Observing System Simulation Experiments to Assess the Potential Impact of New Observing Systems on Hurricane Forecasting

Robert Atlas[1]
Lisa Bucci[1,2]
Bachir Annane[1,2]
Ross Hoffman[1,2]
Shirley Murillo[1]

[1]NOAA-Atlantic Oceanographic and Meteorological Laboratory
Miami, FL 33149

[2]University of Miami-Cooperative Institute for Marine and Atmospheric Studies
Miami, FL 33149

Submitted to

Marine Society Technology Journal
July 2015

Revised October 2015

Keywords: OSSE, Hurricane forecasting

Abstract

Observing System Simulation Experiments (OSSEs) are an important tool for evaluating the potential impact of new or proposed observing systems, as well as for evaluating trade-offs in observing system design, and in developing and assessing improved methodology for assimilating new observations. Extensive OSSEs have been conducted at NASA/GSFC and NOAA/AOML over the last three decades. These OSSEs determined correctly the quantitative potential for several proposed satellite observing systems to improve weather analysis and prediction prior to their launch, evaluated trade-offs in orbits, coverage and accuracy for space-based wind lidars, and were used in the development of the methodology that led to the first beneficial impacts of satellite surface winds on numerical weather prediction. This paper summarizes early applications of global OSSEs to hurricane track forecasting and new experiments using both global and regional models. These latter experiments are aimed at assessing potential impact on hurricane track and intensity prediction over the oceans and at landfall.

Introduction

Since the advent of meteorological satellites in the 1960s, a considerable research effort has been directed towards the design of space-borne meteorological sensors, the development of optimal methods for the utilization of satellite derived temperature soundings and winds in global-scale models, and the 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 existing instruments and 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 (Atlas 1997; Atlas et al., 1985, 2001).

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 or 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 space-borne observing systems, and (4) evaluate and improve data assimilation and/or vortex initialization methodology for hurricane prediction.

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 in which a standard set of observations (typically those that are currently available to NWP models in real time) are assimilated. 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. 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 OSSE system consists of the following elements:

(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. It is also important that the nature run cover a long enough period of time to provide a statistically meaningful sample. Typically, this is greater than 30 days for OSSEs relating to global numerical weather prediction, and greater than 5-10 days for regional OSSEs.

(2) ***Simulated conventional and space-based observations from the nature run***. The reliability of the OSSE results depends critically on the realism of the errors of the simulated observations. All of the observations should be simulated with observed (or expected) coverage, resolution, and accuracy. The simulation process begins by interpolating the nature run to the time and location of an observation. Then a forward operator (i.e., a simulator) calculates the nature run's estimate of the observation, which might be radiances, radar reflectivity, etc. In simple cases, the forward operator is just a vertical interpolation, e.g., linear in log of pressure. For radiances, a complex radiative transfer calculation is used. A forward operator is also used in the data assimilation system to calculate the observation innovation (the difference observation

minus the background estimate of the observation). The forward operator used in the data assimilation system and used in simulating data should be different, approximately as different as the forward operator used in the current data assimilation systems is from reality. Additional bias and horizontal and vertical correlations of errors with each other and with the synoptic situation should be introduced explicitly as needed. The simulated observations may be validated and calibrated by comparing the statistics of the observation innovations in reality and in the OSSE system (Errico et al., 2013).

(3) ***Control and Experimental data assimilation cycles***. These are identical to the assimilation cycles in an OSE except that only simulated data are assimilated. 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. This introduces realistic modeling errors to the OSSE so that forecast skill is not overestimated. It is also important to have realistic differences between the instrument simulators used in the data assimilation and those used to generate data from the nature run as described above.

(4) ***Forecasts produced from the Control and Experimental assimilations***. As with the OSEs, forecasts are generated at regular intervals, typically every 24 hours in global OSSEs and every 1-6 hours in regional OSSEs. 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 (Hoffman et al., 1990).

In a “QuickOSSE,” one or more very accurate numerical model forecasts of up to 5 to 10 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.

Summary of Early OSSEs Aimed at Global Numerical Weather Prediction

An extensive series of global OSSEs has been conducted since 1985 using the methodology described in the previous section (Atlas, 1997). 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 above 500 hPa provided most of the impact on numerical forecasting.

(3) Different orbital configurations and the effect of reduced power for the Laser Atmospheric Wind Sounder (LAWS). 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 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 (Chahine et al., 2006).

In addition, OSSEs were used to:

(1) Develop and test improved methodology for assimilating both passive and active microwave satellite surface wind data (Atlas et al., 1996, 2001, 2011). 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.

Results of Global 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 0.5 degree resolution (Lin et al., 2004), and the assimilation and forecast system was the operational version of the NASA GEOS 3 Data Assimilation System (Conaty et al., 2001) at 1-degree resolution. This nature run covered a three and one half month period, contained several tropical cyclones, and provided a very realistic representation of atmospheric fronts and extratropical cyclone evolution, as well as quasi-realistic representation of tropical cyclones. As an example, Figure 1 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, all conventional and space-based observations (that were assimilated by NASA at this time) were simulated with existing coverages and accuracies. However, for this initial experiment, space-based lidar wind profiles were simulated in a very idealized way, first with the same coverage and resolution as polar orbiting temperature sounding data (Halem et al., 1982), and then as a single line of data to represent a non-scanning wind lidar. Accuracies were assumed to be 1 m/s at all levels, with no attenuation effects due to clouds. The entire OSSE system (with the exception of the wind lidar), was validated through a comparison of parallel real data (OSE) and simulated data (OSSE) impact experiments. Parallel assimilation experiments and 14, 5-day forecasts were then performed with this system to evaluate the impact of idealized space-based lidar wind profiles.

