Realistic Simulations of Intense Hurricanes with the NCEP/NCAR WRF Modeling System

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1. Introduction

A long-standing problem in atmospheric sciences is the prediction of hurricane intensity. The forecast of hurricane track has improved steadily during the past three decades (Goerss 2006), mainly following the improvements in global models. Improvement in coarse-resolution models with grid increments of a few tens of kilometers has had virtually no effect on the prediction and representation of hurricane intensity. The primary reason for the slower progress was stated in Marks et al. (1998), that track prediction depends more on large-scale processes, and intensity depends on the inner-core dynamics and its relationship to the environment. That is, intensity is a multi-scale problem.

Only recently has the computational capability to address multiple scales of convection (cell-scale, mesoscale and synoptic-scale) been achieved. The requirement to resolve the inner core, including the eye wall, the eye and inner, spiral rain bands near the eye wall, has led to the application of models with grid lengths of only a few kilometers. One such model is the Weather Research and Forecasting model (Michalakes et al. 2005, Skamarock et al. 2005) is a non-hydrostatic mesoscale model designed for simulation and prediction of fine-scale atmospheric phenomena, emphasizing horizontal grid lengths of a few kilometers or less. The Advanced Hurricane WRF (AHW) is a derivative of the Advanced Research WRF model which maintains a moving nested grid system that allows local resolution of roughly 1 km or less, making it ideal for the prediction of the multiple length scales present in hurricanes ranging from the scale of outflow (1000 km or more) to the width of the eye wall (10 km).

The present paper illustrates the current state of intensity prediction from the perspective of multiple years of Atlantic hurricane forecasts (2004-2007). The objectives are to examine what benefits result from increasing model resolution to the point where the inner core, particularly the eye wall, is well resolved. This will be done from both a statistical perspective and investigation of multiple simulations for individual tropical cyclones. The emphasis will be on prediction of winds at 10 m altitude and what aspects of the hurricane wind field can be reasonably predicted and which seem beyond our current capability.

2. Wind forecasts for tropical cyclones during 2005

During the past four Atlantic hurricane seasons, the AHW model was run in real time and in retrospective mode to produce forecasts of hurricane track, intensity and structure out to five days lead time. During the 2005 hurricane season, AHW performed comparably to operational models using an innermost nest of 4 km grid spacing, with evidence of improved intensity forecasts beyond 1.5 days during the 2005 season relative to other forecast products.

Intensity and position forecasts from the AHW were verified against the best-track data from the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC) and were compared to several other forecast techniques for the same periods during the 2005 season (Fig. 1). The sample shown in Fig. 1 is homogeneous (i.e., all forecast techniques were initialized and validated at the same times as the AHW). Sample-size decreased from 34 at short time ranges to 19 at 72 h. As the forecast progressed, the relative skill of the 4-km forecasts increased for both position and intensity. Beyond 24 h, the position errors were smaller than either the official forecast or from the GFDL model. By 72 hours, the intensity forecast errors were smaller than for the other techniques shown in Fig. 1. By this time, the intensity bias in AHW4 was +4.5 ms^{-1} (not shown). For all other forecast intervals, intensity biases were smaller than 2 m s^{-1}.

Examples of near-surface wind-field forecasts for Katrina and Wilma (2005) (Fig. 2) indicate that many structural aspects were well predicted, but some systematic errors existed. For observed winds, the HWind product from the Hurricane Research Division of the Atmospheric, Oceanic and Marine Laboratory of NOAA was used. To facilitate comparison of forecast and analyzed winds, the position of the model storm center was shifted to the observed location. The variation of the radius of hurricane force winds (33 ms^{-1}) among the cases was generally well forecast as were major asymmetries.

A central aspect governing the intensity of hurricanes is the exchange of moisture, heat and momentum with the ocean surface. The default surface stress parameterization is based on the Charnock (1955) formulation in which the effective drag increases with wind speed into the hurricane-wind regime. For many reasons, this simple relation is unrealistic. A realistic treatment of surface drag would require a full wave model, but this is impractical for forecasts run in real time. An alternate drag formulation based on the high-wind wind-tunnel studies of Donelan et al. (2004) was also investigated. These results produced values of C_d lower than those from the Charnock relation for low winds with a linear increase up to a maximum near 0.0024 at about 35 ms^{-1}. The Donelan formulation, with less drag than the Charnock formulation, results in higher wind speeds (Fig. 3a) but also higher central pressures and a slightly larger eye wall radius. Each of these changes in storm characteristics represents an improvement in the simulation of Katrina. It must be pointed out that the real drag force on surface winds is determined by the time-evolving ocean wave spectrum, prediction of which requires a wave model (e.g., Chen et al. 2007). Therefore the drag parameterizations discussed above must be considered as crude representations of the bulk effects of waves in hurricanes.

The dependence of heat and moisture fluxes is generally unknown at wind speeds characterizing the inner core of a major hurricane. We have experimented with enthalpy exchange coefficients that either increase slowly with wind speed (Carlson and Boland 1978) or remain steady with increasing surface wind speed (Large and Pond 1981). The effect of using constant C_k =0.001 (as in the Large and Pond formulation) versus the slowly increasing formulation of C_k (to a value of about 0.0015) is more than a 10% reduction of wind speed (Fig. 3b).

A well-known modulating factor of hurricane intensity is the reduction of sea-surface temperature due to wind-driven ocean mixing. This process has the largest detrimental effect on hurricane intensity for storms moving slowly and over areas of low ocean heat content but which may have relatively high sea-surface temperatures prior to the arrival of hurricane winds. A complete treatment of the atmosphere-ocean interaction would require coupling of the AHW to a full ocean model[1]. For modeling ocean current changes to a hurricane, this is essential. But for predicting the change of sea surface temperature to the transient passage of the hurricane, and approximating the feedback to hurricane intensity, we have obtained reasonable results using a simple mixed-layer ocean model of the form derived by Pollard et al. (1973), but with the Coriolis force included to approximate the inertial oscillation of currents in the mixed layer. Near-inertial motions dominate the mixed-layer current response to hurricane passage on the time-scale of order one day (Price 1981). Emanuel et al. (2004) has demonstrated success in using a similar, simplified ocean formulation.

The mixed-layer ocean model requires specification of the surface stress at the top, an initial mixed-layer depth h_0, and a deep-layer lapse rate Γ. To compute the mixing-induced cooling in the AHW, and its effect on storm intensity, the model was initialized at 00 UTC 27 August for hurricane Katrina. The initial mixed-layer depth was set to 30 m everywhere, with Γ chosen to be 0.14 Km^{-1}. As expected, the swath of cooling was confined to the right of the storm track, with a maximum cooling of about 3.5ºC, similar to what was observed by satellite (AVHRR). The net effect of the ocean cooling on the maximum surface winds was a reduction of roughly 8 m s^{-1} prior to landfall (Fig. 3b). This reduction removed the overestimate of maximum wind at landfall that otherwise occurred.

