ANALYSIS OF ENSEMBLE FORECASTS OF TROPICAL CYCLONE STRUCTURE THROUGH EXTRATROPICAL TRANSITION

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1. INTRODUCTION

A key focus of the US THORPEX is to make meaningful improvements in operational forecasts through week 2. The achievement of such a goal will entail improvements in understanding the atmospheric processes and phenomena that contribute to the current errors over the two week timeframe, and related developments to the numerical modeling systems (forecast models and assimilations) that support these forecasts.

Over the last decade, the "boundary" between the tropics and midlatitudes has been increasingly recognized as being more porous than was previously understood. Indeed, forcings between these two regions have become accepted as one source of forecast uncertainty. One example of the tropical-midlatitude interaction problem manifesting in operational forecasting errors is focused on here: extratropical transition of tropical cyclones.

Extratropical transition of tropical cyclones (often referred to simply as *"ET"*) has come to be recognized as both a direct source of intense weather (extreme rain, wind and wave events) at the poleward land boundaries of the tropical cyclone basins and as a driver of downstream developments that may result in extreme weather phenomena far from the original tropical cyclone. Anecdotal records of these events extend back hundreds of years in both the Atlantic and the Pacific basins (Hatada 1965; Reiss 2001), but their relative frequency of occurrence has only become apparent recently (Hart and Evans 2001; Klein et al. 2000). ET systems are important both directly and indirectly as sources of model forecast errors (Evans et al. 2006; Jones et al. 2003).

The lack of predictability associated with the process of ET provides a week 2 forecasting challenge in the vein of the THORPEX focus (Jones et al. 2003). Further, the THORPEX Integrated Grand Global Ensemble (TIGGE) provides the opportunity to study operational ensemble forecasts from centers around the globe. Thus, TIGGE is a substantial resource for furthering the study of forecast predictability.

In this study we propose a novel method for characterizing the spread of operational ensemble forecasts of tropical cyclone evolution around the time of ET. The *Cyclone Phase Space* (CPS) of Hart (2003) is used to characterize the evolving storm structure in each ensemble forecast. To evaluate the model forecast skill of ET, each ensemble member is compared against the deterministic analysis at the verifying time.

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2. METHODS

The CPS provides an objective measure of cyclone structure for model forecast validation and has been shown to capture the onset and completion of ET (Evans and Hart 2003). CPS-derived diagnoses of storm structure from ECMWF ensemble forecasts out to 120 h are compared with verifying analyses from the deterministic operational ECMWF model. We employ the 7-cluster k-means solution of Arnott et al. (2004) as a baseline for these comparisons, with the goal of developing an objective reference frame for the validation of ensemble forecasts of storm structure.

ECMWF Ensemble Prediction System (EPS) structural forecasts during extratropical transition (ET) are investigated using Typhoon Tokage (2004) as the case study. The seventh typhoon to strike Japan in 2004 (JTWC 2004), Super typhoon Tokage was also the deadliest Japanese landfall in almost twenty years. Tokage subsequently underwent ET and made a second landfall – this time in Alaska! The impacts of the Tokage landfall in Alaska included severe coastal erosion.

Archived ensemble forecast fields offer the necessary variables to track the cyclone and derive key structural parameters employed by the CPS. Additionally, analysis fields from the ECMWF EPS and the ECMWF deterministic model are the basis for comparison between forecasted and verified structural characteristics. For each initialization time, 50 perturbed forecasts and one control forecast comprise the ensemble. Each ensemble member produces a 10 day forecast at 12 h time steps. While the ensemble forecast model is a global spectral model with 50 vertical levels, the archived ensemble data used in this study have been converted to gridded fields with a horizontal resolution of 1°×1°, and only five vertical levels are available (1000, 850, 700, 500, and 200 hPa). Archived deterministic analyses and forecasts are gridded with a 0.5°×0.5° resolution. The deterministic forecasts contain the same five vertical levels as the ensemble member forecasts; however, the archived deterministic *analyses* contain 11 vertical pressure levels.

