Cycles and Propagation of Deep Convection over Equatorial Africa

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ABSTRACT

Long-term statistics of organized convection are vital to improved understanding of the hydrologic cycle at various scales. Satellite observations are used to understand the timing, duration, and frequency of deep convection in equatorial Africa, a region with some of the most intense thunderstorms. Yet little has been published about the propagation characteristics of mesoscale convection in that region. Diurnal, subseasonal, and seasonal cycles of cold cloud (proxy for convective precipitation) are examined on a continental scale. Organized deep convection consists of coherent structures that are characteristic of systems propagating under a broad range of atmospheric conditions. Convection is triggered by heating of elevated terrain, sea/land breezes, and lake breezes. Coherent episodes of convection result from regeneration of convection through multiple diurnal cycles while propagating westward. They have an average 17.6-h duration and 673-km span; most have zonal phase speeds of 8–16 m s$^{-1}$.

Propagating convection occurs in the presence of moderate low-level shear that is associated with the southwesterly monsoonal flow and midlevel easterly jets. Convection is also modulated by eastward-moving equatorially trapped Kelvin waves, which have phase speeds of 12–22 m s$^{-1}$ over equatorial Africa. Westward propagation of mesoscale convection is interrupted by the dry phase of convectively coupled Kelvin waves. During the wet phase, daily initiation and westward propagation continues within the Kelvin wave and the cold cloud shields are larger. Mesoscale convection is more widespread during the active phase of the Madden–Julian oscillation (MJO) but with limited westward propagation. The study highlights multiscale interaction as a major source of variability in convective precipitation during the critical rainy seasons in equatorial Africa.

1. Introduction

Our ability to predict convective precipitation depends on understanding of the development and environment of organized mesoscale convective systems (MCSs). Numerical models have low predictive skill for convective precipitation intensity, frequency, and timing. A necessary step in improving convective precipitation forecasts is for models to reproduce these statistics, because of the implications for the hydrologic cycle and feedbacks, such as surface latent heat and radiative effects of cloud systems that persist during nighttime.

This study describes and interprets the propagation characteristics and diurnal cycle of organized convection over equatorial Africa. It contributes to the knowledge essential to realize improvements in convective precipitation forecasting by documenting regional properties of organized mesoscale convection. Satellite and radar observations have increased our understanding of mesoscale convection and precipitation. Carbone et al. (2002) found that heavy precipitation often occurs in organized “episodes” or “streaks” that originate in the lee of the Rocky Mountains and propagate eastward. Episodes display coherent patterns of propagation across the continent with some systems lasting up to 60 h. Cold cloud episodes in East Asia, Australia, and Europe have zonal spans on the order of 1000 km and duration on the order

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of 1 day (Wang et al. 2004; Keenan and Carbone 2008; Levizzani et al. 2010). Organized convection over the Amazon travels over 4000 km and lasts longer than a day (Pereira Filho et al. 2010). Episodes in northern, tropical Africa last longer and travel farther than those in other continental regions, with a few episodes exceeding 100-h duration and 5000-km span (Laing et al. 2008). The long-range influence of topography occurs in all of the regions, with convection initiating over the elevated terrain and then propagating in moderate vertical shear while organizing into mesoscale systems. The diurnal cycle of rainfall is phase locked with the movement of the propagating systems. In the central United States, the transition is from the Rocky Mountains to the Great Plains during the afternoon through the nighttime (Carbone et al. 2002). For northern, tropical Africa, axes of maximum diurnal frequency are associated with several mountain ranges (Laing et al. 2008).

Mesoscale convection is modulated by synoptic perturbations and vice versa. For example, African easterly waves (AEWs) influence the evolution of squall lines (Payne and McGarry 1977; Machado et al. 1993) and vertical shear related to the African easterly jet (AEJ) influences the location of intense convective systems (Mohr and Thorncroft 2006; Laing et al. 2008). Strong MCSs can also lead to the intensification of easterly waves (Berry and Thorncroft 2005; Lin et al. 2005) and mountain ranges help to initiate AEWs and long-lived MCSs (Burpee 1972; Hodges and Thorncroft 1997; Laing et al. 2008). Much of the knowledge of these two-way-scale interactions comes from studies over West Africa or other parts of northern, tropical Africa.

The characteristics of propagating mesoscale convection over equatorial Africa are less well understood than convection in other regions. Satellite data remains the primary option as the meteorological network in the largest countries is almost nonexistent. Tropical Rainfall Measuring Mission (TRMM) satellite data shows that the region experiences the most intense thunderstorms in terms of microwave scattering signature and frequency of lightning flashes globally but has lower annual rainfall amounts relative to other equatorial continents (Zipser et al. 2006).

Some tropical rainfall is organized by equatorially trapped waves (Gruber 1974; Zangvil 1975; Wheeler and Kiladis 1999, hereafter WK99; Kiladis et al. 2009, hereafter K09). Using shallow-water theory, Matsuno (1966) derived solutions for waves propagating along the equator. These now well-known waves of the equatorial atmosphere and ocean, are Kelvin, equatorial Rossby (ER), westward and eastward inertio-gravity (WIG and EIG, respectively), and mixed Rossby–gravity (MRG) waves. Studies have shown that these waves were sometimes coupled with convection (Gruber 1974; Zangvil 1975). Since the 1980s and 1990s, space–time filtering of infrared (IR) satellite imagery and gridded wind data has been used to identify and monitor equatorial waves and their relationship with synoptic and larger-scale tropical convection. For instance, Straub and Kiladis (2002) show that equatorial Kelvin waves are primary modulators of convective activity within the Pacific ITCZ and that their structures resemble theoretical Kelvin waves (Matsuno 1966).

