# INTERPRETATION OF TROPICAL CYCLONE TARGETING GUIDANCE

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## 1. INTRODUCTION

In Majumdar et al 2006, hereafter M2006, 5 targeted observing guidance maps based on 3 different objective techniques for 78 tropical cyclone cases from the 2004 Atlantic Hurricane season are compared. The targeted observing products considered include a product based on the NCEP deep layer mean wind ensemble variance, two ensemble transform Kalman filter (ETKF) products based on NCEP and ECMWF ensembles and two total-energy singular vector (TESVs) products computed by ECMWF and the Naval Research Laboratory, using their respective global models.

The TESV technique considers "dynamics only", ignoring the expected analysis error covariances at target time. The ETKF technique considers both the estimated analysis error covariance at target time and the dynamic growth of perturbations, but is constrained by the finite size and specific characteristics of the ensemble used. Not surprisingly, M2006 note that systematic differences between the techniques are readily apparent. When the targets are remote from the storm, the TESVs usually indicate targets northwest of the storm, often associated with an upstream trough, while the ETKF targets are far more likely to occur northeast of the storm, over the Northern North Atlantic. In this follow-on study, we characterize and examine these differences in further detail, in light of the specific design of the different techniques.

## 2. TARGETING METHODS

M2006 compare 5 guidance products based upon three different techniques – DLM Wind Variance (NCEP), ETKF (NCEP and ECMWF) and TESV (NOGAPS and ECMWF) – for 78 cases of 2-day TC forecasts in the Atlantic Basin during the 2004 hurricane season. The results from four of these products (the ETKF and TESV products) are considered here. The ETKF and TESV methods consider error propagation from the observing (analysis) time $t_a$ into a given forecast verification region at a verification time $t_v$, 2 days after $t_a$ . All sets of guidance use ensembles (ETKF/Variance) or non-linear trajectories (TESVs) initialized at time $t_i$, at least 48h prior to $t_a$.

The current version of the Ensemble Transform Kalman Filter (ETKF, Bishop et al. 2001) is similar to that run operationally at NCEP (Majumdar et al. 2002a) during Winter Storm Reconnaissance Programs. The ETKF uses operational ensemble forecast perturbations to predict the reduction in forecast error variance produced by targeted observations. The 50 ECMWF $T_L$255 L40 ensemble members are generated using T42 L40 singular vectors (Buizza et al. 2003). The 20 NCEP GFS T126 L28 ensemble members are generated using masked breeding (Toth and Kalnay 1997).

The concept of targeted singular vectors (SVs) was introduced by Palmer et al. (1998) and Buizza and Montani (1999). In these experiments, total energy is used to measure the perturbation at both initial and final times, and the SVs are therefore referred to as TESVs. A local projection operator is applied at final time to optimize perturbation energy in the vicinity of the storm. A quadratic "perturbation total energy" is computed, and each "TESV summary map" is then given by the weighted average of the vertically integrated leading TESVs. The NOGAPS SV calculations were performed at a T79L30 resolution based on the operational (T239L30) forecast trajectory (3 SVs used). The ECMWF SV calculations were performed at a TL95L60 resolution (10 SVs used). Both sets of TESVs have been computed using dry tangent linear and adjoint models. The influence of resolution, metric and moist processes on SV structures is presented in Buizza (1998), Palmer et al. (1998) and Coutinho et al (2004) respectively.

Further details on the construction of the targeting products can be found in M2006.

## 3. RESULTS

### *A Typical Example*

The summary maps for Hurricane Charley, targets valid on 00Z 8/14/2004, are shown in Fig. 1 for the TESV methods and in Figure 2 for the ETKF methods. Both TESV methods highlight areas to the northwest of the storm, associated with the western side of a trough. The ETKF methods highlight the region north and north-east of the storm, associated with the eastern side of this trough. The NCEP ETKF summary map also highlights regions in the central Atlantic. This case is quite typical and the differences indicated here are also apparent in the average and composite maps shown in the next subsections.

