NOAA Joint Hurricane Testbed (JHT): TARGETING STRATEGIES TO IMPROVE HURRICANE TRACK FORECASTS

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1. Purpose of Work

Each time a tropical cyclone (TC) is deemed as a potential threat to land, the NOAA Gulfstream-IV (G-IV) aircraft is deployed to release GPS dropwindsondes in the TC environment to improve operational track forecasts. The currently operational method to choose the timing and location of dropwindsonde deployments is based on a subjective decision by examining the 'spread' of the NCEP Global Forecast System (GFS) ensemble forecasts of 850-200 hPa deep-layer-mean winds (Aberson 2003). The subjective targeting strategy does not account for targeting observations to improve specific forecasts (for example, a 3-day forecast of a TC making landfall).

In order to (i) expedite the flight planning process, (ii) *objectively* use numerical model output, (iii) account for specific TC forecasts, and (iv) reduce the likelihood of choosing irrelevant target regions, the suitability of a new targeting strategy is being tested under this JHT project. This strategy, entitled the Ensemble Transform Kalman Filter (ETKF) (Bishop *et al.* 2001), is currently used operationally during annual Winter Storm Reconnaissance programs conducted by the National Weather Service (Majumdar *et al.* 2002, Szunyogh *et al.* 2002). The JHT work aims to extend the ETKF into the domain of TC forecasts, and it fits in closely with JHT priorities EMC-3 and TPC A-5.

2. Timetable in Year 1

The timetable specified by JHT personnel on October 28, 2003 is given in bold, with relevant achievements listed beneath each item.

Aug. 2003 - The 1-degree resolution operational ensembles up to 84h are prepared operationally at EMC and can be used by the ETKF. The scripts that run the GFS, GFDL, and SHIPS models without targeted observations are complete, and were used during the 2003 hurricane season.

Aug.-Nov. 2003 - Reliable ETKF sensitivity maps for planning of synoptic surveillance missions are to be produced.

The sensitivity maps have been computed for several tropical cyclones from 2003; details are given below in Section 3.

Jan. 31, 2004 - First year mid-term report

The following 3 paragraphs summarize the achievements listed in the mid-term report:

The 1° resolution NCEP ensembles through 84 h were made available daily at EMC in January (NOTE: as of May 2004, they are now available up to 180 h). The ECMWF ensembles of the same resolution have been archived at EMC since January 2004. Both these high-resolution ensembles are necessary to provide well-defined ETKF targets in the vicinity of the TC during the 2004 hurricane season. The 2.5° resolution ensembles are often too coarse for this purpose; however, they were the only ensembles available for the 2003 TCs past 84 h. NCEP and ECMWF ensembles at 2.5° resolution have been archived at EMC for these cases. (Toth, Holland and EMC personnel)

The scripts that are used to run the GFS, GFDL, and SHIPS models without targeted observations have been completed. They were used during the 2003 hurricane season, and updated versions will be used for all 2004 surveillance missions in which the NOAA, Air Force, and ASTRA aircraft obtain targeted observations. (Aberson)

The Ensemble Transform Kalman Filter (ETKF) targeting software on the IBM-SP was completely rewritten in Fall 2003. The efficiency of producing the ETKF targeting maps is now greatly improved, and software now provides a unified framework for targeting during Winter Storm Reconnaissance and TC surveillance. This unified framework will smooth the transition to operations, and its operational use on the IBM-SP. One can now easily insert extra subroutines that are necessary for tropical cyclone targeting, without disrupting the rest of the software. The new code was tested extensively during the Atlantic THORPEX Observing Systems Test (ATOST) in Fall 2003, and it can now be run for any arbitrary number of ensemble forecasts, at any resolution. Hence, there is much greater flexibility in the new ETKF software, compared with its predecessor which had been written specifically for Winter Storm targeting. (Majumdar)

Mar. 2004 - Present results at the Interdepartmental Hurricane Conference.
***** Completion of flight-track drawing software including documentation and training of TPC personnel in its use.**
***** Completion of comparative analysis of ensemble-spread targeting scheme versus uniform sampling scheme.**
***** Completion of original JHT Targeting final report.**

ETKF summary maps, a comparison with ensemble spread maps, and signal variance evolution maps were presented at the Interdepartmental Hurricane Conference in Charleston SC on March 4th 2004. Details are given in Section 3.

The three asterixed items have been reported on by Dr. Sim Aberson in his final report for the original JHT targeting project.

May 2004 - The specification of error statistics in ETKF to reduce spurious correlations will be modified. The ETKF will be run for past tropical cyclones. Synoptic assessments of ETKF target locations will be performed at the same time.

