2.1 OBSERVING SYSTEM SIMULATION EXPERIMENTS TO ASSESS THE POTENTIAL IMPACT OF PROPOSED OBSERVING SYSTEMS ON HURRICANE PREDICTION

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1. INTRODUCTION

Since the advent of meteorological satellites in the 1960s, a considerable research effort has been directed towards the design of spaceborne meteorological sensors, the development of optimal methods for the utilization of satellite derived temperature soundings and winds in global-scale models, and an assessment of the influence of existing satellite data and the potential influence of future satellite observations on numerical weather prediction (NWP). This has included both Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs). The OSEs were conducted to evaluate the impact of specific observations or classes of observations on analyses and forecasts. The OSSEs were conducted to evaluate the potential for future observing systems to improve NWP and to plan for the Global Weather Experiment and for the Earth Observing System (EOS). In addition, OSSEs have been run to evaluate trade-offs in the design of observing systems and to test new methodology for data assimilation.

OSSEs for hurricanes are much more limited and first became possible as numerical models acquired sufficient resolution to simulate hurricanes quasi-realistically. The objectives of these OSSEs are to (1) evaluate the potential impact of new (proposed) observing systems on hurricane track and intensity prediction, (2) evaluate trade-offs in the design and configuration of these observing systems, (3) optimize sampling strategies for current and future airborne and spaceborne observing systems, and (4) evaluate and improve data assimilation and/or vortex initialization methodology for hurricane prediction.

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2. METHODOLOGY

Although there are many possibilities for how an OSE may be conducted, the most typical procedure is as follows: First a “Control” data assimilation cycle is performed. This is followed by one or more experimental assimilations in which a particular type of data (or specific observations) are either withheld or added to the Control. Forecasts are then generated from both the Control and Experimental assimilations every few days (to achieve relative independence of the forecast sample). The analyses and forecasts (from each assimilation) are then verified and compared to determine the impact of each data type being evaluated. Experiments performed in this manner provide a quantitative assessment of the value of a selected type of data to the specific data assimilation system (DAS) that was used. In addition, the OSE also provides useful information on the effectiveness of the DAS. This information can be used to improve the utilization of this and other data in the DAS, as well as to determine the value of the data.

The methodology currently used for OSSEs is very similar to that described above for OSEs and was designed to increase the realism and usefulness of such experiments. In essence, the analysis/forecast simulation system consists of the following elements (shown schematically and functionally in Figure 1):

(1) ***A long atmospheric model integration using a very high resolution “state of the art” numerical model***. This provides a complete record of the assumed “true” state of the atmosphere referred to as the “nature run” or “reference atmosphere.” Nature runs may be generated by either global or regional models, or by embedding a regional model within a global nature run. For the OSSE to be meaningful, it is essential that the nature run be realistic, i.e., possess a model climatology, average storm tracks, etc., that agrees with observations to within pre-specified limits.

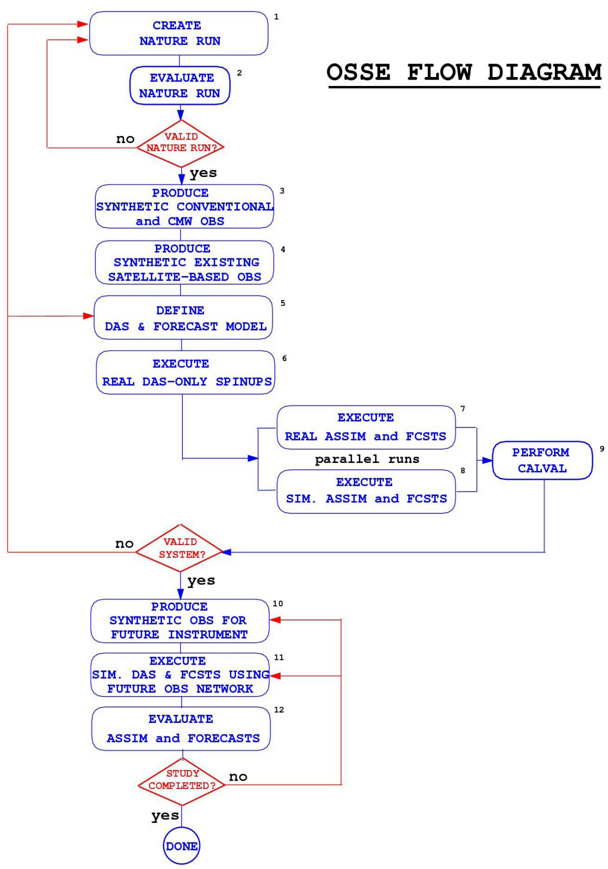

Figure 1. Schematic of the OSSE elements and process.