### *Average Summary Maps*

The summary maps averaged over all 78 cases, along with the locations of the maximum in each case, are shown for the TESV methods in Fig. 3 and for the ETKF methods in Fig. 4. The two TESV average summary maps are qualitatively similar to each other. Both TESV products indicate larger average values and frequent target maxima in the vicinity of the hurricane track region in the southern North Atlantic, as well as frequent targets extending toward the northwest, over North America.

The average summary maps for the ETKF products (Fig.4) also exhibit similar characteristics to each other. Individual maxima are again clustered in the hurricane track region. Both ETKF products show frequent maxima over the northern North Atlantic and few maxima over North America west of 90 W. There are some differences between the two ETKF methods though. The NCEP ETKF has almost no maxima over the northeastern US or eastern Canada, while ECMWF ETKF has a significant number of maxima in this region. The NCEP ETKF has five maxima west of 90 W while ECMWF ETKF has none in this region. In summary, the TESV maxima occur relatively more frequently over central and western North America, while the ETKF maxima occur relatively more frequently over the central and northern North Atlantic.

### *Composite Summary Maps*

As the differences between the average TESV and ETKF summary maps are very significant in regions far from the storm, it is instructive to examine the structures contained in the summary maps as a function of the distance between the storm and the summary map maximum. To highlight differences for these remote targets, the 78 cases are divided into two groups. The “near” group is composed of those cases where the maximum of the summary map lies within 15 degrees of the forecast hurricane position. The “far” group is composed of those cases where the maximum of the summary map lies at least 15 degrees from the forecast hurricane position. The streamlines corresponding to the NOGAPS analyzed 500-hPa wind, likewise composited about the storm center, are superimposed on the summary map composites.

The summary maps composited about the storm center for the near group are shown in Fig. 5 for the TESV methods and in Fig. 6 for the ETKF methods. Both TESVs exhibit an annular structure around the cyclone center, with maximum values approximately 5 degrees from the storm center. The location of this maximum coincides with the change in sign in the vorticity gradient about the storm, and may be associated with vortex instability or vortex Rossby wave propagation (for further discussion, see Peng and Reynolds (2006)). [Mechanisms for rapid perturbation growth occurring at small scales and/or relating to moist processes would be missed by the dry SV calculations performed at relatively coarse resolution.] The maximum for the ETKF composites (Fig. 6) is located directly over the center of the storm. These differences highlight the fact that the TESVs will emphasize rapid dynamic perturbation growth, while the ETKF methods are also influenced by the estimated analysis uncertainty, predicted to be large in the immediate vicinity of the storm.

For the TESV composites for the far group (Fig. 7), sensitivity in an annulus around the storm is still apparent, but now there is a strong signal extending to the northwest of the storm, collocated with west-northwesterly flow towards the storm, in agreement with the numerous targets over North America in Fig. 2. In contrast, the ETKF composites (Fig. 8) show, outside of the immediate storm vicinity, a broad maximum to the north for ECMWF, and a broad maximum to the northeast and east for NCEP. These results are consistent with the average summary plots and maxima shown in Fig. 4.

*Analysis Error Variance*

There are several reasons to expect differences between the ETKF and TESV summary maps, as detailed in M2006. One basic difference is that the TESVs highlight the fastest growing perturbations (i.e. are constrained by the dynamics only), while the ETKF technique also considers spatial differences in the estimated analysis error variance. SVs can also be constrained using information about the estimated analysis error variance and covariance (e.g., Barkmeijer et al. 1999, Gelaro et al. 2002). Here we have calculated "VARSVs" using the NOGAPS adjoint and the analysis error variance estimates produced from the Navy's operational 3D-VAR data assimilation system, NAVDAS (NRL Atmospheric Variational Data Assimilation System, Daley and Barker 2001). The average summary map and maximum locations are shown in Fig. 9. Compared with the TESVs from NRL in Figure 3, it is clear that the variance constraint modulates the summary maps away from the relatively well-observed eastern US. There are also a few more targets between Canada and Greenland in the VARSV summary maps. However, the basic pattern for the VARSVs resembles the pattern for the TESVs more so than the ETKF (Fig. 4).