This is discussed below in Section 3.

May 15, 2004 - First year annual report and renewal proposal

Attached herewith.

Aug. 2004 - Extend ETKF to test verification norms of track and intensity. Test whether ETKF can predict reduction in forecast error variance.

The software has been developed on the IBM SP at NCEP to perform these tests. Preliminary tests have been performed using a 'track' verification norm for the 2003 TCs. Tests will be performed in real-time and disseminated on the Web for the 2004 TCs in which targeted observations will be taken.

3. Recent Results

The main priority of the current project has been to produce a version of the ETKF targeting strategy that gives sensible locations for objective targeting. The new strategy has been tested using 2.5° resolution NCEP and ECMWF ensembles, for the following TCs in which targeted dropwindsonde observations were collected during 2003: Claudette, Erika, Fabian, Isabel. Similar runs have also been performed for 1° resolution NCEP ensembles, although the data have only been available up to 84 h to date. Since the ensemble initialization time needs to be at least 36-48 h prior to the targeted observing time, the ETKF has only been run for targeted forecast times of 2 days or less (i.e. interval between targeting and verification times). Results are being (and will continue to be) disseminated on the following website, to ensure clear and rapid communication among all University, AOML, EMC and TPC personnel:
http://orca.rsmas.miami.edu/~majumdar/tc/

The ETKF predicts a quantity entitled 'signal variance', which gives the expected reduction of forecast error variance in a given verification 'norm' (e.g. wind speed, track, intensity) due to any particular set of targeted observations. An ETKF summary map shows the predicted signal variance for a specific TC forecast of interest, as a function of the observing location. Hence, the locations in which signal variance is highest represent

areas in which the ETKF suggests that targeted observations would be most useful for reducing TC forecast errors with respect to the given verification norm.

An ETKF summary map for Hurricane Fabian is shown in Fig. 1a. The aim is to identify locations for targeting on September 1, 2003, in order to reduce errors of a 2-day wind forecast in the vicinity of the TC. This wind velocity verification norm is the same as that used in Winter Storm Reconnaissance. A 20-member NCEP GFS ensemble initialized 24h prior to the observing time is used here (in practice, this time is 36-48h, but we needed to use 24h in this case given the limited time range of ensemble data in 2003). The summary map (blue shading) indicates that the dominant features for targeting are associated with deep layer easterlies on the south side of the subtropical ridge in which Fabian is embedded. The operationally-used ensemble spread map is shown for the same proposed surveillance time in Fig. 1b. In contrast to the ETKF summary map, the area of maximum ensemble spread is located within an upper-level trough over the continental United States. The ensemble spread map knows nothing about the forecast of interest, and merely locates the region in which there is most uncertainty in NCEP's bred-vector ensemble forecast. In the current objective technique, the ensemble spread maximum closest to the TC is chosen as the region to target.

The corresponding ETKF summary map and ensemble spread map are presented for Hurricane Isabel in Figures 2(a) and 2(b) respectively. The aim is to reduce wind errors in a 2-day forecast of Hurricane Isabel, by taking observations on 14 September 2003. As with Fabian, the ETKF summary map indicates that the subtropical ridge is the preferred region for targeted observations to be collected. The ensemble spread map shows a similar region, and some other regions are also more strongly emphasized in the ensemble spread compared with the ETKF (for example, the cut-off low off the Carolinas). Further synoptic interpretation of the importance of features such as the cut-off low is part of ongoing work this summer.

One initial concern with the ETKF is that spurious long-distance correlations between variables may be produced, due to the limited number of available ensemble forecasts. Using theoretical considerations and by inspecting the summary maps, these long-distance correlations only act to make the ETKF summary maps resemble the ensemble spread. Hence, based on these considerations, targeted observations selected using the ETKF are expected to perform at least as well as targeted observations selected using the ensemble spread. In reality, this statement cannot be guaranteed due to errors in the observations, vortex initialization scheme, background error covariance matrix specified in the operational data assimilation scheme, and the operational forecast model.

Moreover, it has been shown by one of the PI's (Aberson) that the influence of the targeted data on the NCEP GFS analysis and forecast (i.e. the evolving 'signal') can spread out over long distances in a short period of time. Hence, the fact that the ETKF produces long-distance correlations is not necessarily incorrect. Further studies along these lines are being conducted in summer 2004, for all the tropical cyclones in which targeted observations are being (or have been) taken.

