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Role of African Easterly Waves and embedded vorticity features in genesis of tropical cyclones over the Eastern Tropical Atlantic

Introduction:

Atlantic tropical cyclone activity exhibits large variability, which often has been linked to changes in the large-scale environment such as variation in North Atlantic SSTs (Goldenberg et al. 2001; Mann and Emanuel 2006; Landsea et al. 1998), various phases of ENSO (Goldenberg and Shapiro 1996), and tropospheric deep wind shear (Thorncroft and Pytharoulis 2001; Aiyyer and Thorncroft 2005). The timescales of the variability mainly considered a range from year-to-year to multi-decadal (variability in both number, and intensity). While the focus for many of these and numerous earlier studies has been the variability of tropical storms, hurricanes and/or the large scale environment, the variability of the precursor disturbances for these storms has not been discussed as much.

The weather and climate of West Africa has a strong impact on Atlantic tropical cyclone activity. At daily timescales, most Atlantic tropical cyclones form in association with African easterly waves (AEWs) that originate over the African continent (e.g. Avila and Pasch 1992, and Pasch and Avila 1994). At seasonal-to-decadal timescales there is a well known positive correlation between West African rainfall and Atlantic tropical cyclone activity (e.g. Landsea and Gray 1992). Given the known importance of AEWs for downstream tropical cyclone activity on daily and possibly longer timescales, it is important to have a good knowledge and understanding of the nature and variability of AEWs as they leave the West African coast.

AEWs are synoptic scale systems with a preferred wavelength in the 2000-4000km range, and also possess sub-synoptic[1] scale structures that are associated with non-linear developments (e.g. Thorncroft and Hoskins 1994b), potential vorticity anomalies generated by convection in Mesoscale Convective Systems (MCSs, e.g. Schubert et al. 1991) or a combination of these. We also recognize however that other mechanisms may also be operating to encourage tropical cyclogenesis just downstream of West Africa (such as for example wave-accumulation, Webster and Chang 1988). Our knowledge of how waves, the African Easterly Jet (AEJ) and interact with each other and their large scale environment, though subject of intense research, is still not sufficiently well known and its variability is so far not well documented. Similarly, little is known about how the waves are impacted by, or feed back into the climate system.

Thorncroft and Hodges (2001; TH01 from hereon) presented an analysis of the coherent vorticity structures associated with AEWs over West Africa and the tropical Atlantic based on data that included the ECMWF ERA15 reanalysis (Gibson et al. 1997) extended with 5 years of operational analysis.

[1] By sub-synoptic we mean smaller than the wavelength of an AEW; here we are referring to coherent vorticity structures embedded within AEWs.

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Consistent with other studies (e.g. Reed et al. 1988; and Lau and Lau 1990) their study indicated the existence of two dominant storm tracks. One was found south of about 15ºN in the rainy zone, with a track density maximum just offshore of the West African coast and a clear extension across the Atlantic. They suggested that the systems provided by the southern storm track continue downstream along the oceanic storm track, whereas features coming off the West African Coast from the northern storm track rarely propagate far out over the tropical Atlantic Ocean. TH01 showed that the southern storm track exhibits marked interannual variability and suggested that this variability may have some association with tropical cyclone activity. For the second half of their time-series (years 1985 to 1998) the numbers of coherent vortices and named Atlantic tropical cyclones appeared to change in concert. However, firm conclusions could not be made based on this analysis due to the short period of 14 years. Hopsch et al. (2007) have confirmed that the southern track provides the majority of vorticity features that ultimately will propagate into the MDR and thus may play an important part in further tropical cyclogenesis downstream over the tropical Atlantic.

