A dynamically-based method for forecasting tropical cyclogenesis location in the Atlantic sector using global model products

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[1] A real-time forecast method is developed for prediction of the tropical cyclogenesis location over the Atlantic using global model operational products. The method is based on the marsupial theory for tropical cyclogenesis proposed in a recent observational study. A moisture front is usually found ahead of the precursor wave trough, which separates the relatively dry air outside of the wave pouch (a region of closed circulation) from the relatively moist air inside the wave pouch. The propagation speed of the pouch can be determined by tracking the propagation of this moisture front, and the intersection of the critical surface and the trough axis pinpoints the predicted genesis location. Using the global model operational products the genesis location can be predicted up to three days in advance with an error less than 200 km, which can provide useful guidance for forecasters and flight planning. **Citation:** Wang, Z., M. T. Montgomery, and T. J. Dunkerton (2009), A dynamically-based method for forecasting tropical cyclogenesis location in the Atlantic sector using global model products, *Geophys. Res. Lett.*, *36*, L03801, doi:10.1029/2008GL035586.

1. Introduction

[2] Tropical cyclogenesis has been a popular atmospheric science research topic in the past few decades, but it remains the least understood phase of the tropical cyclone life cycle [*Emanuel*, 2005]. There are some well-accepted large-scale conditions for tropical cyclone formation, which include low-level cyclonic disturbances, warm SST, weak vertical shear, and moist unstable air mass [e.g., *Gray*, 1968; *McBride and Zehr*, 1981]. Over the Atlantic and eastern Pacific sectors, the low-level cyclonic disturbances usually manifest as tropical easterly waves [e.g., *Carlson*, 1969; *Burpee*, 1974; *Reed et al.*, 1977; *Thorncroft and Hodges*, 2001]. While nearly 85% of the intense (or major) hurricanes over the Atlantic have their origins as easterly waves [e.g., *Landsea*, 1993], only a small fraction of tropical easterly waves result in the formation of a named tropical storm. To obtain a deeper understanding of the genesis problem, it is necessary to understand how a tropical cyclone vortex is transformed within such a synoptic-scale environment and how a developing system (one that can develop into a tropical storm) is different from a non-developing system.

[3] Recently, *Dunkerton et al.* [2008] (hereafter DMW08) proposed a new "marsupial paradigm" for the formation and development of a proto-vortex within a tropical wave. Using three independent datasets, ECMWF Reanalysis data, TRMM 3B42 3 hourly precipitation and best track data from the National Hurricane Center (NHC), they showed that the critical layer of a tropical easterly wave is important to tropical storm formation because: 1) wave breaking or roll-up of the cyclonic vorticity near the critical surface in the lower troposphere provides the vorticity seedling for TC formation; 2) the wave critical layer is a region of approximately closed circulation (a pouch), where air is repeatedly moistened by convection and protected to some degree from dry air intrusion; 3) the parent wave is maintained and possibly enhanced by diabatically amplified mesoscale vortices within the wave. This is regarded as a marsupial theory in which a proto-vortex is carried along by the parent wave until it is strengthened into a self-sustaining entity. A survey of 55 named storms during 1998–2001 supports the marsupial theory and shows that genesis tends to occur near the intersection of the trough axis and the critical surface of the wave, which is the center of the critical layer (DMW08).

[4] DMW08 showed that proper diagnosis of the critical layer kinematics in the (re)analysis at coarse resolution ($1^\circ \times 1^\circ$ or more) can improve the forecast skill of tropical cyclogenesis and provide valuable information for the location of the tropical cyclone formation. To derive the phase speed of a wave, DMW08 applied digital filters to remove high-frequency variations (period shorter than 2.5 days) from the meridional wind field. Since the filters are symmetric, post-genesis information was blended with pre-genesis information. In this study, we show that precursor wave signals are usually strong enough to be detected prior to genesis. A simple and robust algorithm is developed here to track the "pouch" (or the critical layer), and the genesis location is predicted using global model products with an error less than 200 km up to 3 days prior to the actual genesis over the Atlantic.

2. Data and Illustrative Tropical Storms

[5] Three datasets are used in this study: 1) Global Forecast System (GFS) 6 hourly, one degree by one degree analyses, 2) GFS five-day forecasts at the same temporal and spatial resolution as above, and 3) genesis location (latitude and longitude) and time from the NHC. Unlike the general procedure employed by DMW08 that used low-pass and band-pass filtered ECMWF Reanalysis data, the raw GFS data are used in this study for wave/pouch tracking, and no temporal filters are applied.

