Convective Outbreak over the Red Sea and Downstream Easterly Waves

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ABSTRACT: This study analyzes a convective outbreak over the Red Sea on 25 August 2009 that generated easterly waves over the Sahel, floods in Ouagadougou, and a hurricane in the east Atlantic. The convective outbreak occurred on the equatorward flank of the African easterly jet 18°–22°N and associated meridional heating gradients over the Arabian Peninsula. The Rift Valley mountains induced a vertical orographic undulation and cyclonic perturbation. Two thunderstorm clusters over the southern Red Sea received moist inflow from the Ethiopian highlands and northern Red Sea. This group of three easterly waves intensified downstream over the Sahel. One of the convective triggers was enhancement of the Arabian Ridge by the northern subtropical jet. Statistical analyses indicate that African easterly waves and subsequent tropical storms are more influenced by upstream kinematic shear than thermodynamic energy. The work offers new insights on the formation of easterly waves over the northern Rift Valley.

KEYWORDS: Geographic location/entity; Africa; Circulation/dynamics; Mesoscale systems; Waves, atmospheric; Physical meteorology and climatology; Thermodynamics

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1. Introduction

There are two weather phenomena over northeast Africa that can produce substantial rains: the southwestern (SW) trough in spring and autumn (Knippertz 2007; Krichak et al. 2004, 2012) and African easterly waves (AEW) in summer (Kiladis et al. 2006). Both weather systems have expression in the lower troposphere and are influenced by Rift Valley orography and African moisture sources (Krichak et al. 1997a,b). The seasonal thermal wind ($\partial T/\partial y \sim \partial U/\partial z$) is a distinguishing factor; the SW trough has cool-north positive shear (Kahana et al. 2002), while the AEW has warm-north negative shear. Naturally, intertropical convergence between the Hadley cells reaches a northern limit during summer [July–September (JAS)], so moisture can be fed into AEW despite their limited equatorward extent. The SW trough relies on upper kinematic forcing by the subtropical westerly jet stream (Saaroni et al. 1998; Kahana et al. 2004; Ziv et al. 2005; Tsvieli and Zangvil 2005), while AEW—our focus here—require cyclonic vorticity $\partial U/\partial y$ from the midlevel African easterly jet (AEJ; Norquist et al. 1977; Reed et al. 1977; Albignat and Reed 1980).

AEW play a dominant role in synoptic weather variability across the African Sahel (Payne and McGarry 1977; Duvel 1990; Diedhiou et al. 1999; Fink and Reiner 2003; Mekonnen et al. 2006) by promoting thunderstorm clusters in the trough (Machado et al. 1993). The convective response to dynamical forcing produces a heating perturbation that feeds back to the disturbance (Wheeler and Kiladis 1999; Yang et al. 2003; Poan et al. 2014). Further knowledge on kinematic–thermodynamic coupling may contribute to improved medium-range weather forecasts.

AEW seldom form east of Sudan (30°E) for a number of reasons. First, the AEJ rarely extends into the Arabian Peninsula (Kiladis et al. 2006). Second, moisture from the Congo Basin is often channeled west of the Rift Valley (Viste and Sorteberg 2013). Third, thermodynamic energy is minimal over the western Arabian Sea due to seasonal upwelling (Schott 1983; Izumo et al. 2008). Cool water spreads from Somalia to Oman beneath a divergent wind jet (Findlater 1969; Fischer et al. 2002). The marine layer is capped by an inversion, and moisture is exported to India (Vecchi and Harrison 2004). Despite the convective inhibition, AEW can form in the sheared flow over Ethiopia (Berry and Thorncroft 2005; Hsieh and Cook 2005; Mekonnen et al. 2006). Modeling studies (Schubert et al. 1991; Hall et al. 2006; Hsieh and Cook 2007; Thorncroft et al. 2008) suggest that precursor convection conspires with AEJ instability.

Transverse perturbations ($\partial V/\partial x$) on the AEJ are initiated by mountains of the northern Rift Valley (Dickinson and Molinari 2000; Lin et al. 2005). Modern reanalysis datasets underpinned by satellite water vapor (WV) winds and regular radiosonde profiles on the Arabian coast reveal a 600-hPa zonal wind of $<-6\text{ m s}^{-1}$ ~ 22% of the time during summer. But cyclonic vorticity may not coincide with thermodynamic energy in the dry desert air [~68% of the time in JAS the convective available potential energy (CAPE) is $<1000\text{ J kg}^{-1}$].