Examination of the analysis error variance provides information on why there isn't a bigger shift of the SV targets when constrained using the NAVDAS analysis error variance estimates. Fig. 10 shows the average estimated analysis error variances (normalized by the maximum value in the domain) derived from the ETKF technique using the ECMWF and NCEP ensembles. The patterns shown in the analysis error variance plots are quite similar to those produced for the 2-day ensemble variance (not shown). The ETKF summary maps reflect the relatively small estimates of analysis error variance over North America, and relatively large estimates of the analysis error variance in the northern North Atlantic for both ensembles (the NCEP ensemble also has relatively large variance over the middle North Atlantic). On a case-by-case basis, the analysis error variance maxima are significantly more localized, with the maximum values associated with particular features several times larger than the estimated variance outside these localized regions. The analysis error variance for the Hurricane Charley case highlights this localization in the ETKF analysis error variance (Fig. 11). Comparison of Fig. 11 with Fig. 2 illustrates how the ETKF targets reflect the specific characteristics of the ensemble scheme from which they are produced. The accuracy of these estimates is difficult to gauge, especially given that neither forecasting system is an ensemble-based Kalman filter.

The bottom panels of Fig. 10 and Fig. 11 show the analysis error variance estimate produced from NAVDAS (for the time average, and Charley case, respectively). This estimate (a strong function of the prescribed static background error variance) indicates relatively small values over North America, just as in the ETKF case. Fig. 12 shows the summary map for the NRL VARSVS for the Charley case. Comparison of Fig. 12 with Fig. 1 shows that the variance constraint does modulate the summary map, pushing the maximum values further north into Canada. However, the relative difference between the variances estimates over the North Atlantic and over North America are considerably smaller in the NAVDAS estimates then in either of the ETKF estimates. Therefore, constraining the SVs using analysis error variance estimates produced from the ETKF method would probably modulate the SV summary maps away from North America and towards the North Atlantic even further, and these experiments are planned.

## 4. SUMMARY

As noted in M2006, there are considerable differences in the targeting products produced using TESV and ETKF methods. When the targets are remote from the storm, the TESVs usually indicate targets northwest of the storm, often associated with an upstream trough, while the ETKF targets are far more likely to occur northeast of the storm, over the Northern North

Atlantic. While the ETKF techniques often produce targets that are significantly different than those based purely on 48-h ensemble spread, they are nonetheless constrained by ensemble characteristics, specifically the estimate of analysis error covariance produced by the 48-h ensemble, which often has maximum variance over the northern North Atlantic. Unlike the ETKF techniques, the "dynamics only" TESV method is not designed to consider spatial differences in the likely analysis errors (e.g., relatively small over land and large over oceans). Constraining the SV calculation using estimated analysis error variances results in a shift of the target areas away from well-observed regions, such as the eastern US. However, each analysis error estimate has different liabilities. The NAVDAS estimate currently has no flow-dependent component. The ETKF estimates are constrained by the ensemble construction methods. Data denial experiments are planned to examine the impact of data in target regions on the forecast error.

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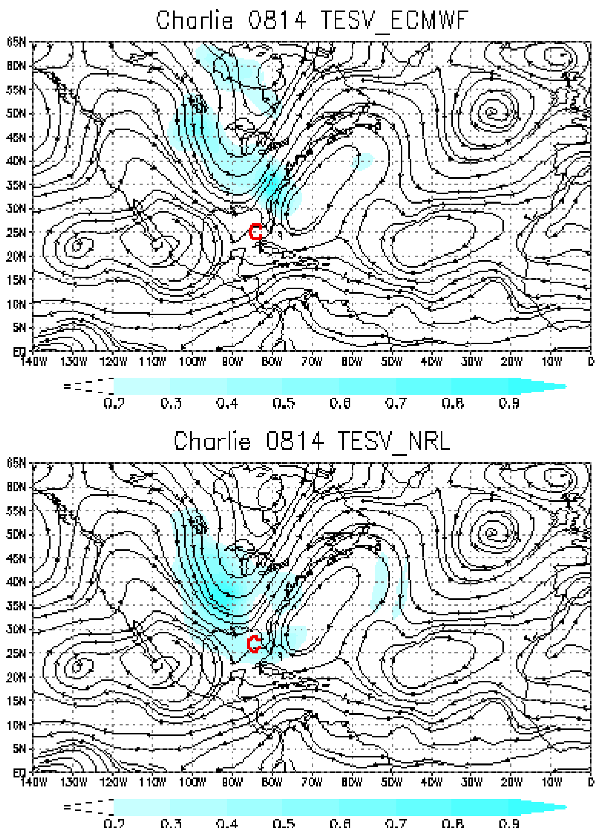


