Observing System Simulation Experiments: Preliminary Report on the Impact of Unmanned Aircraft System Observations on Atlantic Hurricane Forecasts

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Executive Summary

A preliminary global OSSE was conducted to evaluate the potential impact of high-altitude, long-endurance (HALE) UAS dropsonde observations on hurricane track prediction. The results from this initial experiment show potential for UAS to improve hurricane track forecasts. In particular, the extended spatial and temporal coverage permitted by HALE UAS demonstrate the potential for further improvement. More experiments will be needed to establish statistical significance and to determine the optimal flight patterns for actual application. The status of a high-resolution regional OSSE for studies of UAS impact on hurricane intensity is also reported.

1. Background

Unmanned Aircraft Systems (UAS) are an emerging technology with many potential uses in support of NOAA's mission. These platforms are able to reach areas of the planet that are poorly observed due to remote locations and/or dangerous conditions. The observing capabilities of UAS vary greatly depending on platform type, with tradeoffs between flight duration, payload capacity, and expense. While there are many different potential applications for UAS in the global atmospheric observing system, it is currently unclear how best to employ UAS in the field.

Tropical cyclone forecasting is of particular interest to NOAA, as landfalling tropical cyclones are high-impact events with serious economic and safety concerns for the public. Uncertainty in the forecast track and intensity of a hurricane can lead to unnecessary evacuations (or worse, failure to evacuate the appropriate regions) and reluctance of the public to heed forecast warnings. Hurricanes offer a hostile environment for making direct observations, and are frequently located in remote oceanic regions, so that most observations are currently provided by satellites. UAS have the potential to observe the hazardous environment within the hurricane, and to continuously monitor storms in central ocean basins.

One framework to investigate the potential value of UAS is through an Observing System Simulation Experiment (OSSE). OSSEs are modeling studies for evaluating the potential impact of a new observing system on numerical weather prediction (NWP). If test flights with UAS were simple or inexpensive to achieve, it would be possible to perform many missions in the field and then ingest the UAS observations into an NWP model to determine if there is significant forecast improvement as a result of the new data. OSSEs are a similar exercise, but with modeled UAS

flights instead of actual flights in the real world - in this fashion, many test flights can be simulated for different scenarios with relatively little expense or investment.

This report details two OSSE efforts to evaluate the potential impact of UAS observations on hurricane forecasts in the Atlantic basin. The goal of these OSSEs is to inform the NOAA UAS Program as to whether investments in UAS would have significant benefits to numerical weather prediction, and if so, what mission scenarios would yield the greatest improvement to forecasts.

1.1 UAS Platforms

Unmanned Aircraft Systems range from micro-UAS that have a minimal payload capacity and limited flight capability, to full size aircraft capable of carrying thousands of kilograms of payload and flying more than 20,000 km per mission. NOAA has already performed observing missions with both low-altitude long-endurance (LALE) UAS such as Aerosonde and high-altitude long-endurance (HALE) UAS such as Altair and Global Hawk. New platforms that may be of interest are also under development, such as the extremely long-endurance Zephyr, or expendable Coyote UAS.

The focus of these preliminary OSSE studies will be on HALE UAS platforms since they can carry large payloads for extended periods. The main types of instruments considered are *in situ* measurements and dropsondes, that could be deployed remotely from the UAS. Small expendable UAS deployable from a HALE platform can also be simulated in the OSSE. Although HALE platforms are capable of carrying many other types of instruments, such as Doppler lidar or remote sensors commonly mounted on satellites, these instruments will not be addressed in this first set of experiments.

High-altitude UAS have multiple potential uses in monitoring hurricanes. The long flight duration capabilities of the UAS enable the craft to reach tropical cyclones too far from land for manned aircraft missions, and also to loiter in the vicinity of a storm for extended periods. If multiple UAS were available, the tropical cyclone could be continuously monitored. Because the high-altitude UAS can fly in the lower stratosphere, the aircraft can fly over the hurricane without flying directly through hazardous conditions. The Global Hawk flight capabilities in hurricanes have recently been demonstrated in Hurricane Earl and Hurricane Karl as part of the NASA Genesis and Rapid Intensification Processes (GRIP) field experiment.