3. Results from the 2007 Season

During the 2006 and 2007 hurricane seasons, the innermost nest of 1.33 km grid spacing was implemented in real-time forecasts. The 2006 season was noted for a series of hurricanes far out in the Atlantic that underwent a transition to frontal cyclone structure. Simulations of two of these storms, as well as several transitioning storms in 2005, appear in Davis et al. (2007).

The 2007 Atlantic hurricane season featured a total of 13 named storms (through October), two of which were Category 5 storms (Dean and Felix), two of which developed rapidly into hurricanes adjacent to land and quickly moved onshore (Humberto and Lorenzo) and the rest were tropical storms. During the season, forecasts were initialized at 00 UTC, and integrated to 120 hours, beginning from the GFDL initial conditions, using the NCEP GFS forecast lateral boundary conditions. For each case, the mixed-layer ocean model was run, wherein the mixed layer depth was treated as a surrogate for ocean heat content. Prior to each run, this parameter was reset to a value characteristic of the anticipated hurricane track. For high heat content such as found in the Caribbean, the parameter was set to 100 m, effectively removing ocean-surface cooling from wind driven mixing. Over the Gulf of Mexico and western Atlantic, the mixed layer depth was set to 30 m.

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[1] Coupling of the AHW to the Hybrid Coordinate Ocean Model (HYCOM, Bleck 2002) has recently been performed and is being tested on observed cases at this time.

A summary of forecast maximum intensity for six cases appears in Fig. 4. These were the cases for which at least two forecasts were run. It is apparent that the AHW was generally able to distinguish the storms that would not develop from the storms that developed into major hurricanes. The outlier to this was Gabrielle, for which the early forecasts dramatically over-predicted intensity. This was the only storm of the six that formed from an extratropical precursor rather than a tropical wave, and actually began its evolution as a sub-tropical storm.

Another facet of the results summarized in Fig. 4 was the relatively poor prediction of the first forecast for each case, particularly for Dean, Felix, Gabrielle and Karen. These forecasts were initialized before the system became a tropical depression, and generally prior to the incorporation of aircraft reconnaissance data into operational analyses. Some of the other large errors for Dean, Felix and Gabrielle were due to errors in track, particularly, where and when each storm made landfall. The early forecasts of Gabrielle had the storm remaining over the Gulf Stream for an extended period whereas the real storm came ashore in North Carolina. Exacerbating the forecast error for Gabrielle was a lack of vertical wind shear in the forecast whereas significant northeasterly shear was observed.

One may also discern from Fig. 4 that the temporal fluctuations in predicted maximum wind are typically greater than observed. Even in the weaker cases such as Karen, the highly asymmetric structure associated with strong vertical wind shear still contained locally strong winds in banded features near the center. The realism of details in the wind field cannot easily be verified in the absence of reconnaissance data, but precipitation patterns may be evaluated (Fig. 5b, c). Comparison between the Tropical Rainfall Measurement Mission (TRMM) precipitation radar image and the AHW instantaneous rain water concentration field (directly proportional to precipitation rate), indicates that the highly asymmetric structure and major rainbands are well-captured in this 26 hour prediction (valid 02 UTC 27 September, 2007). Shortly after this time, the rainband intensified and migrated around to the western side of the cyclone. Co-located with this feature was a transient velocity maximum, also on the west side (Fig. 5c) exceeding hurricane strength. This highly localized wind maximum was maintained, with some intermittency, for about 12 h. The feature cannot be confirmed from QUIKSCAT observations because the storm occurred between successive swaths of data. Features such as this are relatively common in the high-resolution simulations of other cases as well, particularly when storms are asymmetric. At issue is whether these small-scale features are realistic and if so, whether there is a substantive ocean wave response to such transients.

Other aspects of the wind distribution are important for characterizing the accuracy of the predicted wind field. Two that we examine here are the radius of maximum wind r_m and the integrated kinetic energy, the latter defined as in Powell et al. (2007) for the HRD Wind analyses (HWind). The former measures the scale of the inner core and therefore the area subjected to the extreme winds. The integrated kinetic energy, defined consistent with the HWind analyses as $I = \int_{dV} \rho U^2$, for $U > U_0$, where U_0 is either tropical-storm-force winds (34 knots, I_{TS}) or hurricane-force winds (64 knots, I_H), is a macroscopic measure of intensity. The volume of integration is the horizontal area covered by winds exceeding a given threshold, times the arbitrary depth of 1 m. Only forecasts for hurricane Dean are considered, because this storm had the longest period as a hurricane, and the longest period of data coverage.

The predicted radius of maximum wind decreases notably during the intensification phase of Dean on 14-16 August (Fig. 6, red and orange lines). It then slowly increases from a quasi-steady minimum near 20 km to more like 40 km prior to the first landfall on the Yucatan Peninsula at about 200 h (08 UTC 21 August). After that, the core collapses rapidly, leaving the shell of outer winds, some still over water. Rather than a gradual, monotonic increase of r_m, the HWind analyses indicate cyclic changes that are the result of two eye-wall replacement cycles. These are notoriously difficult to predict, and although individual forecasts contain evidence of rapidly fluctuating eye wall sizes and secondary eye walls in some cases, there is no coherent signal in phase with the observations.

The integrated kinetic energy forecasts and observations appear in Fig. 7. It is apparent that the AHW overestimates the kinetic energy in the mature phase of Dean during several successive forecasts. Thus, despite the realistic prediction of both the maximum wind and the radius of maximum wind, the total kinetic energy exhibits substantial errors. In this case, it is the winds at large radii (more than 100 km), that are in error, especially for I_{TS}. Note that I_{TS} in the observations does not reflect landfall. As long as the outer wind field remains over water, the collapse of the core is virtually irrelevant to this measure of intensity owing to the small area it occupies.

4. Model Initialization

An acknowledged deficiency in all hurricane forecast systems, including AHW, is a proper initialization of the hurricane and its surrounding environment. There are several examples in Fig. 4 in which it is obvious that significant discrepancies between winds in the observed storm and the model initial condition exist. These initial errors project well into the forecast, sometimes throughout the lifecycle of the storm. Most initialization methods prescribe a synthetic vortex whose structure only loosely resembles the real hurricane. The GFDL model initial condition that we use to initialized AHW also prescribes a quasi-idealized vortex obtained from an off-line integration of an axisymmetric version of the GFDL model. This vortex is then surgically transplanted into the initial state and blended with the observations around the storm (Bender 2005). The approach of synthetic-vortex initialization has recently been seen as an impediment to advances in data assimilation (Abersen 2003) because there is no guarantee that the vortex will be consistent with other observations. Clearly, a vastly improved initialization method is required to substantively advance the skill of short-term forecasts (< 2 days) of tropical cyclones and their attendant sensible weather as they approach land.