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. A number of additional metrics, such as impact on the central pressure and position of cyclones and the position of hurricanes at landfall, were also evaluated (Terry and Atlas, 1996).

The results of this evaluation agreed with earlier OSSEs and showed a very substantial improvement in forecast accuracy resulting from the assimilation of space-based wind profiles. 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 2 illustrates a significant (approximately 240 km) improvement in hurricane landfall prediction as a result of assimilating the full swaths of lidar data (the blue curve in Figure 2), but a much poorer impact when only a single line of data from a non-scanning lidar is assimilated (the purple curve in Figure 2). This result was obtained for the first hurricane in the nature run, shown in Figure 1. The predicted landfall position error for another tropical cyclone to hit the U.S. mainland in the nature run was also improved very significantly by the assimilation of the full swaths of lidar data, and an evaluation of all tropical cyclones over the global oceans during this period also showed significant improvement.

These results demonstrate the considerable potential for space-based lidar wind profile measurements to improve hurricane track forecasting provided sufficient coverage and accuracy can be obtained. Additional experiments (not shown) were conducted to evaluate the relative impact of upper and lower level winds on hurricane track predictions, as well as to isolate the specific lidar data responsible for the improvements. These experiments showed that mid-upper level winds contributed more than did the lower level wind data, and that lidar data assimilated over several days contributed to the beneficial impact on track forecasting.

The results presented in Figure 2 are for a simulated hurricane within the three and one half month 0.5 degree fvGCM nature run, described earlier. Next, the QuickOSSE methodology was conceived to answer observational and dynamical questions related to 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 5-day 0.25-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 cycle (using all of the standard observations, including those from hurricane reconnaissance aircraft) and an ideal lidar assimilation cycle (adding simulated lidar winds to the control) generated using a coarse 1.0 by 1.25 degree resolution version of the GEOS-3 data assimilation system. A series of forecasts were then generated from both the control and lidar assimilations first at coarse 1.0 by 1.25 degree resolution and then at 0.25 degree resolution. The results from all of the forecasts showed a major improvement in the predicted direction of movement of the hurricane resulting from the assimilation of lidar winds. This was due to a significant improvement in the divergence profile associated with the storm (not shown) that may have enabled it to be more accurately steered by the large-scale flow. Figure 3 illustrates this improvement for one of the high resolution forecasts.

Regional Hurricane OSSEs

New, more realistic OSSEs related to hurricane analysis and hurricane track and intensity prediction are being conducted at the present time under NOAA's Quantitative Observing System Assessment Program (QOSAP), 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 (1) to determine the potential impact of unmanned aerial systems and new space-based observing systems, and (2) to conduct experiments to evaluate issues related to hurricane predictability. For the first set of these experiments, the Weather Research and Forecasting Advanced Research WRF (WRF ARW; Skamarock et al., 2008) 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 (Baker et al., 2014). The first high-resolution nature run to be generated covered a 13-day period and included tropical cyclone formation, movement, and rapid intensification (Nolan et al., 2013). Figures 4 and 5 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 (See Nolan et al., 2013 for additional details).

A well-known issue in regional hurricane modeling is the spindown or rapid weakening that is typically observed for model predictions of strong hurricanes after assimilation (Gopalakrishnan et al., 2012; Hendricks et al., 2011; Vukicevic et al., 2013). This impacts the short-term evolution of the vortex and, hence, potentially limits the predictability of intensity. The 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 6), we investigated whether spindown would occur if a sufficiently accurate initial state could be provided to the HWRF model, which is used as the assimilation and forecast model in our hurricane OSSE system. The resolutions, dynamic cores, grids, projections, and physical parameterizations are substantially different between the WRF ARW and HWRF models (Gopalakrishnan et al., 2012).

The left panels of Figure 6 show that a strong hurricane in the WRF nature run (representing the “truth” for this experiment) intensifies over the 6-hour period from August 4 12 UTC to August 4 18 UTC. Providing “near perfect” initial conditions to the HWRF model by interpolating directly from the high-resolution WRF ARW nature run to the HWRF model gridpoints does not result in spindown as shown in the middle panels of Figure 6. The right panels of Figure 6 show an analysis of “error free” wind, moisture, and temperature profiles from the nature run and the subsequent 6-hour forecast. Here profiles of each of these types of data were taken directly from the nature run and assimilated as observations using the Global Statistical Interpolation (GSI) analysis method (Kleist et al., 2009). GSI is a unified variational data assimilation system that has been used by NOAA for both global and regional applications. As can be seen from the right panels in Figure 6, the initial representation of the hurricane is somewhat weaker but, once again, no spindown occurs. Hence, early results suggest that an accurate and consistent set of initial conditions leads to forecasts that do not suffer spindown. This is an encouraging result suggesting the need for the assimilation of complementary multi-parameter observations to provide the required initial states. These experiments are continuing with the objective of determining the minimum observational data needed to routinely eliminate the spindown effect in regional model predictions of hurricanes.