Figure 1. Summary map for Hurricane Charley, target valid 00Z 8/14/2004 for the ECMWF (top) and NLR (bottom) TESV guidance. Streamlines of the deep-layer mean wind from the analysis valid at the target time are also shown. The forecast position of Charley is given by the red C.

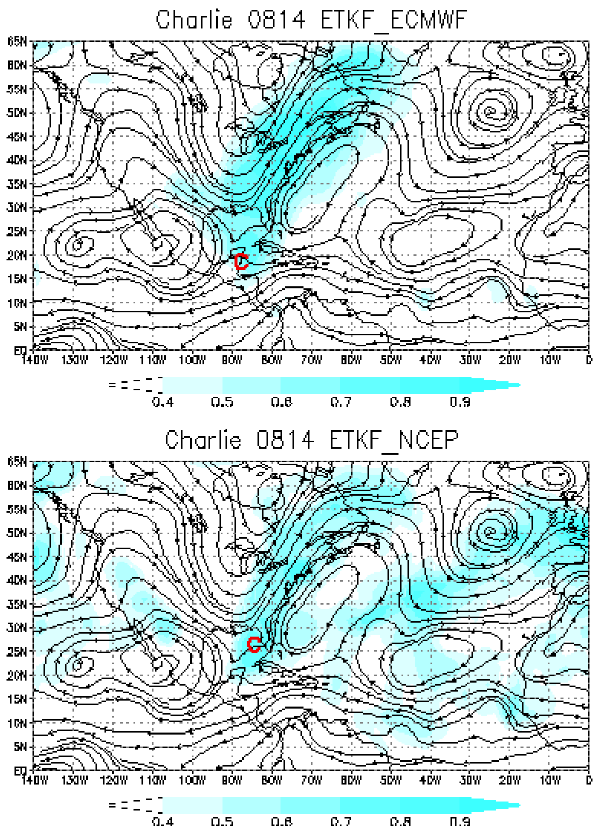


Figure 2. Summary map for Hurricane Charley, target valid 00Z 8/14/2004 for the ECMWF (top) and NLR (bottom) ETKF guidance. Streamlines of the deep-layer mean wind from the analysis valid at the target time are also shown. The forecast position of Charley is given by the red C.

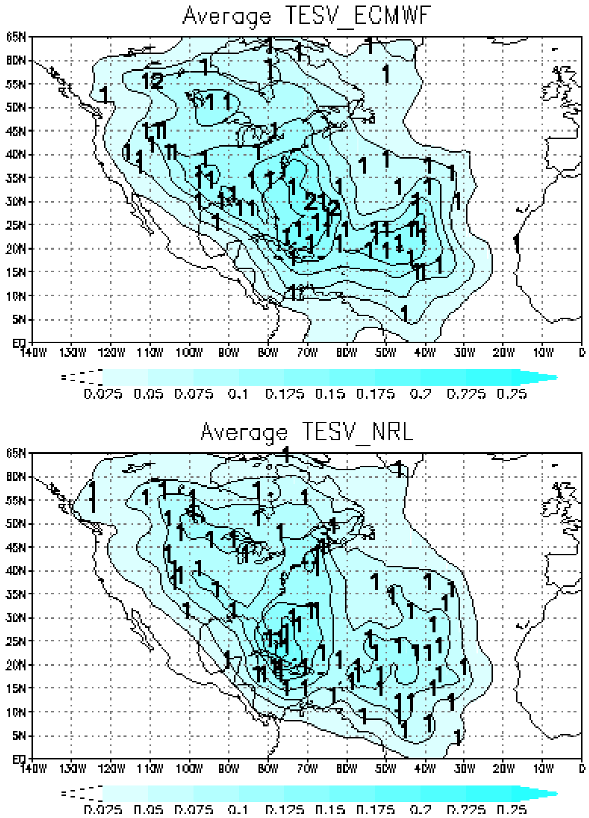


Figure 3: Average of the 78 TESV summary maps for ECMWF (top) and NRL (bottom). Numbers indicate the locations (and number of occurrences) of the maximum for each map.