During the past decade, remote sensing technology using Doppler radars has advanced rapidly to the point where synthetic dual Doppler observations are now available in real time from reconnaissance aircraft (Marks, 2003). Storms threatening the coastline of North America are precisely those that are best sampled by airborne radars. These data are not being used in the operational prediction of hurricanes, but, in principle, the technology already exists to make of use these data.

Assimilation of airborne Doppler radar data is herein demonstrated for hurricane Jeanne (2004). Jeanne was chosen because it was a major landfalling hurricane whose intensity was poorly predicted by the real-time forecasts using the Weather Research and Forecasting (WRF) model. The primary reason for the poor prediction was deemed an inadequacy of the vortex intensity and structure in the initial condition of the model.

On the afternoon of 24 September, two days prior to landfall, Jeanne was surveyed with two NOAA P-3 research aircraft, each equipped with tail Doppler radars each having fore and aft conically scanning beams. Each antenna rotates about the longitudinal axis of the aircraft at an angle of about 20º. Where the two beams intersect, the two radial velocity measurements are translated into a horizontal wind vector. The spatial resolution is roughly 2 km, and the range is roughly 50 km on either side of the flight track.

To mimic real-time conditions, the data used in this study were obtained from the automatic editing and wind synthesis system used aboard the NOAA P-3 aircraft during flight operations. Each three-dimensional synthesized wind field represents data collected during one flight leg of the aircraft, typically lasting about ~ 30-40 minutes. To minimize the occurrences of erroneous vectors the data are heavily edited and filtered resulting in a ~ 50% reduction of data coverage. Because the data are collected over a period of 30 minutes or longer, the winds fields are advected to a common analysis time using the mean hurricane motion along with the flight level positional/heading information. The advected data are then used in the data assimilation scheme.

An example of the data used appears in Fig. 8a, showing time-space corrected winds centered on 1825 UTC 24 September. The flight track extends south-southwestward through the storm center. The circulation features the strongest winds on the north side of the cyclone, and the radius of maximum winds is about 75 km at this time.

The assimilation is performed using the WRF three-dimensional variational assimilation (3DVAR) system (Barker et al. 2004). The assimilation occurs on a domain of 4 km horizontal grid spacing, nested within an outer domain with 12-km spacing, but no assimilation is performed on the outer domain thus far. The observations, time-space corrected following the vortex, are assumed to be simultaneous. Thus, motions with periods less than roughly 30 minutes cannot be incorporated. The goal is the assimilation of the symmetric vortex and dominant low-azimuthal-wavenumber asymmetries.

A key to 3DVAR is the background error covariance matrix. At present, we are using statistics gathered from a series of short-range forecasts on the 4-km grid over a two-week period ending with the landfall Jeanne (00 UTC 27 September). Background errors are obtained by computing the difference between 24-h and 12-h forecasts valid at the same time, and covariances are accumulated over 16 forecasts. In practice, such forecasts would be routinely available if the model were running daily.

As is apparent from Fig. 8b, the addition of the radar observations was crucial for the initialization of a vortex with an intensity (and size) comparable to observations. Furthermore, the effect of these additional data persist for at least 24 h. This time scale is longer than is typically found for the incorporation of Doppler radar data for convection forecasting and may be attributed to the relatively long intrinsic period of this hurricane vortex (several hours versus tens of minutes). Not shown is the substantial reduction in position error realized using 3DVAR. However, this improvement resulted more from the incorporation of conventional observations than from radar observations. These results are consistent with the well-known result that hurricane track prediction is sensitive to synoptic-scale flow features (>1000 km scale) whereas intensity change has much more to do with the inner core structure of the vortex.

The initialization of hurricanes Katrina and Rita using Doppler radar data has also been investigated using the same 3D-VAR technique. From Fig. 9, it is apparent that the benefit of radar data to the initialization of Katrina is greater than that for Rita. Neither case shows quite the dramatic improvement from radar data as hurricane Jeanne, especially regarding the improvement in forecast lead time. The improvement lasted about 12-24 h in Katrina and even less in Rita. Possible reasons for the differences are that both Katrina and Rita were rapidly intensifying, so that just the tangential wind field is not enough to specify the state of the hurricane. In addition, the radar coverage for Rita was asymmetric owing to the aircraft path. Thus, no little information was available to the east of the center.

The significance of the above result is that the forecast of storm intensity, a notoriously difficult parameter to predict, is improved using 3DVAR alone, without use of a synthetic vortex, and the improvement lasts for at least one day into the forecast. The 3DVAR method is relatively inexpensive computationally and can easily be run in real time. Because we used only data available in real time, it appears that that a significant improvement of short-range intensity forecasts is possible using existing technology.

It is also suggested in Fig. 9 that the incorporation of the radar observations reduced the large variability of maximum wind early in the simulation compared to later times. In general, reduction of erroneous variability at early times, referred to as model “spinup”, is treated with data assimilation schemes that incorporate data over a time interval characteristic of the dynamics. Whereas 3D-VAR remaps data to a particular instant, methods such as four-dimensional variational assimilation (4D-VAR) minimize the mismatch between forecast and observation over a finite time window, usually at several hours for phenomena on scales of order 100 km (Park and Zou 2004). This allows a dynamical adjustment of the model to the data, minimizing the shock as the forecast begins.

5. Summary

The use of a nonhydrostatic mesoscale model (the Advanced Hurricane WRF model, AHW) for hurricane prediction has been investigated in the context of real-time prediction and restrospective simulations of observed hurricanes during the hurricane seasons 2004-2007. From these studies we can conclude the following:

a. A minimum grid spacing of roughly 1 km is capable of producing rapid intensification.
b. Rapid intensification is often not accurately predicted, apparently suffering from inadequate initialization of the hurricane.
c. Predictive skill seems particularly small in the earliest stages of intensification when the storm is not well organized and observations may be lacking.
d. Fine-scale structures are often produced in these simulations, but there is often no means of verifying their existence.
e. The model is able to distinguish storms that will become strong hurricanes from those that will develop weakly.

f. There is some tendency to over-develop weak depressions (cases not shown here).
g. Doppler radar-derived winds can drastically improve initial conditions, but more sophisticated assimilation methods are probably needed to make full use of the data.