To extend our knowledge on easterly wave formation over the northern Rift Valley, a convective outbreak over the Red Sea on 25 August 2009 is studied. This event is the highest ranked case in the July to September season over the period 2005–15, based on a transient AEW index (M. R. Jury 2016, unpublished manuscript). The convective
outbreak initiated a group of easterly waves that induced floods over Ouagadougou, Berkina Faso (12.4°N, 1.5°W), on 1 September and Hurricane Fred off Dakar, Senegal, on 6 September with rain, central pressure of 958 hPa (category 3), and winds up to 50 m s⁻¹ in the southern Cape Verde islands.

Following a description of the methods and a regional overview, a case study is analyzed with high-resolution maps, vertical section anomalies, and Hovmöller plots. Specific causes and interannual variability are studied, followed by a summary of findings.

2. Data and methods

The data used to study the convective outbreak over the Red Sea and subsequent AEWs include 3-hourly CMORPH multisatellite rainfall at 25-km resolution (Joyce et al. 2004) and 6-hourly MERRA reanalysis at ~60 km (Rienecker et al. 2011). Meteorological parameters are the winds, vertical motion, relative vorticity, air temperature, specific humidity, and latent heat flux (LHF). The Red Sea oceanography is studied using daily HYCOM reanalysis surface salinity and temperature at 9-km resolution (Chassignet et al. 2009); transpiration is characterized by NOAA satellite vegetation fraction at 1-km resolution (Tucker et al. 2005).

AEW over northeast Africa were identified using CMORPH rainfall and MERRA 600-hPa relative vorticity in the 10°–15°N latitude zone in three adjacent 10° longitude boxes west of Ethiopia. An AEW index was formed by adding the vorticity ($\times 10^6$ s⁻¹) and rain (mm h⁻¹) values (both with a standard deviation of ~5) for 3 successive days in three successively westward locations across the eastern Sahel (cf. Figure 1c), such that high values refer to a convective vortex propagating westward at >10 m s⁻¹. Various indices to identify AEW are reviewed in Fink (2012). The 600-hPa streamfunction over the northern Red Sea (15°–25°N, 30°–45°E) was used to further screen cases (Spinks and Lin 2015), and 25 August 2009 had the highest rank in the period 2005–14.

Regional maps and a Meteosat IR image were analyzed over 5°–30°N, 10°–60°E, while Red Sea maps and vertical sections cover 12°–26°N, 35°–45°E. Anomalies were calculated by subtracting the JAS 2009 mean from 25 August values. The JAS 2009 mean is close to the 30-yr climatology, with <2 m s⁻¹ deviation of the AEJ and <10 W m⁻² deviation of OLR over northeast Africa (Arndt et al. 2010). Hovmöller longitude–time plots of 3-hourly CMORPH rainfall and 6-hourly MERRA 600-hPa winds and specific humidity were averaged 8°–20°N latitude from 10° to 60°E, 22–29 August 2009. MERRA boundary layer winds over the Red Sea and a 25 August radiosonde profile at Abha, Saudi Arabia (18.2°N, 42.6°E; 2093 m), provide insights.

HYSPLIT ensemble back trajectories in the 48 h before the convective outbreak were calculated at two end points (18°N, 39°E and 13°N, 42°E) in three vertical levels (1000, 3000, and 5000 m), based on NCEP-GFS 0.5° meteorology. Midlatitude influences on the Arabian Ridge were investigated by analysis of MERRA 500-hPa winds and vorticity and 850-hPa temperature over a wide domain from 23 to 25 August 2009. Total and anomaly fields were calculated and compared with key station data.

Statistical relationships were studied by calculation of the annual cycle for daily CAPE and 600-hPa zonal winds (U600) averaged over the Red Sea (12°–26°N, 30°–45°E) from 2005 to 2014.
Figure 1. (a) Regional topography, (b) daily AEW index in JAS 2009 (units of rain + vorticity) with the case circled and 10-yr mean index, (c) Meteosat IR image 1200 UTC 25 Aug 2009, and (d) 600-hPa wind (max vector = 14 m s$^{-1}$) and 850-hPa specific humidity on 25 Aug 2009 with the high elevation masked. The box in (a) highlights focus area (cf. Figure 2), the crosses in (c) are back trajectory end points (cf. Figure 3), the boxes refer to AEW index and lags, and the 850-hPa blue wind flow lines west of Ethiopia in (d) highlight the poleward channeling of moisture.
Pairwise relationships were tested with CAPE, U600, and the downstream AEW index lagged by 1 day, using daily data over the period 2005–14. CAPE is calculated by the standard procedure, subtracting the moist adiabat from the environmental lapse rate and integrating vertically from theoretical cloud base to cloud top.