This study focuses on convectively coupled equatorial Kelvin waves because they have much higher variance of IR brightness temperature $T_b$ over Africa than other tropical modes (K09). Convectively coupled Kelvin waves have horizontal scales of 3300–6600 km and time scales of <10 days (Nakazawa 1988; Wheeler et al. 2000, hereafter WKW00). They have eastward phase speeds of 15–25 m s$^{-1}$ over the west Pacific and 12–15 m s$^{-1}$ over the Indian Ocean and tropical Africa during the boreal summer (Mekonnen et al. 2008; K09). Kelvin waves can be considered as synoptic-scale, gravity waves trapped at the equator with the dry Kelvin waves having phase speeds of 30–60 m s$^{-1}$ in the lower stratosphere. The horizontal structure of a zonally propagating Kelvin wave at about 200 hPa has the low west of the high, mass divergence between them (see Fig. 1 of WK99). Mounier et al. (2007) and Mekonnen et al. (2008) examined convectively coupled Kelvin waves and precipitation over northern tropical Africa during the boreal summer. They found that few and very weak convective systems occurred during the dry phase of the Kelvin wave (upper-troposphere convergence), while the wet phase (upper-troposphere divergence) is associated with more and highly developed convective systems. Wang and Fu (2007) suggested that convectively coupled Kelvin waves modulated convection in the intertropical convergence zone (ITCZ) between South America and Africa during the boreal spring. One of the few studies that focus on central Africa is by Nguyen and Duvel (2008), who found that MCSs were larger and longer-lived during the wet phase of the Kelvin wave than during other periods. Nguyen and Duvel (2008) focused on a small continental region (mainly the Congo basin) and used 0.5° gridded, 3-hourly data to identify MCSs. Most recently, Jackson et al. (2009) used TRMM data to document the spatial distribution and diurnal cycle of mesoscale precipitation features, lightning frequency, and continental-scale circulation patterns over western equatorial Africa. These studies and others (e.g., Yang and Slingo 2001) examined the mean diurnal progression of clouds and precipitation at 3-hourly time scales, which is useful but lacks the clarity as to the life cycle of individual mesoscale convective events.
Tropical convection is also modulated by the Madden–Julian oscillation (MJO), the 30–60-day oscillation with convection organized into envelopes of about 10,000 km that move eastward at 4–5 m s$^{-1}$ (Madden and Julian 1971, 1972; Zhang 2005). Within the MJO envelope of convection are equatorial waves and MCSs (Zhang 2005). Matthews (2004) and Pohl and Camberlin (2006a, b) found that MJO influences large-scale convective activity over Africa.

This study adds to our knowledge of convection over equatorial Africa by (i) documenting the systematic propagation and evolution of mesoscale cold cloud clusters across equatorial Africa (at higher spatial and temporal resolution than previous studies); (ii) computing the mean diurnal cycle for subseasonal and seasonal periods; (iii) identifying the large-scale influences on propagating convection; and (iv) comparing those characteristics with deep convection over other continental regions. The results provide long-term statistical benchmarks for numerical weather prediction over tropical Africa.

2. Data and methods

The study domain is 10°S–10°N and 15°W–50°E (Fig. 1). The domain is expanded farther west than in previous studies (e.g., Nguyen and Duvel 2008; Jackson et al. 2009) facilitating examination of oceanic and continental differences and the transition between them. The focus periods are the two rainy seasons in equatorial Africa, March–May and September–November for the years 2000–03. Figure 2 shows the mean precipitation for the peak months of April and October and the near-surface synoptic flow. The eastern domain has its annual peak in April (the 3 mm day$^{-1}$ contour is at its easternmost extent) coinciding with the ITCZ and confluence over the eastern Congo. Western equatorial Africa has precipitation maxima during both rainy seasons, but its highest monthly mean amount occurs in October and the gradient of precipitation along the coast is much stronger than in April.

a. Mesoscale cold cloud statistics

Primary data are IR (10.5–12.5 μm) $T_b$ from the European geostationary satellite Meteorological Satellite-7 (Meteosat-7). The images are available at 30-min intervals and sampled to 0.2° grids. Brightness temperature thresholds identify cloud systems that are most likely to be precipitating. Threshold $T_b$ for propagation statistics over central Africa is 233 K in keeping with Arkin (1979), Arnaud et al. (1992), and Mathon et al. (2002). While IR $T_b$ does not always indicate precipitation, it has high correlation with precipitation areas spanning 50–250 km over 3–24 h (Arkin 1979). Although satellite IR cannot detect rain from warm clouds, it is optimal for high temporal analysis of cold clouds as a proxy for precipitation in this data-sparse region.

Reduced-dimension (Hovmöller) techniques determine the propagation of cold clouds. Each pixel colder than the threshold $T_b$ constitutes an “event” at a given distance–time coordinate. Averages are taken between
A 2D autocorrelation function is stepped through all points in the distance–time–space and rotated until the correlation coefficient is maximized. Contiguous fits to the function define coherent patterns or streaks (diagonally slanted solid black lines in Fig. 3). Only correlation coefficients of 0.35 or higher are accepted. The autocorrelation function for the cloud streaks was 30 grid points long (≈6 h) and 20 grid points (≈10 h) in its cosine-weighted dimension. Propagation speeds of the cloud streaks are computed from the slopes in the Hovmöller space. For periods where deep convection is intermittent (e.g., downstream systems are triggered from the cold pool of decaying convection; Tuttle and Carbone 2004), those systems are considered as parts of one episode, as long as there is a continual correlation along an established phase line. Satellite images were used to assess the autocorrelation results. A correction for those occurrences was needed for only 0.3% of the episodes. Carbone et al. (2002) provides further details of the technique.