1.2 OSSEs

There are many benefits of performing an OSSE to evaluate a potential new observing system. Although OSSEs are difficult and computationally expensive, they are much less expensive than developing and launching the actual observing system. The OSSE can also help to guide the design and development of new observing systems, and to pave the way for the integration of new observations into operational data assimilation schemes. In most cases, an OSSE can also determine whether the new observing system is a prudent investment or not and yield a quantitative estimate of its impact (Atlas 1997).

In an OSSE, the new observing system can be tested in many different configurations with relatively little effort. In the case of UAS, many possible flight scenarios, combinations of aircraft platforms, and instrument sampling strategies can be tested. The OSSE can provide information as to how UAS can best be used in conjunction with manned reconnaissance flights, how frequently dropsondes should be launched, and what the platform requirements are for the UAS under development.

One particularly useful product of an OSSE is an evaluation of how well operational data assimilation is able to utilize the new observations. The incorporation of a new type of observation into a data assimilation system is not trivial, and the data assimilation may require modification in order to maximize the utility of new data types. The OSSE begins this process of integration, and can also be used for detailed evaluation of the data assimilation scheme.

Two different OSSEs were developed in support of the NOAA UAS Program: a global OSSE focused on hurricane track forecast improvements, and a regional OSSE intended for hurricane intensity forecasts. This report will address the current status and preliminary results from both of these OSSEs.

2. Global OSSE

Global models have reasonable depiction of large-scale atmospheric features, but are not suitable for the study of small-scale phenomena, which may not be properly resolved. While tropical cyclones are present in global numerical weather prediction models, the inner structure of the storms is not well represented, and thus the global modeling study is best suited for hurricane track forecasting but not intensity forecasting.

2.1 OSSE Setup

The global OSSE is part of a collaborative effort, or Joint OSSE, involving multiple institutions that are listed in the Appendix. These agencies have been participating in the Joint OSSE since 2005, but the OSSE presented in this report is the first to utilize this system to answer specific questions related to an observing system.

An OSSE consists of several components: a Nature Run, synthetic observations generated from the Nature Run, a data assimilation system, and a forecast model. The Nature Run is a long free-cycling run from a numerical weather prediction model, using the highest feasible resolution, which is intended to act as the 'truth' or replacement for reality in the OSSE system. This Nature Run should have similar behavior to that seen in the real world, and must undergo evaluation to determine if there are any deficiencies in the behavior of the Nature Run atmosphere. Synthetic observations are generated using the Nature Run fields in order to create an entire set of data for all observation types that are currently used by operational numerical weather predication models. These observations should be calibrated to ensure that the impact of assimilating each observation type in the OSSE is similar to that seen in the real world. In addition to the currently used observations, synthetic observations are also generated for the new observing system to be tested in the OSSE. These synthetic observations are assimilated into a forecast model system to generate experimental forecasts. This model system should be different from the model used to generate the Nature Run. By running comparative forecasts with and without assimilation of the synthetic data from the new observing system, the impact of the new observations on the forecasts can be quantitatively evaluated.

2.1.1 Nature Run

The Nature Run for this OSSE was provided by ECMWF, using their operational model at T511 (~30 km) spectral resolution with 91 levels. The Nature Run was started at 12Z 1 May 2005, and run until 18Z 21 May 2006. The only fields input to the model during the run were sea surface temperature, sea ice, and land snow cover. Evaluation of the Nature Run shows that tropical cyclones in the Atlantic basin are realistically modeled (Reale et al. 2007) in general, although the inner structure of the tropical cyclone cannot be simulated in detail at this model resolution.

Twelve hurricanes in total occurred in the Atlantic basin in the Nature Run; of these storms,

four make landfall in North America, as shown in Figure 1. Five of the storms show "early recurving" tracks - these storms form from African easterly waves and intensify and move poleward in the eastern Atlantic. Three storms form and recurve in the western Atlantic with one making landfall. All three of the storms that form in the Gulf of Mexico/Caribbean region are landfalling systems. In this report, we focus on one storm that occurs during the month of August: AL01, which forms in the central Atlantic and recurves over the ocean.