(2) ***Simulated conventional and space-based observations from the nature run***. All of the observations should be simulated with observed (or expected) coverage, resolution, and accuracy. In addition, bias and horizontal and vertical correlations of errors with each other and with the synoptic situation should be introduced appropriately. Two approaches have been used for this purpose. The simpler approach is to interpolate the nature run values to the observation locations and then add appropriate errors. The more realistic (and expensive) approach is to attempt to retrieve observations from the nature run in the same way as observations are retrieved in the real atmosphere.

(3) ***Control and Experimental data assimilation cycles***. These are identical to the assimilation cycles in an OSE except that only simulated data are assimilated. To avoid the identical twin problem that occurred in the earliest OSSEs, a different model from that used to generate the nature run is used for assimilation and forecasting. Typically, this model has less accuracy and resolution than the nature model. Ideally, the differences between the assimilation and nature models should approximate the differences between a "state of the art" model and the real atmosphere.

(4) ***Forecasts produced from the Control and Experimental assimilations***. As with the OSEs, forecasts are generated every few days to develop an independent sample. The analyses and forecasts are then verified against the nature run to obtain a quantitative estimate of the impact of proposed observing systems and the expected accuracies of the analysis and forecast products that incorporate the new data.

An important component of the OSSE that improves the interpretation of results is validation against a corresponding OSE. In this regard, the accuracy of the analyses and forecasts and the impact of already existing observing systems in simulation is compared with the corresponding accuracies and data impacts in the real world. Ideally, both the simulated and real results should be similar. Under these conditions, no calibration is necessary, and the OSSE results may be interpreted directly. If this is not the case, calibration of the OSSE results can be attempted by determining the constant of proportionality between the OSE and OSSE impact, or the OSSE system may be modified to produce more realistic results.

In a "QuickOSSE," one or more very accurate numerical model forecasts of up to five to ten days duration may be used as a mini-nature run. Observations are then simulated, and data assimilation experiments are performed in a manner similar to that described above. The advantage of the QuickOSSE approach is that the impact of a proposed observing system can be evaluated with regard to a specific storm. In addition, the cost of a QuickOSSE is much lower and the results are obtained more rapidly. Nevertheless, a QuickOSSE by itself cannot yield the statistical significance that might be required and, therefore, QuickOSSEs should only be used as an adjunct to the complete OSSE methodology described above.

3. SUMMARY OF EARLY OSSES

An extensive series of global OSSEs has been conducted since 1985 using the methodology described in the previous section. These OSSEs evaluated quantitatively:

(1) The relative impact of temperature, wind, and moisture profiles from polar-orbiting satellites. These experiments showed wind data to be more effective than mass data in correcting analysis errors and indicated significant potential for space-based wind profile data to improve weather prediction. The impact on average statistical scores for the northern hemisphere was modest but, in approximately 10% of the cases, a significant improvement in the prediction of weather systems over the United States was observed.

(2) The relative importance of upper and lower level wind data. These experiments showed that the wind profile

data from 500 hPa and higher provided most of the impact on numerical forecasting.

(3) Different orbital configurations and the effect of reduced power for a space-based laser wind sounder. These experiments showed the specific quantitative reduction in impact that would result from a proposed degradation of the LAWS instrument.

(4) The relative impact of the ERS and NSCAT scatterometers prior to their launch. This relative impact was confirmed after the launch of these instruments.
(5) The quantitative impact of AIRS and the importance of cloud clearing, which was later confirmed with real AIRS data. In addition, OSSEs were used to: (1) develop and test improved methodology for assimilating both passive and active microwave satellite surface wind data. This led to the first beneficial impact of scatterometer data on NWP, as well as to the assimilation of SSM/I wind speed data. (2) determine the specific requirements for space-based lidar winds for the Global Tropospheric Wind Sounder (GTWS) mission.