[6] Hurricane Felix and Hurricane Dean in August 2007 are used to demonstrate the forecast procedures. Both storms originated from tropical easterly waves. The former was declared as a tropical depression by the NHC in real time at 21Z 31 August 2007, (11.8 N, 58.6 W), and the latter at 15Z

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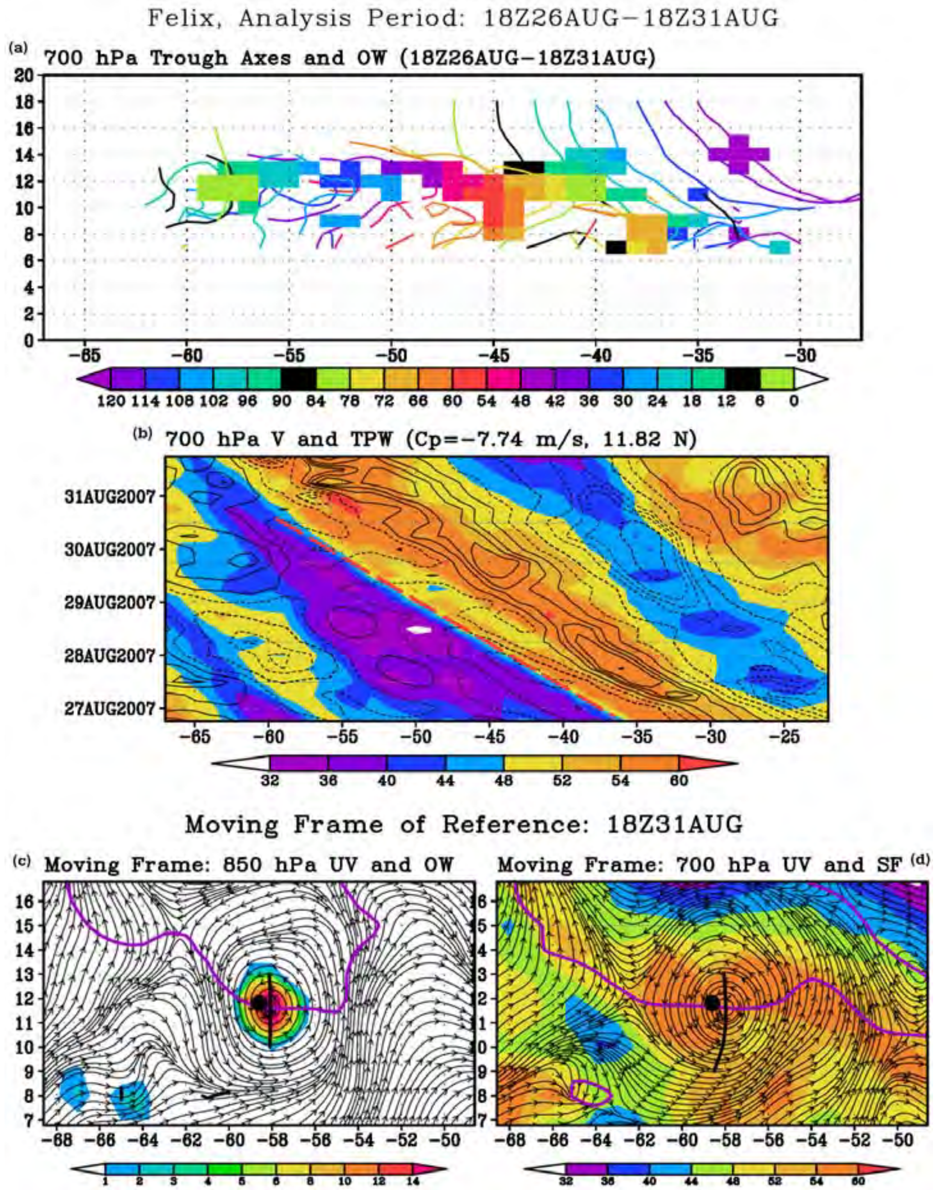