Significant effort is ongoing to improve data assimilation methods for tropical cyclone initialization. Some promising methods include 4DVAR and ensemble data assimilation (the Ensemble Kalman Filter and related variants). The latter is actively being explored in the context of hurricane initialization (Chen and Snyder 2006).

Another avenue of current research is exploring horizontal and vertical resolution approaching “large-eddy” resolving scales of tens of meters. The AHW model can be integrated with a turbulence closure appropriate for such scales. The goals of these high-resolution simulations are to explore the intrinsic variability of the inner-core wind structures, particularly asymmetries in the eye wall.

Finally, the work discussed herein represents the state-of-the-art for atmospheric models not coupled to wave or ocean models. Longer term simulations, appropriate for dynamical seasonal prediction, or climate change projection of hurricane trends will clearly rely on coupling to full ocean models. From the point of prediction, an important area of investigation is the incorporation of wave models of minimum complexity and computational expense needed to model the asymmetries in hurricane wind-wave coupling that are well known. High-resolution simulations such as those addressed herein will be vital for resolving atmospheric processes beneath the eye wall thereby giving more realistic forcing of the couple atmosphere-ocean system than is possible at coarser resolution of order 10 km.

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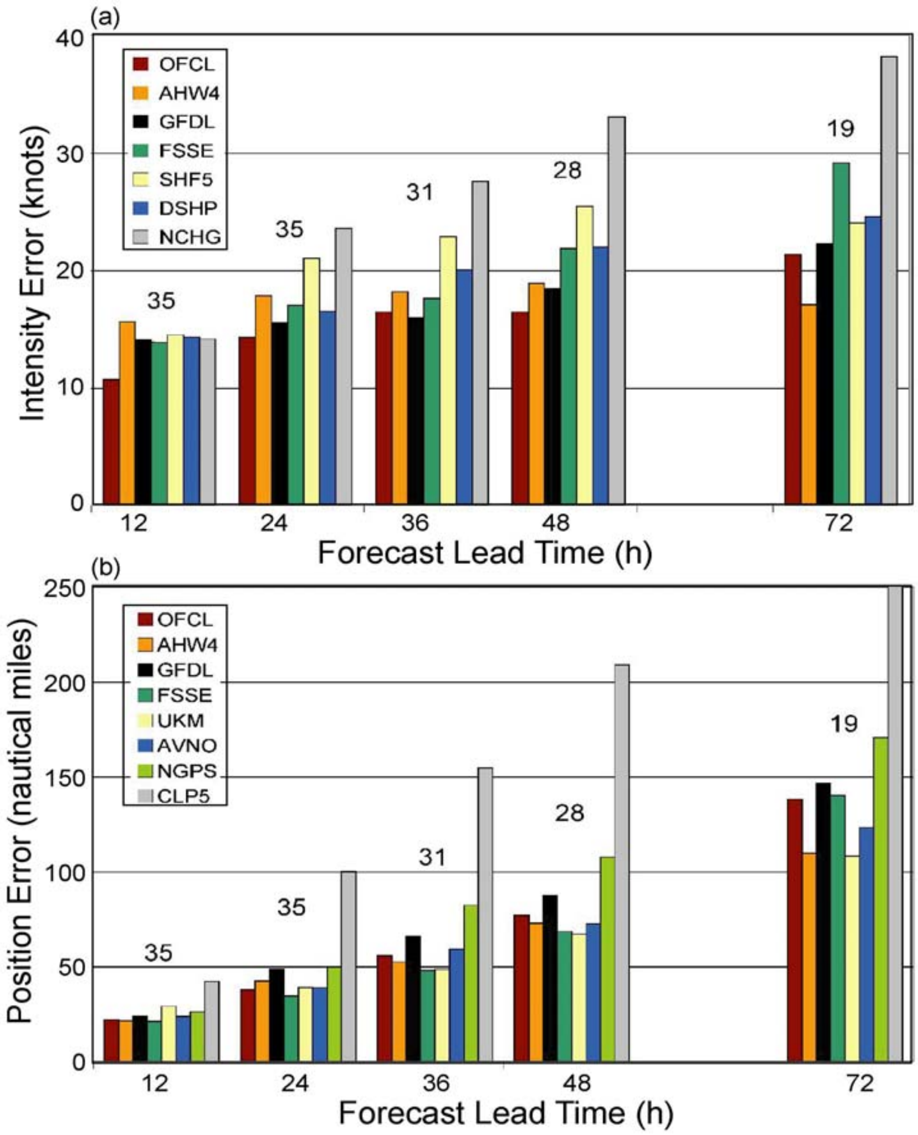


Figure 1. Intensity (knots) and position (nautical miles) errors for the AHW forecasts run with an inner moving nest of 4-km grid spacing during 2005. Results from other forecast techniques are defined as: The techniques are: Official (OFCL), AHW 4 km (AHW4), GFDL hurricane Model (GFDL), Florida University Super Ensemble (FSSE), the statistical SHF5 and DSHP techniques, the UK Met Office (UKMO), the NCEP Aviation Model (AVNO), the Navy NOGAPS model (NGPS), the statistical CLIPER (CLP5) and no change (NCHG). Sample sizes appear above each set of color bars.

