14A.2 Validation of TC-LAPS Structure Forecasts of Some Significant 2004-2005 US Hurricanes

Noel E. Davidson, Lawrie J. Rikus, Richard A. Dare, Chris I. W. Tingwell and Harry C. Weber[#]

Bureau of Meteorology Research Centre, PO Box 1289K, Melbourne, Australia. 3001
[#]Meteorological Institute, University of Munich
Email : n.davidson@bom.gov.au

Introduction

The Australian Bureau of Meterology's Tropical Cyclone Limited Area Prediction System (TC-LAPS, Davidson and Weber, 2000) has been operational over the Australian Region and northwest Pacific since 1999. Forecast verification has been encouraging and has generally improved throughout the period. Long-term mean track and intensity errors at 48 hours are ~261 km and 22 hPa. Some remarkable forecasts of intensity have been obtained, but the quality tends to be inconsistent, suggesting that the system is capable of making skilful intensity forecasts, but the skill is often limited by errors in either initial vortex structure or the large-scale environment. For the present study, we have implemented a configuration of TC-LAPS over the North Atlantic to: (a) validate the system with the more comprehensive data sets available to define vortex structure and the large-scale environment, (b) determine which component of the system is most in need of enhancement, (c) revisit the TC initialization problem at higher resolution, and (d) develop an archive of validated high-resolution forecasts that can be used to investigate TC structure change.

To validate TC-LAPS, we have made 39 forecasts for 7 significant US hurricanes, Charley, Ivan, Frances, Jeanne, Katrina, Rita and Wilma. The forecasts were run in real-time mode, equivalent to 8 hours after the base time, and as such may be considered as late forecast guidance.

TC-LAPS has 5 main components:

1. Data assimilation, to build from conventional observational data, the large-scale environment and outer structure of the storm. (assimilation resolution is 0.375^0 latitude-longitude on 29 sigma levels.)
2. TC vortex specification, to construct the inner-core, impose asymmetries consistent with the past motion, and to re-locate the circulation to its observed position.
3. High resolution objective analysis, to insert the specified TC circulation into its large-scale environment via the use of synthetic observations.
4. Initialization, to re-define the vertical motion field to be consistent with the satellite cloud imagery, build the secondary circulation, and initialize (balance) the vortex.
5. High-resolution prediction, to make the forecast with the generalized LAPS model (Puri et al., 1998), which includes advanced numerics and sophisticated parameterizations. (Current operational resolution in steps 2 to 5 is 0.15^0 latitude-longitude on 29 sigma levels.)

Standard Verification

Table 1 shows verification statistics of track and intensity for the forecast sample. Note that a simple correction to the intensity forecasts has been made by adding on the difference between the initialized and observed intensity at t = 0 to all subsequent forecasts. Comparisons with 10-year mean NHC forecast errors suggest the results are encouraging. The sample is small and further comparisons are not homogeneous, however the track errors are similar to, to somewhat larger than the 2004 single year NHC means of 58, 101 and 151 nm at 24, 48 and 72 hours. *The increase in error relative to NHC, as forecast duration increases may be indicative of the need for improved data assimilation and hence prediction of the environmental flow at longer lead times.*

Forecast Duration (hrs)	**0**	**24**	**48**	**72**
#Forecasts	39	39	34	27
MDPE (nm)	5	54	104	169
MAIE (knots)	0	12	16	20

Table 1. Verification statistics for forecast sample. MDPE is Mean Direct Position Error in nm. MAIE is Mean Absolute Intensity Error in knots.

Specific examples, which illustrate two of the high quality forecasts, are shown in Fig. 1. For these cases the estimated intensities, past motion and structure (the latter is not illustrated here) were preserved during initialization, possibly suggesting that at least short-term forecast skill would be high.

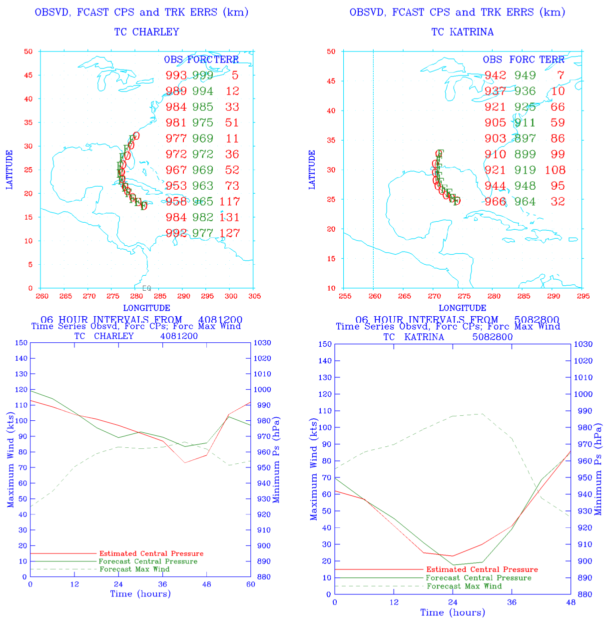

Figure 1: Observed and forecast tracks and intensities for Charley (left panels) and Katrina from base times 00 UTC 12 August 2004, and 00 UTC 28 August 2005, respectively. Column values in upper panels show observed and forecast central pressures in hPa and track errors in km.