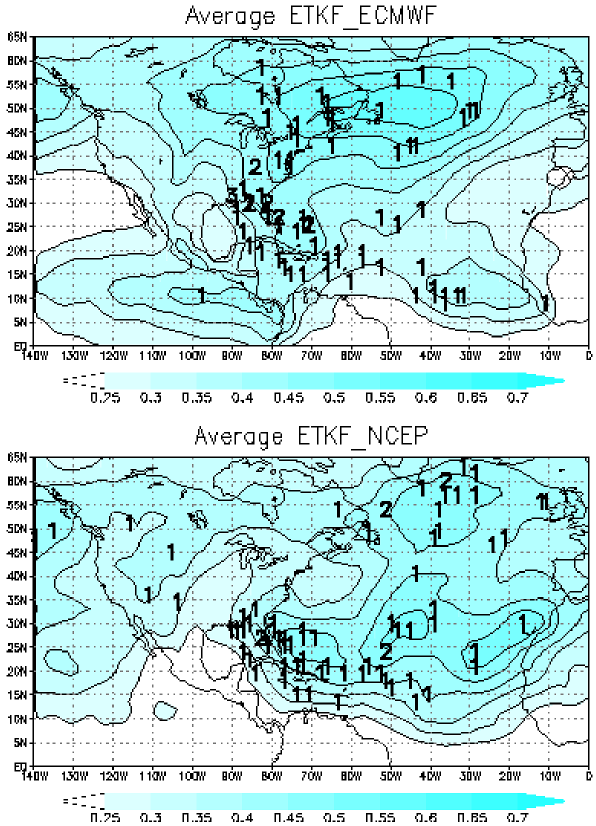


Figure 4: Average of the 78 ETKF summary maps for ECMWF (top) and NCEP (bottom). Numbers indicate the locations (and number of occurrences) of the maximum for each map.

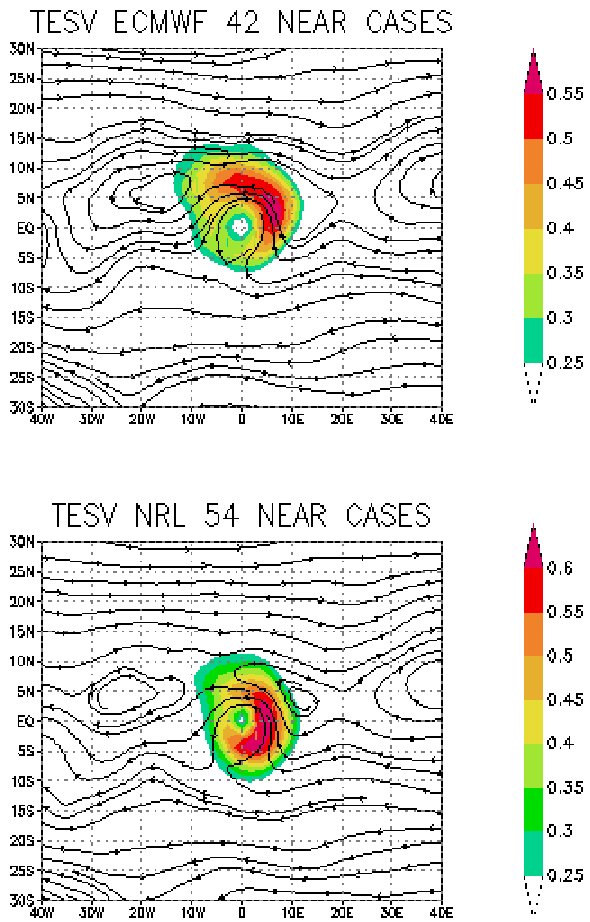


Figure 5: ECMWF (top) and NRL (bottom) TESV summary maps composited about the storm center for “near” cases where the maximum target guidance is within 15 degrees of the storm center (shading). The streamlines corresponding to the composited 500-hPa wind are also shown.