Conclusions

OSSEs, when conducted 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 methodologies. 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 an evaluation of the impact of proposed observing systems on smaller-scale phenomena and for other earth system components, including the ocean (e.g., Halliwell et al., 2014, 2015). These have included global OSSEs to evaluate their 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 generated by ECMWF. These OSSEs are beginning to evaluate the potential impact of 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. OSSEs are currently underway to evaluate unmanned aerial systems, advanced concepts for hyperspectral infrared sounding from both polar and geostationary orbit, alternative concepts for space-based lidar winds, and to evaluate hurricane predictability issues.

Acknowledgments. The lead author wishes to thank Professor David Nolan for generation of the WRF nature runs being used in our current studies, as well as all of his previous and current colleagues in OSSEs over the past 30 years, especially J. Terry, E. Brin, J. Ardizzone, S.C. Bloom, J.C. Jusem, D. Bungato, G.D. Emmitt, L.P. Riishojgaard, S. Boukabara, L. Cucurull, S. Tucker, E. Kemp, Y. Xie, S. Koch, Z. Toth, N.C. Prive, and T. Vukicevic.

References

Atlas, R. 1997. Atmospheric observations and experiments to assess their usefulness in data assimilation. J Meteor Soc Japan. 75(1B):111–30.

Atlas, R., E. Kalnay and M. Halem. 1985. Impact of satellite temperature sounding and wind data on numerical weather prediction. Opt Engineer. 24(2):341–46.

Atlas, R., R.N. Hoffman, S.C. Bloom, J.C. Jusem and J. Ardizzone. 1996. A multiyear global surface wind velocity dataset using SSM/I wind observations. Bull Amer Meteor Soc. 77(5):869–82.

Atlas, R., R.N. Hoffman, S.M. Leidner, J. Sienkiewicz, T.-W. Yu, S.C. Bloom, E. Brin, J. Ardizzone, J. Terry, D. Bungato and J.C. Jusem. 2001. The effects of marine winds from scatterometer data on weather analysis and forecasting. Bull Amer Meteor Soc. 82(9):1965–90.

Atlas, R., R.N. Hoffman, J. Ardizzone, S.M. Leidner, J.C. Jusem, D.K. Smith and D. Gombos. 2011. A cross-calibrated, multi-platform ocean surface wind velocity product for meteorological and oceanographic applications. Bull Amer Meteor Soc. 92(2):157–74.

Baker, W.E., R. Atlas, C. Cardinali, A. Clement, G.D. Emmitt, B.M. Gentry, R.M. Hardesty, E. Kallen, M.J. Kavaya, R. Langland, M. Masutani, W. McCarty, R.B. Pierce, Z. Pu, L.P. Riishojgaard, J. Ryan, S. Tucker, M. Weissmann and J.G. Yoe. 2014. Lidar-measured wind profiles: The missing link in the global observing system. Bull Amer Meteor Soc. 95(4):543–64.

Chahine, M.T., T.S. Pagano, H.H. Aumann, R. Atlas, C. Barnet, J. Blaisdell, L. Chen, M. Divakarla, E.J. Fetzer, M. Goldberg, C. Gautier, S. Granger, S. Hannon, F.W. Irion, R. Kakar, E. Kalnay, B.H. Lambrigtsen, S.-Y. Lee, J. LeMarshall, W.W. McMillan, L. McMillin, E.T. Olsen, H. Revercomb, P. Rosenkranz,W.L. Smith, D. Staelin, L.L. Strow, J. Susskind, D. Tobin, W. Wolf and L. Zhou. 2006. AIRS: Improving weather forecasting and providing new data on greenhouse gases. Bull Amer Meteor Soc. 87(7):911–26.

Conaty, A.L., J.C. Jusem, L. Takacs, D. Keyser and R. Atlas. 2001. The structure and evolution of extratropical cyclones, fronts, jet streams, and the tropopause in the GEOS general circulation model. Bull Amer Meteor Soc. 82(9):1853–67.

Errico, R.M., R. Yang, N.C. Prive, K.-S. Tai, R. Todling, M. E. Sienkiewicz and J. Guo. 2013. Development and validation of observing-system simulation experiments at NASA’s Global Modeling and Assimilation Office. Quart J Roy Meteor Soc. 139:1162–78. doi:10.1002/qj.2027.

Gopalakrishnan, S.G., S. Goldenberg, T. Quirino, F. Marks, X. Zhang, K.-S. Yeh, R. Atlas and V. Tallapragada. 2012. Towards improving high-resolution numerical hurricane forecasting: Influence of model horizontal grid resolution, initialization, and physics. Wea Forecast. 27(3):647–66. doi:10.1175/WAF-D-11-00055.1.

Halem, M., E. Kalnay, W.E. Baker and R. Atlas. 1982. An assessment of the FGGE satellite observing systems during SOP-1. Bull Amer Meteor Soc., 63(4):407–26.

Halliwell, Jr., G.R., A. Srinivasan, V. Kourafalou, H. Yang, D. Willey, M. Le Hénaff and R. Atlas. 2014. Rigorous evaluation of a fraternal twin ocean OSSE system for the open Gulf of Mexico. J Atmos Oceanic Technol. 31:105–30. doi:10.1175/JTECH-D-13-00011.1.

