9A.3 VARIABILITY IN AFRICAN EASTERLY WAVES AND INTERACTIONS WITH THE ENVIRONMENT FOR TROPICAL CYCLOGENESIS OVER THE EASTERN ATLANTIC

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1. INTRODUCTION

The relationship between tropical cyclogenesis over the Atlantic main development region (MDR) and precursor westward propagating disturbances, typically originating from Africa, has been well documented (Reed *et al.* 1977; Landsea 1993, Thorncroft & Hodges 2001). Many papers have focussed on the mean structure and evolution of these African easterly waves (AEWs), documenting their relationship to the African easterly jet (AEJ) and convection over Africa. More recently focus has switched to differences in the waves and why only ~14% of waves trigger cyclogenesis over the MDR (e.g. Hopsch et al. 2010, Agudelo et al. 2011).

Hopsch *et al.* (2010) was one of the earlier papers to analyse the difference between waves that later developed (developing waves; DW) and those that did not (non-developing waves; NDW). The authors showed that on average, developing waves have different structures to non-developing waves over the African continent. As the waves left the West African coast, DW's were associated with higher low-level vorticity, and a transition to a more warm core structure at low-levels. NDW's were associated with a dry anomaly ahead of the wave at ~400hPa, though the causality and relationship was not explained, the signal was evident in composites of all NDWs and a separate composite of 33 NDWs with the highest low-level vorticity. DWs were also associated with a stronger cold core structure 2 days prior to reaching the coast and showed more convective activity in the 5 days around their coastal transition.

Agudelo *et al.* (2011) provided a comprehensive study of the variability and evolution of AEWs, with regard to developing and non-developing waves. Through statistical analysis the authors analysed the relevance of the eulerian environmental conditions the waves were propagating into as well as the lagrangian characteristics of the waves. This analysis confirmed the relationship between the wave amplitude as it crossed the coastline, with more convectively active waves having a more well defined structure and thus more likely for development. The environmental conditions played a strong seasonal restriction on genesis events, though were shown to be generally conducive to genesis for July through September. The most useful predictors in determining whether a wave would develop were column integrated heating, specific humidity and vertical velocity, all representing the convective activity in the wave. Leppert *et al.* (2013) came to similar conclusions focussing on the IR and lightning activity within the wave troughs. They showed that the area of moderate to deep convection was more important, than the intensity. DWs were associated with troughs with high fractional coverage of cloud top temperatures ≤240K. Peng *et al.* (2012) found similar results from tracking filtered 850hPa Relative Vorticity signals across the Atlantic and East Pacific. Developing systems had generally higher humidity 3 days prior to genesis, with higher SSTs, increased convective activity and weak shear the day prior to genesis. The large composite studies such as those above, typically agree on conditions leading up to genesis. These results also agree with the larger scale conditions as included in more general tropical cyclogenesis potential indices (e.g. DeMaria 2002, Carmago *et al.* 2007).

These papers have shown that developing waves have distinct characteristics prior to development. However as included in Hopsch *et al.* (2010) and Agudelo *et al.* (2011) there is great variability in wave structures. It is therefore possible to observe waves and determine whether they have the characteristics for development downstream, however there are still a large number of non-developing waves that possess these characteristics.

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This research will therefore focus on those waves that left the coast with mesoscale characteristics for development but were unable to further intensify. Analysis will focus on the environmental differences in the days after the troughs leave the coast of Africa.

Section 2 will present the datasets and methodology of the research including detail about a wave tracking algorithm. Section 3 will then present distributions of the waves characteristics over the West African coast highlight the variability in both developing and non-developing waves. This is used to construct a statistical model to objectively diagnose the waves structure as it leaves the coast. Section 4 will present analysis of those waves determined to be favourable for development but did not experience any significant intensification. The presentation will feature analysis from cases introduced in this section.