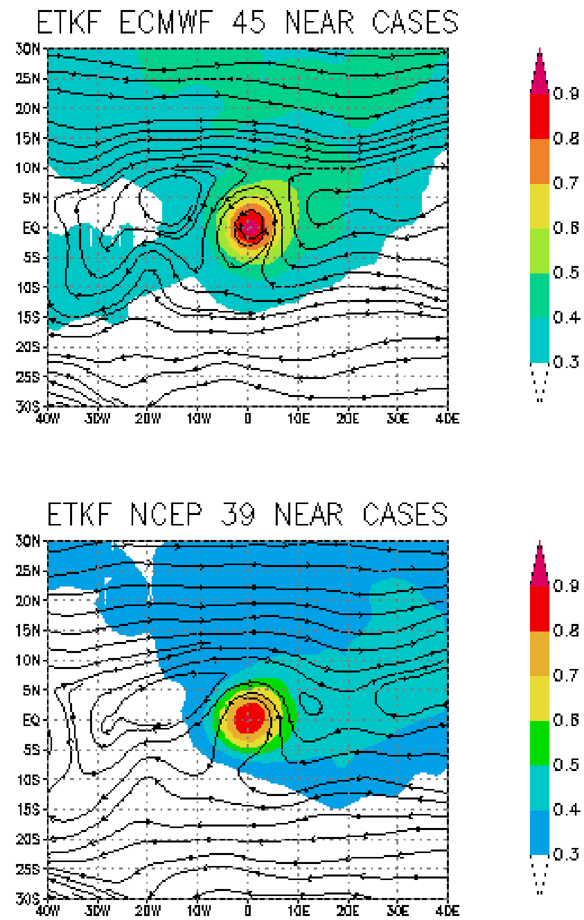


Figure 6: ECMWF (top) and NCEP (bottom) ETKF summary maps composited about the storm center for “near” cases where the maximum target guidance is within 15 degrees of the storm center (shading). The streamlines corresponding to the composited 500-hPa wind are also shown.

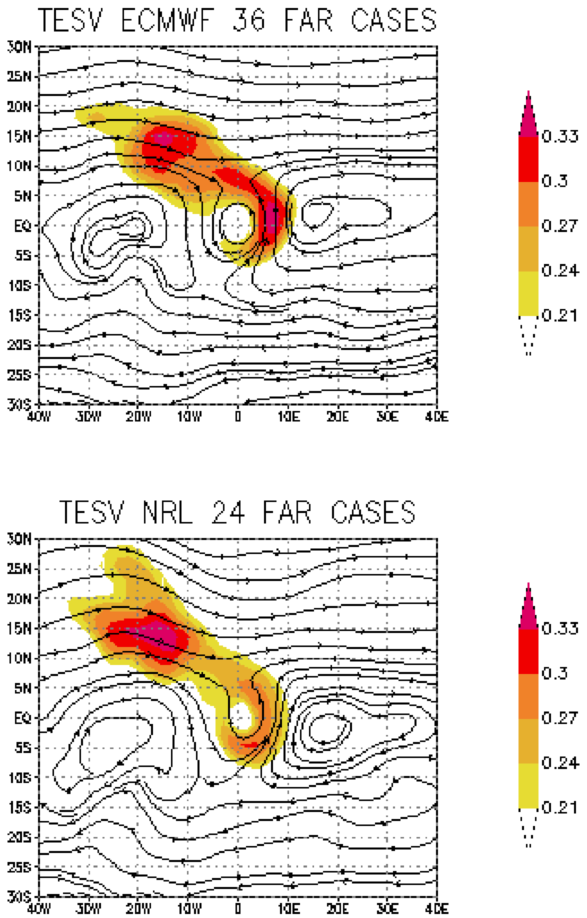


Figure 7: ECMWF (top) and NRL (bottom) TESV summary maps composited about the storm center for "far" cases where the maximum target guidance is further than 15 degrees from the storm center (shading). The streamlines corresponding to the composited 500-hPa wind are also shown.