Halliwell, Jr., G.R., V. Kourafalou, M. Le Hénaff, L.K. Shay and R. Atlas. 2015. OSSE impact analysis of airborne ocean surveys for improving upper-ocean dynamical and thermodynamical forecasts in the Gulf of Mexico. Prog Oceanogr. 130:32–46. doi:10.1016/j.pocean.2014.09.004.

Hendricks, E.A., M.S. Peng, X. Ge and T. Li. 2011. Performance of a dynamic initialization scheme in the Coupled Ocean-Atmosphere Mesoscale Prediction System for tropical cyclones (COAMPS-TC). Wea Forecast. 26(5):650–63. doi:10.1175/WAF-D-10-05051.1.

Hoffman, R.N., C. Grassotti, R.G. Isaacs, J.-F. Louis and T. Nehrkorn. 1990. Assessment of the impact of simulated satellite lidar wind and retrieved 183 GHz water vapor observations on a global data asssimilation system. Mon Wea Rev. 118(12):2513–42. doi:10.1175/1520- 0493(1990)118<2513:aotios>2.0.co;2.

Kleist, D.T., D.F. Parrish, J.C. Derber, R. Treadon, W-S. Wu and S. Lord. 2009. Introduction of the GSI into the NCEP Global Data Assimilation System. Wea Forecast. 24:1691–1705. doi: http://dx.doi.org/10.1175/2009WAF2222201.1.

Lin, S.-J., R. Atlas and K.-S. Yeh. 2004. Global weather prediction and high-end computing at NASA. Comp Sci Eng. 6(1):29–34.

Nolan, D.S., R. Atlas, K.T. Bhatia and L.R. Bucci. 2013. Development and validation of a hurricane nature run using the joint OSSE nature run and the WRF model. J Adv Model Earth Syst. 5(2):382–405. doi:10.1002/jame.20031.

Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, M.G. Duda, X.-Y. Huang, W. Wang and J.G. Powers. 2008. A description of the advanced research WRF version 3. NCAR Tech. Note. 475+STR, Boulder, Colorado, pp. 113.

Terry, J. and R. Atlas. 1996. Objective cyclone tracking and its applications to ERS-1 scatterometer forecast impact studies. 15th Conference on Weather Analysis and Forecasting, Amer Meteor Soc. Boston, MA, Norfolk, Virginia, 146–49.

Vukicevic, T., A. Aksoy, P. Reasor, S. Aberson, K. Sellwood and F. Marks. 2013. Joint impact of forecast tendency and state error biases in ensemble Kalman filter data assimilation of inner-core tropical cyclone observations. Mon Wea Rev. 141(9):2992-3006. doi:10.1175/MWR-D-12-00211.1.

Figure Captions

Figure 1. Sea level pressure analyses for the first hurricane in the fvGCM nature run at 24-hour intervals.

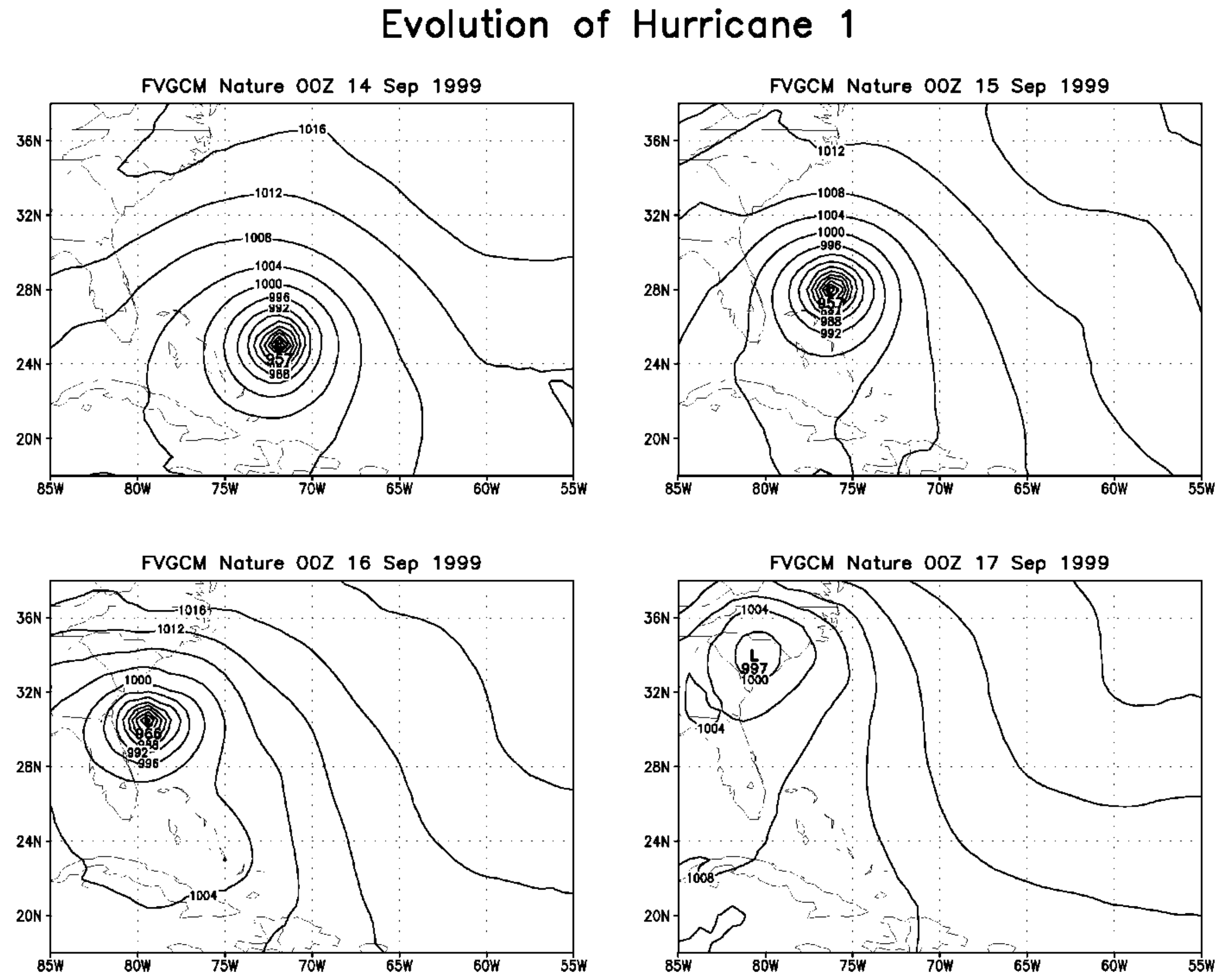
Figure 2. Illustration of the potential impact of lidar winds on hurricane track forecasting. Green: actual track from nature run. Red: forecast beginning 63 hours before landfall with all currently used data. Blue: improved forecast for the same time period with simulated wind profile data from a scanning lidar added. Purple: forecast for the same time period with simulated wind profile data from a non-scanning lidar added.