The evolution of the 'signal' in the NCEP GFS analysis and forecast produced by targeted observations was mentioned in the previous paragraph. It is the variance of this quantity that the ETKF attempts to predict. Fig. 3(a) shows the ETKF prediction of the variance of the signal evolution based on the dropwindsonde locations from the G-IV synoptic surveillance mission on 14 September 2003. The signal variance is predicted to be maximal in the vicinity of Hurricane Isabel, and it is forecast to spread out away from the TC over the following 48h after the observation time. Fig. 3(b) shows the actual NCEP GFS signal evolution from the G-IV flight plus a C-130 flight that took place at the same time. (Note: the C-130 dropwindsonde release locations were not easily available at the time of writing). In addition to qualitative comparisons such as Fig. 3, quantitative tests of the ETKF's ability to predict signal variance will also be made for all targeting cases in 2004 (using the techniques of Majumdar *et al.* 2001).

In addition to the verification norm of wind speed shown in Figures 1-3, the ETKF software is being extended to test verification norms of track and/or intensity. The NCEP GFS, GFDL and SHIPS models are being tested. It now takes very little time to compute the maps shown in Figs. 1-3, since the ETKF software is nearly fully automated.

4. Work plan for Summer 2004

The 1° resolution NCEP GFS and ECMWF ensembles are now available daily at EMC up to 180h. Furthermore, the number of NCEP GFS ensemble members available daily has recently doubled from 20 to 40. Due to the availability of many more ensemble members out to longer forecast times, significant improvements in the ETKF outputs are likely for the upcoming 2004 cases. The high-resolution NCEP and ECMWF ensembles will be used to test the ETKF for all 2004 Atlantic and Northwest Pacific tropical cyclones in which synoptic surveillance missions are planned. It is also possible that the Canadian Meteorological Centre ensemble will be available at EMC for testing by this time. The ETKF maps will be run in real-time by Drs Majumdar, Etherton and Aberson, and they will be disseminated on the website http://orca.rsmas.miami.edu/~majumdar/tc/.

In addition to regular communications with TPC personnel, the PIs currently have communication with personnel in Taiwan (Dr Chun-Chieh Wu) and will be advising on this year's DOTSTAR typhoon surveillance missions. Moreover, communication of targeted observations in the environment of typhoons has recently been established with the Japanese Meteorological Agency.

A summary of the work plan between May-August 2004 is given below:

1. Increase number of NCEP GFS members in the ETKF software to 40 (Majumdar)
2. Finish synoptic interpretations of ETKF summary maps and signal variance maps for 2003 cases (Etherton, Aberson)
3. Finish extension to new verification norms (Etherton, Majumdar)
4. Continue to investigate long-distance correlations (Etherton, Aberson)
5. Produce real-time ETKF summary maps for all 2004 season targeting cases in Atlantic and Northwest Pacific, display on Web (Majumdar, Etherton, Aberson)
6. Provide parallel 'signal' plots for 2004 cases using NCEP GFS model (Aberson)

5. Year 2

A near-satisfactory version of the ETKF for planning synoptic surveillance missions is already available. The main goal of Year 1 has been to develop the software to provide ETKF summary maps, whose locations are at least as sensible for targeting as the benchmark of operational ensemble spread maps. By August 2004, the extensions and tests listed in the previous Section will have been completed for the few available 2003 cases and the 2004 cases to date. Consistent with the initial proposal and timelines for this JHT project, the following tasks will be completed in Year 2:

(a) Continued runs and tests of the ETKF for tropical cyclones in 2004, using 1-degree resolution ensembles for a variety of forecast times (Majumdar, Etherton, Aberson)

(b) Coupling of the ETKF code with flight track design software designed by Dr Sim Aberson under a recent JHT grant (Etherton, Aberson)

(c) Quantitative tests of the ETKF's ability to predict signal variance, for all available TCs in which synoptic surveillance missions took place (Majumdar, Etherton, Aberson)

(d) Evaluation of whether the targeted observations collected in regions deemed important by the ETKF were at least as beneficial as targeted observations collected in regions deemed important by the ensemble spread (note: these regions often coincide). The parallel NCEP GFS analysis-forecast cycles will be used for this task. It is anticipated that this evaluation will also be conducted in 2005 to increase the sample size (Aberson, TPC personnel)

(e) Full automation of ETKF software on the IBM-SP supercomputer at EMC. Training of EMC and TPC personnel on the software and interpretation of the ETKF products (Majumdar, Etherton, Aberson, EMC and TPC personnel)

As Year 1 has gone to plan, no revisions to the Year 2 proposal or budget are required.