The upstream–downstream relationships of AEW were analyzed via HURDAT tropical storms (TS; Landsea et al. 2004) in the east Atlantic in the July–September season 1979–2014. TS emerge from an area of 10°–15°N, 20°–30°W, south of Cape Verde islands, so time series of TS and satellite outgoing longwave radiation (OLR; Lee 2014) in the downstream area were regressed onto fields of OLR, 500-hPa winds, and CAPE over northeast Africa (upstream) to study interannual variability in JAS 1979–2014 (35 yr). Long-term trends over the twenty-first century were analyzed using CMIP5, ensemble-projected, 500-hPa geopotential height and surface air temperature fields with RCP6 scenario (Taylor et al. 2012).

3. Results

3.1. Temporal and regional characteristics

The AEW index during JAS 2009 (Figure 1b) reveals oscillations of ~6 days and a seasonal cycle that crests about 2 weeks later than other years. There is a large peak during the case study (26 August) that is preceded and followed by smaller peaks (19 and 31 August). The regional convection and circulation are described by Meteosat IR image on 25 August 2009 (Figure 1c) and MERRA 600-hPa winds and 850-hPa specific humidity (Figure 1d). Satellite cloud-top temperatures below 250°C were observed over the southern Red Sea in two thunderstorm clusters centered on 18°N, 39°E and 13°N, 42°E. Surface temperatures over the Arabian Peninsula and Sahara Desert along 22°N latitude exceeded 50°C. Midlevel easterly winds flowed in a narrow axis along 18°N (AEJ), generating cyclonic vorticity along the southern flank, especially over Sudan; 850-hPa specific humidity was high west of the Rift Valley due to the poleward channeling of moisture. Weather stations north of the AEJ reported temperature > 40°C and dewpoint < 10°C; to the south, the temperature and dewpoint were ~25°C. This was the situation during the initial convective outbreak; transient and downstream AEW features are covered later in section 3.4.

3.2. Red Sea convective outbreak 25 August 2009

Surface and marine conditions for the event are described by vegetation fraction, LHF, salinity, and SST in Figure 2. Naturally, the vegetation fraction is low except over the highest mountains of Ethiopia and Yemen. The contribution to LHF from these sources was substantial (Figure 2a). Similarly over the Red Sea, SST > 30°C yielded LHF > 150 W m⁻² in the north. The salinity field reflects a strong gradient from north to south (Figure 2b), as expected from the distribution of evaporation and rainwater flux. Surface ocean currents during the period were northward, despite the winds.

Low-level winds of 25 August 2009 (Figure 2c) reflect confluence of Arabian easterlies, Mediterranean northwesterlies, and African southwesterlies. Two rotors
were evident, infolding the winds southeastward in the Red Sea. The radiosonde profile at Abha (Figure 2d) reveals a moist unstable lapse rate ($-7^\circ$C km$^{-1}$, 700–500 hPa) and midlevel easterly wind jet (17 m s$^{-1}$ at 580 hPa).

3.3. Cross-section anomalies and back trajectories

Meridional vertical sections of anomalous meteorological features averaged 35°–45°E are illustrated in Figure 3. The zonal winds show a 10 m s$^{-1}$ anomalous
wind jet over Jeddah, Saudi Arabia (22°N), in the 700–500-hPa layer (Figure 3a). Surprisingly, the upper tropical easterly jet is weaker than usual in association with the Indian monsoon (Arndt et al. 2010). The meridional winds (Figure 3b) have an interleaving pattern dominated by anomalous surface and midlevel poleward flow.
Air temperature departures (Figure 3c) show an enhanced $-\delta T/\delta y$ in the 925–700-hPa layer supporting the negative zonal wind shear. The anomalous gradient between cool-south/warm-north is $-6^\circ C (800 km)^{-1}$. Moisture anomalies are positive below 700 hPa as expected (Figure 3d), especially in the zone 17$^\circ$–20$^\circ$N.