### b. Large-scale environments

Large-scale environments are diagnosed from the operational National Centers for Environmental Prediction (NCEP) Global Final Analyses (FNL), which are on a 1° × 1° grid at 6-hourly synoptic intervals, and the global reanalysis conducted by NCEP–National Center for Atmospheric Research (NCAR), which is on a 2.5° × 2.5° grid (Kalnay et al. 1996). Emphasis is given to the winds at 850 hPa, representative of the monsoonal flow; 600–700 hPa, the level of the AEJ; and 200 hPa, just below the tropical easterly jet (TEJ), which has maximum amplitude at about 150 hPa.

### c. Tropical convective modes

Daily interpolated OLR data produced by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory Physical Sciences Division are used to identify convectively coupled Kelvin waves and the MJO in a similar manner to previous studies (WKW00; Wheeler and Weickmann 2001; Straub and Kiladis 2002; Zhang 2005, and references therein). The daily OLR averages, based on twice-daily polar-orbiting satellite measurements, are on a 2.5° grid (Liebmann and Smith 1996). Anomalies are calculated relative to the 30-yr period January 1979–December 2000.
2008. The Kelvin wave and MJO circulations are identified by filtering OLR and zonal wind anomalies at 850 and 200 hPa (for the same period as the OLR) using the typical period of the oscillations and their signature in wavenumber–frequency space (WK99; Wheeler and Weickmann 2001). Kelvin wave filtering retains eastward-propagating OLR signals within the 2.5–17-day period and wavenumbers 1–14 (see Fig. 1 of Straub and Kiladis 2002). The results are based on spectral quantities that have been calculated for many successive overlapping (by 1 month) 96-day segments of the multiyear OLR dataset (WK99). The MJO signals are objectively evaluated using diagnostics developed by the U.S. Climate Variability (CLIVAR) Working Group (Waliser et al. 2009). The MJO is diagnosed using a 30–96-day bandpass Lanczos filter on daily OLR anomalies. While filtering allows these circulation features to be identified more easily, some can be observed without filtering. Examples in section 5 show circulations detected with unfiltered high-resolution $T_b$ and zonal wind anomalies at 850 and 200 hPa. The zonal wind fields are from the NCEP–NCAR reanalysis, which is on a similar 2.5° grid as the daily OLR data. The frequency and phase speeds of convectively coupled Kelvin waves is computed for those that traverse more than 5000 km and lasted at least 3 days over equatorial Africa. This limitation is based on Mekonnen et al. (2008) who found that the length scale of Kelvin waves contracted from about 7000 km over the east Pacific to about 5000 km over central and eastern Africa during the boreal summer. The period decreased from 8 to 4 days.

3. Zonal propagation characteristics

a. Cloud streak pattern

Deep convection in equatorial Africa is organized as coherent episodes that occur on an almost daily basis and propagate westward (e.g., Fig. 4). Enhanced IR satellite images (Figs. 4a–g) show MCSs forming and moving westward from the mountains of East Africa. The corresponding Hovmöller diagram to the right shows a coherent pattern of cold cloud streaks (Fig. 4h). Both show a consistent continent-scale coherent propagation of deep convection, primarily westward from the mountains of East Africa (note elevation map in Fig. 4). The letters A, B, and C identify three of those episodes. Dashed lines on the satellite images track convective systems that are a part of each cloud streak. The letter “D” marks thunderstorms that initiated over the Cameroon Mountains. Deep convective systems initiate during mid to late afternoon and peak during the nighttime. By around 2100 UTC (0100 LT in East Africa), the MCSs are west or west-southwest of the initial thunderstorm locations. MCSs decay or weaken during the morning (e.g., Figs. 4a,c,e,g). Some MCSs regenerate, which can result in a streak that extends into multiple diurnal cycles. An example is streak A, which can be traced from 30°E, near the highest average elevation, at 2100 UTC 1 April to 0° by 0900 UTC 4 April.

An average of 6–7 episodes occurs daily; episodes whose span exceeds the median are fewer, an average of 3 days $^{-1}$. Tables 1 and 2 summarize the propagation and frequency statistics for the boreal spring and autumn, respectively. In both seasons, a large fraction of the episodes initiate in the lee of high terrain, such as the mountains of East Africa, Cameroon, and west-central Africa. The highest peaks, the East Africa mountains, have the greatest impact. Figure 5 shows most of the
deep convection starting west of the highest peaks nearly every day (average elevation shown at bottom of figure). The influence of the annual cycle is evident in the organization of daily convection (Fig. 5). For example, during September, hardly any deep convection is observed west of 0° longitude because, at those western longitudes, the ITCZ (Fig. 2) and the bulk of the convection are north of our domain. Also, deep convection is less frequent over the ocean compared with the land (Zipser et al. 2006) so that deep convection develops over a relatively narrow continental zone in September.

Other features to note are envelopes of convection propagating eastward, within which are westward-moving events (e.g., between 20 and 26 March 2000). These eastward-propagating envelopes will be discussed in section 5.

b. Duration, span, and phase speed

The coherence and phase speed characteristics of the cold cloud episodes are computed using the two-dimensional autocorrelation function described in section 2. Some cold cloud streaks are continuous while
Duration (h) 17.3 18.3 18.3 17.3 17.8
Span (km) 691.5 625.0 694.7 654.2 691.4
Std dev 2.52 2.13 2.43 2.13 2.30
Average per day 7.23 7.27 6.67 6.46 6.91
No. of streaks 665 669 614 594 635.5
Phase speed (m s$^{-1}$) 11.7 11.7 11.2 11.4 11.5

The duration and span of convective episodes are highly correlated during both the boreal spring and autumn with $R^2$ of 0.89 and 0.87, respectively (Fig. 6). The zonal mean phase speed of 11.3 m s$^{-1}$ is slightly slower than the phase speed of convective episodes in northern tropical Africa. The fastest phase speeds were observed during the boreal spring (Fig. 6).

