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Propagation of convection in Africa: implications for predictability of precipitation

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Abstract Knowledge of the spatial and temporal variability of precipitation is needed for African societies to manage agriculture, water resources, public health, renewable energy, and hazard mitigation. This study examines the occurrences of organized convection in Africa using five years (1999–2003) of digital infrared imagery. Domains are: 0° to 20°N and 20°W to 40°E; 15°S to 15°N and 20°W to 45°E; 35°S to 15°S and 10°E to 45°E. Reduced-dimension techniques are used to document properties of cold clouds, proxies for precipitation. Large-scale environments are diagnosed from global analyses. A sizeable fraction of the rainfall in Africa results from long-lived "episodes" of deep convection. Episodes are coherent sequences of organized convection that propagate and regenerate on regional and continental scales. Most episodes have phase speeds of 10–20 m s^{-1}. A major generating factor for convection is thermal forcing associated with large elevated heat sources. Episodes occur with moderate vertical wind shear. Study results infer the potential for increased predictive skill in sub-seasonal weather prediction, which could enable substantial societal benefits.

Key words convection; diurnal cycle; southeast Africa; Central Africa; Sahel; West African monsoon; tropical precipitation

INTRODUCTION

The ability of African societies to reduce their vulnerability to environmental disasters is tied to the quality and application of weather and climate information. On a daily basis, knowledge of the spatial and temporal variability of precipitation is needed to manage agriculture, water resources, public health, and renewable energy.

Improvement of prediction of precipitation is dependent on better knowledge of the initiation and evolution of organized mesoscale convective systems (MCSs). This study examines the propagation and evolution of cold-cloud clusters, which serve as a proxy for precipitation, in Africa. Comparisons are made to warm season precipitation on other continents.

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. Wang *et al.* (2004) and Levizzani *et al.* (2006) used infrared (IR) brightness temperatures (T_b) from geostationary satellites to show similar patterns for cold-cloud clusters in East Asia and Europe, respectively. Given the similarities of MCSs globally (Laing & Fritsch 1997), similarity in coherence is not unexpected. Laing *et al.* (2004)

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found coherence in convective patterns over northern tropical Africa for two seasons. If coherence is found for other parts of Africa, inferences can be made regarding the predictability of precipitation on a continent where the variability of precipitation has tremendous societal impact.

In Sahelian Africa, the Jos Plateau, Darfur Mountains and the Ethiopian Highlands are regions where squall lines and mesoscale convective complexes originate (Tetzlaff & Peters 1988; Laing & Fritsch 1993). Squall lines and cloud clusters are modulated by African Easterly Waves (AEWs), the African Easterly Jet (AEJ), and moisture convergence in the lower troposphere (e.g. Payne & McGarry, 1977; Machado *et al.*, 1993; Rowell & Milford, 1993; Thorncroft & Haile, 1995). In subtropical southern Africa, convection initiates along the South African escarpment then propagates eastward (Garstang *et al.*, 1987; Laing & Fritsch, 1993).

Mathon & Laurent (2001) found that, for Sahelian convective systems larger than 5000 km^2, the mean system speed increased with longer lifetime. They found that the mean MCS speed was similar to the mean zonal component of the AEJ (maximum at about 650 hPa), except to the west of 5°E, where the mean MCS zonal speed was greater. MCSs that occurred between 12° and 16°N lasted an average of eight hours. Desbois *et al.* (1988) calculated average speeds of 12–19 m s^{-1}, but their study used three-hourly data while Mathon & Laurent (2001) used higher resolution 30-min data. Barnes & Seickman (1984) found that fast-moving cloud lines had speeds ranging from 7 to 15 m s^{-1}. Most of the aforementioned results were from case studies or studies that tracked individual systems. This study presents systematic long-term statistics of convection on a continental scale.

DATA AND METHODS

Primary data are digitized infrared (11.5 μm) images from the European geostationary satellite (Meteosat) for five years (1999–2003). Images are available at 30 minute intervals and sampled to 0.2 degree grids for three domains (Fig. 1).