Taking a Lagrangian perspective, HYSPLIT back trajectories 48 h prior to the convective outbreak at the northern and southern end points are given in Figure 4. Vertical shear is evident. Inflow to the northern end point at 1000 m arrives from Sudan, while at 3000 m inflow varies from Red Sea and Arabian origin. At 5000 m, the inflow is all easterly as expected, and the vertical section shows a wave oscillation over the Rift Valley orography. Inflow lifts quite near the northern end point. Back trajectories to the southern end point are different. Inflow at 1000 m arrives from the northern Red Sea, whereas at 3000 m many back trajectories originate over Ethiopia and show recirculation. At 5000 m, the inflow skirts the southern Arabian coast with no appreciable wave oscillation. Hence, the Red Sea and Ethiopian highlands act as sources of inflow below 3000 m in this case.

### 3.4. Transient wave analysis 22–29 August 2009

Hovmöller plots of 6-hourly meteorological data and 3-hourly satellite rainfall averaged 8$^\circ$–20$^\circ$N (Figure 5) show westward movement of a disorganized group of AEW following the convective outbreak over the Red Sea. The speed of
propagation appears slower for the 600-hPa meridional wind and specific humidity $\sim 4.4 \text{ m s}^{-1}$. In contrast, the zonal wind minimum and rainfall propagate westward at $\sim 11.6 \text{ m s}^{-1}$. There is a surge of easterlies over the Red Sea from 24 to 27 August 2009. The meridional wind is dominated by northerlies that translate westward in front of the AEW, followed by sustained southerlies over Sudan ($\pm 32^\circ$E) behind the AEW. The moisture field reflects a dry-east, moist-west pattern divided by the Ethiopian highlands. Satellite rainfall (masked outside the AEW) reveals disorganized propagation following the convective outbreak. Precursor convection reaches 10$^\circ$E by 28 August 2009, while a secondary system that spawns Hurricane Fred reaches 10$^\circ$E 2 days later. Diurnal forcing and variable thermodynamic and kinematic interactions modulate thunderstorm clusters within the AEW envelope. Here and in other cases, AEW appear as packets of two to three waves, with the upstream wave dispersing energy to the trailing waves (Diaz and Aiyer 2013). This particular case led to floods in Ouagadougou that displaced

Figure 5. Hovmöller plots averaged 8$^\circ$–20$^\circ$N of MERRA (a) 600-hPa $U$ wind, (b) $V$ wind, (c) specific humidity, and (d) satellite rainfall. (a) is the minimum over latitude, (c) has a color bar inverted, and (d) is masked beyond one wavelength; arrow points to Red Sea convection. Dashed lines highlight coherent features in AEW propagation. Mean topographic profile given; data are $2 \times 2$ smoothed.
150,000 people following 263 mm of rainfall on 1 September 2009 and the failure of the Loumbila reservoir in the city center (Arndt et al. 2010; Lasailly-Jacob and Peyraut 2015).

3.5. A midlatitude trigger

For the AEJ to accelerate over the Red Sea, the anticyclone over the Arabian Peninsula should spin up. But what drives that process? Earlier studies (Vizy and Cook 2009; Chauvin et al. 2010; Leroux et al. 2011; Roehrig et al. 2011) have found AEW excitation by midlatitude troughs. In this case, a cutoff low developed over the Caspian region of southern Russia from 23 to 25 August 2009 (Figure 6a). The subtropical jet was diffluent (weak) over the Mediterranean and confluent...
(strong) from Turkey to Iran between a low-north and high-south pair in the 500-hPa wind field. Behind the trough, temperatures were cool for August ($< -3^\circ$C). Weather stations in the Caucasian area such as Astrakhan, Russia, reported 14$^\circ$C and northwest winds $> 10$ m s$^{-1}$; 850-hPa air temperatures (Figure 6b) show that cool air pushed southward into Turkey, while the air mass over the Persian Gulf and Arabian Peninsula remained warm ($> +3^\circ$C anomaly). Hence, the surge of easterlies over the Red Sea was partially triggered by a midlatitude perturbation. Anticyclonic vorticity on the equatorward flank of the jet streak generates a sinking motion that reinforces the surface heat low over the Arabian Peninsula, consequently extending the midlevel Arabian Ridge and associated AEJ eastward.