2. METHODOLOGY.

Throughout this research the climate forecast system reanalysis data have been used, version 1 spans 1979-2011 with a change to version 2 in early 2011 (Saha *et al.* 2010; Saha *et al.* 2011). In this research a contiguous dataset has been assumed, while there are minor differences in the two versions it is assumed to be negligible for the purposes used here.

Anomalies presented in this research are calculated from a 6-hour climatology to ensure the results are not artefacts of the diurnal cycle. Composites presented here have been shifted so that all troughs are aligned with the mean trough location at that time. For the short lag times included here this does not make a significant difference in the results.

2.1 Wave Tracking

AEWs were tracked using a methodology similar to Agudelo *et al.* (2011) and Bain *et al.* (2013). In this research curvature vorticity at 700hPa was used with a 5:12.5°N hovmöller to track waves through time and longitude. Once a track was determined for each wave, the latitude and longitude were refined to the nearest maxima in curvature vorticity within 250km of the initial estimate. These tracks were matched to disturbances listed in the HURDAT2 dataset, to determine developing and non-developing waves. Day 0 for waves is determined by the time of transition over the West African coast, developing waves were restricted to those that are at least TD before reaching 40°W. This was an arbitrary cut off, however there is a relative minima in this region for genesis cases from AEWs. This subset are effectively Cape Verde storms, with genesis typically occurring within 2 days of leaving the coast.

3. DEVELOPMENT OF AEW DIAGNOSTIC

Based on previous literature reviewed in section 1, numerous variables for each wave were analysed to determine where distributions between developing and non-developing waves had the the greatest separation.

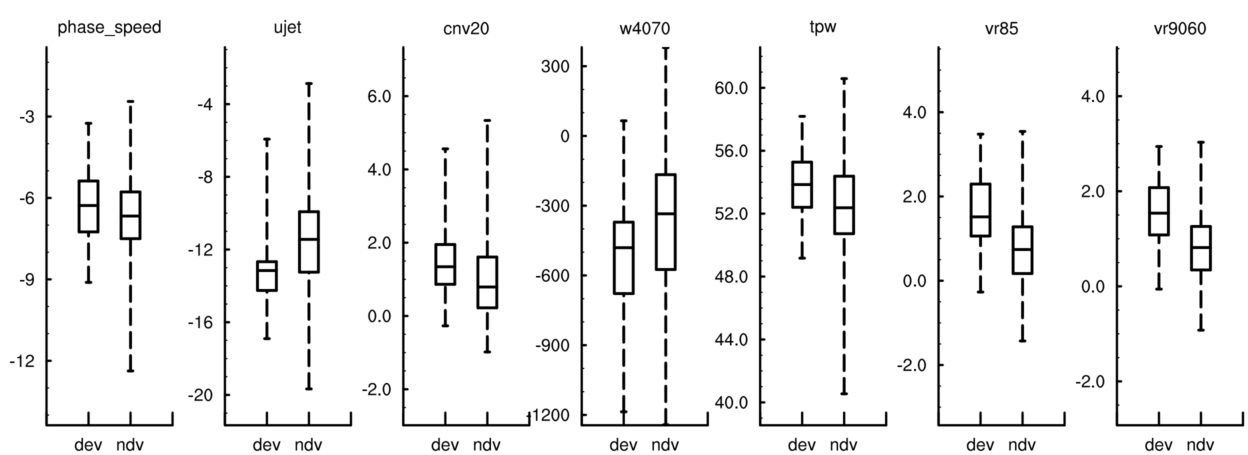

Fig 1. Distribution of AEW characteristics, from left to right; phase speed of waves [ms^{-1}], area averaged (5:15N, 20:10W) zonal wind over 700-600hPa layer, 200hPa convergence [10^{-6} s^{-1}], 700-400hPa layer average omega [Pa hr^{-1}], total precipitable water [mm], 850hPa relative vorticity [10^{-5} s^{-1}], 900-600 layer averaged vorticity [10^{-5} s^{-1}]. The latter 5 variables were taken over an area average of 5:15N and 17.5:12.5W. This location was varied and not particularly significant.