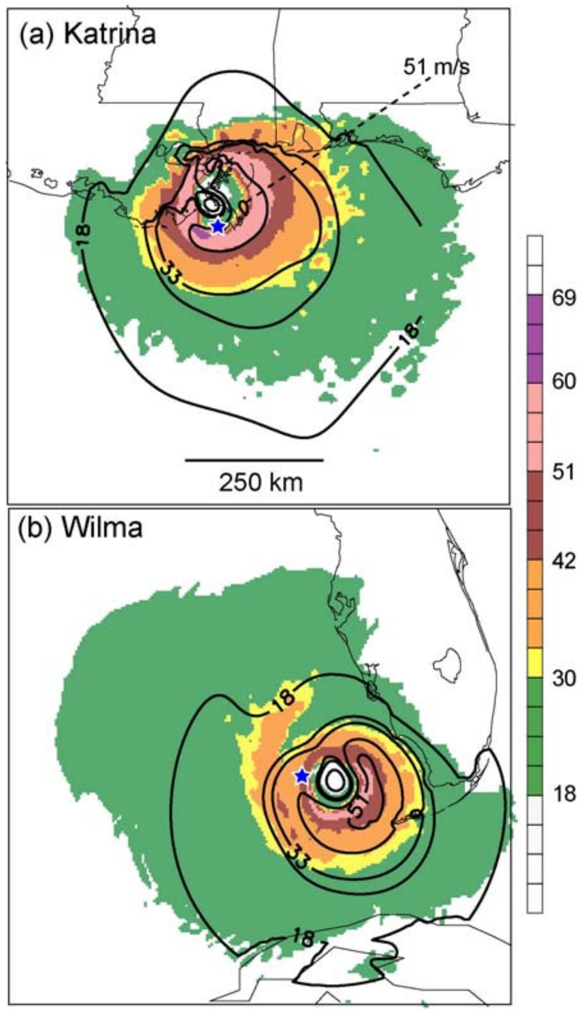
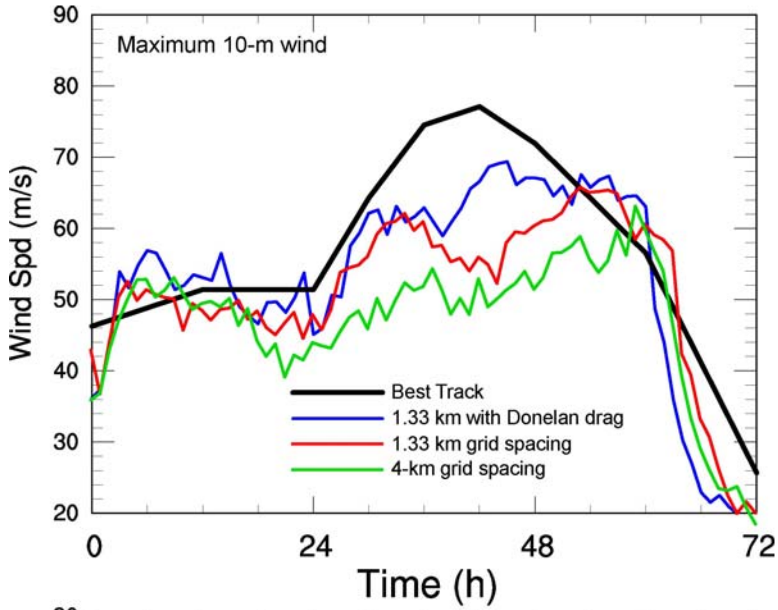


Figure 2. 10-m wind from AHW real-time forecasts performed during 2005, with contours of HWind analyses overlaid. Predicted storm center location at indicated valid times (below) is denoted by blue star in each figure. Wind field from AHW forecasts have been shifted to observed locations to facilitate comparison. Model valid times are (a) Katrina, valid time = 1200 UTC 29 August (60-h forecast); (b) Wilma, valid time = 0900 UTC 24 October (69 h forecast). HWind valid times are (a) 1132 UTC 29 August and (b) 0730 UTC 24 October.



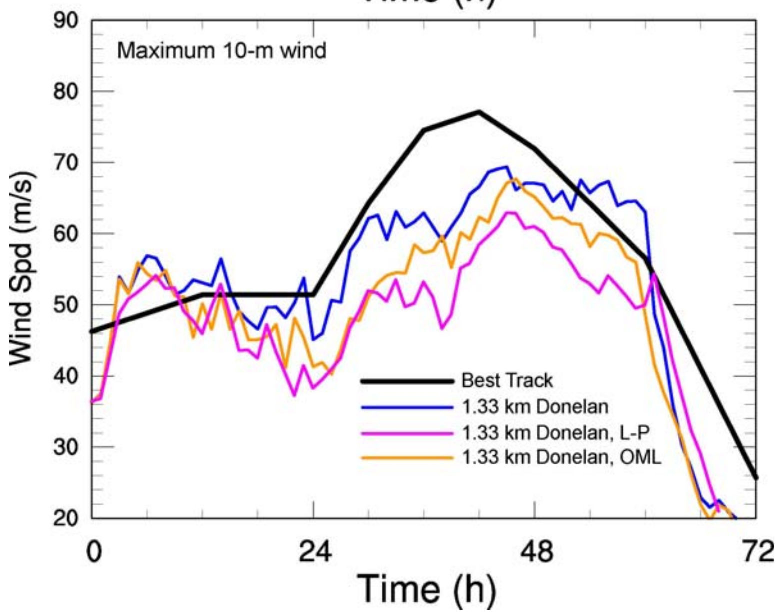


Figure 3. (a) Maximum 10-m wind for forecasts of Katrina beginning 00 UTC 27 August. The green curve denotes the forecast integrated with an finest grid increment of 4 km. The red curve denotes a forecast integrated with a 1.33-km innermost grid spacing and the default (Charnock) drag, whereas the blue curve shows the results with the Donelan drag formulation with the 1.33-km finest grid spacing; (b) as in (a) but showing maximum wind forecast using the Large and Pond enthalpy flux (magenta) and with the Carlson and Boland enthalpy flux with the ocean mixed layer active (orange). All time series in (b) are derived from simulations with innermost grid spacing of 1.33 km initialized with GFDL. Heavy black line denotes best track data in (a) and (b)