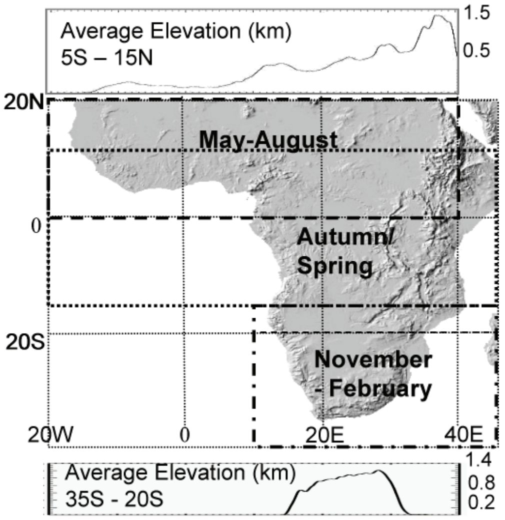

Fig. 1 Study domains overlaid on a shaded-relief map and cross-sections of average elevation (km).

Threshold brightness temperatures (Tb) are used to identify likely precipitating cloud systems. Duvel (1989) used the 253 K threshold to distinguish deep convection. Arkin (1979) used 235 K to identify accumulated convective precipitation. Arnaud *et al.* (1992) used 233 K to find convective clouds that are most likely to precipitate. Mathon *et al.* (2002) defined a subset of organized convection in the Sahel using 233 K. Those convective systems accounted for 90% of the seasonal rainfall observed by the Etudes des Précipitations par Satellite (EPSAT)-Niger raingauge network for a nine-year period. The primary threshold for propagation statistics over tropical Africa is 233 K; for subtropical-to-midlatitude southern Africa the 235 K threshold is used.

Reduced-dimension techniques are used to identify the propagation of cold cloud clusters (Carbone *et al.*, 2002). Each pixel colder than the threshold Tb constitutes an "event" at a given distance–time coordinate. A 2-D auto-correlation function is stepped through all points in the distance–time (Hovmoller) space and rotated until the correlation coefficient is maximized. Contiguous fits to the function define coherent patterns or "cloud streaks" (Fig. 2). Only correlation coefficients of 0.35 or higher are accepted. Further details of the technique are provided in Carbone *et al.* (2002). Statistics of cloud streaks with durations greater than 3 h and span greater than 300 km are compiled. Zonal phase speeds of the cloud streaks are computed from the slopes in