Initialization

Figure 2 shows for Katrina at 00 UTC, 27 August 2005, the network of conventional wind observations at 850 hPa overlain on the analyzed wind field, for (a) analysis with synthetic vortex and (b) large-scale analysis without synthetic vortex. Some size differences and inconsistencies at small radii are evident between the conventional observations and the synthetic vortex. The system currently uses the Holland (1980) profile and our results are generally consistent with Willoughby and Rahn (2004), who document some systematic differences between the idealized vortex and observations. The differences and the inhomogeneity of the conventional observational network sometimes cause the objective analysis to produce poor vortex structures (and accordingly poor forecasts) if both the synthetic and conventional observations are used. The synthetic observations are thus forced to over-ride the conventional observations in the analysis at small radii to at least produce a consistent structure. *Techniques to improve the synthetic vortex structure and to fit the available conventional observations are being developed.*

The worst forecast in the sample was for Wilma from 00UTC 21 October 2005 and is shown in Fig. 3. The forecast system was unable to initialize the vortex at the t = 0 intensity estimate and failed to forecast the motion change and acceleration to the northeast beyond 48 hours from this base time. The case highlights the need for improved vortex specification and prediction of the large-scale environment via improved data assimilation.

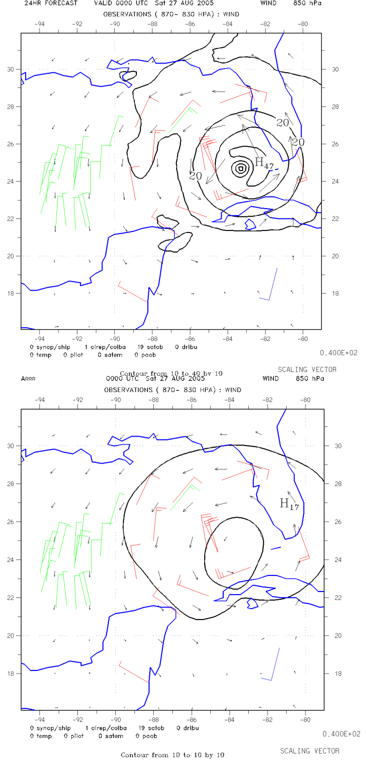

Figure 2. 850 hPa wind analysis valid 00UTC 27 August 2005, with and without synthetic vortex. Units are ms^{-1}, and contour interval is 10 ms^{-1}.

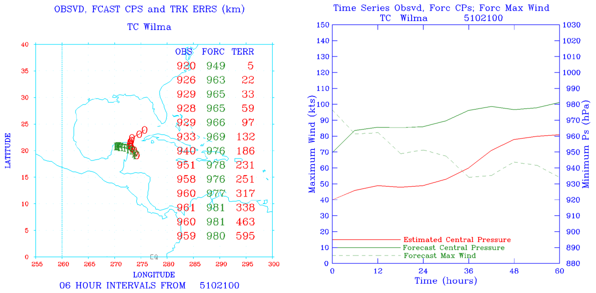

Figure 3: Observed and forecast tracks and intensities for Wilma from base time 00UTC 21 October 2005. Column values in the left panel show observed and forecast central pressures in hPa and track errors in km. Dashed line in right panel shows forecast maximum wind in knots.

Structure

Some aspects of the forecast low-level structure are illustrated in Fig. 4, which shows the 24-hour forecast and verifying large-scale analysis of mean sea level pressure for Katrina at the valid time of 00UTC 28 August 2005. Comparison of the region enclosed by say the 1000 hPa isobar suggests that, in this case, the size of the forecast (and initialized) storm was slightly too large. *Refinements to the size and radial structure of the specified vortex, and to the fitting of the conventional observations are works in progress.*

To further explore initialization and validate forecast structures we have run a series of 5 km forecasts for cases when the 15 km forecasts were particularly skilful (eg, see Fig. 1). These forecasts were (a) nested in the 15 km forecasts, (b) initialized from the 15 km analyses (with vortex specification included), as in step 4 above, (c) run using a Bulk Explicit Microphysics (Dare, 2004) without a convective parameterization, and (d) based on the hydrostatic formulation of the forecast model.