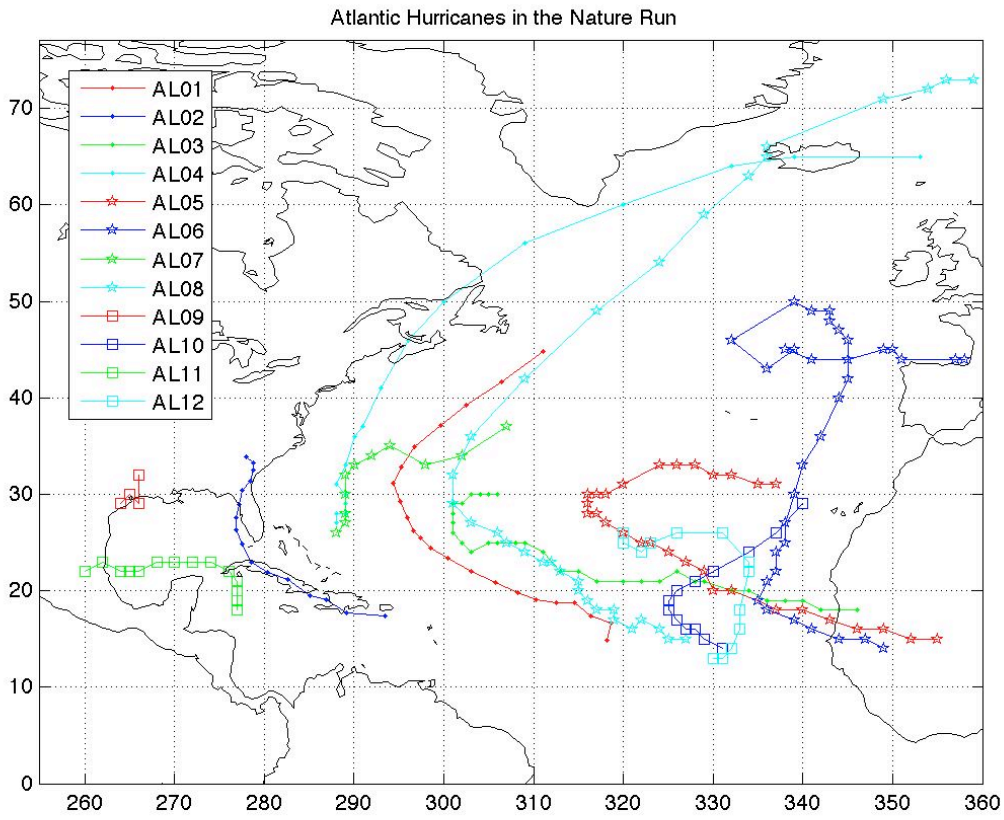

Figure 1. Tracks of all Atlantic basin tropical cyclones in the ECMWF Nature Run.

2.1.2 Forecast Model

The forecast model used for the experiments is the NOAA/NCEP Global Forecast System (GFS) operational model from spring 2007, run at T382 (~35 km) resolution with 64 levels. The data assimilation system coupled to the GFS is the Gridpoint Statistical Interpolation (GSI) package, also from spring of 2007. Because this model version was used to evaluate the performance of the synthetic observations, it is important not to make alterations to the model or update to a newer model version without re-evaluating the behavior of the OSSE system.

2.1.3. Synthetic Observations

Synthetic observations for the current global observational network were created by NASA/GMAO and by NCEP/EMC. The general method used to generate the observations was to determine the spatial and temporal distribution of satellite and conventional observations based on archived data sets from 2005—2006. This positional information was then used in conjunction with the Nature Run to interpolate new, "perfect" observations possessing no errors (with respect to the Nature Run). The synthetic data sets used for this OSSE consist of radiance data for AIRS, AMSU-A, AMSU-B, HIRS-2, and HIRS-3 from the GMAO data set, and conventional data and radiance data from GOES and OSBUV from the NCEP data set. Details of the methods used to generate the GMAO synthetic observations can be found in Errico et al. (2010).

There are some known deficiencies in the methods used to generate the synthetic observations. One major difficulty in creating synthetic radiance observations involves treatment of clouds in the Nature Run. Some radiance observations are significantly impacted in the real world by the presence of clouds, including extremely thin cirrus clouds invisible to the human eye. Representation of clouds is particularly challenging for numerical models, and the cloud distribution overall in the Nature Run is not sufficiently close to reality for accurate calculations in making synthetic observations. For expediency, the distribution of cloud-impacted radiance observations used for generation of the synthetic observations is taken from the archived real observations from the same date and time. While this retains the desired characteristics of the spatial and temporal impacts of clouds, the location of the clouds does not match the Nature Run clouds. Similarly, rawinsonde observations were generated using the mandatory and significant levels from archived soundings, and without advection of the sondes in space. In addition, certain channels of the AMSU-A, AMSU-B, and MSU observations were removed from the synthetic observations over land and sea ice due to uncertainty in how to treat surface emissivity in these areas.