4. EARLIER OSSES FOR HURRICANES

The first OSSE to evaluate observing system impact on hurricanes was conducted as part of a series of experiments to evaluate the potential impact of space-based lidar wind profiles (and other advanced remote sensing systems). The nature run was generated using an early version of the Finite Volume General Circulation Model (fvGCM) at .5 degree resolution, and the assimilation and forecast system was the operational version of the NASA GEOS 3 Data Assimilation System at 1-degree resolution. This nature run covered a three and one half month period and contained several tropical cyclones, as well as a very realistic representation of atmospheric fronts and extratropical cyclone evolution. As an example, Figure 2 shows the evolution of the first hurricane in the nature run as it moved towards the southeast coast of the United States and then weakened after making landfall.

Following a very detailed assessment of the realism of the nature run and the differences between the nature run model and the assimilation/forecasting model, the entire OSSE system was validated through a comparison of parallel real data and simulated data impact experiments. Parallel assimilation experiments and 14 five-day forecasts were then performed with this system to evaluate the impact of idealized space-based lidar wind profiles and AIRS hyperspectral temperature soundings (not shown here). As in earlier OSSEs, one of the major metrics for assessing the potential impact of lidar winds was the anomaly correlation for sea level pressure and 500 hPa height forecasts. In addition, a number of additional metrics, such as impact on the central pressure and displacement of cyclones or the landfall of hurricanes, were also evaluated.

The results of this evaluation agreed with earlier OSSEs and showed a very substantial improvement in

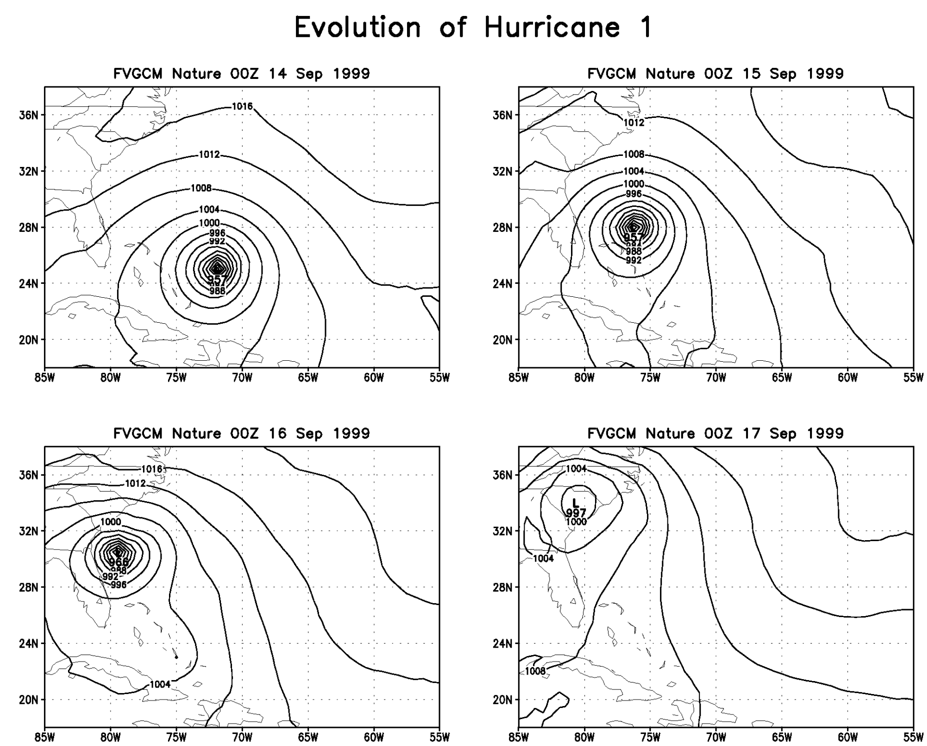

Figure 2. Sea level pressure analyses for the first hurricane in the fvGCM nature run at 24-hour intervals.

forecast accuracy resulting from the assimilation of space-based lidar winds. In the Southern Hemisphere, average forecast skill was extended by 12-18 hours while, in the Northern Hemisphere, average forecast skill was extended by 3-6 hours. This was associated with a meaningful (10%) reduction in position error for all cyclones averaged over the globe and all time periods. For very intense cyclones (those with a central pressure less than 945 hPa), the reduction of position error exceeded 200 km. Figure 3 illustrates a significant improvement in hurricane landfall prediction as a result of assimilating lidar data. This result was obtained for the first hurricane in the nature run, shown in Figure 2. The predicted landfall position error for this and another tropical cyclone to hit the U.S. mainland in the nature run was improved by approximately 150 miles for both storms. These results demonstrate the considerable potential for space-based lidar wind profile measurements. Additional experiments were conducted to evaluate the relative impact of upper and lower level winds, as well as to isolate the specific lidar data responsible for the improvements, and the effects of horizontal coverage. These experiments showed that mid-upper level winds contributed more of the beneficial impact on track forecasts and that the improvements were lost when only a single line of data was assimilated.