Figure 1 shows the distribution of a number of these variables, these distributions confirm the results in previous literature with developing waves typically having stronger low-level vorticity within the trough, coincident with stronger vertical velocities through the mid and lower level; indicative of convective activity. Phase speed alone is a poor determinant between developing and non-developing waves but when combined with other environmental variables in section 5 it became a significant variable. The metric of the AEJ (ujet) is picking up on a strengthening of the jet on the northern side of the trough (not shown here) and is in part a strengthening of the jet level vortex. This strengthening of the jet was also shown by Ross *et al (2009;2012)* in developing waves through "super-convective bursts", the daily lagged composites show that the trough vortex was not significantly stronger 24-hours before reaching the coast. This indicates that coastal convection is helping to strengthen the mesoscale vortex associated with the wave.

As no single variable does a particularly good job of distinguishing developing from non-developing waves, variables were combined through a linear binomial logistic regression model. This combines multiple characteristics of the wave and calculates a probability of the wave developing downstream. Initially only trough scale characteristics were used in the statistical model, multiple iterations were tested to find the combination of characteristics that returned the highest number of correctly diagnosed developing waves to lowest number of falsely diagnosed non-developing waves. The best combination found used 4 variables; mean zonal wind along the AEJ axis, relative vorticity averaged over 900-600hPa, vertical velocity averaged over 700-400hPa and total precipitable water in the wave trough. This model correctly diagnoses 55 of 62 developing waves with 152 non-developing waves also diagnosed as favourable for development. While this is

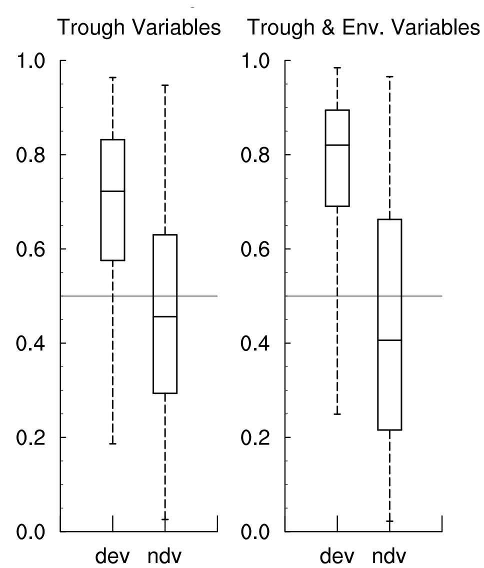

Figure 2. Distribution as in fig 1 for diagnostic of waves at the coast. a) statistical model based on trough scale characteristics (see section 3.), b) new model including precipitable ahead of the wave over the eastern atlantic (see section 5.).