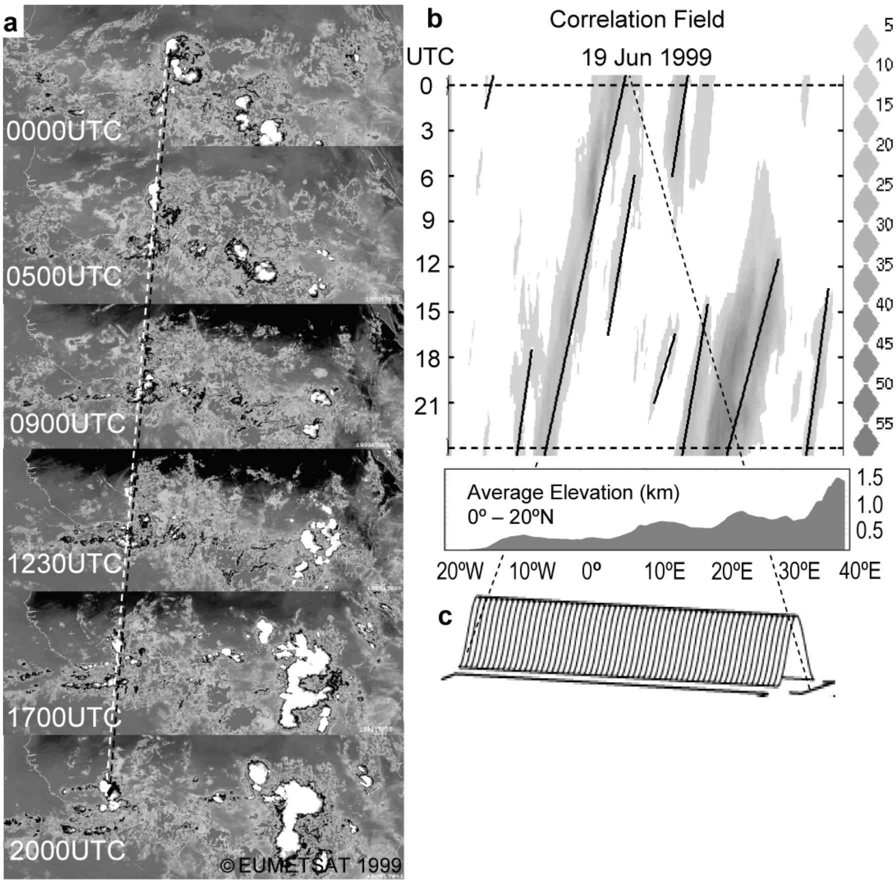

Fig. 2 (a) Enhanced IR images for 19 June 1999. (b) Longitude–time plot of the frequency of Tb < 233 K (shaded contours, %); black lines are objectively defined cold cloud episodes. (c) Conceptual model of the cosine-weighted autocorrelation function. Dashed line in (a) shows a cold-cloud episode or streak.

Hovmoller space. Mean diurnal cycles are determined by computing the histogram of deep convection as a function of longitude and time of day. Global re-analysis data from the National Centers for Environment Prediction (NCEP) and National Center for Atmospheric Research (NCAR) are used to analyse the large-scale environment. The analyses are available daily at 00:00, 06:00, 12:00 and 18:00 UTC.

PROPAGATION OF COLD-CLOUD EPISODES

Tropical Africa

Deep convection in tropical Africa (northern and central Africa) is organized as coherent episodes that occur on an almost daily basis (Fig. 3). A large fraction of the episodes initiate in the lee of high terrain (e.g. the Ethiopian Highlands, Darfur Mountains, Jos Plateau, Guinea Highlands, Lake Victoria highlands). While insufficient in itself, a major generating factor is thermal forcing associated with large elevated heat sources. The phase speed for most cold-cloud streaks in tropical Africa is 10–20 m s^{-1}; similar to phase speed of episodes in the USA, East Asia, and Europe (Wang *et al.*, 2004; Levizzani *et al.*, 2006). The average span (1062 km) and duration (25 h) of northern tropical Africa episodes are greater than other domains. A few episodes travelled more than 5000 km and lasted several diurnal cycles (e.g. 19–25 July 2002, Fig. 3). The northern African domain was 60° longitude compared with 37° for the USA and 50° for other continents. While many convective episodes in the USA mainland and East Asia are triggered along a large and high mountain range, convection in Africa is triggered along several mountains ranges (cf. Figs 1 and 3).