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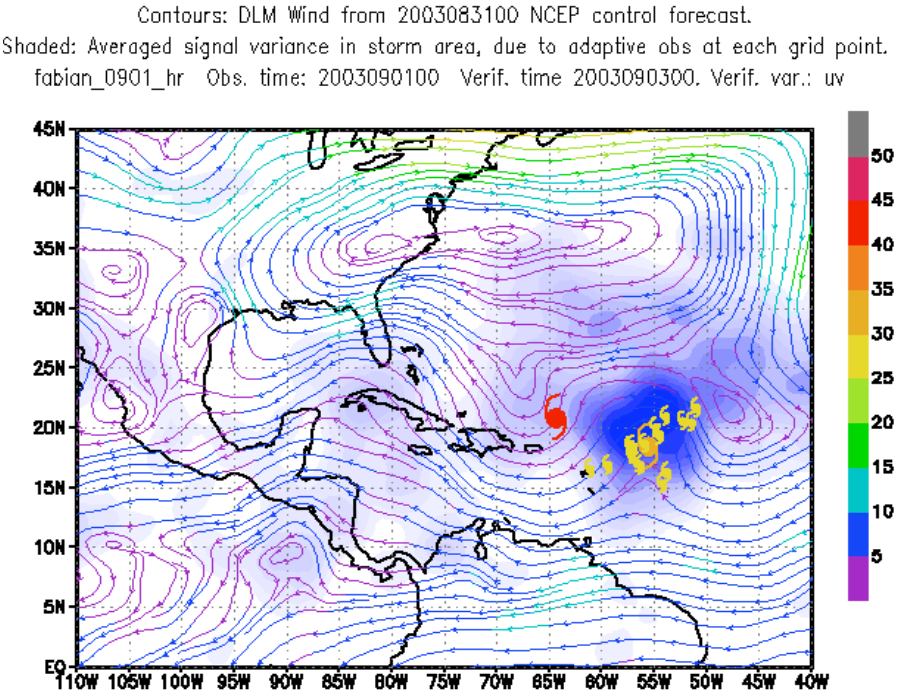
FIGURE 1: FABIAN. (a) ETKF Summary map. (b) NCEP GFS ensemble spread. Yellow hurricane symbols represent the NCEP GFS ensemble forecast tracks at the targeted observing time. Orange and red hurricane symbols represent the ensemble mean track forecast, valid at the targeted observing and verification times respectively.

(a)



(b)

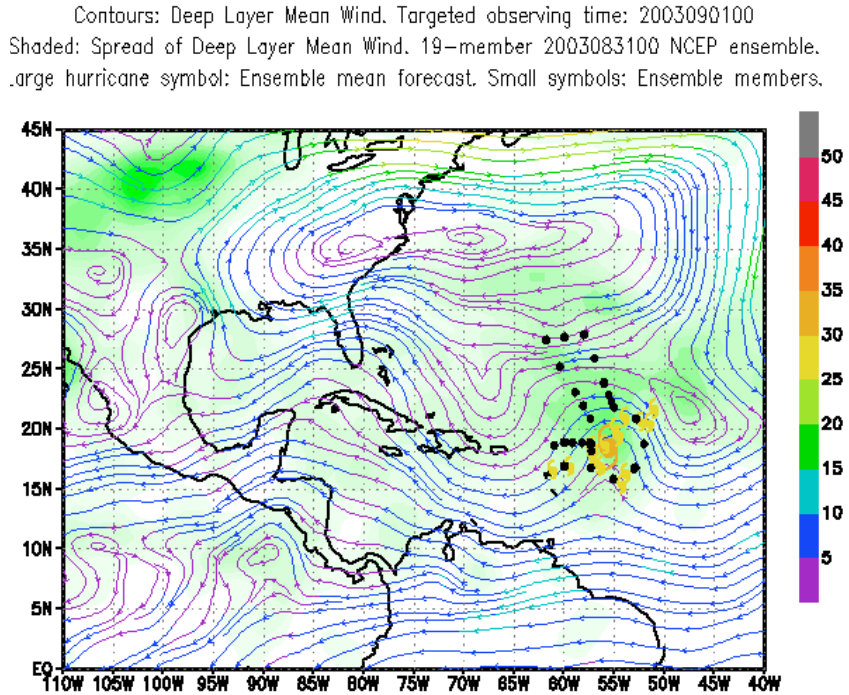


FIGURE 2: ISABEL (a) ETKF Summary map. (b) NCEP GFS ensemble spread. Yellow hurricane symbols represent the NCEP GFS ensemble forecast tracks at the targeted observing time. Orange and red hurricane symbols represent the ensemble mean track forecast, valid at the targeted observing and verification times respectively.