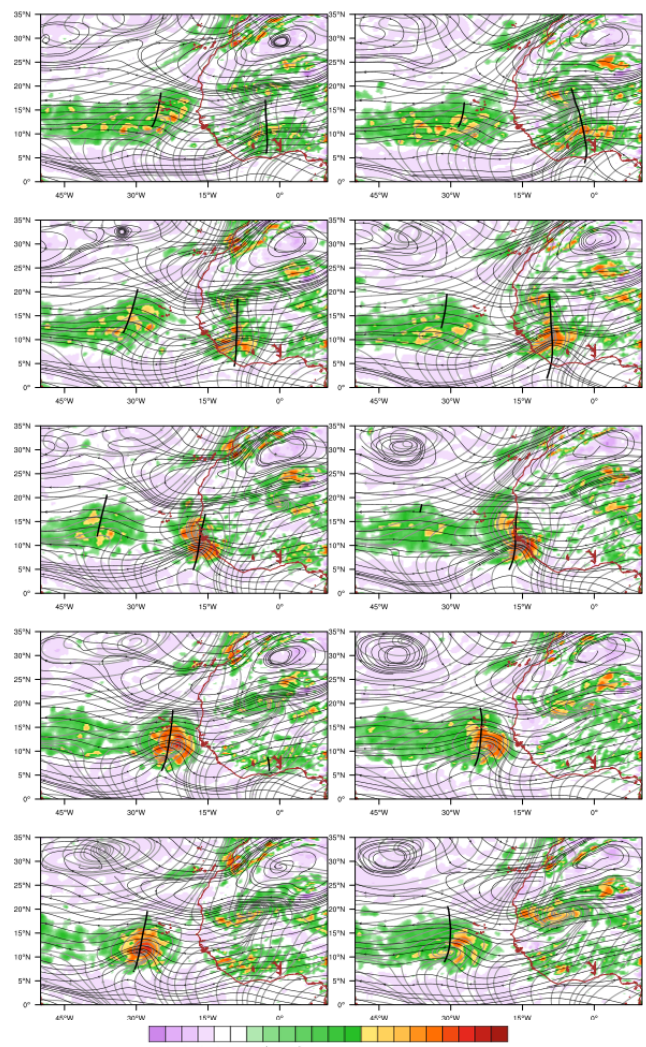

Figure 3. 850hPa Relative Vorticity (10^{-6} s^{-1}), 700hPa and 925h-Pa streamlines, black and grey respectively. From top to bottom shows daily lags from day -2 to day +2 of wave passage of the coastline. Left column shows 55 most favourable developing waves and right column 55 most favourable non-developing waves.

not a skilful prognostic tool it has provided a method to quantitively characterise waves based on a combination of parameters.

4. COMPOSITE ANALYSIS OF AEWS

Waves diagnosed with 50% or greater probability for development downstream are categorised as favourable for development. Here the top 55 developing and non-developing waves are subset for comparison. Analysis of the low-level flow shows little difference over land preceding coastal transition fig 3. Both the developing waves (fig 3:left column) and the non-developing waves (fig 3:right column) show strong low-level vorticity as the wave transitions over the coastal region. Both composites also show a weak trough preceding the passage of the composite favourable trough. At day 0 the favourable troughs are seen to be dynamically similar in the lower level flow with both composites matching the characteristics of developing waves.

Analysis of the environmental low-level thermodynamics of the favourable developing waves reveals an area to the north-northwest of the trough of moist air (fig 4). Though not shown here this moisture anomaly is significant to 99%. This region of moisture appears coincident with the weak trough preceding the developing trough. The moisture anomaly propagates with the weak trough from the African coast in the days preceding the developing trough passage. The wave relative streamlines overlaid on figure 4 show relative westerly flow in these low-levels through the region ahead of the developing system. This indicates that the preceding trough is preconditioning the environment and low-level flow into the developing waves. It is