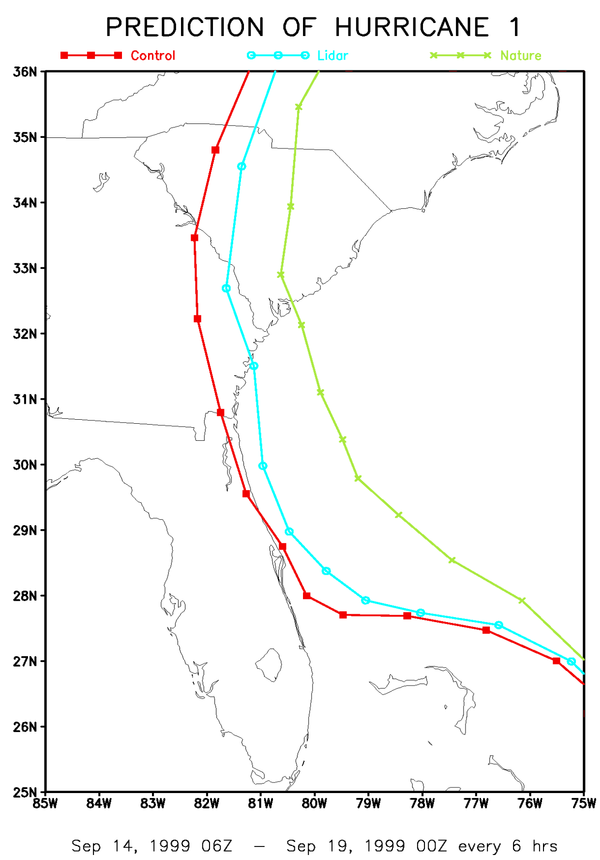

Figure 3. Illustration of the potential impact of lidar winds. Green (easternmost track): actual track from nature run. Red (westernmost track): forecast beginning 63 hours before landfall with all currently used data. Blue (middle track): improved forecast for the same time period with simulated wind lidar added.

The results presented in Figure 3 are for a hypothetical hurricane within the three and one half month .5 degree fvGCM nature run, described earlier. The 2004 hurricane season was extremely active with several major hurricanes striking the United States. The QuickOSSE methodology (described below) was conceived to answer observational and dynamical questions related to these specific hurricanes. Results are presented here from one such QuickOSSE for Hurricane Ivan to address the potential impact of space-based wind profile observations, as well as to better understand the role of the area averaged divergence profile in the movement of this storm.

A .25 degree resolution fvGCM forecast of Hurricane Ivan was used as the nature run for this experiment. From this nature run, all of the standard and special reconnaissance observations that were available in real time, as well as hypothetical lidar wind profiles covering the storm, were simulated. This was followed by a control assimilation and forecast (using all of the standard observations) and an ideal lidar assimilation and forecast (adding simulated lidar winds to the control) generated using a coarse 1.0 by 1.25 degree resolution version of the model. Figure 4 shows a major improvement in the predicted direction of movement of the hurricane resulting