### 3.6. Statistical patterns and long-term variability

The environmental conditions modulating Red Sea convection are studied in this section by statistical analysis of area-averaged time series. The annual cycle of CAPE and U600 (Figure 7a) reveal an April–May peak in thermodynamic energy
prior to the onset of easterly shear. Both reach the annual maximum by the end of August, followed by a rapid decline of thermodynamic energy. CAPE exhibits a bimodal distribution and follows terrestrial heating, while U600 is delayed similarly to SST. Although both annual cycles peak in the July–September season, CAPE is weakly correlated with U600 ($r = -0.38$) at the daily time scale. The scatterplot is incoherent (Figure 7b) because the Red Sea is surrounded by dry subsiding air masses, and midlevel shear from the AEJ ($\partial U/\partial y$) does not guarantee moist inflow from central Africa ($V\partial q/\partial y$). On the other hand, 600-hPa zonal winds are closely linked with the downstream formation of AEW (Figure 7c; $r = -0.67$).

Tropical storms in JAS 1979–2014 emerge from an area south of the Cape Verde islands (Figure 8a) where mean OLR is $<230 \text{ W m}^{-2}$. Shipping density in the same period is high along the coast of Africa and between Europe and the United States. Although most TS that intensify off Africa tend to recurve, they impact transbasin shipping. Indices of downstream TS and OLR 10°–15°N, 20°–30°W were regressed upstream to study interannual variability. It should be noted that TS and OLR are weakly correlated ($r = -0.21$; JAS 1979–2014) because TS in the east Atlantic are absent ~26% of the time. The OLR index versus OLR field regression (Figure 8b) shows a one-to-one relationship that extends to the Red Sea along 15°N. The axis tilts across the Sahel, consistent with the AEJ skirting the anticyclonic ridge (along the 4440-m geopotential). The TS index versus 500-hPa zonal wind regression (Figure 8c) reveals a zone of negative values over the Red Sea at 19°N that spreads across Sudan along 15°N. TS emergence in the east Atlantic is thus linked with an eastward extension of the AEJ. The regression of TS onto upstream CAPE and OLR gave incoherent results. Hence, kinematic modulation of east Atlantic TS by the AEJ prevails at interannual time scales. Given that relationship, CMIP5 ensemble trends in the 500-hPa geopotential height and surface air temperature were analyzed over the twenty-first century (Figure 8d). The 25-model average under RCP6 scenario predicts an intensifying Arabian Ridge (>0.5 m yr$^{-1}$), suggesting extension of the AEJ over the northern Rift Valley. Surface air temperatures are predicted to increase by $>+0.03^\circ\text{C yr}^{-1}$, thus strengthening the heat low in agreement with Cook and Vizy (2015).

4. Conclusions

This study analyzed a convective outbreak over the Red Sea on 25 August 2009. A companion paper, which formulated an African easterly wave (AEW) index, found this case to be top ranked (M. R. Jury 2016, unpublished manuscript). An easterly wind jet at 580 hPa of 17 m s$^{-1}$ was observed at 18°N, 43°E, supported by anomalous heating gradients in the boundary layer. The Rift Valley mountains induced a vertical oscillation and cyclonic perturbation. Two thunderstorm clusters formed over the southern Red Sea, following moist inflow from the Ethiopian highlands and northern Red Sea. The AEW gradually intensified over the Sahel into a hurricane in the east Atlantic. Anticyclonic vorticity in the Arabian Ridge was enhanced by an intrusion of the northern subtropical jet. This happened farther east than the Mediterranean intrusions described in Vizy and Cook (2009). Statistical analyses suggest that AEW transiting Sudan and tropical storms entering the Atlantic are more influenced by upstream kinematic shear than thermodynamic energy. Climate change could bring an extension of the AEJ into the Arabian

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Figure 8. July–September 1979–2014: (a) the mean TS density (orange shaded), mean OLR (contour), and index box. High shipping density gray with schematic TS track; (b) regression of OLR index downstream with OLR field upstream with the 4440-m geopotential (thick) contour; and (c) regression of TS index downstream with 500-hPa zonal wind upstream (inverted color bar). (d) CMIP5 ensemble trend of 500-hPa geopotential height (shaded) and surface air temperature (contour > 0.03°C yr⁻¹) in JAS 1980–2100 with RCP6 scenario: the Arabian Ridge.
Peninsula and more AEW formation over the northeast Africa in agreement with Skinner and Diffenbaugh (2014).

The case study and statistical analysis has revealed factors contributing to AEW formation over northeast Africa. These include 1) AEJ entrance shifted eastward by midlatitude interaction, 2) convergence of northerly winds in the Red Sea, 3) an unusually deep layer of moisture, and 4) downstream intensification.

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