The exceedance frequency for duration and span are shown in Fig. 7. The exceedance frequency is the frequency of events (number per day) that exceeds a given magnitude (hours or kilometers, respectively) over a specified interval (four seasons). The distribution of exceedance frequency is nearly exponential, represented by the straight black line on the log–linear plots. Also plotted on Fig. 7 is the recurrence interval in days, the average time interval for the recurrence of an event that equals or exceeds a given magnitude. It is calculated as the inverse of the exceedance frequency. Although the distributions shown are for the full study period, the duration and span distributions are relatively similar for each year.

These statistical properties of the cold cloud episodes are valuable for improving prediction of convective precipitation in a probabilistic sense (e.g., serving as benchmarks for forecasts). They may also be useful for evaluating biases in numerical weather forecasts or regional climate forecasts. The distributions are useful for answering climate questions, such as, what is the probability of the occurrence of episodes of a particular span or duration. Duration and span for particular points on the distributions (Fig. 7) are presented in Table 3. The values for the boreal spring exceed those for the austral spring. At the 1 day$^{-1}$ exceedance frequency are episodes with $\geq$30-h duration and $\geq$1180-km span. This indicates that organized episodes of deep convection can be spawned daily (e.g., Fig. 4) and last longer than a day. For the 3-day recurrence interval, the span exceeded 1980 km and duration exceeded 49 h. At intervals between 3 and 7 days, some of the episodes are likely to be coincident with westward-moving synoptic waves for some fraction of their lifetime; phase speeds may differ at some stages. Westward-moving synoptic waves are not objectively analyzed here but, during the West African monsoon they occur every 3–5 days, have wavelengths of 1500–3000 km (Carlson 1969; Reed et al. 1977; Kiladis et al. 2006), and move at about 8 m s$^{-1}$. Episodes with $\geq$64-h duration and $\geq$2600-km span are at the weekly recurrence interval.

The average span and duration of equatorial Africa cold cloud streaks are about one-third smaller than for northern tropical Africa. With favorable orographic forcing combined with local diurnal heating, convection can undergo as many as five regeneration cycles across northern, tropical Africa (Laing et al. 2008). Only a few episodes traversed more than 5000 km and only in the boreal spring. The rarity of such long-lived episodes in equatorial Africa could be due to the following:

- A smaller landmass; only 30° longitude south of the equator compared with more than 60° longitude north
N. Organized mesoscale convection is more intense and prevalent over tropical continents than oceans (Mohr and Zipser 1996).

- The near-equatorial zone has fewer elevated heat sources. The dominant topographic features within 5° of the equator are the Rift Valley and the west coast mountains. In between is the Congo basin (Fig. 1). By comparison, over northern tropical Africa, convection is triggered by several mountain ranges from the Ethiopian Highlands to the Guinea Highlands.
- During September, the ITCZ over West Africa is on the northern boundary of the study domain and sea surface temperature (SST) in the Gulf of Guinea is near the annual minimum. Thus, a narrower zone is favored for organized convection (e.g., Fig. 5c) relative to northern tropical Africa.
- The shear associated with high terrain and the AEJ has been found to be critical to the occurrence of intense convective systems over northern tropical Africa (Mohr and Thorncroft 2006; Laing et al. 2008). With fewer mountain ranges in near-equatorial Africa, it is expected that the contribution of local shear near high terrain will be reduced. The large-scale shear will be examined in section 5.

**Fig. 5.** (top) Examples of convective episodes for March 2000, May 2001, September 2002, and November 2003. Averages are taken between 7.5°S and 7.5°N. (bottom) The corresponding average elevation (km).
The occurrence of submonthly equatorial Kelvin waves that can limit the westward propagation of convection is a topic that is also explored in section 5.

4. Diurnal cycles

a. Spatial and hourly distribution of deep convection

In both rainy seasons, the diurnal cycle and geographic distribution of continental convection is generally similar, in that deep convection is most frequently initiated in the lee of high terrain during the mid- to late afternoon (Figs. 8 and 9). The maximum frequency in cold cloud is observed downstream of the mountain ranges of the African Rift Valley over the Congo basin. These observations are consistent with Zipser et al. (2006) who found the world’s most intense thunderstorms in this region. Maxima in deep convection are also associated with sea–land breezes and Lake Victoria breezes. The convection pattern mimics the topographic shape (e.g., Figs. 8a–d).

1) BOREAL SPRING

More frequent and widespread deep convection over the ocean and coastal areas during April, compared with October, is consistent with near-surface circulation (Fig. 2). Heavy rainfall occurs over the northern Gulf of Guinea during spring (April peak) in response to warm SST gradients (Gu and Adler 2004; Adejuwon and Odekunle 2006; Odekunle and Eludoyin 2008).

(i) Rift Valley, Lake Victoria, and Lake Tanganyika

The most prominent features in the cold cloud patterns are those associated with the Rift Valley area. The eastern Rift Valley and Ethiopian Highlands experience a minimum in cold cloud area between 0700 and 0800 LT (Fig. 8h). Small areas of deep convection form an arc along the slopes of the East African mountain ranges by

![Figure 6](https://example.com/figure6.png)
1100–1200 UTC, where it is early afternoon locally. These results are compatible with the forcing of boundary layer circulation in response to heating of elevated terrain. The initial thunderstorms grow, merge, and propagate westward to a maximum intensity between 1700 and 1800 UTC, early nighttime locally. Weaker maxima move westward downstream of the Ethiopian Highlands. A local maximum occurs over Lake Victoria during early nighttime (Figs. 8b,c), while downstream has little or no convection; which is consistent with nocturnal land-breeze convergence over the lake (Flohn and Fraedrich 1966; Nicholson and Yin 2002). Conversely, a local maximum is downstream (west) of the lake during early to midmorning (Figs. 8e–h). The convection just west of the lakes could be due to a land breeze in easterly mean flow; where air flowing over the lake is warmed and moistened and overruns the cooler nocturnal inversion to the west. Lake Tanganyika (Fig. 1) has a similar effect but with a weak and narrow band of convection (Fig. 8h). By 2300–0000 UTC, fewer intense convective systems exist but the cold cloud areas continue to expand and the maxima shift westward across the Congo basin, indicating the presence of propagating systems. This region is much like the central U.S. Great Plains in that its peak thunderstorm maximum occurs during the nighttime. The frequency of convection between 0500 and 0600 UTC is drastically reduced except for convection around with the lakes (Figs. 8d–g).