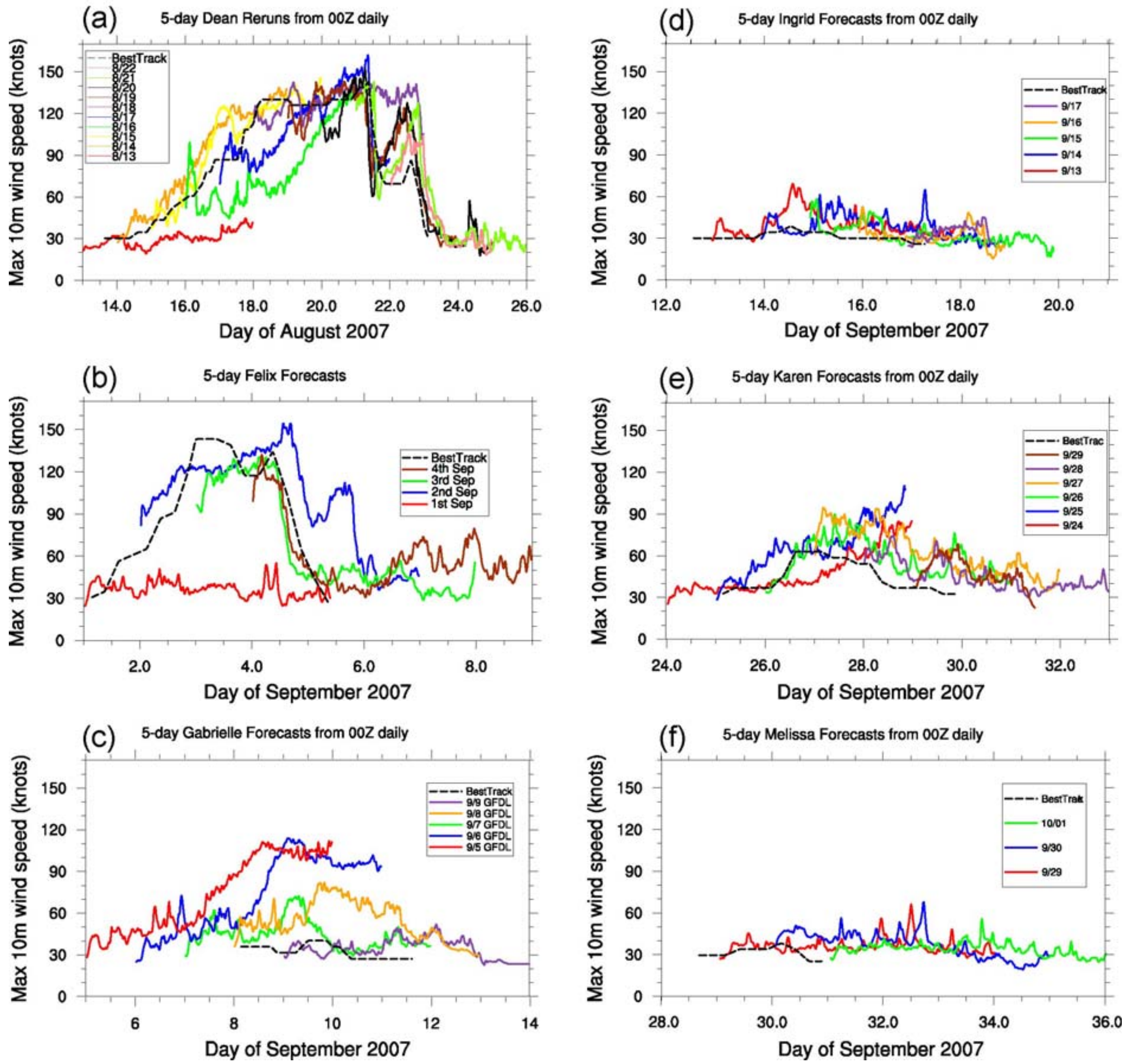
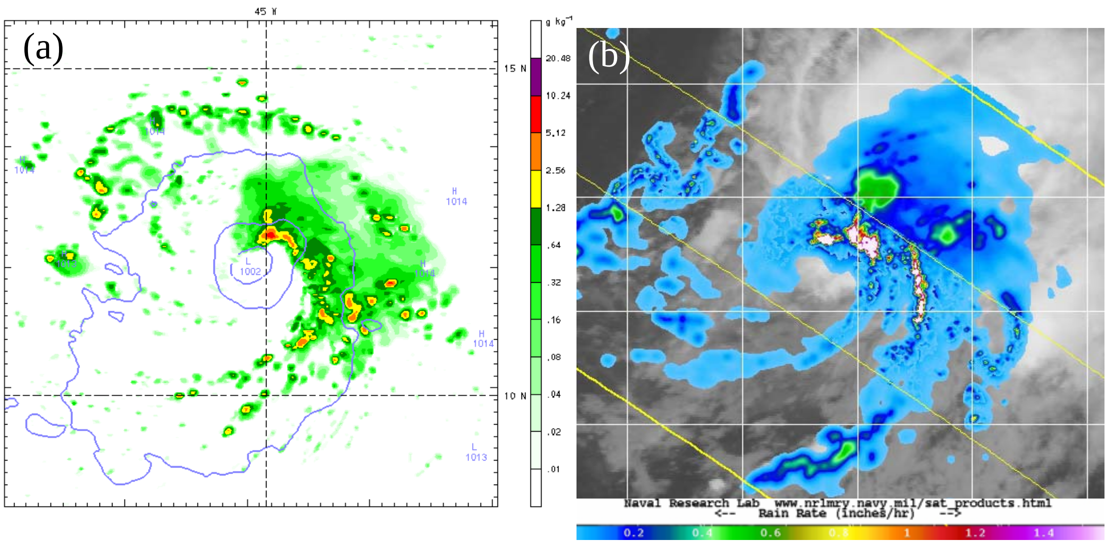


Figure 4. Maximum sustained (knots) wind from best-track data (black, dashed) and from forecasts of six storms during the 2007 season. Colors are used to distinguish forecasts but have no specific meaning (except that red lines denote the first forecast for a particular storm); (a) Dean; (b) Felix; (c) Gabrielle; (d) Ingrid; (e) Karen; and (f) Melissa.



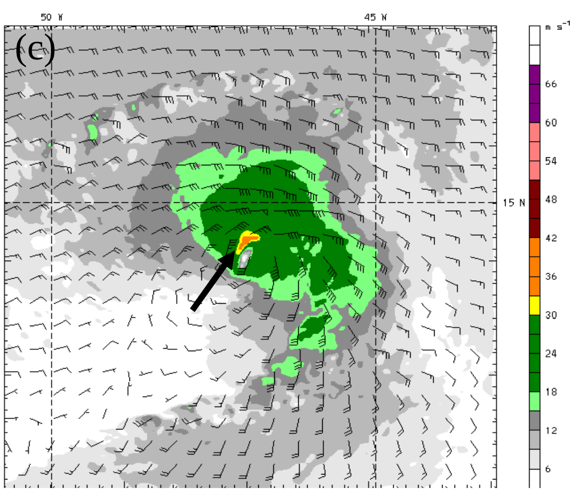


Figure 5. (a) total rain water mixing ratio value 02 UTC 27 Sept. (note 1.2 g kg^{-1} ~ 1 in. h^{-1} assuming a terminal velocity of rain of 6 ms^{-1}), and sea-level pressure (contour interval = 4 hPa); (b) TRMM precipitation radar from 0119 UTC 27 Sept. (scale in inches per hour); (c) wind at 10 m predicted by AHW at 18 UTC 27 September. Model fields have been averaged to a grid increment of 4-km from 1.33 km. Domain is 800 km x 800 km.