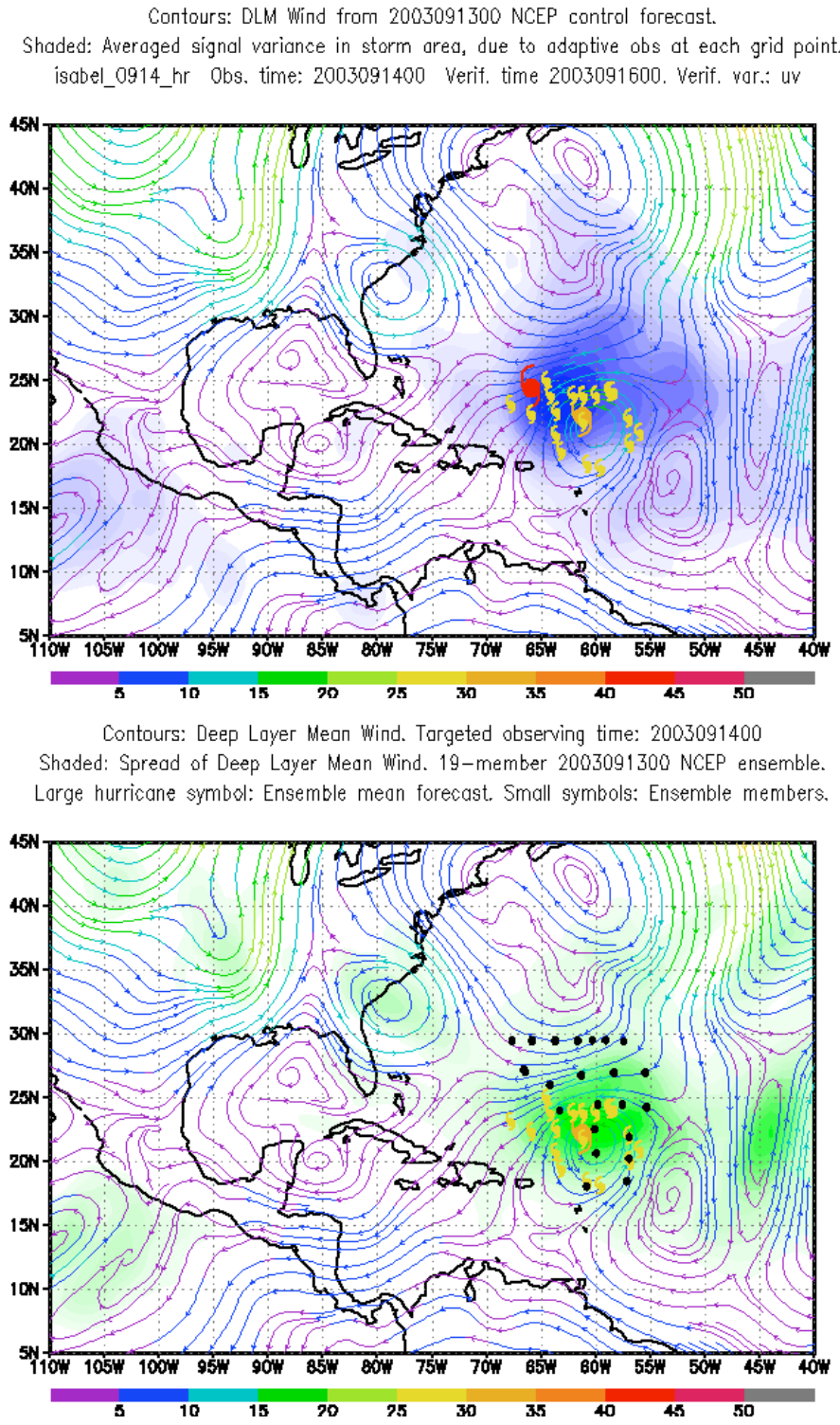


FIGURE 3: ISABEL

(a) Left column: ETKF predicted evolution of signal variance due to targeted wind observations (locations shown as black dots) at +00h, +24h and +48h after the targeted observation time of 00Z, September 14th 2003. Results use a 20-member, 1 degree resolution NCEP GFS ensemble initialized at 00Z, September 13th 2003.

(b) Right column: Evolution of operational signal of deep layer mean wind, given by the difference between two parallel NCEP GFS analysis-forecast cycles initialized at 00Z, September 14th 2003.. One cycle ('operational) uses all available observations, whereas the other ignores the targeted observations ('control').

(a) (b)