(ii) East coast and Indian Ocean

Land–ocean temperature contrast leads to sea- and land-breeze convection (Fig. 8). Between 1400 and 1500 LT, a line of high cold cloud frequency parallels the eastern coast (Fig. 8a). During the evening into early nighttime hours, the line moves inland, becoming more intense and broader (Figs. 8b,c). The southern branch of the east coast convection is much weaker but more persistent, exceeding 10% frequency between 0200 and 0600 UTC. An outstanding feature over the Indian Ocean is a weak maximum centered around 7°S and east of 45°E during all periods except 1700−1800 UTC (2000−2100 LT), when it all but disappears. This feature is associated with a confluence zone and a low-level easterly wind maximum (Fig. 2).

(iii) West coast and mountain ranges

The west coast convection is as intense as the convection triggered by the Rift Valley ranges, with maximum intensity in the lee of the Cameroon Mountains and the high terrain farther south during late evening to early nighttime (Fig. 8c). The highest frequency near the

**TABLE 3.** Exceedance span and duration for selected recurrence frequencies. The top number is for March–May and the bottom number for September–November.

<table>
<thead>
<tr>
<th>Recurrence frequency</th>
<th>Zonal span (km)</th>
<th>Duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day⁻¹</td>
<td>1220</td>
<td>31.5</td>
</tr>
<tr>
<td>2 day⁻¹</td>
<td>1140</td>
<td>30</td>
</tr>
<tr>
<td>3 day⁻¹</td>
<td>1960</td>
<td>46.5</td>
</tr>
<tr>
<td>4 day⁻¹</td>
<td>1700</td>
<td>42</td>
</tr>
<tr>
<td>1 week⁻¹</td>
<td>2420</td>
<td>56.5</td>
</tr>
<tr>
<td>2 week⁻¹</td>
<td>1980</td>
<td>49</td>
</tr>
<tr>
<td>14 day⁻¹*</td>
<td>3280</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>2600</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>3760</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>2880</td>
<td>72.5</td>
</tr>
</tbody>
</table>

* Event statistics at this frequency are biased low.
Guinea Highlands occurs during 2000–2100 UTC (1900–2000 LT) midnight local time. The peak in convection may be explained by the up slope movement of ambient southwesterly monsoonal flow (Fig. 2) and favorable timing in diurnal heating. During the afternoon, sea-breeze convection moving inland along the Guinea coast interacts with westward-propagating convection triggered by the mountains of Cameroon. The shape of the coastline creates local convergence zones and a local maximum in morning convection over the northeast corner of the Gulf of Guinea (Figs. 8a,g,h) in agreement with Negri et al. (1994), whose study compared morning and evening observations from the Special Sensor Microwave Imager (SSM/I). The pattern during 1700–1800 UTC is nearly an inverted view of the pattern during 0500–0600 UTC. The former is the continental peak intensity, while the latter is the oceanic peak.

2) AUSTRAL SPRING

(i) Rift Valley, Lake Victoria, and Lake Tanganyika

The periods of maximum and minimum frequency are similar to the boreal spring. The peaks are still associated with the highest mountains and Lake Victoria but the envelope of high frequencies has expanded farther north over the midcontinent (Figs. 9b,c). The frequency maximum west of the Ethiopian Highlands exceeds the boreal spring (cf. Figs. 8b and 9b). A region of relatively high frequency occurs over the south-central part of the domain and moves westward with time from its peak near 1500 LT to decay after 0700 LT (Figs. 9b–h).

(ii) East coast and Indian Ocean

Very little cold cloud is observed east of 30°E during the austral spring. Where present, the frequency is less than half that of the boreal spring. A line of sea-breeze thunderstorms still occurs, but is reduced in amplitude and area and occurs only north of the equator.

(iii) West coast and mountain ranges

The Gulf of Guinea is nearly empty of cold clouds during the austral spring, except for the northeast corner, which has a similar diurnal cycle as the boreal spring. Oceanic deep convection is prevalent during the morning hours and absent during the evening. The Cameroon Mountains triggers deep convection that

![Diagram of cold cloud frequency and elevation maps for April 2000-2003 in the Guinea Highlands and Rift Valley.]
moves westward. A region of minimum frequency occurs over the southwestern coastal region where a maximum existed during the boreal spring (cf. Figs. 8d and 9d). Deep convective precipitation in this region depends on systems propagating from the east (Figs. 9b–f).

MCSs moving from the Rift Valley contribute to the fertility of the Congo basin and the maintenance of the rain forest, which is nearly one-fifth of the world’s rain forest. Studies have shown that the longevity, propagation, and upscale growth of organized deep convection requires moderate vertical wind shear balanced by convectively generated cold pools that can trigger new cell formation (e.g., Rotunno et al. 1988; Lafore and Moncrieff 1989). However, without adequate observations, the exact mechanisms that are influencing the mesoscale circulations in this region are undetermined.

b. Zonal progression of deep convection over the diurnal cycle

The seasonal average diurnal cycle of deep convection for March to May and September to November are shown in Figs. 10a,b, respectively. The figure shows the fraction of time during which deep convection ($T_b < 233$ K) is present at the given longitude–UTC hour coordinate. A few features stand out:

- A diurnal oscillation with broad maximum between 1600 and 2200 UTC and a minimum 1–2 h before noon (black dotted lines mark local noon),
- Peak frequency in the lee of the west Rift Valley mountain ranges (near 25°E),
- Propagation of deep convection westward from the eastern mountain ranges,
- Eastward propagation from the west coast inland (from 1600 UTC, 5°–7°E), and
- A semidiurnal signal between the eastern ranges and the western coastal mountains.