Figure 1. Diagnosis of Felix using GFS analyses. (a) Curves represent the locations of trough axes from 18Z 26 August to 18Z 31 August with a 6-hour interval, and shadings indicate areas of strong cyclonic OW (larger than 25% of the local maximum). The tracking time from 120 hours prior to genesis is represented by different colors. (b) Hovmoller diagram of meridional wind (contours) and column total precipitable water (kg m^{-2}; shading) along 11.82 N. The red dashed line denotes the estimate of the propagation speed (-7.74 m s^{-1}). (c) 850 hPa translated streamlines and OW (10^{-9} s^{-2}) and (d) 700 hPa translated streamlines and TPW at 18Z 31 Aug (the genesis time of Felix). The purple curve indicates the critical surface and the black curve is the wave trough axis. Their intersection pinpoints the center of the pouch and predicts the genesis location. In the top and bottom panels the x and y-axes are longitude and latitude, respectively.

13 August 2007, (12.0 N, 31.6 W). As shown by *Pasch et al.* [2008], GFS predicted the formation of Dean a few days in advance but failed to accurately predict the formation of Felix. Therefore, these two cases offer useful estimates of the range of predictability of storm genesis, which depends on the performance of the NOAA/GFS global model.

3. A Robust Forecast Procedure Using the GFS Data

[7] The GFS analysis data are used first to demonstrate the forecast procedure for Felix (Step 1-Step 3 as detailed below). The same procedure is then applied to the GFS forecasts for a real-time prediction using only the analyses available at forecast time, and forecast data thereafter.

3.1. Examine the Precursor Wave Propagation and Select the First Guess of Genesis Latitude

[8] Propagation of the precursor wave from five days before the genesis of Felix declared by the NHC is illustrated in Figure 1a by identifying the wave trough axes, as done by forecasters at the NHC. Over the Atlantic, wave signals are typically best detected at the easterly jet level,

falling in the range between 600–850 hPa. For simplicity, only a single vertical level (700 hPa) is shown.

[9] Superimposed on the trough axes is the Okubo-Weiss (OW) parameter [*Rozoff et al.*, 2006; DMW08], highlighting the region where cyclonic rotation dominates shear deformation. A first guess of the genesis latitude is chosen to be 11.8 N, the latitude at which trough axes with strong cyclonic rotation occurred most frequently.

3.2. Estimate the Propagation Speed of the "Marsupial Pouch"

[10] The westward propagation of the precursor wave can be seen in the Hovmoller diagram of the 700 hPa meridional wind. Without a low-pass filter, the meridional wind field is usually a bit noisy due to high-frequency variations or mesoscale vortices within the wave pouch, and it is often difficult to obtain a robust phase speed estimate from the propagation of the trough axis or the Hovmoller diagram of the meridional wind field.

[11] DMW08 suggested that the wave critical layer (or the pouch) is a region of closed circulation, where air is repeatedly moistened by convection and protected from dry air intrusion (Hypothesis H2 of DMW08). This implies that the boundary of the pouch acts approximately as a material boundary between the (relatively) dry and (relatively) moist air, and the propagation of the pouch can be tracked based on the propagation of the moist air mass. This is consistent with the operational practice of identifying the Lagrangian features of the wave/pouch evolution using the moisture or low-cloud fields. The high-resolution total precipitable water (TPW) product from the Cooperative Institute of Meteorological Satellite Studies (CIMSS) is especially useful for this purpose.

[12] TPW from the GFS analyses is shown (shadings) in Figure 1b. Although the meridional wind field has considerable high-frequency variability, the TPW has a sloping zone of strong moisture gradient ahead of the wave trough that separates the dry air outside of the pouch from the moist air inside the pouch; this serves as a useful indicator of the western boundary of the propagating pouch. (The recirculation time scale inside of the pouch is on the order of 3–6 days (DMW08). In the early stage of the pouch life cycle, moisture may not spread over the entire pouch, and the moisture distribution may resemble the "inverted-v" pattern as the vorticity distribution in Figure 1a of DMW08. For a mature storm, moisture may be coiled up into a spiral pattern enclosed by the pouch boundary.) This sloping zone is nearly straight in the Hovmoller diagram, which indicates a constant westward propagation speed of about -7.7 m s^{-1}. Inside the pouch, TPW is controlled by mesoscale and cloud-scale convective processes [*Montgomery et al.*, 2006; DMW08], which likely account for the higher values and the structure of the TPW contours. Behind (east of) the trough, no clear boundary exists between the moist and dry air, perhaps due to the escape of moisture to the east.