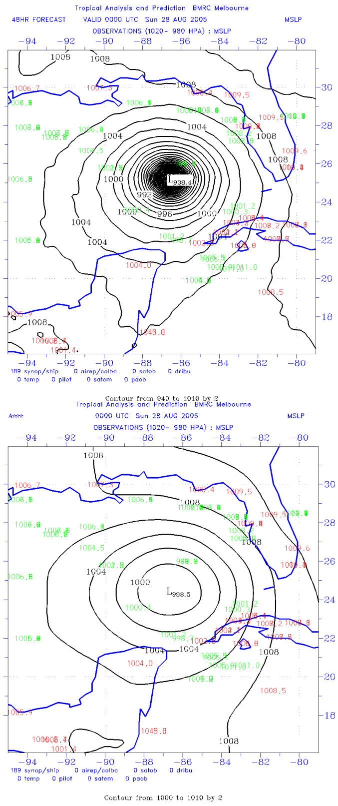

Figure 4: 24-hour forecast and verifying large-scale analysis of mean sea level pressure, overlain with conventional observations, for Katrina for valid time 00 UTC 28 August 2005. Contour interval is 2 hPa.

As part of our structure validation, we compare in Fig. 5 actual and synthetic cloud imagery obtained from the forecast (Rikus, 1997). The actual imagery is processed by calculating mean cloud top temperatures averaged over a 10 km square surrounding each grid point. The synthetic imagery is generated by a radiative transfer calculation with a spectral response function corresponding to the GOES IR channel and uses the cloud and thermodynamic fields directly from the model. Figure 5 shows for Charley, processed and synthetic imagery at valid time 1200 UTC 13 August 2004 (36 hour forecast), from a 5k forecast. The depiction of the scale, horizontal structure and evolution of the forecast cloudiness is quite encouraging. Similar quality is also evident at other forecast times and for the Katrina forecasts. More detailed validation of the cloud structures is ongoing.

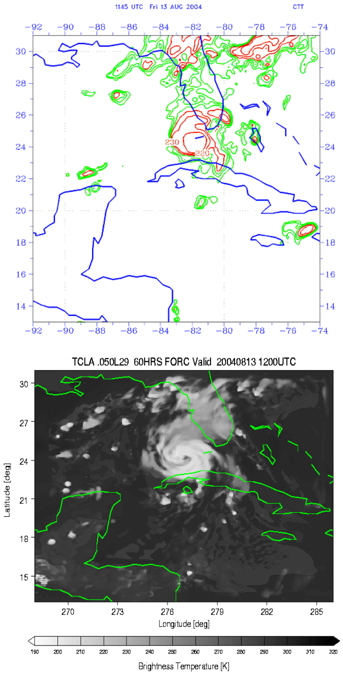

Figure 5. *Processed GOES imagery (upper panel)* and synthetic forecast cloud imagery for Charley at valid time 1200 UTC 13 August 2004.

Figure 6 shows from a 36-hour forecast for Charley, azimuthal-mean tangential and radial wind components corresponding to the imagery in Fig. 5 (lower panels). Of note are: 1. The RMW of ~ 35km, and radius to gales of ~ 200km, suggesting that the forecast was representing reasonably well the structure of this rather small storm; 2. the outward slope with height of the region of maximum winds; 3. *at small radii*, the inflow concentrated in the boundary layer, overlain by a deep layer of outflow; 4. *at outer radii*, deeper inflow overlain by a concentrated outflow in the upper troposphere; 5. outflow extending to beyond 300k from the center; and 6. upper convergence inside the RMW.

Finally, to illustrate an interesting feature of the horizontal structure at small radii, Fig. 7 shows the 500 hPa vorticity and vertical motion fields from the 36-hour forecast of Charley. The asymmetries in both fields, evident in the diagram, appear to be associated with convective bursts at small radii, which rotate in the flow and interact with each other and with the mean flow. Follow-up work is planned to validate these structures, determine if these asymmetries are manifestations of Vortex Rossby Waves, and to understand the role they play during intensification.

Summary

For the limited number of TC-LAPS forecasts made so far over the US, results have been encouraging. Not only does the observational network appear to provide more reliable analyses of the large-scale flow than in the Australian Region, but also the availability of reconnaissance data and ground truth for intensity and vortex structure, generally allows for specification of TC vortices which are more consistent with their environments. The competitive forecast quality from TC-LAPS over the US suggests the system is performing well in the Australian Region and at a skill level limited mostly by the observational network and the vortex specification.