The broad late-evening maximum can be explained by surface heating and boundary layer destabilization, but the local maxima seem to be related to the differential heating of elevated terrain.

The diurnal cycle is shifted by the superposition of remotely forced convective systems onto convection that is due to the local diurnal heating maximum. The pattern shows local evening and nighttime maxima connected by axes of higher frequency during the morning hours.

FIG. 9. As in Fig. 8, but for October 2000–03.
(Fig. 10). Those axes are associated with propagating systems that are triggered along different mountain ranges. The peak frequency is associated with systems that initiate on the western slopes of the west Rift Valley Mountains. The second highest frequency is in the lee of the mountains near the west coast, such as the Cameroon Mountains. A weaker maximum occurs in the lee of the east Rift Valley. The eastward-propagating sea breeze shows up as a line of relatively higher frequency sloping eastward along the west coast between 1500 and 2000 UTC. During that same period, a peak in westward-propagating convection exists at that same longitude. Note the suppression of the in-phase diurnal maximum near 30°–33°E over Lake Victoria and the eastern slope of the West Rift Valley mountains.

By tracing the axes of maximum frequency, it can be surmised that some fraction of the initial convection propagates westward decays or weakens and regenerates during the next diurnal cycle, by which time, new convection is being triggered by the daily heating maximum. Thus, convection that initiates along the slopes of the East Africa mountains can move to the west coast over three diurnal cycles of regeneration or can trigger new convection downstream along the propagation phase line.

5. Large-scale influences

a. Vertical shear

Moderate vertical shear of the horizontal wind helps to organize ordinary convection into propagating MCSs (e.g., Rotunno et al. 1988; Lafore and Moncrieff 1989). In equatorial Africa, this is a common condition associated with the day-to-day variability of the low-level monsoon westerlies, the midlevel AEJ, and the upper-level TEJ (Fig. 11). Averages of the zonal wind and vertical velocity (omega, Pa s⁻¹) show that the northern AEJ is the strongest equatorial wind maxima for the study period (Fig. 11a). It is farther south and west during the boreal spring. A midlevel jet occurs in the Southern Hemisphere during the austral spring but is weaker than the northern AEJ (Fig. 11). Averages of the zonal wind and vertical velocity (omega, Pa s⁻¹) show that the northern AEJ is the strongest equatorial wind maxima for the study period (Fig. 11a). It is farther south and west during the boreal spring. A midlevel jet occurs in the Southern Hemisphere during the austral spring but is weaker than the northern jet (Figs. 11a,b). The maximum upward motion during the boreal spring is slightly north of the core of the AEJ (Fig. 11a) where the vertical shear between the low-level westerlies and the midlevel jet is about 12 m s⁻¹. For the austral spring, although maximum rising motion has shifted to the south side of the AEJ, it is also collocated with the maximum in lower-tropospheric shear (Fig. 11b). In the zonal direction, upward motion in the lower and upper troposphere is over

![Figure 10](image_url)
west equatorial Africa, where shear is due to the low-level westerlies, the northern and southern midlevel jets, and the TEJ (not shown). The mean longitude–height cross section has sinking motion east of 45°E, over the Horn of Africa and the Indian Ocean (not shown).

**LOW-LEVEL VERTICAL SHEAR**

Closer examination of the low-level shear (925–600 hPa) and deep convection at the subseasonal scale shows the impact of the migration of the AEJ and the low-level winds (Fig. 12). Areas of maximum deep convection occur in the lee of high terrain and along the coast but are within a wide latitudinal band that shifts northward (Figs. 12 a–c). Between March and May, the band of deep convection moves northward following the band of strongest northeasterly shear (Figs. 12d–f), where most of the shear is generated by the AEJ. At 925 hPa, the zone of maximum winds expands northward from March to May including an increase in wind velocity along the equator between April and May with a similar pattern to the April mean surface flow in Fig. 2. The peak in the meridional shear is over the central Congo (not shown).

Weak maxima in convection are associated with local maxima in low-level shear during April and May (Figs. 12b,c) and a low-level jet that flows from the Indian Ocean through the gap between the Ethiopian Highlands and other East Rift Valley mountains (see inset elevation map below Fig. 12d). The low-level winds show considerable variability and the shear varies from northeasterly over the Horn of Africa to northerly and north-northwesterly over the Indian Ocean (nearly opposite to the low-level flow). In May, the 925–600-hPa shear exceeds 8 m s\(^{-1}\) across the northern half of the domain. Within the axis of maximum shear, local peaks (>14 m s\(^{-1}\)) are coincident with frequent deep convection near the mountains of Cameroon, west of the Ethiopian Highlands, and the Tondou Massif (Figs. 12a–c). The results are similar to Laing et al. (2008), who found that frequent deep convection is associated with maxima in the 925–600-hPa shear over northern, tropical Africa during May to August. Mohr and Thorncroft (2006) also found similar intraseasonal variations in the latitude of intense convective systems, AEJ shear, and high terrain features over West Africa.

During the austral spring (Figs. 12d–f), the picture becomes more complex as a midlevel jet is also present over the Southern Hemisphere. Because the AEJ core is at a lower level during September to November, we analyzed the 925–700-hPa shear (Figs. 12d–f). The core of the southern midlevel jet is over southwestern equatorial Africa during September to October and is the main cause of the low-level shear maximum near 5°S (Fig. 12d). Like the northern AEJ, the southern AEJ moves poleward with the solar heating maximum and the maximum shear axis follows (Figs. 12d,e). The northern AEJ migrates southward so that by November, the maximum shear axis is about 4°N (Fig. 12f) and low-level winds over the Gulf of Guinea are predominantly southeasterly (not shown). By this time, deep convection is most frequent over the Southern Hemisphere with peaks near the high terrain and coasts indicating the dominance of the topographic forcing in those regions. Another maximum is associated with the southward-migrating Southern Hemispheric midlevel jet. To the east, the shear pattern in September is similar to that during May but with strong shear offshore and less deep convection over East Africa. In November, the eastern domain has very weak shear, similar to the March pattern in that region.