3.3. Predict the Genesis Location

[13] The OW and TPW values are superimposed on the 850 and 700 hPa streamlines (Figures 1c and 1d) in a frame of reference that translates zonally at the constant propagation speed of the pouch as estimated in Step 2. At both levels a pouch is clearly present. The center of the pouch given by the intersection of the critical surface ($u = C_p$) and the trough axis ($v = 0$ with cyclonic vorticity) is less than 100 km from the genesis location as declared by the NHC. The maximum of OW coincides nicely with the center of the pouch.

[14] The same procedure was applied to Hurricane Dean 2007 (not shown). The genesis location determined from the analysis data is again about 100 km from that declared by the NHC.

4. Real-Time Prediction of the Genesis Location Using the GFS Forecasts

[15] In section 3, GFS analyses were used for pouch tracking five days prior to the genesis time. We now investigate whether we can use the GFS forecasts to track the pouch and predict the genesis location for a real-time forecast.

[16] A real-time forecast was attempted at 00Z 31 August 2007, which is 18 hours prior to the genesis of Felix (Figure 2). The fields prior to this forecast time are GFS analyses and the fields after this forecast time are GFS forecasts initialized at 00Z 31 August 2007. We should point out that the success of this prediction depends on the forecast skill of the global model. While the GFS model has evidenced an improvement in forecast skill in recent years, Felix was actually a failure case in the 2007 Atlantic hurricane season [*Pasch et al.*, 2008]. The GFS forecasts initialized before 00Z 31 August had a northward drift in the wave track and did not forecast the formation of the storm. The forecast initialized at 00Z 31 August did not predict the formation of the storm either (Figure 2c shows a very weak cyclonic rotation at the genesis time). A moisture front, however, was present ahead of the wave trough from 28 August to 1 September, and the propagation speed was determined to be -6.8 m s^{-1} by fitting the moisture front. Using this propagation speed, we predict the location of the pouch center about 300 km from the actual genesis location (Figures 2c and 2d).

[17] In contrast, the GFS predicted the formation of Dean quite well. Using the GFS forecasts initialized three days prior to the genesis of Dean, we can predict the genesis location of Dean with an error less than 100 km (see Figure 3).

[18] The five-day forecast of the pouch tracks for Felix and Dean is summarized in Figure 4 along with a comparison of the genesis locations as declared by the NHC. It is worthwhile to note that the pouch tracks largely follow the zonal flow isotachs or the local critical latitude, which supports the marsupial theory. To examine the Lagrangian characteristics of the pouch, the five-day forecasts of the 700 hPa relative vorticity, 700 hPa OW, TPW, and column relative humidity (SF) are averaged in a 3° × 3° box following the pouch center, as shown in Figures 4b–4e. Since the GFS model failed to predict the formation of Felix, the relative vorticity, OW, TPW, and column relative humidity all broadly decreased in time, and there was no closed circulation in the moving frame at Hour +60 (not shown). In Dean, the 700 hPa relative vorticity and OW are significantly larger than those in Felix (note the scale change on the ordinate), and both steadily increased in