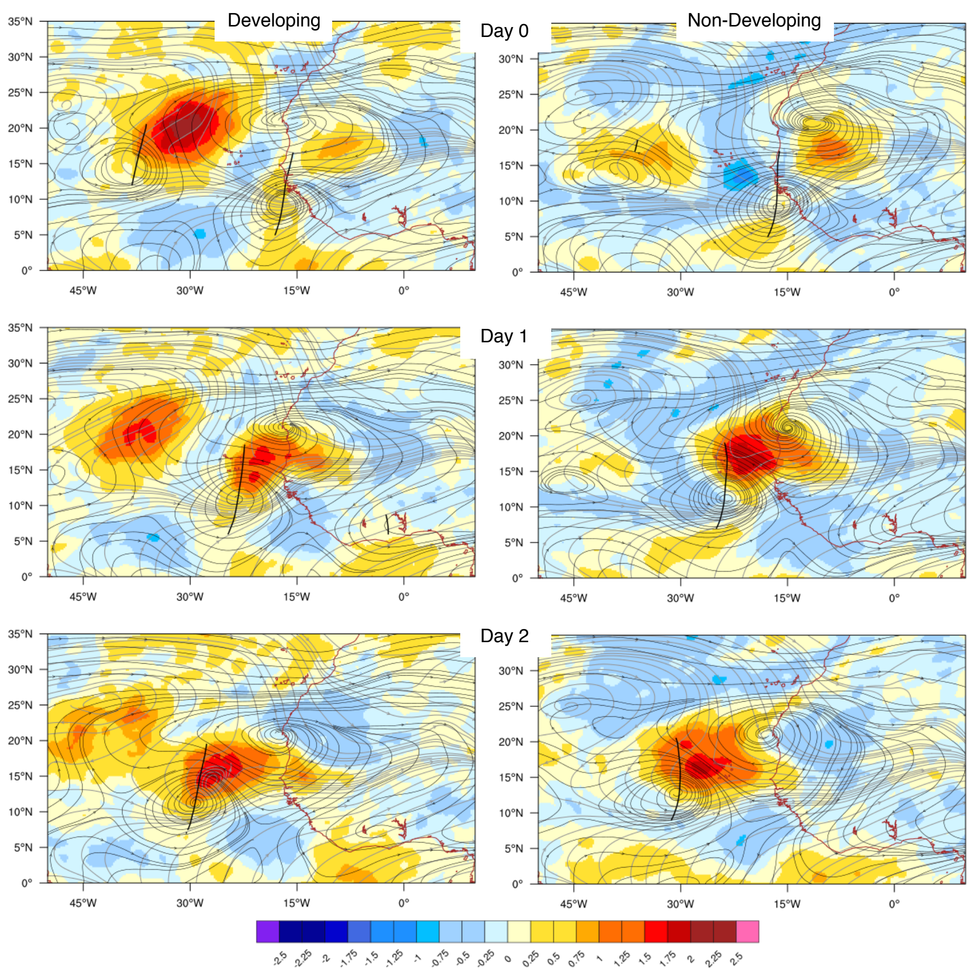

Fig 4: As Fig 3 but 850hPa specific humidity (g/kg) shaded for Days 0 to +2. Streamlines now show storm relative flow.

therefore suggested that the relative westerly flow through the moist region ahead of the wave helps to feed moisture into the low-levels of the developing trough. By day+2 the developing trough has a closed circulation indicating that as development continues the storm then begins to protect it self from the environment (e.g. Dunkerton *et al.* 2009) but in those first 2 days of life cycle over the Eastern Atlantic the low-levels were open to the environment ahead of the wave.

When the moisture over the Eastern Atlantic ahead of the wave is considered in the statistical model the skill of the model improves with greater number of correctly diagnosed developing waves and a reduced number of false alarms. This is shown in figure 3b, 75% of developing waves are now diagnosed as more favourable than 75% of non-developing waves.

There are still a large number of favourable non-developing waves and research is continuing to refine the environmental and convective scale differences between these favourable non-developing and developing waves.

4.1 Developing Wave Cases

The low-level relative westerly flow has been confirmed with trajectory analysis in two developing case studies, these will be presented in detail in the presentation. The genesis of Hurricane Ike 2008 showed a weak trough leave the coast 3 days prior to the pre-Ike trough. This early trough transported high humidities across the Eastern Atlantic. Trajectory analysis using the HYSPLIT model shows that in the first 2 days of the pre-Ike trough being over the Eastern Atlantic the low-level flow was coming from the moist anomaly to the west-north-west of the wave.

Hurricane Nadine (2012) showed a similar evolution to that of Ike (2008). Preceding the developing trough a weak moist trough preconditioned the Eastern Atlantic. As the pre-Nadine trough left the coast, low-level flow was in part sourced through the moist region ahead of the wave, favouring convection and development of the low-level vortex. Figure 5 (left) shows the relative low-level flow and anomalously high low-level humidity to the west of the coastal transitioning trough.