Figure 3. Tracks of Hurricane Ivan from nature run, Control forecast, and forecast with lidar winds added.

Figure 4. Comparison of WRF and ECMWF nature run hurricane tracks and intensification rates.

Figure 5. Hurricane structure (precipitation rate) for ECMWF and WRF nature runs.

Figure 6. 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).



Evolution of Hurricane 1

FVGCM Nature 00Z 14 Sep 1999

FVGCM Nature 00Z 15 Sep 1999

FVGCM Nature 00Z 16 Sep 1999

FVGCM Nature 00Z 17 Sep 1999

Figure 1

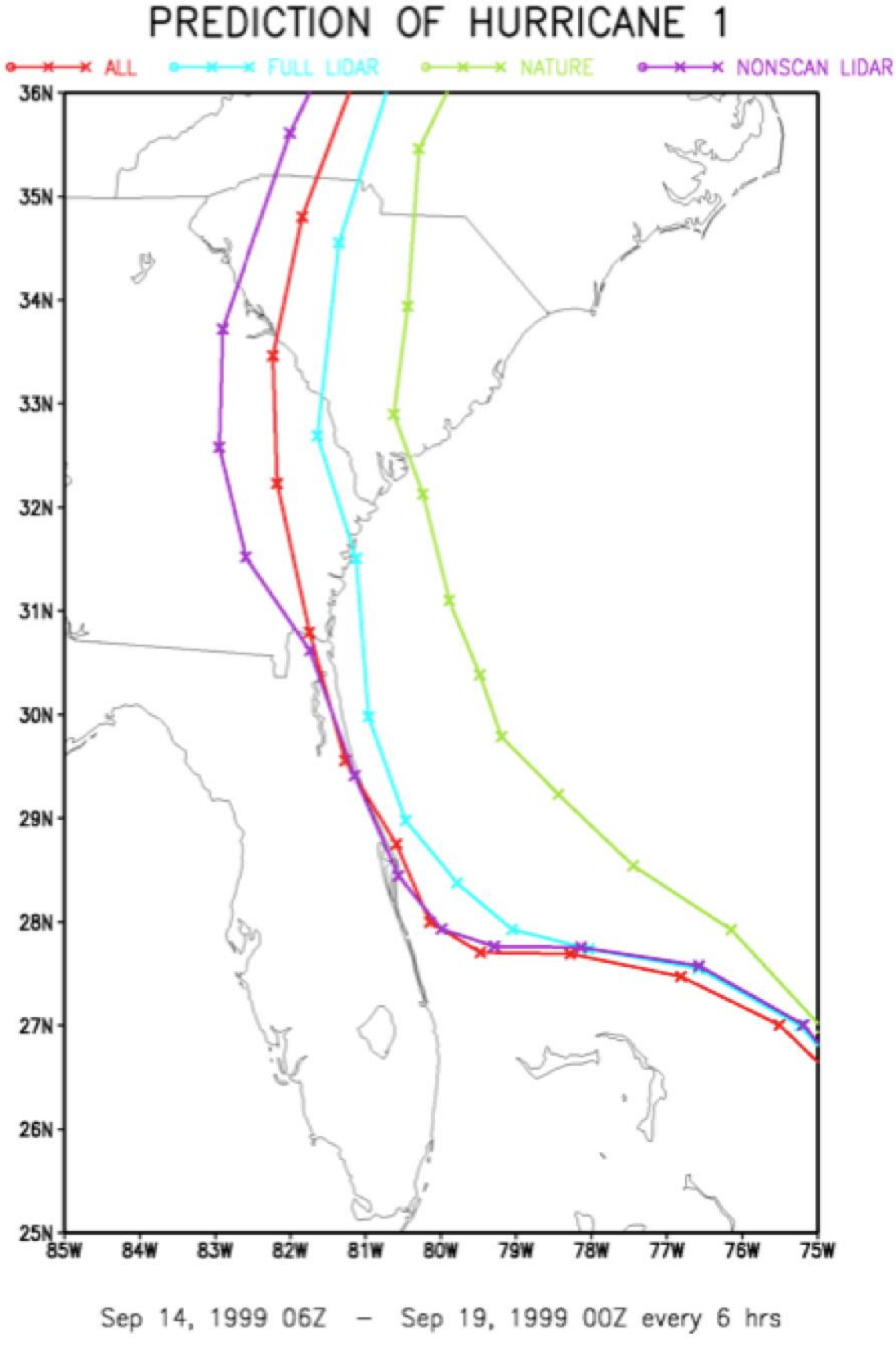

PREDICTION OF HURRICANE 1
ALL
FULL LIDAR
NATURE
NONSCAN LIDAR
36N
35N
34N
33N
32N
31N
30N
29N
28N
27N
26N
25N
85W
84W
83W
82W
81W
80W
79W
78W
77W
76W
75W
Sep 14, 1999 06Z – Sep 19, 1999 00Z every 6 hrs

Figure 2

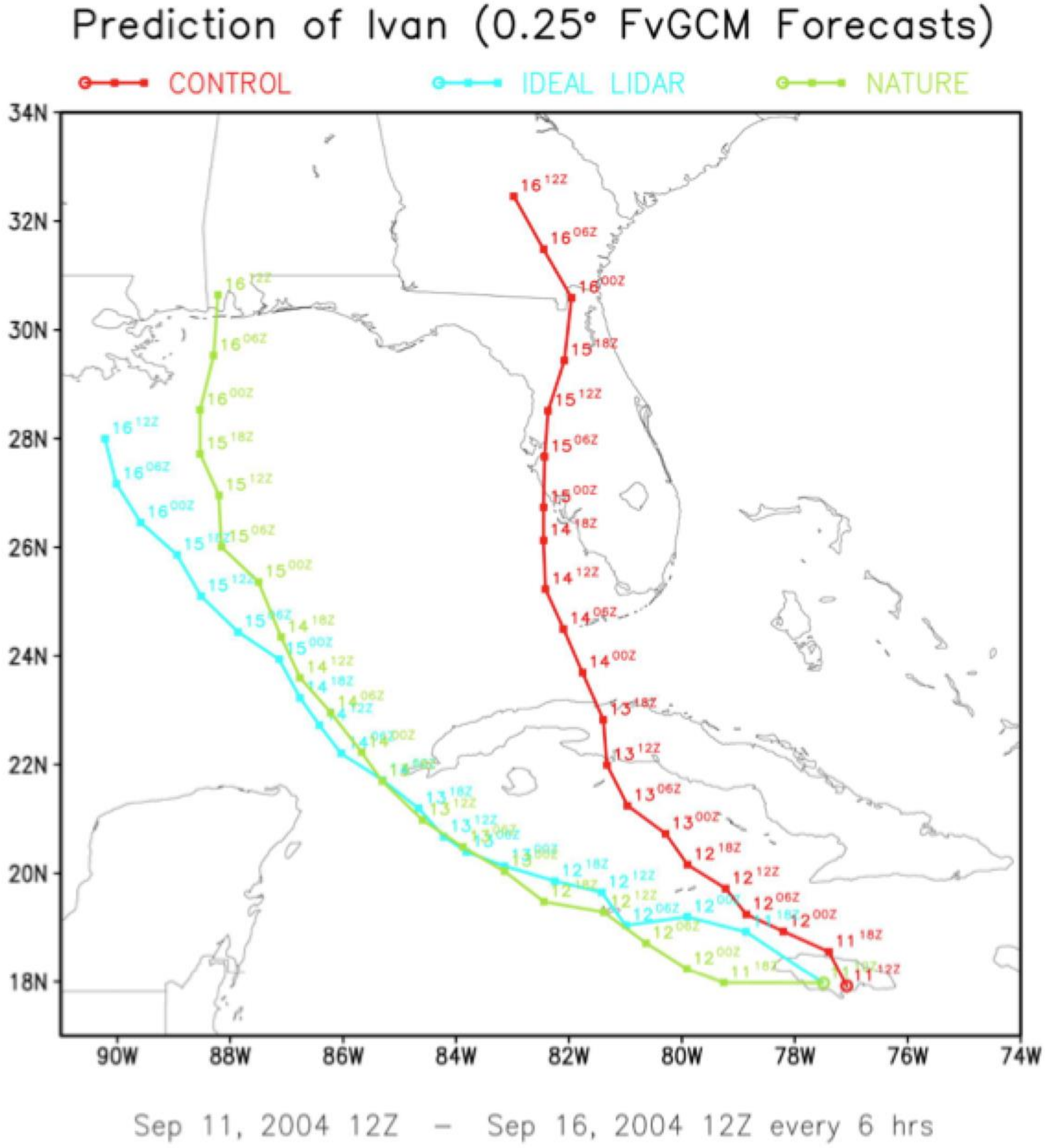
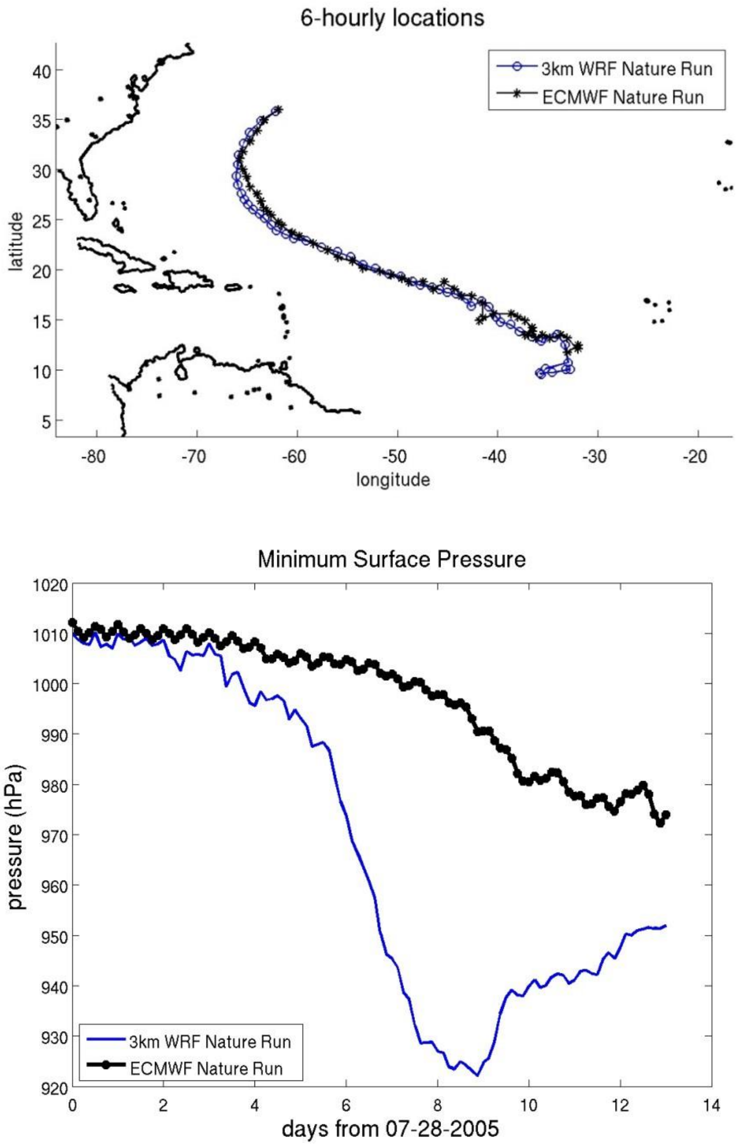