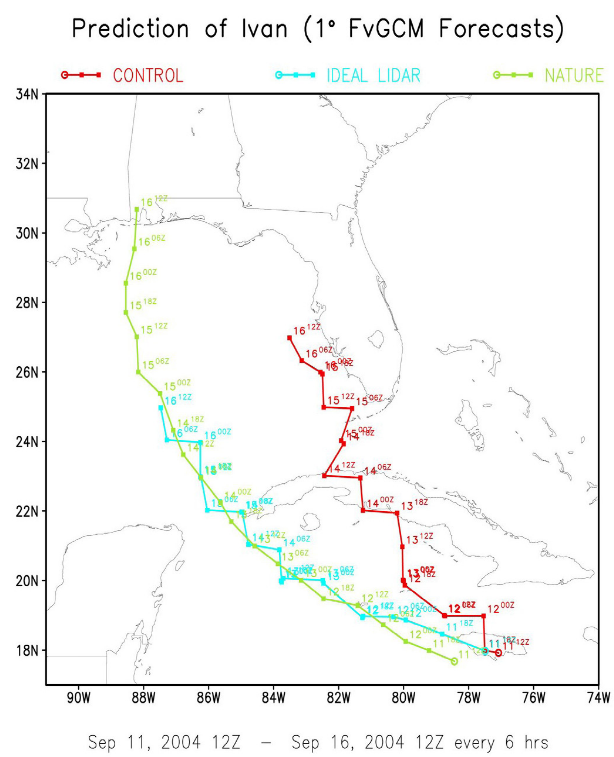

Figure 4. Tracks of Hurricane Ivan from nature run, Control forecast, and forecast with lidar winds added.

from the assimilation of lidar winds. This was due to a significant improvement in the divergence profile associated with the storm (not shown) that enabled it to be more accurately steered by the large scale flow.

5. CURRENT OSSES FOR HURRICANES

New, more realistic OSSEs related to hurricane analysis and hurricane track and intensity prediction are being conducted at the present time as a collaboration between NOAA, NASA, Simpson Weather Associates, the University of Miami, and the Joint Center for Satellite Data Assimilation. The objectives of these OSSEs are to determine (1) the potential impact of unmanned aerial systems, (2) the relative impact of alternative concepts for space-based lidar winds, and (3) the relative impact of alternative concepts for polar and geostationary hyper-spectral sounders. For these experiments, the Weather Research and Forecasting (WRF ARW) mesoscale model at 1- and 3-km resolutions was embedded in a T511 global nature run that had previously been generated by the European Centre for Medium Range Weather Forecasting (ECMWF). The first nature run to be generated covered a 13-day period and included tropical cyclone formation, movement, and rapid intensification. Figures 5 and 6 present comparisons of the structure, track, and intensification for the WRF nature runs relative to the global nature run in which it is embedded. While the tracks are very similar, the intensification rate and structure are substantially more realistic for an intense hurricane.

The OSSE system (that we and our colleagues at the Joint Center for Satellite Data Assimilation have employed in our recent experiments) consists of either the ECMWF T511 or the embedded WRF ARW 1-km resolution simulations as nature runs. Global assimilation is performed using NOAA's Global Forecast System (GFS). Regional assimilation uses NOAA's operational hurricane forecast model (HRWF) at 9-km resolution and either 3D VAR or EnKF analysis schemes. Forecasts are generated using the HWRF model at 3-km resolution. In these experiments, the potential impact of assimilating data either globally or regionally can be evaluated.

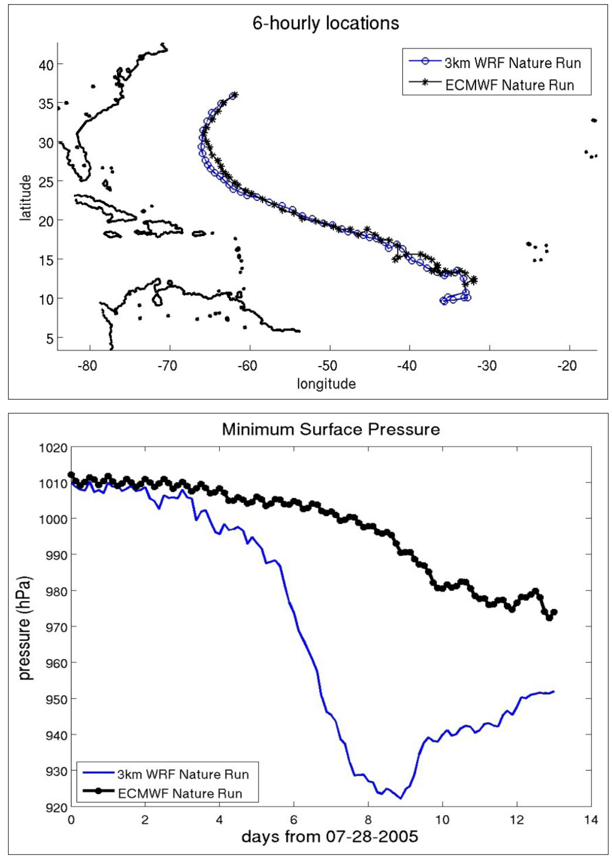

Figure 5. Comparison of WRF and ECMWF nature run hurricane tracks (top) and intensification rates (bottom).