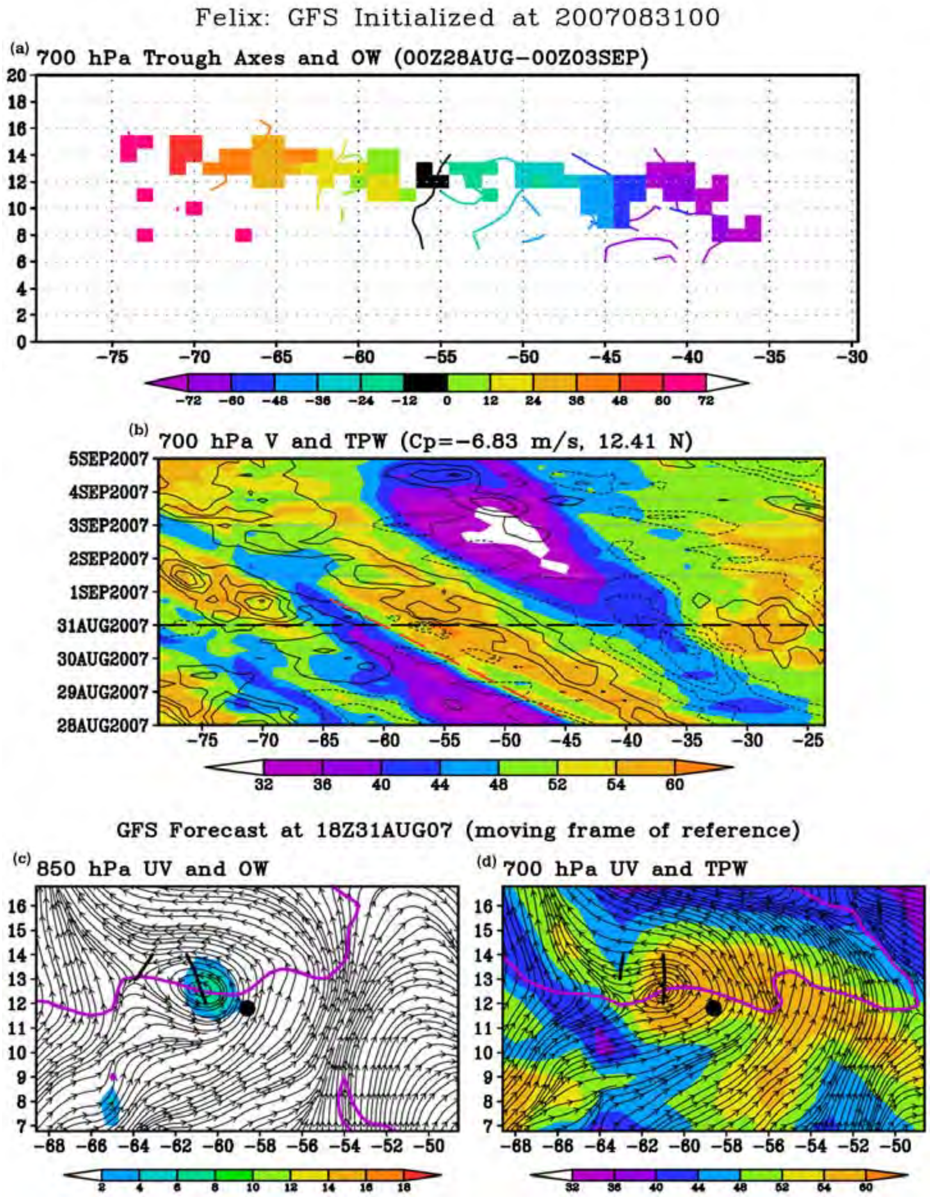

Figure 2. (a–d) Real-time forecast of Felix at 00Z 31 August 2007. The layout is the same as Figure 1, but the data before the forecast time (00Z 31 August 2007) are GFS analyses and the data after the forecast time are GFS forecasts, as separated by the black trough axis in Figure 2a and the black dashed line in the Hovmoller diagram. Note that the time interval in Figure 2a is 12 hours.

time. In particular, the 700 hPa relative vorticity derived from the GFS analyses doubled within 72 hours.

5. Discussion

[19] In this algorithm, the wave pouch is tracked based on the moisture front in the TPW field. Since TPW is a vertically integrated product, the tracking is independent of the vertical levels. Our diagnosis of many cases suggests that the tracking method is not sensitive to 1–2 degrees changes in the first guess of the genesis latitude, along which the Hovmoller diagram is constructed. Furthermore, DMW08 have shown that the genesis location determined by the pouch center is usually not sensitive to 1–2 m/s errors in the phase speed. Another advantage of this method is that it tracks the wave pouch. This is inherently different from tracking of vorticity maxima or meridional wind perturbations, which may track the multiple mesoscale vortices inside the pouch (the ‘‘joeys’’), especially when high-resolution data are used.

[20] DMW08 suggest that a closed circulation in the wave moving frame in the lower troposphere is a necessary condition for the formation of a tropical storm. Our experience gained from the 2008 hurricane season in the eastern Pacific and Atlantic sectors suggests that most of the precursor waves are associated with a leading moisture front and that the moisture front in the TPW Hovmoller diagram may be a useful indicator of the existence of a pouch in the lower troposphere. The moisture front may be interrupted by land, however, and the wave may also lose its