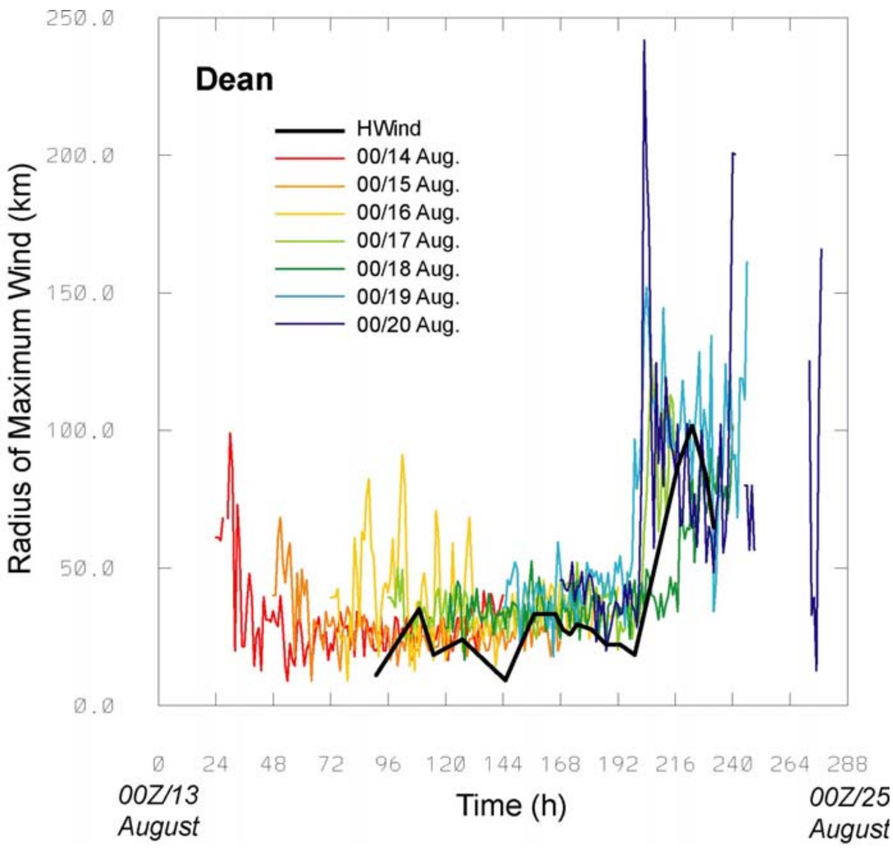


Figure 6. Time series of radius of maximum wind (r_m) from multiple forecasts of Dean, initialized 24 h apart (colors) and rm based on HWind analysis (black). Units are km. Forecast initialized 00 13 September does not appear.

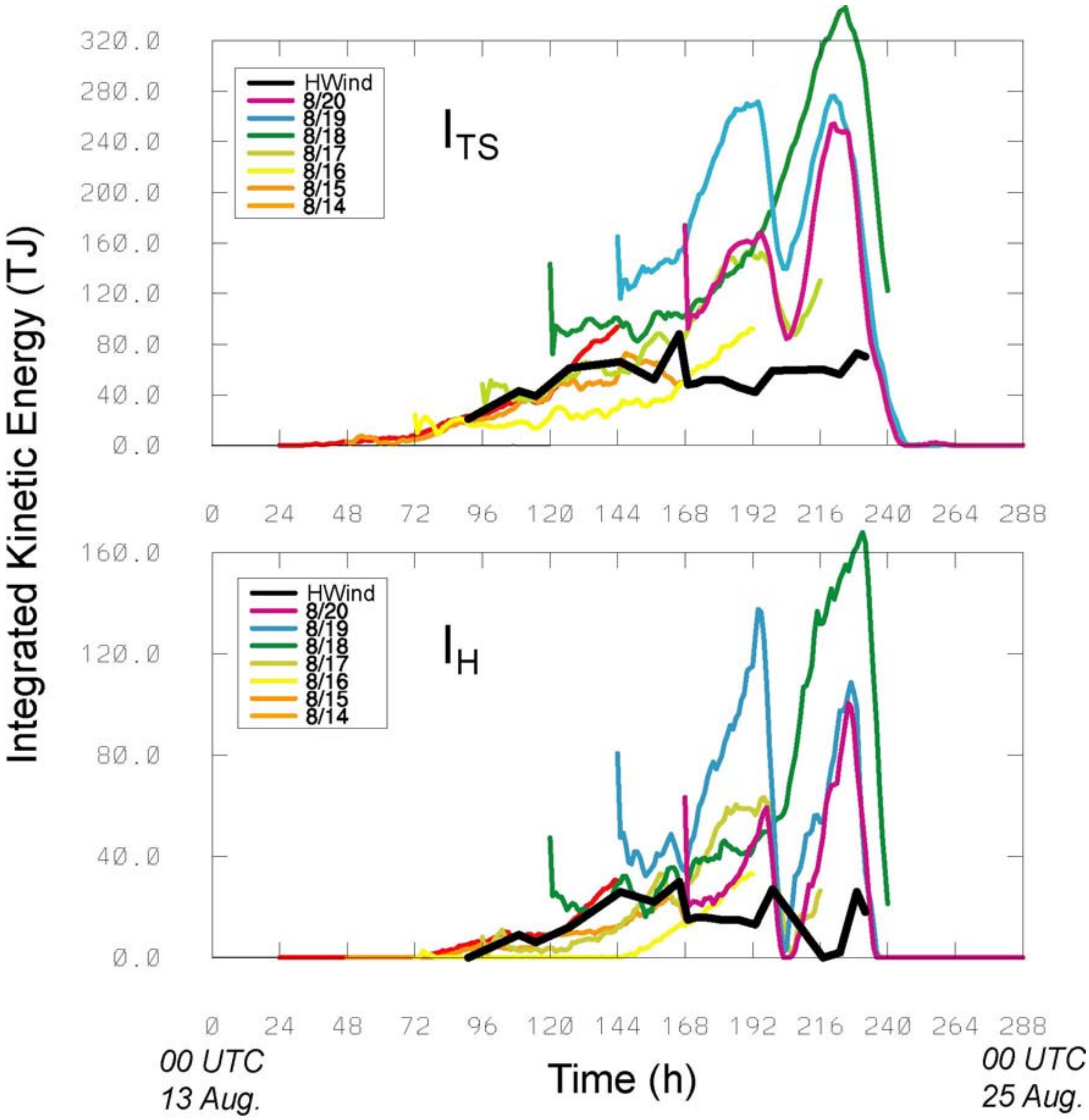


Figure 7. Integrated kinetic energy for (a) tropical storm and (b) hurricane wind speed thresholds for forecasts of hurricane Dean. Units are TeraJoules (TJ). Forecast initialized 00 13 September does not appear.