Figures 7-9 show selected results from OSSEs to evaluate the potential impact of two alternative lidar technologies for wind profiling from the International Space Station. The Control for these experiments assimilated all standard meteorological observations. The WISSCR experiment added coherent lidar wind profiles to the control, while the OAWL experiment added wind profiles obtained by an optical autocovariance wind lidar (OAWL) to the control. As shown in **Figure 7**, both lidars reduce wind analysis errors in the tropics, but the

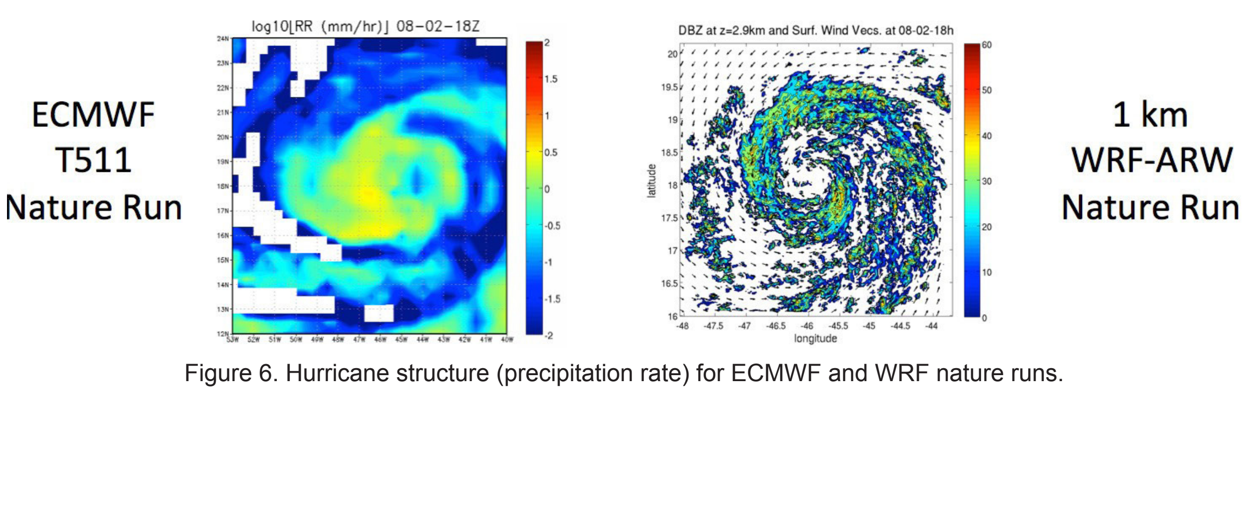

Figure 6. Hurricane structure (precipitation rate) for ECMWF and WRF nature runs.

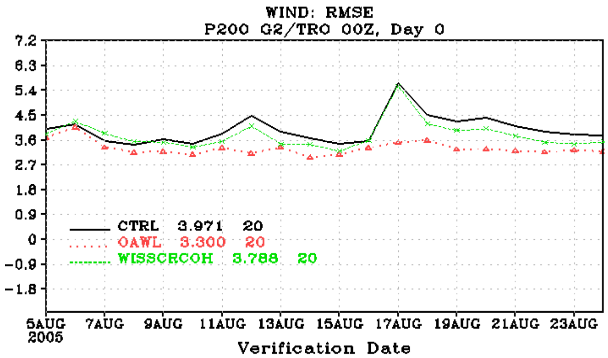

Figure 7. Relative accuracy of Control, OAWL, and WISSCR 200 mb wind analyses in the tropics.

impact of OAWL is substantially larger than for WISSCR. HWRF track forecasts (not shown) were also found to be substantially better when OAWL data were assimilated using the regional 3D VAR analysis.

Figure 8 shows the impact of the global assimilation of OAWL data on hurricane track and intensity predictions using HWRF. The global assimilation of OAWL data improves track forecasts significantly after 36 hours, while improving intensity forecasts for the first 60 hours. Figure 9 compares the relative accuracy of HWRF forecasts resulting from either global or regional assimilation of OAWL data. Global assimilation improves the boundary conditions for the HWRF regional model and has a significantly larger impact on track forecast accuracy than does the regional assimilation. In contrast, regional assimilation has a significantly larger impact on the forecast of maximum wind.