Since organized deep convection moves on a west-southwesterly path (Figs. 4, 8, and 9), the relationship with the northeasterly low-level shear is not surprising. Observations and simulations of West Africa squall lines
have found significant low-to midlevel shear with convective lines aligned approximately perpendicular to the shear vector (e.g., Barnes and Sieckman 1984; Lafore and Moncrieff 1989; Laing and Fritsch 2000). Development of a better understanding of the relationship between low-level shear and organized deep convection will require observations and model simulations that can resolve mesoscale circulations.

b. Convectively coupled Kelvin waves and the MJO

The propagation of organized convection in equatorial Africa is affected by variations in the large-scale wind velocity in the lower troposphere and near the tropopause, such as occurs with the passage of convectively coupled Kelvin waves (Mounier et al. 2007; Mekonnen et al. 2008). Anomalies of OLR and zonal winds at 850 and 200 hPa for early April 2002 indicate the passage of convectively coupled equatorial Kelvin waves (Fig. 13). The patterns are similar to Wang and Fu (2007). Black arrows show zonal flow associated with positive and negative OLR anomalies. Anomalous westerlies at 850 hPa (Fig. 13) will bring moisture from the Gulf of Guinea into the region of convergence. At 200 hPa, flow away from the negative OLR anomalies enhances divergence and upward motion (Fig. 13). These particular Kelvin waves can also be detected in unfiltered satellite brightness temperature and zonal wind anomalies (Fig. 14). During the first 2 days of April 2002, the daily pattern consists of convection initiating in the lee of the East Africa mountains and moving westward (Fig. 4). MCSs continued to propagate west from the eastern mountains within a weak Kelvin wave starting on 3 April (Fig. 14i). Then on 5 April, the westward propagation is interrupted by a period of little convection and 200-hPa westerly wind anomalies exceeding 8 m s$^{-1}$ (Fig. 14i). Over the next 4 days, the peak convection shifts east from the west coast and the Gulf of Guinea. Meanwhile only weak, scattered convection occurs over East Africa.

Figure 14h illustrates the theoretical solution for an equatorially trapped Kelvin wave derived by Matsuno (1966). The phase speed and length scale of the eastward-moving circulations in Figs. 13 and 14 are consistent with convectively coupled Kelvin waves (K09 and references therein). Upper-level easterly anomalies (turquoise shade) are to the west and near the enhanced convection, while westerly anomalies (orange shade) occur with the region of suppressed convection (Figs. 13 and 14i); consistent with the structures observed by Mekonnen et al. (2008) and WKW00). The size and intensity of mesoscale convection, as measured by brightness temperature, increase during the wet phase of the Kelvin wave. In comparing the size of MCS observed
near 2100 UTC during 1–3 April (Fig. 4) with those observed near 2100 UTC during 7–11 April (Fig. 14), the latter have more extensive and colder cloud tops. The formation of larger and more intense MCSs during the wet phase of the Kelvin wave agrees with the findings of Nguyen and Duvel (2008). The differences can be also seen in the size of the darker gray shades of Fig. 14i with thicker, darker areas indicating larger, intense MCSs during 7–11 April compared with narrow, lighter shaded areas during 1–3 April 2002. Note that the diurnal cycle remains prominent. Convective cloud streaks are initiated each afternoon and move westward within the larger Kelvin wave (Fig. 14i). For a region that is dependent on rain-fed agriculture, information about the circulations that can limit rainfall is valuable. Figure 15 illustrates the contrast in distribution of deep convection during different regimes. The period of westward propagation during 1–4 April is similar to the mean April distribution (Figs. 15a,b). During the dry Kelvin wave phase, cold clouds are reduced across the continent and what occurs does not propagate very far from their initiation points (Fig. 15c). During the peak wet phase of the Kelvin wave (8–11 April), the cold cloud frequency is dramatically higher than average. During
Fig. 14. (a)–(g) Enhanced IR images for 6–12 Apr 2002; (h) theoretical equatorially trapped Kelvin wave circulation at 200 hPa; (i) Hovmöller of $T_b < 233$-K frequency (solid contours >10%, gray shade >21%) overlaid on 200-hPa zonal wind anomaly (orange shades are easterly, turquoise shades are westerly) and Kelvin waves filtered from daily OLR anomaly (negative is dashed black, positive is solid black at 20 W m$^{-2}$ intervals). (h) Adapted from WKW00 with shading (hatching) for divergence (convergence). Unshaded contours are geopotential, negative contours are dashed, and the 0 contour is omitted. The largest wind vector is 2.3 units. Dimensional scales are as in Matsuno (1966). Average elevation (m) is below the Hovmöller diagram in (i). Averages are taken between 7.5°S and 7.5°N.
this particular period, the peak covers the western domain and leaves the east dry. Having shown that convectively coupled Kelvin waves can have a significant impact on propagating deep convection over equatorial Africa, the next step is to examine the variability of Kelvin waves over Africa. Convectively coupled Kelvin waves occur most frequently over Africa during March–May. The most active season of the study period was March–May 2000 with 10 wave passages; 5 of which occurred in March. The least active season was September–November 2002 when only one event matched our criteria. Only 28% of Kelvin waves occurred during September–November. The study period average frequency is 2–3 month \(^{-1}\), which is in agreement with Roundy and Frank (2004), Masunaga (2007), and K09. The mean phase speed was 16.2 m s\(^{-1}\) with a range of 12–22 m s\(^{-1}\).