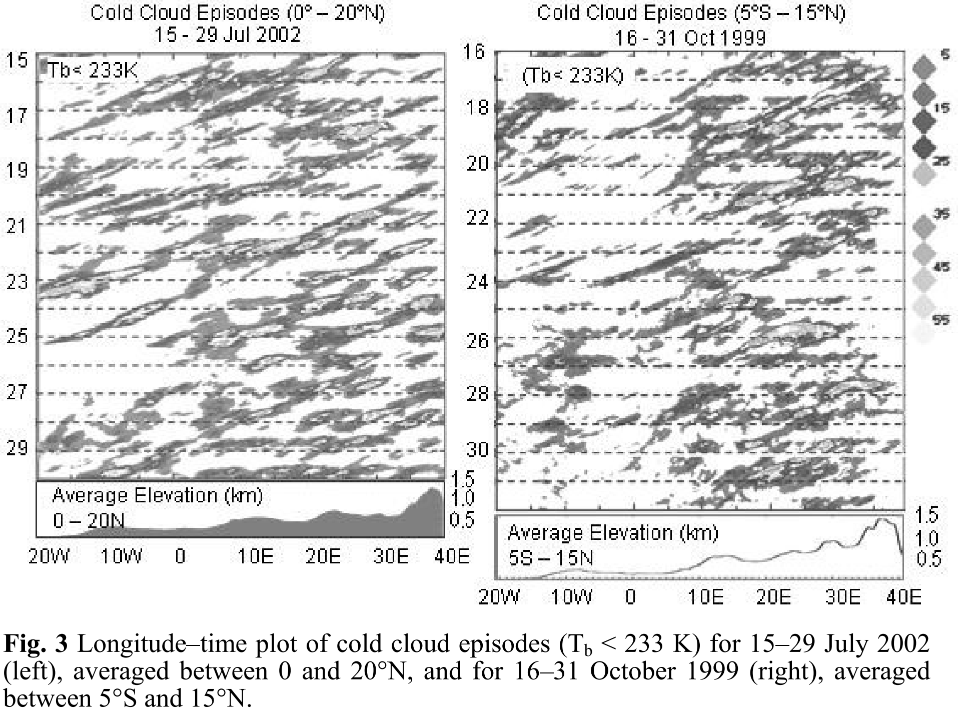

Fig. 3 Longitude–time plot of cold cloud episodes ($T_b < 233$ K) for 15–29 July 2002 (left), averaged between 0 and 20°N, and for 16–31 October 1999 (right), averaged between 5°S and 15°N.

Subtropical and mid-latitude southern Africa

South of 20°S, episodes propagate eastward, in the direction of the prevailing westerly flow (Fig. 4). They are coherent in phase with mean zonal phase speeds that are similar to those of other continental domains (Table 1). However, periods of propagating convection are less frequent than localized convection, which is unlike other domains where new episodes occur almost daily (Fig. 3). Although the phase speeds are similar, southern Africa results are preliminary as only 1999 and 2003 have been analysed. Analysis of the remaining seasons is in progress.

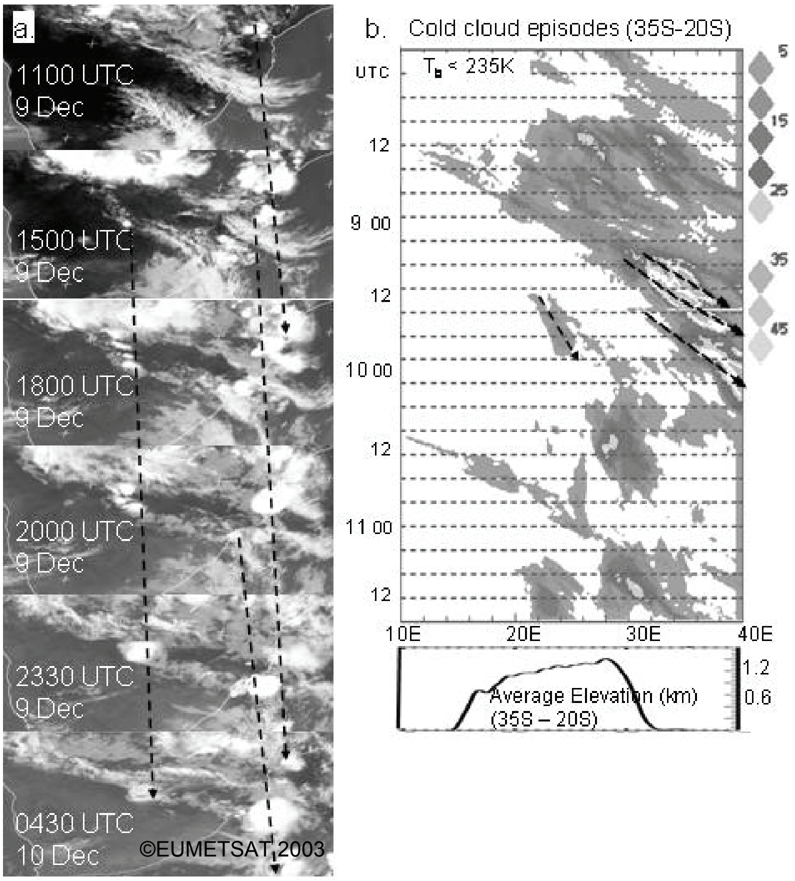

Fig. 4 (a) IR images, and (b) corresponding longitude–time plot of cold clouds. Black arrows mark cold-cloud streaks for the period in the satellite images.

Table 1 Mean and median zonal phase speed of convection and precipitation episodes over continents.