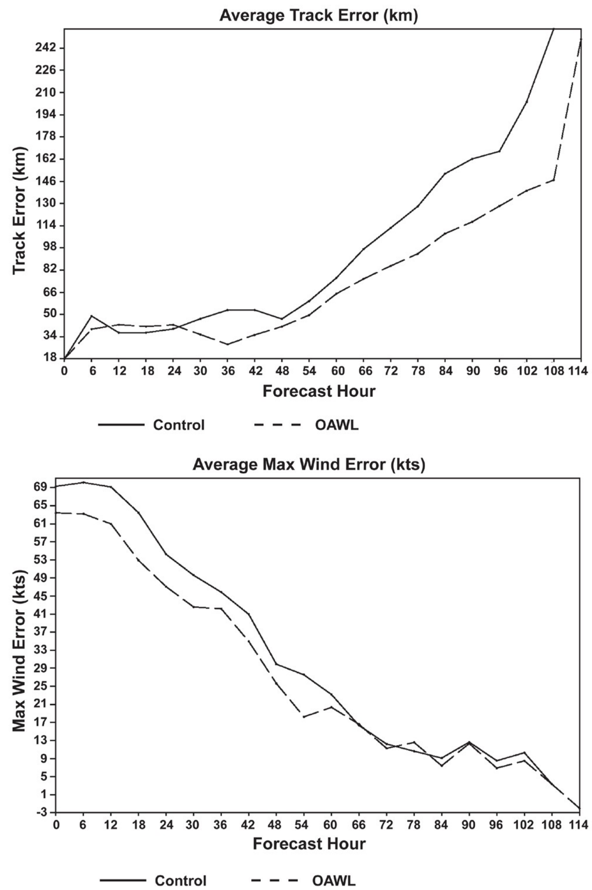

Figure 8. Relative accuracy of HWRF forecasts of track and maximum wind resulting from the global assimilation of OAWL data. The Control is shown by the solid line, while the OAWL forecast accuracy is shown in dashed line.

6. PREDICTABILITY EXPERIMENTS

A well-known issue in regional hurricane modeling is the spindown commonly observed for strong hurricanes. This impacts the short-term evolution of the vortex and hence potentially limits the predictability of intensity. Our goal here is to investigate, in an OSSE environment, whether there exists a necessary minimum complement of observations that would eliminate the spin-down. In the first of our experiments (shown in Figure 10), we investigated whether spindown would occur if a sufficiently accurate initial state could be provided to the HWRF model. The left panels of Figure 10 show that a strong hurricane in the WRF nature run intensifies over the 6-hour period from August 4 12Z to August 4 18Z. Providing “near perfect” initial conditions to the HWRF model by interpolating directly from the nature run does not result in spindown as shown in the middle panels of Figure 10. The right panels of Figure 10 show a GSI analysis of wind, moisture, and temperature profiles from the nature run and the subsequent 6-hour forecast. Here the initial representation of the hurricane is somewhat weaker but, once again, no spindown occurs. These experiments are continuing with the objective of determining the minimum observational data needed to routinely eliminate the spindown effect in regional model predictions.

7. CONCLUSIONS

OSSEs, when done correctly, provide an effective means to evaluate the potential impact of a proposed observing system, as well as to determine tradeoffs in their design, and to evaluate data assimilation methodology. Great care must be taken to ensure the realism of the OSSEs and in the interpretation of OSSE results. While early OSSEs focused on large-scale NWP, more recent OSSEs have included evaluation of the impact of proposed observing systems on smaller-scale phenomena. These have included global OSSEs to evaluate impact on hurricane track forecasting and regional OSSEs aimed at evaluating both track and intensity prediction. Two global OSSEs conducted using the fvGCM nature runs showed a substantial impact of space-based lidar wind profiles on hurricane track predictions. Current OSSEs are using multiple nature runs in which the WRF model, at very high resolution, is embedded within a global T511 nature run that had been