Mesoscale convection in equatorial Africa is also influenced by the MJO. Maximum MJO activity near the equator tends to occur around the equinoxes (e.g., Salby and Hendon 1994; Zhang and Dong 2004), coincident with our study periods. While the MJO is most common and strongest over the Indian and Pacific Oceans, its signals are sometimes observed over Africa. Figure 16 shows MJO events over Africa during the boreal springs of 2002 and 2003 (Fig. 16). Modulation of mesoscale convection by the MJO and Kelvin waves is demonstrated using April 2003 examples (Fig. 17). The first two weeks have coherent, periodic westward-moving features but the latter two have a more varied pattern with much less westward propagation (Fig. 17a). Starting on about 15 April, deep convection is observed across the entire domain. The convection is part of the active stage of the MJO, identified from filtered daily
The increase in deep convection is associated with a large band of anomalous easterly winds at 200 hPa. The MJO also influences the first half of the month when very little deep convection is observed east of 30°E (Fig. 17a). That period has anomalous westerly winds at 200 hPa (Fig. 17b), which is characteristic of the suppressed phase of the MJO (Madden and Julian 1971; Zhang 2005 and references therein). A hierarchy of convective activity occurs. Intense convection features (bright red areas in Fig. 17a) are either aligned with the diurnal heating maximum or they exhibit westward or eastward propagation. Kelvin waves are within the slower-moving MJO (Figs. 17b,c); a fairly common occurrence (Masunaga 2007; K09). One Kelvin wave moves east from about 25°E on 18 April. Another crosses from the Atlantic to the Indian Ocean after 16 April. The suppressed phase (positive OLR anomaly) of this Kelvin wave is stronger than those of the Kelvin waves on 3 and 10 April. At 200 hPa (Fig. 17b), the maximum in OLR anomaly occurs between anomalous easterlies and westerlies where upper-level convergence is expected (Fig. 14h). A third Kelvin wave follows the dry period during late April. The anomalies are quite prominent even in the unfiltered wind field.

Given the relationship between Kelvin waves, the MJO, and organized, propagating mesoscale convection, improvements in tropical intraseasonal forecasts are expected to benefit forecasts of convective precipitation in equatorial Africa. Recent studies indicate a measure of predictability, especially where extratropical forcing is significant. For example, Liebmann et al. (2009) found that sea level “pressure surges” moving from midlatitude South America northward along the eastern slope of the Andes into the deep tropics often preceded Kelvin wave activity over the Amazon, an upstream source of Kelvin waves for equatorial Africa. Pereira Filho et al. (2010) noted a few eastward-moving features in their Hovmöller diagrams of Amazon cloud clusters that could be Kelvin waves heading toward equatorial Africa. It could be argued from this study and from Molinari et al. (2006) that equatorial waves need to be incorporated into synoptic tropical weather forecasting.

6. Summary and conclusions

Organized convection appears as coherent sequences or episodes that propagate on regional and continental scales over equatorial Africa. From a multiyear dataset, it was found that statistics, such as zonal propagation speeds, are similar across continental regions, which indicate common environmental conditions that favor increasingly organized precipitation regimes. A large fraction of episodes have their origin in the lee of major mountain ranges such as the East African mountains and Cameroon Mountains. A major generating factor is thermal forcing associated with large elevated heat sources, a mechanism that is supported by the geographical distribution of hourly cold cloud frequency, which reflects the complex topography. A highly unstable boundary layer is favored where elevated terrain interacts with strong diurnal heating, which promotes the formation of long-lived episodes of deep convection.
The mean zonal progression of convective precipitation over equatorial Africa is similar to deep convection in northern, tropical Africa and the Amazon as well as warm-season precipitation in North America, East Asia, and Australia. Propagating convective systems modulate the diurnal cycle so that instead of a single period of maximum precipitation in the late afternoon, precipitation maxima occur as axes across the domain. This pattern supports the notion of convection regenerating through more than one diurnal cycle. Low-level convergence resulting from decaying systems that trigger new convection downstream is another mechanism for this pattern. However, without adequate observations or definitive simulations, it is impossible to confirm the mesoscale influences on convective organization and orographic initiation. Detailed field observations and high-resolution simulations are needed to help isolate and confirm the hypotheses advanced in this study.

Episodes of convection propagate across equatorial Africa at an average speed that is slightly faster than the average speed of the AEJ [similar to observations over West Africa and Atlantic by Barnes and Sieckman (1984)]. On average, its counterpart in the Southern Hemisphere is weaker and slower than the phase speed of most convective events. Episodes occur in the presence of moderate vertical shear of the horizontal wind. This is a common condition associated with the deep westerlies in the United States, China, and Europe. In equatorial Africa, vertical shear results from the low-level monsoonal flow, the northern AEJ, and a weaker southern AEJ.

The propagation of convection is also modulated by convectively coupled, equatorial Kelvin waves. With the active phase of these eastward-propagating large-scale waves, mesoscale convective systems are larger and more intense. These intense convection features occur farther east on each subsequent day and propagate westward.
within the Kelvin wave envelope. With the dry phase (upper-level convergence), deep convection is suppressed and westward propagation of convective episodes ceases. The MJO inhibits organized, deep convection during its suppression phase and favors widespread deep convection across equatorial Africa during its active phase, but with significantly less westward propagation than in its absence.

This study provides new information about daily convective precipitation patterns, propagation characteristics, and the impact of different large-scale regimes. The response of mesoscale convection to the phases of the large-scale wave perturbations supports the need for further study and better prediction of multiscale interactions in tropical Africa. This need is especially critical because interruptions in the daily rainfall can adversely affect agricultural economies that depend on the seasonal rains. These results show a potential for improvement in predictability and for regional climate characterization in equatorial Africa.

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