4.2 Non-Developing Cases

The diagnostic model and composite analysis has shown that developing waves are commonly associated with a moist anomaly ahead of the wave. The composite of favourable non-developing waves does not however show the converse. However it could be assumed that if the wave relative flow is similar, a dry anomaly ahead of the wave would have a detrimental impact.

To assess this, a brief case study from 2013 will analyse the impact of a dry low-level environment ahead of a favourable wave (figure 5-right). The trough was briefly listed as an invest as it transitioned to the Eastern Atlantic but organised convection struggled to

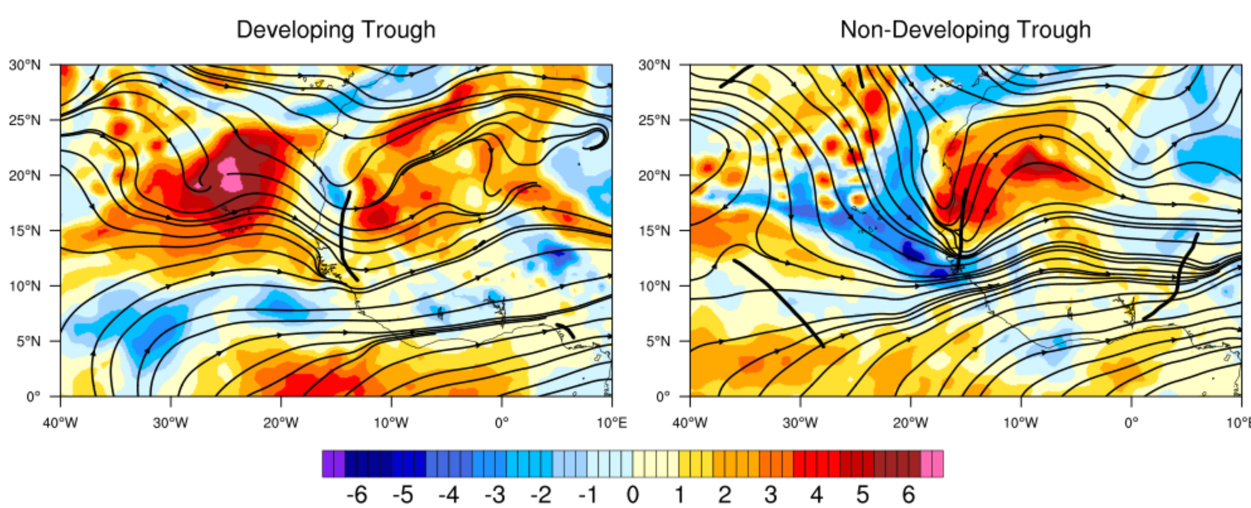

Figure 5: 850hPa anomalous specific humidity [g/kg], 925hPa storm relative streamlines, thick black contours are objective trough lines. left: pre-Nadine Trough. right: non-developing trough.

persist for more than ~18 hours after leaving the coast. The low-level vortex then dissipated within ~3 days. Trajectory analysis from this case again shows low-level inflow from the north-west region of the trough before the low-level vortex has formed a closed circulation. While the trajectories do show a moistening of the inflow, this influx of drier air is deemed a lot less favourable compared to the same flow transporting moist air into the system.

5. CONCLUSIONS

Using trough scale characteristics in the reanalysis dataset, a diagnostic for how favourable a wave is for genesis has been defined. Initial analysis of these favourable waves reveals a significant importance of the low-level environment ahead of the trough. It is suggested that due to the wave relative flow the low-levels in this region are effectively westerly and thus the environment to the west-north-west of the trough play an important role in conditioning the low-levels for the trough. The low-levels are on average initially open to environmental flow for the first 2 days after leaving the coast, as the low-level vortex strengthens a closed circulation then develops.

The presentation will include further analysis of variability in these favourable developing and non-developing waves. Trajectories will analyse the relative flow into waves in the first days of life over the Eastern Atlantic and the importance of the surrounding environment.

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