In that paper Hopsch et al. (2007) have shown that there exists a large variability on multi-decadal to monthly timescales in activity of African Easterly Waves (AEWs) and their embedded sub-synoptic vorticity features that propagate off the West African coast and over the tropical Atlantic. By using statistics maps of track- and genesis densities of coherent vorticity features on the 850hPa level in the ERA40 dataset, the Guinean Highland region was identified as the most important source region for vorticity tracks that can later be found over the mid-ocean inside the Main Development Region (MDR), where most Atlantic tropical storms form (Goldenberg and Shapiro 1996). A second, but weaker genesis maximum area was found over the tropical Atlantic at around 35-40ºW. One surprising result of the study was that the interannual variability of these coherent vorticity tracks were not well correlated with West African rainfall, or tropical storms. However, a significant positive correlation was found between the interannual variation of the 2-6 day filtered meridional wind (a synoptic-scale measure of AEW activity), and Atlantic tropical cyclone activity.

Data and Methodology:

Data from the reanalysis project, ERA40, from ECMWF is used (Uppala, et al., 2005). The low-resolution dataset (2.5° grid resolution) has been used for vorticity tracking (following TH01) and to obtain the large-scale measure of AEWs. The high-resolution dataset (1.125° grid resolution) is used for the composite study. Other datasets used include the NHC Best-track dataset for genesis points of TCs, the CLAUS Brightness temperature data (0.5° resolution), Hulme precipitation data (2.5°lat, 3.75° lon; Hulme 1992), and Hadley SSTs (1° grid resolution).

To quantify the synoptic scale measure of AEWs we calculated the 2-6day filtered winds on several pressure levels. By calculating the variance for these on various timescales (e.g. monthly, seasonal averages), a better estimate of the variability for areas of enhanced AEW activity can be obtained. A slightly smoothed version of AEWs was further generated by calculating the streamfunction of the 2-6day filtered wind.

For the storm-relative composites, data from 1979 onwards to 2001 is used. The reason being that this coincides with operational satellite observation coverage. The reanalysis should therefore be less reliant on the model and its physics parameterizations during this time period. Likewise, since I am using NHC best-track data for compositing the genesis points of tropical storms, the ambiguity in defining the "exact" position of genesis should be reasonably minimized.

Composite study:

Preliminary results indicate that the July through October synoptic scale measure of the AEWs over West Africa, as given by the variance of the 2-6 day filtered meridional wind at 850hPa, is not exhibiting the pronounced low-frequency variability as was observed for the storm tracks over the southern track region at the same vertical level, see Fig. 1. Considering the absence of the low-frequency variation, the 2-6day variance time series reminds us more of the Northern storm track from Hopsch et al. 2007 (their Fig.11). The figure shows the existence of year-to-year variability in both large-scale AEW-measure (2-6day V variance), taken here over the Sahel (Sahel = 15ºW -10ºE, 10ºN-17.5ºN) and the number of precursors from the storm tracks in the Guinea Highland area on 850hPa. For comparison, the figure also shows July through October variability of precipitation over the Sahel using Hulme precipitation data and the number of Tropical storms, Hurricanes and Major Hurricanes in the MDR. The precursors show extreme maximum and minimum years to occur in 1988 and 1989. Curiously, these two years also showed contrasting behavior with regard to differences in regions of preferred tropical cyclogenesis within the MDR, where more storms formed directly off shore off West Africa in 1989, whereas the storms formed further west during 1988. In contrast, these two years don't exhibit any particular extremes in laerge-scale AEW activity (neither max nor min) over the Sahel, which suggests that indeed the sub-synoptic structures and possible differences in AEW structure might indeed have quite an important role in this.

In order to help answer how the large-scale AEW variability relates to Atlantic tropical cyclone activity we therefore generated storm-relative composites that focus on these two different genesis areas. Figure 2 shows the obtained West-East cross sections of storm-relative composites for the genesis points of named Atlantic tropical cyclones from 1979-2001 in the eastern tropical Atlantic from NHC best-track data. Figure 2a shows the cross section for all named storms that formed over the mid-Atlantic area (between 30°-45°W, 7° -20°N) and has a sample size of 32 storms. The cross section stretches from 60°-10°W along 12.5°N. Figure 2b stretches from 50°W -0° along12°N and shows the cross section composite for all named storms that formed further east in close proximity to the West African coast (between 15°-30°W, 7°-20°N). The sample size of that box consists also of 32 storms.

