its link with the large-scale atmospheric circulation was analyzed on intraseasonal timescales.

Kilimanjaro station data were first compared with global analysis products to determine the link with the regional precipitation variability. It is especially important to examine the similarities between the datasets due to the significant differences in their spatial scales. Results suggest that the annual precipitation cycle is reasonably portrayed by the Kilimanjaro snowfall data, showing close resemblance to the GPCP, NCEP/NCAR reanalysis, and OLR datasets. Furthermore, the agreement between various datasets suggests that the Kilimanjaro snowfall data indeed represent regional rather than local precipitation events. In retrospect, the agreement among the datasets indicates that the global analysis products, despite their coarse resolution, can provide useful tools for analyzing snowfall events on the mountain.

Through the spatial superposed epoch analyses of snowfall events on Kilimanjaro, distinct atmospheric features are observed during both the *long rains* and *short rains* seasons, respectively. During the *long rains* season, a west to east propagation of convective activity is observed across the continent, which over East Africa merges with precipitation induced by moisture influx from cyclonic airflow centered over northern Madagascar. The snowfall on Kilimanjaro is associated with the passage of this wave over the mountain, propagating eastward from the continental interior. Interestingly, wind speed exhibits an important link to the snowfall events on Kilimanjaro during the *long rains* season, indicating the highly convective nature of precipitation. The largest snowfall events tend to be associated with low wind speed, favorable for the development of surface radiative heating, thereby destabilizing the atmospheric column and initiating upward motion and deep convection. The higher specific humidity observed near the surface is a necessary ingredient to trigger moist convection during large snowfall events.

The *short rains* season on the other hand is clearly dominated by east to west moisture transport. This easterly flow extends vertically through much of the troposphere and horizontally from the western Indian Ocean westward across the African continent. Two centers of most pronounced upward vertical motion and convection are observed over the rainforest areas in the continental interior and over the western Indian Ocean near the East African coastline. It is this latter center of convection, which is responsible for easterly moisture transport and spill-over of precipitation into the East African domain. Large snowfall events again tend to occur under low wind speed conditions, but the signal is much weaker than during the *long rains* season.

The Indian Ocean, due to its close proximity, exhibits a strong influence on East African precipitation variability. The dominant mode causing such variability is the IOZM, a quasi sea-saw, related to an anomalous east–west SST gradient across the Indian Ocean. While the IOZM generally has little effect on the East African *long rains* season, the *short rains* season is heavily influenced by the IOZM, with enhanced precipitation along the East African coast and over the continental interior during positive IOZM phases. In addition, strong trade winds are often observed across the Indian Ocean, while westerlies prevail over the continental interior. This leads to significantly enhanced low-level wind and moisture convergence over Kilimanjaro and the East African coastline, with the Indian Ocean being the primary moisture supplier. During the negative IOZM phase, however, the trade winds across the Indian Ocean and the westerly flow from the Atlantic Ocean are weaker than during positive IOZM. As a result, moisture convergence is reduced and less moisture is available to initiate deep convection over Kilimanjaro.

The observational data from Kilimanjaro summit provide a means to examine Kilimanjaro snowfall and East African precipitation variability on intraseasonal timescales. However, additional years of AWS measurements – providing more snowfall events – will be needed for final conclusions, due to interannual and multiyear variability in the regional climate system. Future work should therefore try to corroborate the results presented here by comparing global analysis products (e.g., GPCP) with low-lying station data surrounding the mountain. This would provide a better indication of the regional character of Kilimanjaro precipitation and potentially identify anomalous precipitation events that did not leave a recognizable snow layer on top of Kilimanjaro. Such an analysis would help improve our understanding of current climatic conditions in East Africa, and it would also provide a modern benchmark for paleoclimatic reconstructions and projections of future climate scenarios in this region.

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