Region (zonal domain longitude)	Zonal phase speed (m s^{-1})	
Contiguous USA (37°)	Median – 13.6	
East Asia (50°)	Mean – 12.4	
Europe (50°)	Mean – 14.88	Median – 13.6
Northern tropical Africa (60°)	Mean – 12.0	Median – 11.2
Central Africa (50°)	Mean – 11.8	Median – 10.7
Mid-latitude southern Africa (35°)	Mean – 12.1	Median – 11.2

AVERAGE DIURNAL CYCLE

The mean diurnal cycle is diagnosed from histograms of cold clouds at each longitude at the same time of day. Figure 5 shows the bi-weekly average diurnal cycle of deep convection. A domain-wide maximum occurs between 18:00 and 22:00 LT and the minimum occurs one to two hours before noon.

The diurnal cycle is complicated by the superposition of remotely-forced convective systems onto the convection due to the local diurnal heating maximum. The typical pattern for tropical Africa shows several maxima connected by axes of higher frequency associated with propagating system (Fig. 5(a) and (b)). For subtropical-to-mid-latitude southern Africa, convection propagates east from high terrain (Fig. 5(c)), except for the swath associated with the passage of Tropical Cyclone Cela.

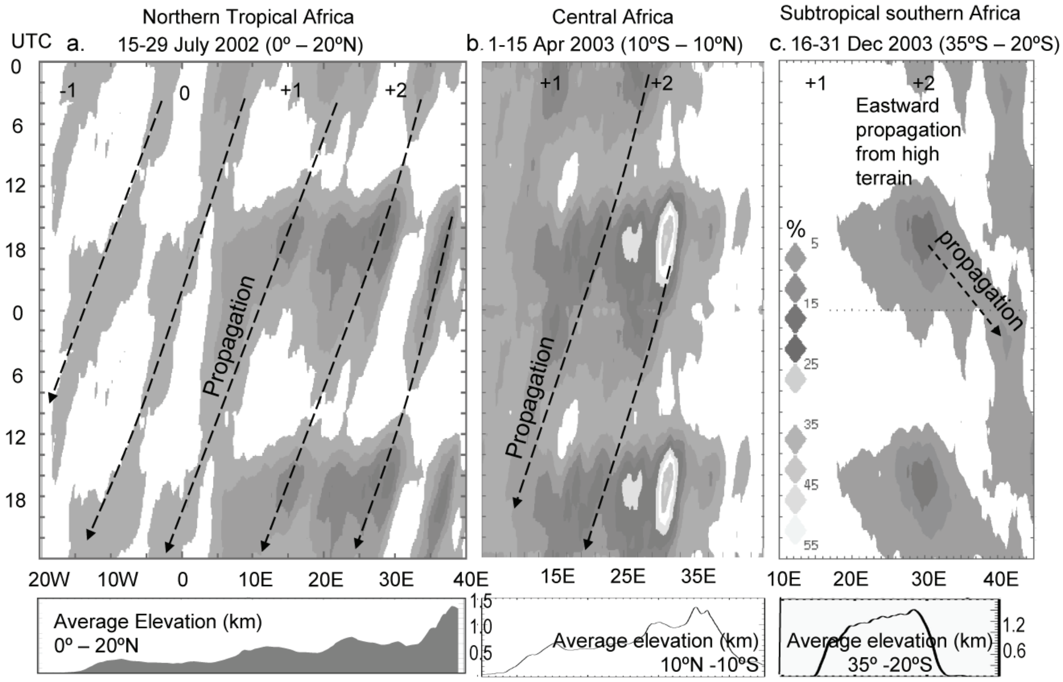

Fig. 5 Average percentage of time with cold cloud at a given longitude at the same time of day for: (a) northern tropical Africa, (b) central Africa, and (c) subtropical-midlatitude southern Africa. Shaded contours are average percentage of occurrence. Time is given in UTC. Axes of maximum frequency are marked, subjectively, by black dashed lines. Time zones are noted as hours relative to GMT. The diurnal cycle is repeated. Cross-sections of average elevation are shown for each domain.