Prediction of Ivan (0.25° FvGCM Forecasts)
CONTROL
IDEAL LIDAR
NATURE
34N
32N
30N
28N
26N
24N
22N
20N
18N
90W
88W
86W
84W
82W
80W
78W
76W
74W
Sep 11, 2004 12Z – Sep 16, 2004 12Z every 6 hrs

Figure 3


6-hourly locations
3km WRF Nature Run
ECMWF Nature Run
latitude
40
35
30
25
20
15
10
5
-80
-70
-60
-50
-40
-30
-20
longitude
Minimum Surface Pressure
pressure (hPa)
1020
1010
1000
990
980
970
960
950
940
930
920
0
2
4
6
8
10
12
14
days from 07-28-2005
3km WRF Nature Run
ECMWF Nature Run

Figures 4

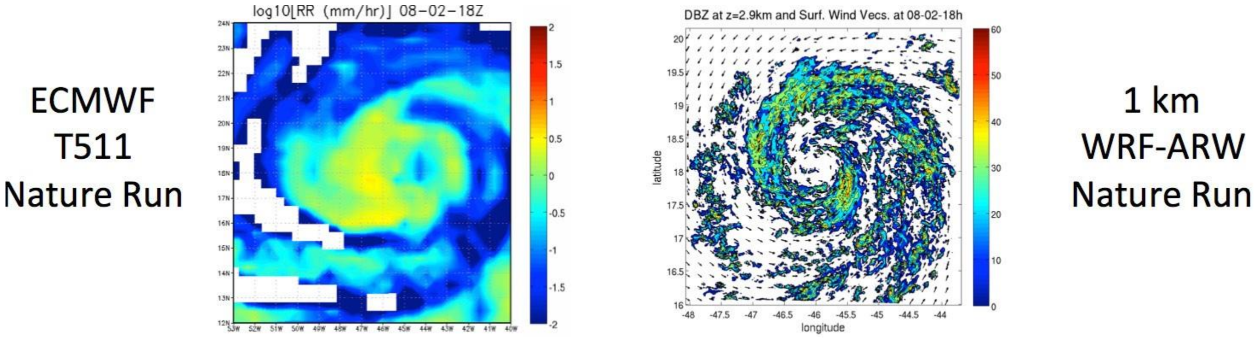

ECMWF
T511
Nature Run
log10[RR (mm/hr)] 08-02-18Z
24N
23N
22N
21N
20N
19N
18N
17N
16N
15N
14N
13N
12N
53W 52W 51W 50W 49W 48W 47W 46W 45W 44W 43W 42W 41W 40W
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
DBZ at z=2.9km and Surf. Wind Vecs. at 08-02-18h
latitude
20
19.5
19
18.5
18
17.5
17
16.5
16
-48 -47.5 -47 -46.5 -46 -45.5 -45 -44.5 -44
longitude
60
50
40
30
20
10
0
1 km
WRF-ARW
Nature Run