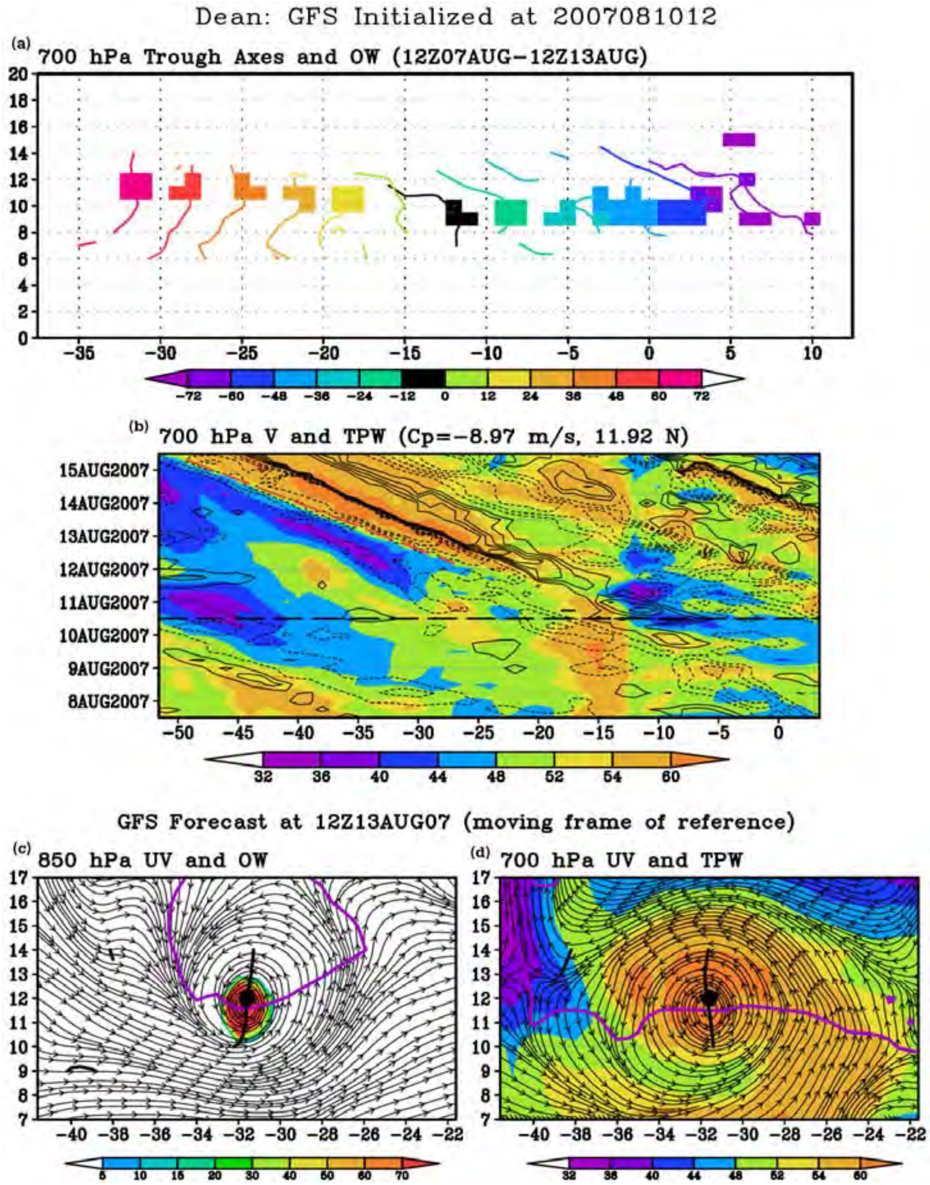

Figure 3. (a–d) Same as Figure 2, except for the real-time forecast of Dean at 12Z August 10 2007, three days prior to the genesis time (15Z 13 August).

leading moisture front as it interacts with another system. While a shallow pouch that does not link with the top of the atmospheric boundary layer can still possess a moisture front (as in the early pre-genesis stage of Felix), it is plausible that a moisture front is absent if there is only weak convection inside the pouch (a dry pouch). In the latter case, the disturbance may be regarded as a non-developer since it is not likely to develop into a tropical storm in a couple of days. Investigation of the differences between developers and non-developers is currently underway.