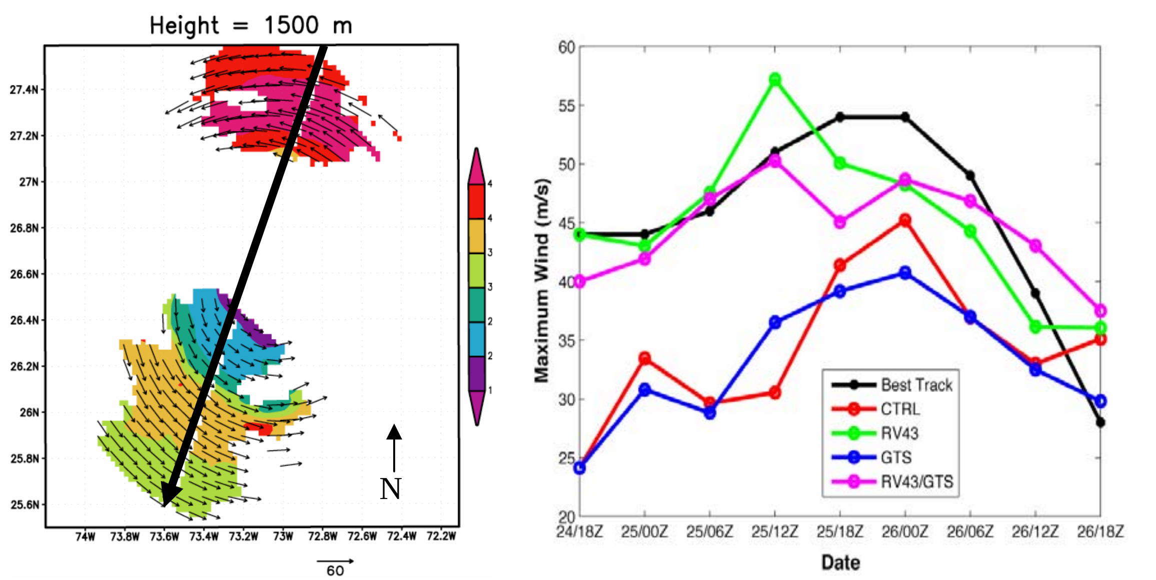


Figure 8. (a) Time-space corrected Doppler-derived winds from the NOAA-43 aircraft centered on 1825 UTC 24 September. The flight track is indicated by the heavy black line; (b) Maximum sustained wind at 10 m AGL as a function of forecast length for simulations initialized at 18 UTC 24 September (black = observations from the National Hurricane Center; red = forecast without data assimilation; blue= forecast assimilating only conventional surface and sounding data; green = assimilation of NOAA 43 radar-derived winds only; purple = assimilation of conventional data plus NOAA 43 radar winds).

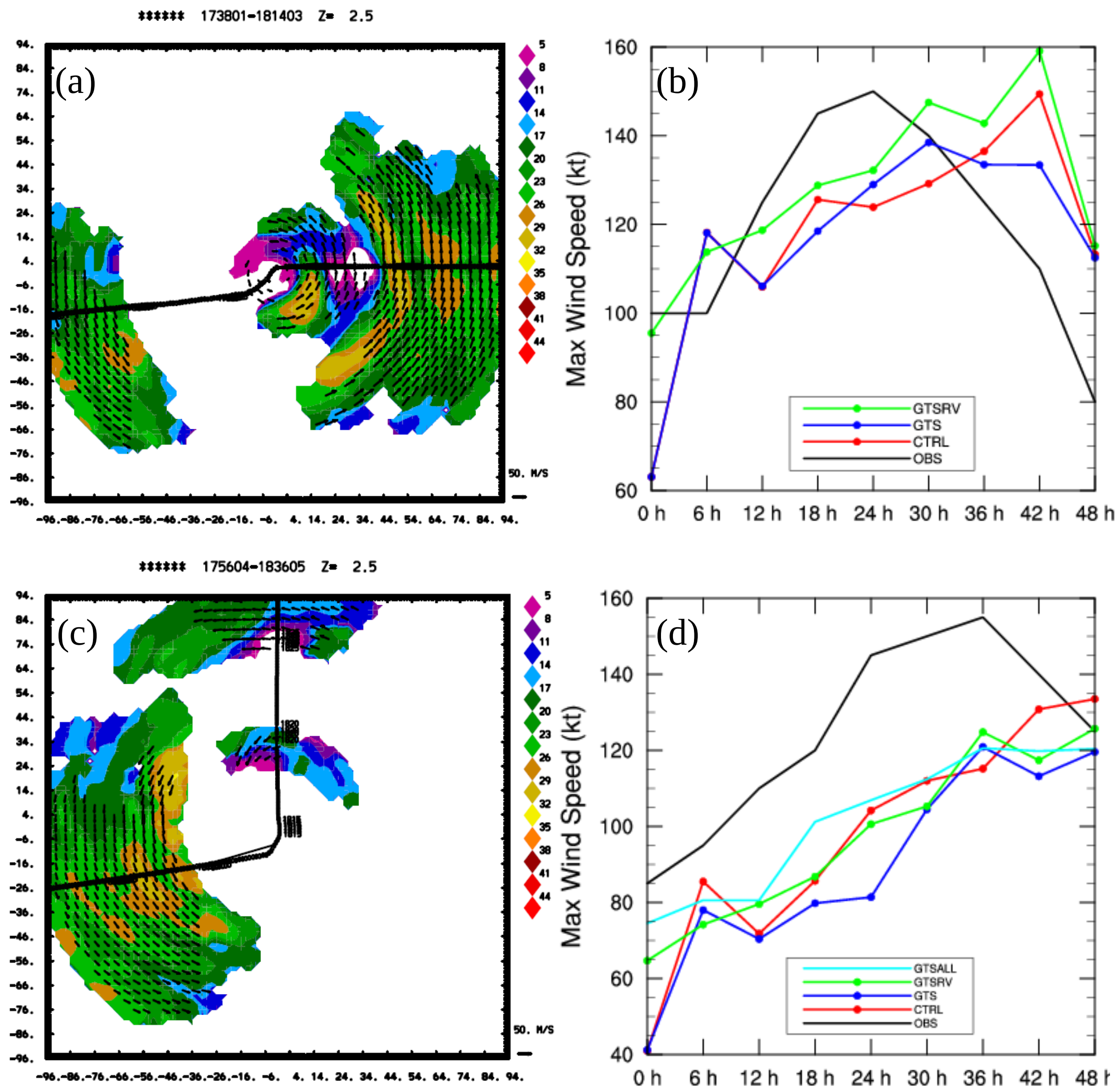


Figure 9. (a) as in Fig. 8a, but for hurricane Katrina, 1738-1814 UTC 27 August, 2005; (b) Maximum sustained wind at 10 m AGL as a function of forecast length for simulations initialized at 18 UTC 27 August (black = observations from the National Hurricane Center; red = forecast without data assimilation; blue= forecast assimilating only conventional surface and sounding data; green = assimilation of NOAA 43 radar-derived winds only); (c) as in (a) but for hurricane Rita, 1756-1836 UTC 20 September, 2005; (d) as in (b) but for Rita forecasts initialized at 18 UTC 20 September. Green line shows result of assimilating data shown in (c); turquoise line shows result of assimilating a wider time window of radar observations.