The storm-relative composite for the storms forming in close proximity to West Africa shows a warm core structure with enhanced relative vorticity at low levels. The strongest updrafts are found at around 850 to 700hPa in North-Northeasterly flow. In comparison, the composite for the storms that form further west show a less well-defined low-level maximum of relative vorticity. The strongest updrafts are found at mid-to upper levels at around 500-300hPa, overlying a layer of Southeast-Easterly flow at lower levels.

Figure 3 shows horizontal maps of the storm-relative composite of PV, and streamfunction of the 2-6day filtered wind at 600hPa, and relative vorticity at 850hPa for the storms forming in the mid-Atlantic areas (a) and in close proximity to the West African coast (b). Consistent with the cross-sections, one can note that the relative vorticity maximum is found in the South-Westerlies for mid-Atlantic development, and in North-Easterlies for the coastal developers. This might be expected, as most relative vorticity tracks in the ERA40 dataset show a temporary spin-up as the features propagate off the West African coast. The large scale measure of the AEWs-composite as presented by the streamfunction at 600hPa also shows interesting differences. Figure 3a indicates that the developing tropical system is embedded in a barotropic growth configuration-pattern of the streamfunction of the 2-6 day filtered wind. In comparison, Fig. 3b indicates that the horizontal extent of the large-scale AEWs is confined to the Guinea Highland region and the southern storm track area, which is a region where most low-level relative vorticity tracks (i.e. possible precursors for tropical cyclones) are generated (Hopsch et al. 2007).

Final remarks:

It has long been known that AEWs often serve as precursors for Atlantic tropical cyclones in predominantly the MDR. While it is often assumed that the year-to-year number of AEWs is fairly constant, our work has nevertheless shown that there exists a rich variability in the nature and characteristics of these weather systems on multiple space- and timescales – from decadal and interannual to day-to-day variations.

We use the ECMWF ERA40 dataset for the analysis of a storm-relative composite analysis for developing storm systems. Our investigation here focuses on important differences in the horizontal and vertical structure of the precursors over West Africa, and how this affects the further outcome towards cyclogenesis. In particular, we analyzed the characteristics of the large-scale and sub-synoptic scale measures of AEWs for two tropical cyclone genesis regions in the Eastern tropical Atlantic. It is found that the storm-relative composite for tropical cyclones that form in close proximity to the West African coast show a well developed warm-core structure with a strong core of low-level relative vorticity. The upward vertical motion is strongest in the lower half of the troposphere with the AEW trough axis just to the east of the high-vorticity core. The developing disturbance is found in north-easterlies at the leading edge of a large-scale AEW trough, which furthermore is most prominent over the southern storm track area over West Africa (10°-15°N). In comparison, the composite for the tropical cyclones that form further west over the tropical mid-Atlantic region indicates a slightly weaker low-level relative vorticity maximum at low levels, and the strongest ascent is found at higher altitudes. The area of local vorticity maxima shifts to the east relative to the large-scale AEW and is now found in south-westerly flow. The structure of the large-scale AEW also indicates a barotropic growth configuration.

In currently ongoing and future work we will continue to analyze the various characteristics for these systems prior to the day of tropical cyclogenesis (i.e. before their appearance in the NHC best track dataset) and of the characteristics for non-developing systems.

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Figures

Figure 1: The figure shows the existence of year-to-year variability in both number of precursors (ST track on 850hPa, as used in first paper) and the large-scale AEW-measure (2-6day V variance), taken here over the Sahel (Sahel =15°W -10°E, 10°N-17.5°N). For comparison, the figure also shows July through October variability of precipitation over the Sahel using Hulme PPN data and the number of Tropical storms, Hurricanes and Major Hurricanes in the MDR respectively.