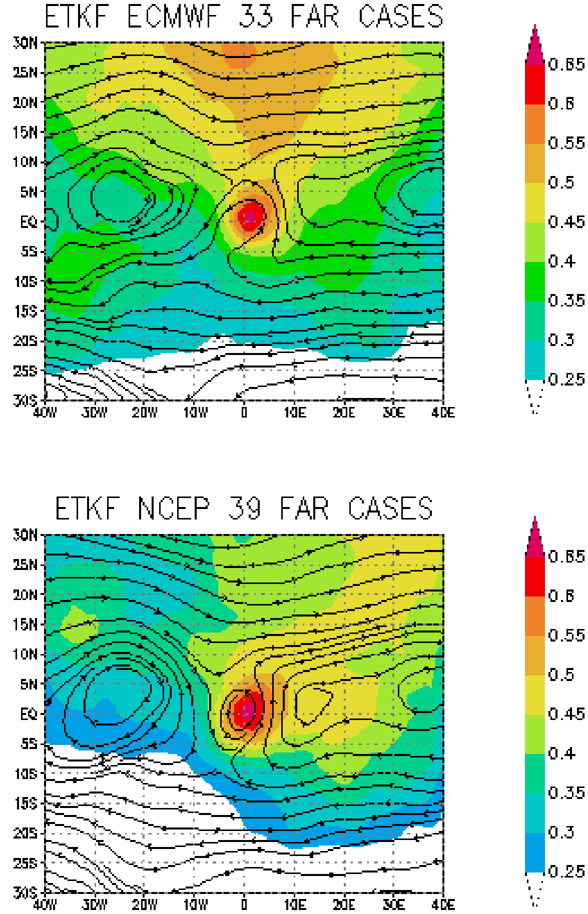


Figure 8: ECMWF (top) and NCEP (bottom) ETKF summary maps composited about the storm center for "far" cases where the maximum target guidance is further than 15 degrees from the storm center (shading). The streamlines corresponding to the composited 500-hPa wind are also shown.

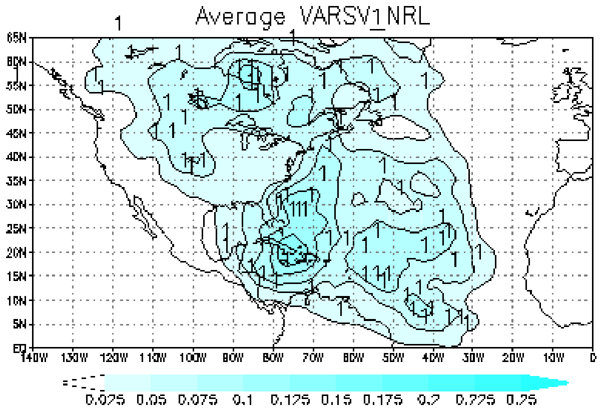


Figure 9: Average of the 78 NRL VARSV summary maps. Numbers indicate the locations (and number of occurrences) of the maximum for each map.