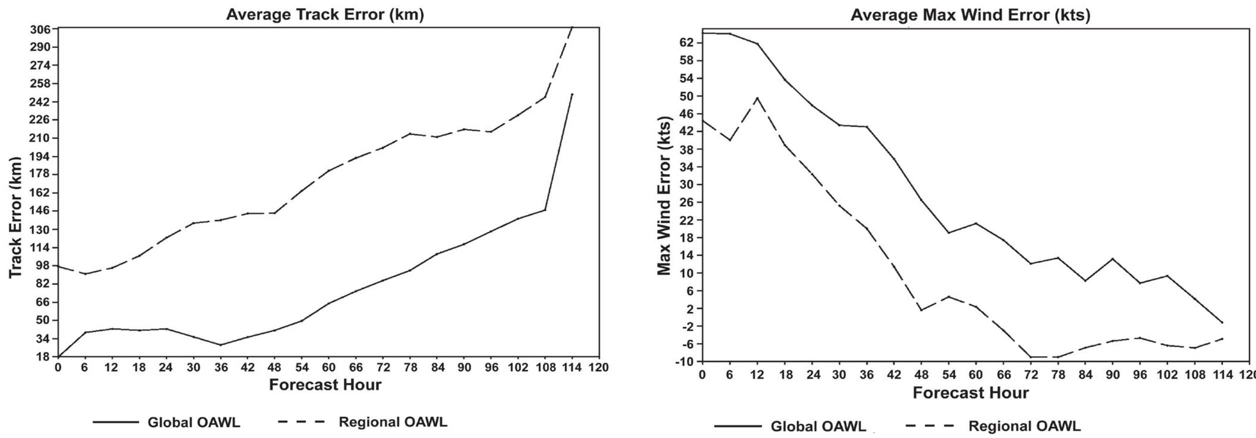

Figure 9. Relative accuracy of the HWRF forecasts resulting from either global (solid line) or regional (dashed line) assimilation of OAWL data.

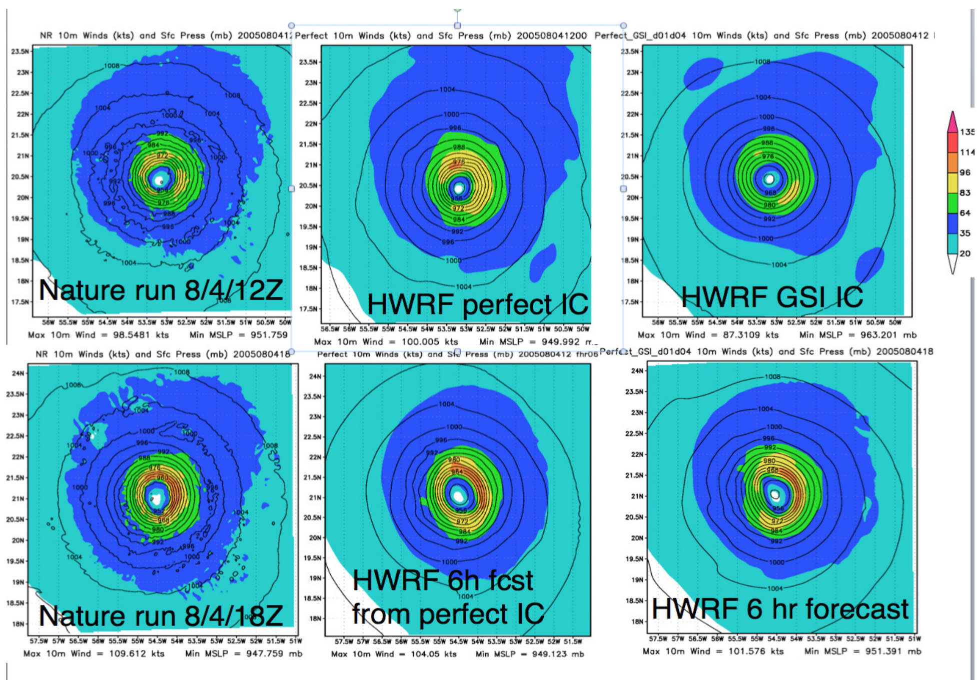

Figure 10. Evolution of the simulated hurricane wind speeds over a 6-hour period for the WRF nature run (left panels), HWRF with near perfect initial conditions (middle panels), and HWRF with initial conditions from GSI (right panels).

generated by ECMWF. These OSSEs are beginning to evaluate the potential impact of new (proposed) observing systems on hurricane track and intensity prediction and trade-offs in the design and configuration of these observing systems. They are also being used to optimize sampling strategies for current and future airborne and spaceborne observing systems and to evaluate and improve data assimilation and vortex initialization methodology for hurricane prediction. Results from recent OSSEs show the relative impact of alternative lidar technologies and the relative impact of global and regional assimilation on hurricane track and intensity prediction. OSSEs are currently underway to evaluate advanced concepts for hyperspectral infrared (IR) sounding from both polar and geostationary orbit, and to evaluate hurricane predictability issues.

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