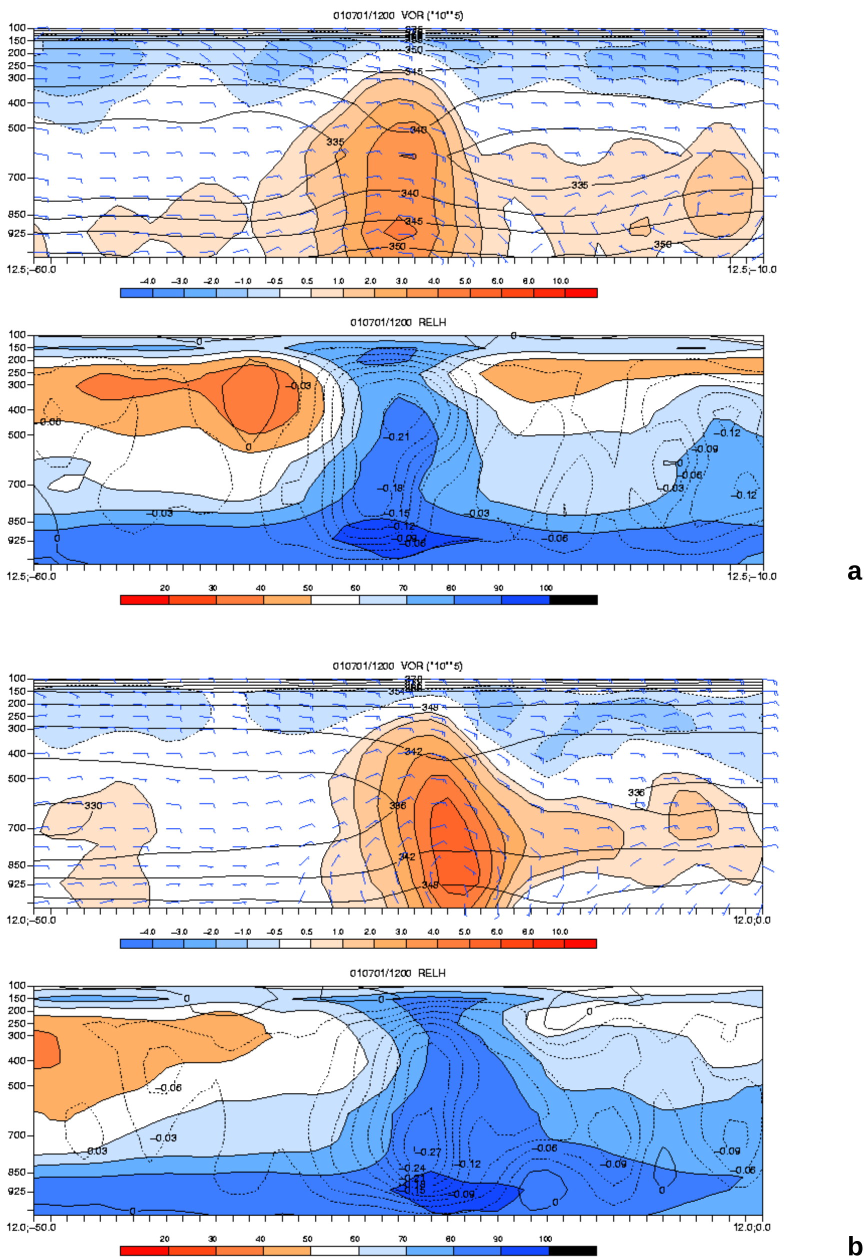

Figure 2: Cross sections of storm-relative composites for the genesis points of named Atlantic tropical cyclones from 1979-2001 in two genesis areas in the eastern tropical Atlantic from NHC best-track data. The plots show two panels, with relative vorticity (x10^5 s^{-1}, shading), theta-e (K, contours) and horizontal winds (kt, barbs) in the top panel, and relative humidity (%, shading), vertical velocity (hPa/s, contours) in the bottom panel.

a) cross section for all named storms that formed over the mid-Atlantic area (30°-45°W, 7°-20°N). Sample size: 32 storms.
b) cross section for all named storms that formed further east in close proximity to the West African coast (18°-30°W, 7°-20°N). Sample size: 32 storms.