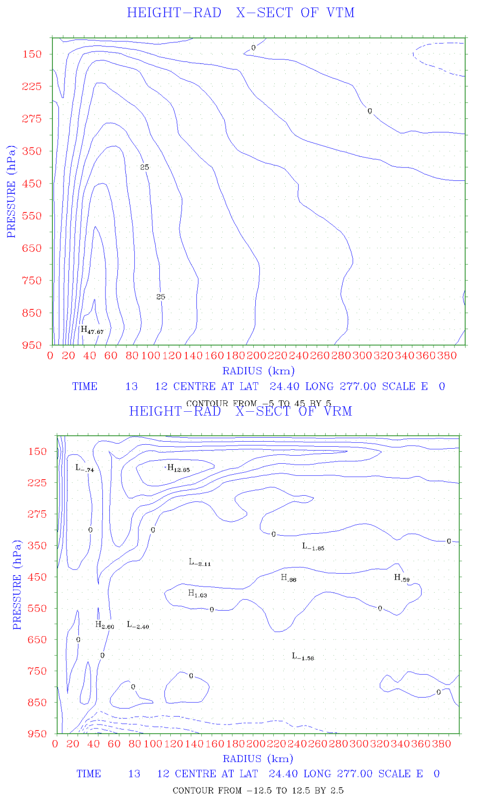

Figure 6: Height-radius sections of azimuthal mean tangential and radial winds from 36-hour forecast for Charley from base time 00UTC 12 August 2004. Contour intervals for tangential and radial winds are 5ms^{-1} and 2.5 ms^{-1} respectively.

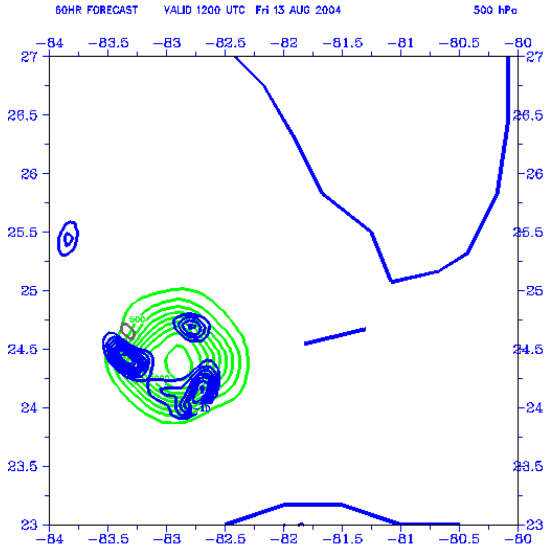

Figure 7: 36-hour forecast of 500 hPa vorticity (green) and vertical motion (blue is ascent, grey is descent), for Charley from base time 00UTC 12 August 2004. Contour Interval for vorticity is 250X10^{-6} s^{-1}, and for vertical motion is 5 Pa/s.

A number of operational and basic research projects are suggested by the preliminary validation presented here.

Based on the experiments, the main operational aspects that are being addressed for this forecast system are: 1. improved specification of initial vortex structure (size, intensity, horizontal and vertical structure, new surface level pressure profile and pressure-wind relationship), and 2. improved prediction of the large-scale environment via improved initial state specification from data assimilation.

More comprehensive validation is ongoing. Further model diagnostics to understand vortex motion, structure change and intensification will be the focus of strategic research on TC behavior. Use of observed and synthetic cloud imagery will form an important component of this work.

References

Dare, R.A., 2004: The BMRC Bulk Explicit Microphysics Scheme. *BMRC Research Report No. 99*, Bur.Met., Australia, PO Box1289, Melbourne, 3001.

Davidson, N.E. and H.C. Weber, 2000 : The BMRC high resolution tropical cyclone prediction system : TC-LAPS. *Mon. Wea. Rev.*, **128,** 1245-1265 .

Holland, G.J., 1980: An analytic model of wind and pressure profiles in hurricanes. *Mon. Wea. Rev.*, **112,** 1212-1218.

Puri, K., G.S. Dietachmayer, G.A. Mills, N.E. Davidson, R.A. Bowen and L.W. Logan, 1998: The new BMRC Limited Area Prediction System, LAPS. *Aust. Meteor. Mag.*, **47**, 203-223.

Rikus, L. 1997. Application of a scheme for validating clouds in an operational global NWP model. *Mon. Wea. Rev.*, **125**, 1615-1637.

Willoughby, H.E. and M.E. Rahn, 2004: Pararmetric representation of the primary hurricane vortex. Part I: Observations and evaluation of the Holland (1980) model. *Mon. Wea. Rev.*, **132,** 3033-3048.