LARGE-SCALE INFLUENCES

Organized episodes of deep convection occur in the presence of moderate vertical shear of the horizontal wind. In Sahelian Africa, this is a common condition associated with the migration of the African Easterly Jet (Fig. 6), while in subtropical to mid-latitude southern Africa, it is associated with the deep westerlies (Fig. 7). For the southern domain, organized convection develops and propagates where low-level, northerly winds bring warm, moist air from the equatorial zone, e.g. after 5 December 2003 (Fig. 7(a)). Without westerly wind shear very little propagation occurs (Fig. 7(c)).

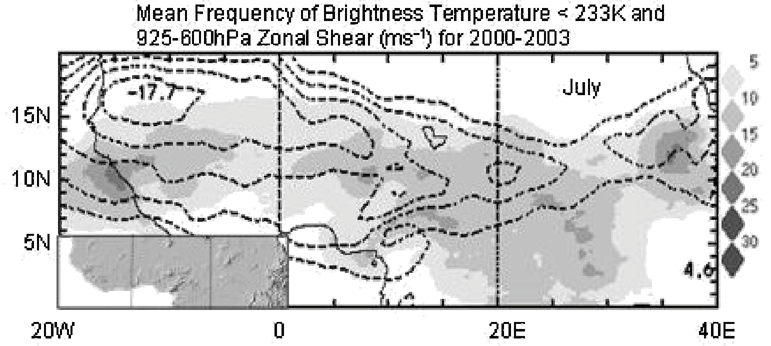

Fig. 6 Mean frequency of cold clouds (shaded contour, %) and 925–600 hPa shear (dashed lines, m s^{-1}) for July, 2000–2003. Inset map shows shaded relief.

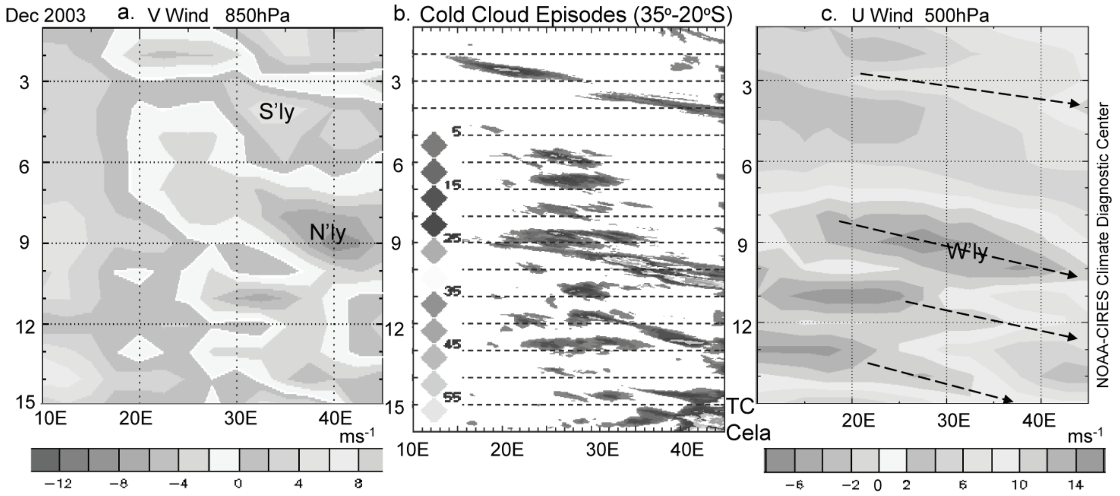

Fig. 7 (a) Daily averaged meridional wind at 850 hPa (m s^{-1}), (b) cold-cloud episodes averaged between 35° and 20°S, and (c) daily averaged zonal wind at 500 hPa (m s^{-1}) for 1–15 December 2003. Dashed arrows mark eastward propagation of the zonal wind at 500 hPa.

In central Africa, propagation is most affected by variations in the large-scale wind velocity in the lower troposphere and near the tropopause, such as occurs with the passage of Kelvin waves (Straub & Kiladis, 2003; Nguyen & Duvel, 2006). For example, during the first half of April 2003, episodes are propagating across the continent almost daily until 18 April when the large-scale circulation changes (Fig. 8).