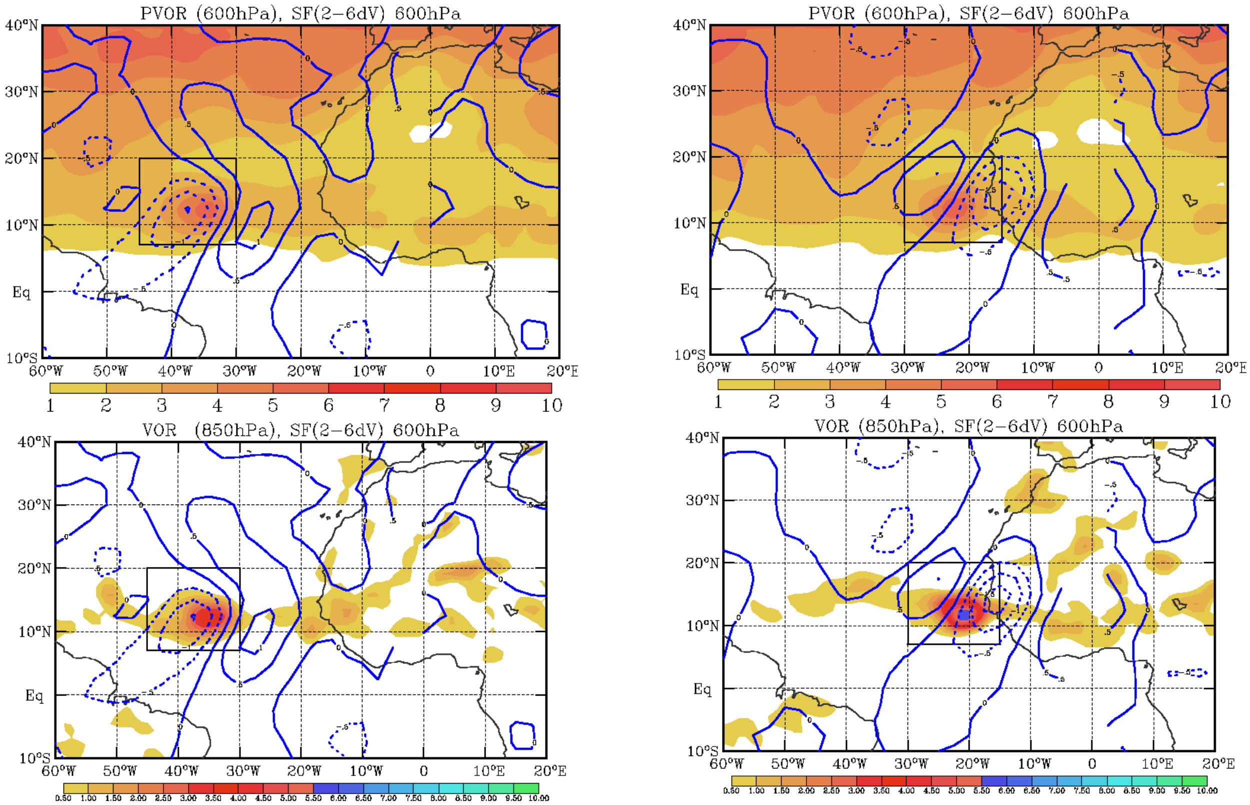

Figure 3: Storm relative composite maps for the genesis points of named Atlantic tropical cyclones from 1979-2001 in two genesis areas in the eastern tropical Atlantic from NHC best-track data. The top panels show the obtained 600hPa Potential vorticity ($x10^{7}$ s^{-1}, shading) and composite streamfunction of the 2-6day filtered wind on 600hPa. The bottom panels show the relative vorticity ($x10^{6}$ s^{-1}, shading) and composite streamfunction of the 2-6day filtered wind on 600hPa. The left hand panels (a) show the storm relative composite of the mid-Atlantic storms (30°-45°W, 7°-20°N, as indicated by the black, solid box), and the right hand panels (b) show the storm relative composite of the storms that formed close to West Africa (18°-30°W, 7°-20°N, as indicated by the black, solid box).