6. Conclusions

[21] In this study we have shown that the moisture front in the TPW product (a zone of strong moisture gradient) ahead of easterly wave troughs over the Atlantic separates the relatively dry air outside of the mother wave pouch from the relatively moist air inside, and indicates the boundary of the pouch. The moisture front in the Hovmoller diagram of TPW may therefore be used to track the pouch and estimate its propagation speed. Based on the marsupial theory proposed by DMW08, the intersection of the critical latitude ($u = C_p$) and the trough axis ($v = 0$) pinpoints the center of the pouch and predicts the most likely genesis location. When applying this method to the global model forecasts, we can predict the genesis location of Hurricane Dean with an error less than 100 km three days prior to the actual genesis. Our real-time forecasts of the 2008 tropical storms over the Atlantic and the East Pacific using this algorithm (http://met.nps.edu/∼mtmontgo/marsupial.html) suggest that we can usually predict the genesis location of a storm one to three days prior to the actual genesis with an error less than 200 km. (In this study we only examined zonally propagating waves, which are common over the Atlantic. This method may be extended to cover the northwestward propagating disturbances over the Gulf of Mexico and the

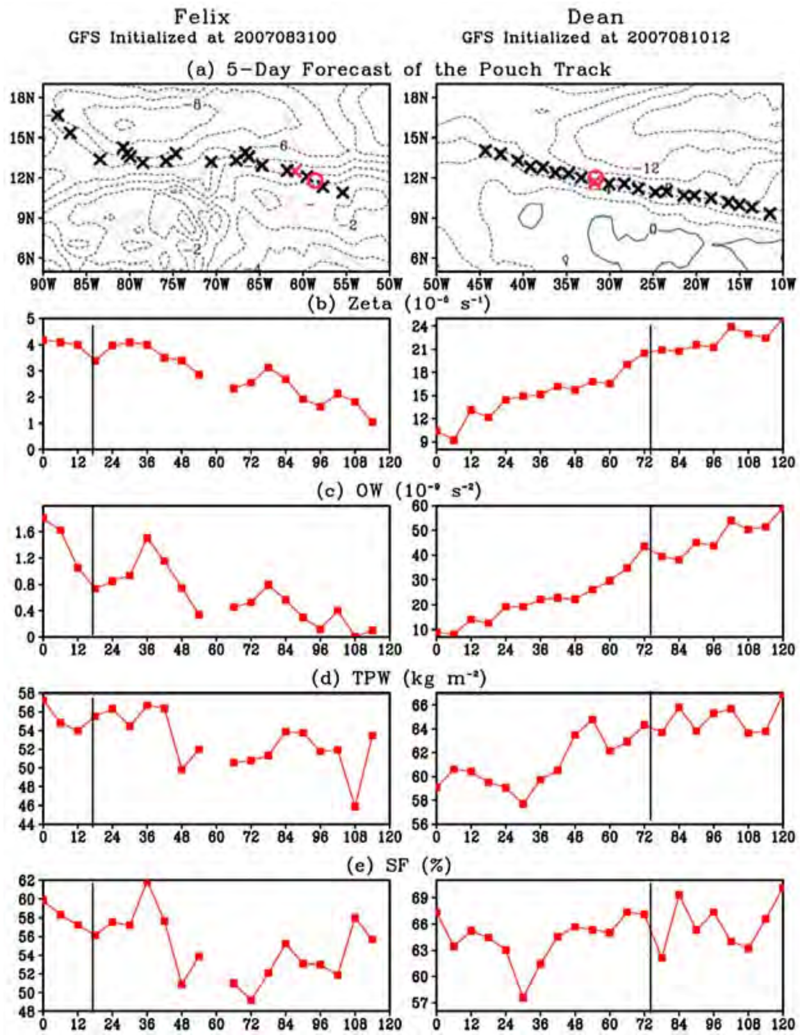

Figure 4. (a) Five-day forecast of the pouch tracks (crosses) based on the GFS five-day forecast initialized at 00Z 31 August (Felix; left) and 12Z 10 August (Dean; right). The red circles indicate the genesis locations declared by the NHC, and the red crosses are the predicted pouch center locations at the genesis time. The background contours are 700 hPa zonal wind averaged during the five-day forecast period. Also shown are five-day (120-hour) forecast of (b) 700 hPa relative vorticity (zeta), (c) 700 hPa OW, (d) TPW, and (e) column relative humidity (SF) averaged over a $3^\circ \times 3^\circ$ box following the pouch center. (left) Felix and (right) Dean (note the scale change on the ordinate) are shown here. The vertical black lines indicate the genesis time as declared by the NHC. Missing values at Hour 60 in Felix indicate an open wave in the moving frame.

western North Pacific, and the estimate of propagation speed can be improved by using linear regression.) Such forecast guidance should prove useful in the planning and execution of airborne sorties into candidate tropical cyclogenesis regions during tropical cyclone formation field experiments.

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