An automated cyclone tracker locates minima on a mean sea level pressure field that exhibit at least a 0.4 hPa drop within a 5° box. The domain used in this study ranges from 10°N–80°N, and from 100°E–270°E (90°W) in longitude in order to capture the full range of possible range of forecasted tracks. Detection of minima is performed for each forecast time for a particular ensemble member, recording the central pressure and latitudinal/longitudinal location for each minimum. To be classified as a cyclone, a particular minimum must persist for at least 24 consecutive hours and must meet criteria specified by the speed and direction of motion of the minimum. Additionally, the cyclone must be moving with a forward speed of less than 40 ms^{-1}. This tracking algorithm was performed for every ensemble member for all forecast initialization times, as well as for the deterministic analyses and forecasts, to produce the forecast and analyzed tracks of Typhoon Tokage.

The three CPS parameters are: (i) the lower- and (ii) upper- tropospheric thermal winds (referred to as $-V_T^L$ and $-V_T^U$ respectively) and (iii) the lower-tropospheric thermal asymmetry (*B*) (Hart 2003). These three parameters are sufficient to distinguish when a TC commences and completes ET (Evans and Hart 2003). These are evaluated for the analyses, deterministic forecasts, and each EPS member.

3. RESULTS AND DISCUSSION

K-means clustering of all of the ensemble forecasts for a number of initialization times from tropical through ET resulted in a lifecycle description for the ensemble forecasting system. The resulting clusters are shown in Fig. 1 (only *B* vs. $-V_T^L$ shown) and the CPS track and cluster membership for the verifying analyses are given in Fig. 2. Clusters 2 and 3 are the "tropical" clusters, with most intense hurricanes in cluster 3; storms *undergoing* transition are in clusters 1 or 4. Correspondence between the cluster distribution for the ECMWF 7-cluster solution and the previous 7-cluster distributions derived for the AVN and NOGAPS models (Arnott et al. 2004) is obvious, confirming the ability of the CPS to represent key structural factors and the ability of the clustering algorithm to identify like structures.

To determine forecast success, the CPS locations for the ensemble members are clustered and the forecast and verifying analysis cluster numbers are compared. A forecast is evaluated to be "correct" if the analysis and forecast clusters at that storm time are the same. A summary statistic, S, is used to record the percentage of successful forecasts for each forecast lead time for each model (e.g. Evans et al. 2006).

Key results from this analysis include that structure forecasts are shown to depart from the verifying analysis as forecast lead time increases. By 36h, almost none of the ensemble members have the correct cluster membership.

Ensemble forecasts of additional western North Pacific ET cases will be explored. Analyses to determine the optimal number of clusters will continue. In addition, track clustering of the CPS paths is being developed in our group. This work is ongoing.

4. ACKNOWLEDGEMENTS

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FIGURES

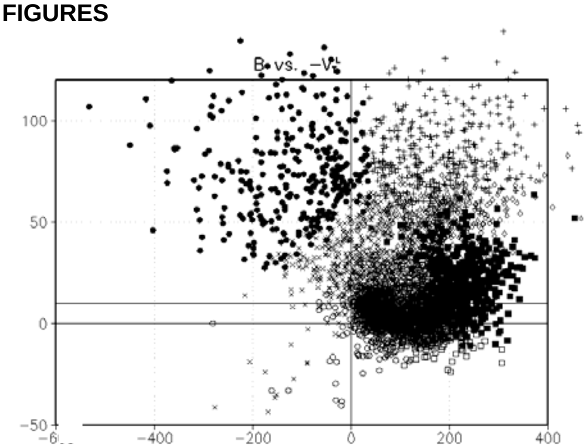

Figure 1. ECMWF EPS k-means solution for seven clusters. Only the $-V_T^L$ vs. *B* projection of the CPS is shown here.

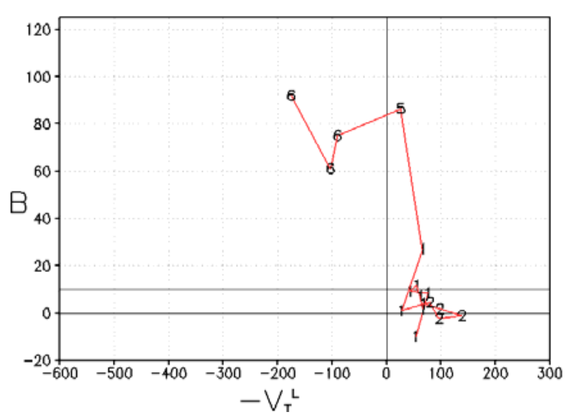

Figure 2. ECMWF deterministic forecast track through the CPS from 13 August 2004 at 1200UTC through 18 August 2006 at 1200UTC. Cluster numbers for each verifying analysis time are labeled.