Figure 5

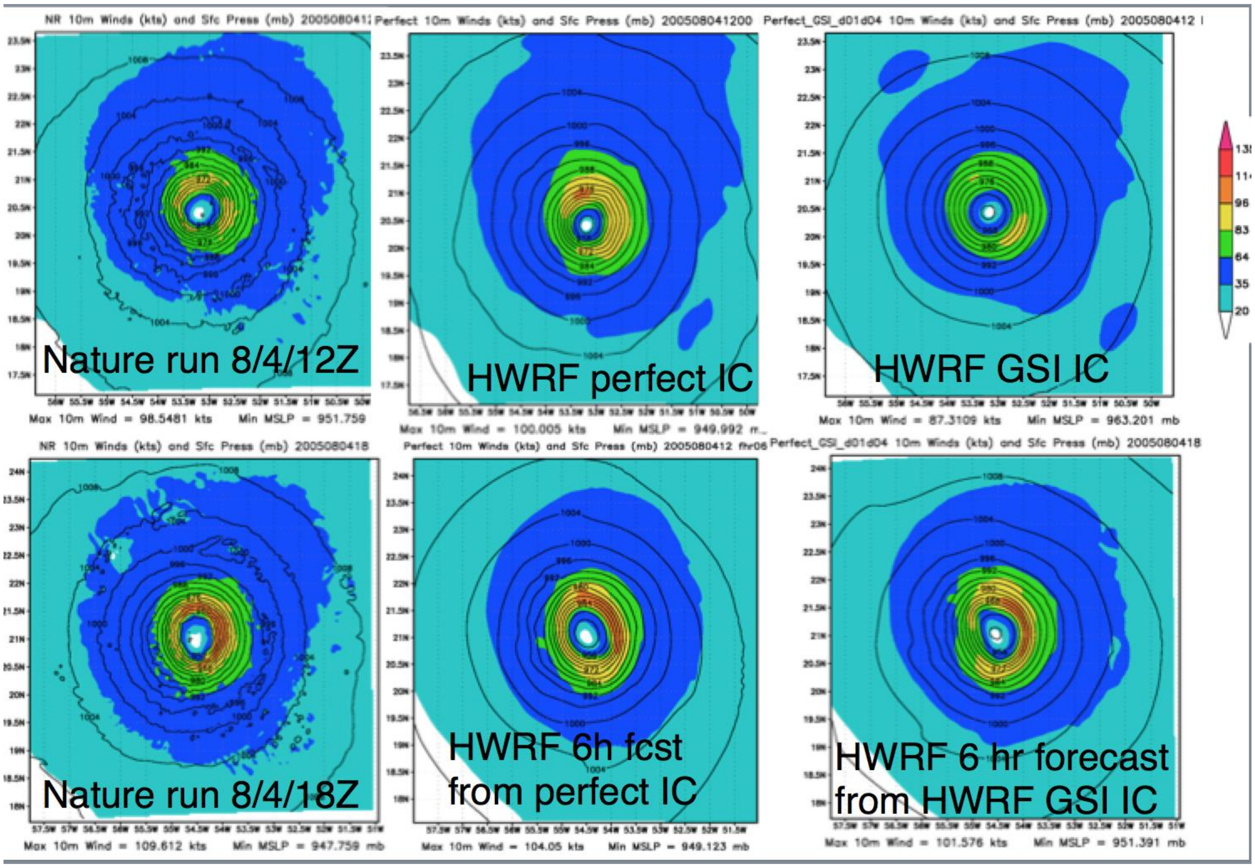

NR 10m Winds (kts) and Sfc Press (mb) 200508041
Perfect 10m Winds (kts) and Sfc Press (mb) 2005080412001200
Perfect_GSI_d01d04 10m Winds (kts) and Sfc Press (mb) 2005080412
Nature run 8/4/12Z
HWRF perfect IC
HWRF GSI IC
Max 10m Wind = 98.5481 kts Min MSLP = 951.759
Max 10m Wind = 100.005 kts Min MSLP = 949.992
Max 10m Wind = 87.3109 kts Min MSLP = 963.201 mb
NR 10m Winds (kts) and Sfc Press (mb) 2005080418
Perfect 10m Winds (kts) and Sfc Press (mb) 2005080412 fhr06
Perfect_GSI_d01d04 10m Winds (kts) and Sfc Press (mb) 2005080418
Nature run 8/4/18Z
HWRF 6h fcst from perfect IC
HWRF 6 hr forecast from HWRF GSI IC
Max 10m Wind = 109.612 kts Min MSLP = 947.759 mb
Max 10m Wind = 104.05 kts Min MSLP = 949.123 mb
Max 10m Wind = 101.576 kts Min MSLP = 951.391 mb
96
83
64
35
20

Figure 6