Between 18 and 27 April 2003, the daily propagation of convection ceased during the passage of an eastward-moving envelope of strong easterly winds at 200 hPa. A weak 850 hPa westerly wind maximum propagates ahead of the strong 200 hPa easterly maximum. Meridional winds at 700 hPa have become weak northerlies, a switch from the strong southerly flow in the previous weeks. This example demonstrates why more attention should be paid to the organization of propagating mesoscale systems in different phases of the large-scale wave perturbations in order to understand how they are coupled. April is the main rainy season for Central Africa and interruptions in the daily rainfall can adversely affect the agricultural economy. Prediction is needed beyond forecasting the onset of the rainy season. Knowledge of daily precipitation patterns and the impact of different large-scale synoptic regimes are also critical.

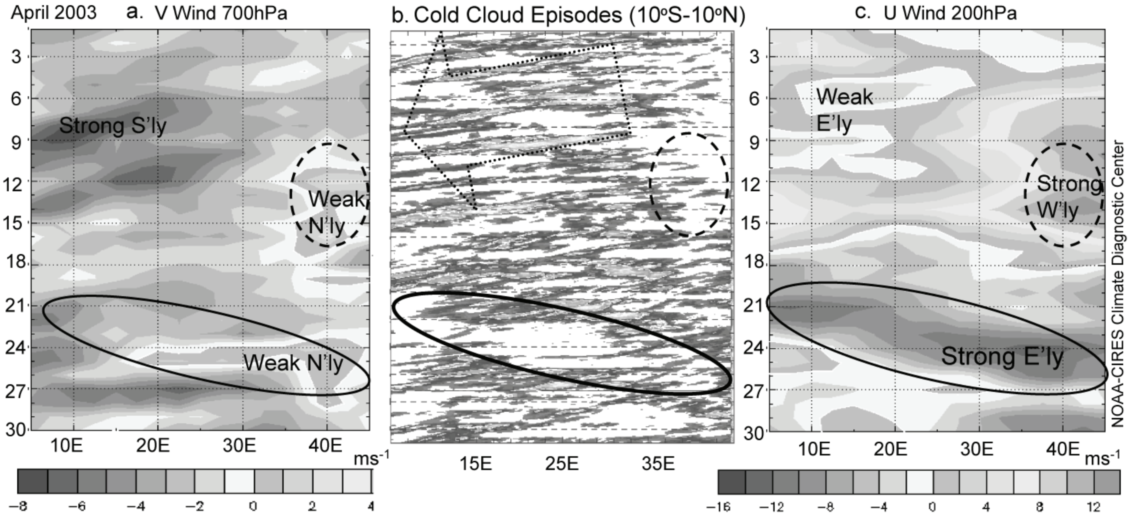

Fig. 8 (a) Daily averaged meridional wind at 700 hPa, (b) cold-cloud episodes between 10ºS and 10ºN, and (c) daily averaged zonal wind at 200 hPa for 1–30 April 2003. Large arrow marks period of daily propagation. Ovals mark period where propagation was inhibited (b) and where wind direction shifted by as much as 180º (a, c).

SUMMARY AND CONCLUDING REMARKS

A multi-year climatology demonstrates that a sizeable fraction of the deep convection (and associated rainfall) in Africa exists as "episodes" that propagate in a coherent manner on regional and continental scales. Convection is triggered in the lee of high terrain, with the mountains of East Africa acting as the main elevated heating sources.

In the presence of steering winds and moderate shear of the horizontal wind, the organized convective systems steadily propagate across Africa, while undergoing periods of dissipation and phase-coherent convective regeneration. Daily frequency maxima result from the local convection (that forms in response to the diurnal heating maximum) and the delayed-phase arrival of remotely-forced convective systems. Diurnal patterns with a delayed-phase shift in the frequency of convective precipitation are also observed in USA mainland, East Asia, and parts of Australia (Carbone *et al.*, 2006). While convection is triggered almost every day in tropical Africa, convection in subtropical and mid-latitude southern Africa requires northerly low-level inflow and synoptic westerly wind shear. In tropical Africa, a few episodes lasted five days or more, which may be due in part to the larger domain and the presence of several high terrain features where convection is initiated. The finding of coherent patterns of propagation and the large-scale circulations that influence propagation support the notion that organized precipitation events may be predictable in the probabilistic sense well beyond one or two days.

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