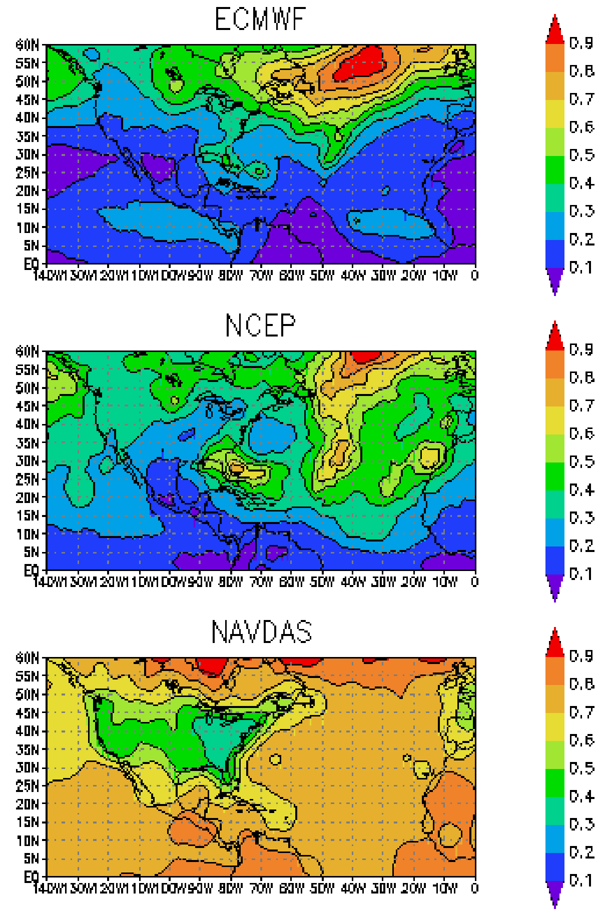


Figure 10: The vertical- and time-average analysis error variance in the wind field, estimated from the ECMWF ETKF (top), NCEP ETKF (middle) and NAVDAS (bottom). Values are normalized by the maximum value in the domain.

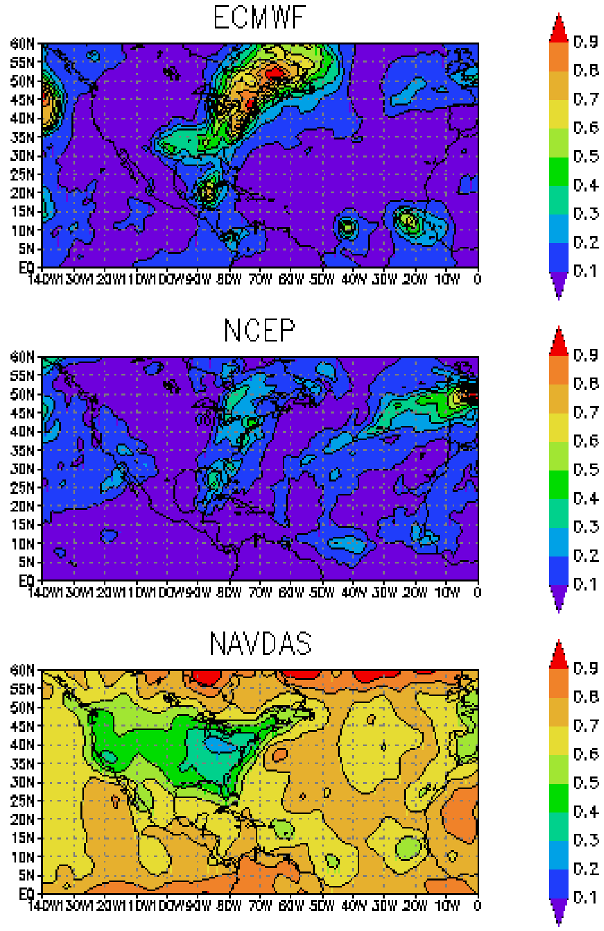


Figure 11: The vertically averaged analysis error variance in the wind field, estimated from the ECMWF ETKF (top), NCEP ETKF (middle) and NAVDAS (bottom) valid on 00Z 8/14/2004. Values are normalized by the maximum value in the domain.

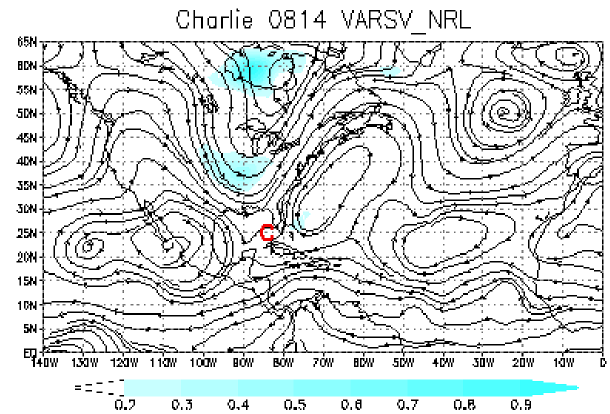


Figure 12. Summary map for Hurricane Charley, target valid 00Z 8/14/2004 for the NRL VARSV guidance. Streamlines of the deep-layer mean wind from the analysis valid at the target time are also shown. The forecast position of Charley is given by the red C.