Synthetic observations for UAS were generated at ESRL by simulating the "flight" of the UAS through the Nature Run. The flight path of the UAS is given as a series of prescribed waypoints, with the relative airflow in the Nature Run fields being taken into account when calculating the speed of the aircraft. The UAS are assumed to travel along great circle paths between waypoints. A synthetic dropsonde is released at each waypoint, and the advection of the falling sonde is calculated using the Nature Run wind field.

2.1.3.1 *Observation Error*

It is important to modify the "perfect" interpolated synthetic observations to include an appropriate representation of observation error. There are multiple sources of errors that affect real data: observation bias, instrument errors, and representativeness errors. Since the data assimilation package includes bias correction which removes known bias from observations, no bias was introduced to the synthetic data, for otherwise known biases would simply be removed, and unknown biases are not understood. Representativeness errors stem from the difference in resolution between the forward model and the observation space. Because the Nature Run is at higher resolution than the GSI/GFS, some representativeness error will be inherent to the synthetic observations, although the errors are likely to be smaller than those seen in real data.

In order to account for instrument error and uncaptured representativeness error, errors were calculated and added to the perfect synthetic observations as described by Errico et al (2010). For all conventional observation types except for soundings, uncorrelated random errors were added to the perfect observations; for soundings, vertically correlated errors were added. The errors were taken from a normal distribution with mean of zero and adjustable standard deviation. For radiance observations, horizontally correlated errors were added to each independent satellite channel.

2.1.3.2 *Calibration*

The OSSE system was calibrated to ensure that the impact of the synthetic observations is similar to that obtained with real observations. The calibration method used for this OSSE consists of paired data denial experiments, in which an observation type is withheld from the data ingest, and the model results are then compared to a "control" case in which all observation types are included. These data denial experiments were conducted both using synthetic observations and also using archived real data, so that the observation impact could be compared exactly with the real world. The results were evaluated, and the synthetic observations then adjusted until the observation impact in the OSSE system matched that of the real world as closely as possible. This exercise improves the reliability of the OSSE results and provides guidelines for the limit of the usefulness of the OSSE. In this OSSE calibration, five major observation datasets are considered since it is too costly to calibrating all data types,

RAOB, Aircraft, AMSU-A, AIRS and GOES. These datasets are well-known high impact datasets. The first two are conventional *in-situ* and the rest are satellite remote sensing ones.

The conventional synthetic observations were 'tuned' during the calibration process so that the impact of the observations on the analysis field matched the real world impact. This tuning was effected by modifying the standard deviation of the random errors applied to the perfect observations. The radiance observations were not able to be tuned in this fashion, and were thus not adjusted during the calibration process. The relative impacts of five select observation types upon the analysis fields are shown in comparison to the real-data impact in Figure 2. Overall, the match between the OSSE system and the real-world system was judged to be acceptable. Some discrepancies are evident, such as too low impact due to AMSU-A in the lower troposphere in the OSSE, which is likely due to removal of AMSU-A channels from the synthetic observation, as previously discussed.

A more informative test of the OSSE calibration is the impact of observations on the model forecasts. Figure 3 shows the impact of five observation types on the anomaly correlation of the forecast, a measure of how well the forecast represents features in the atmosphere. The OSSE system does not perform as well in relation to the real world for anomaly correlation in comparison to the analysis impact. The relative impact of the observation types on anomaly correlation is the same in the OSSE system as in the real world with the exception of AIRS data, which has too strong an impact in the OSSE in the extended forecast period. The impact of RAOB is also too small in the OSSE for forecasts exceeding two days.

There are many factors that can contribute to significant differences in the behavior of observational data in the OSSE in comparison to the real world. The global anomaly correlation of geopotential height (Figure 4) is too high in the OSSE, which indicates that the Nature Run behavior is closer to the GFS than to the real world. Forecast errors in relation to the Nature Run are thus expected to grow more slowly in the OSSE system than real world forecast errors. This kind of problem is intrinsic to most OSSEs. The current OSSE system is the best effort possible given available resources; future improvements will be predicated on significant advances in modeling and computing resources.

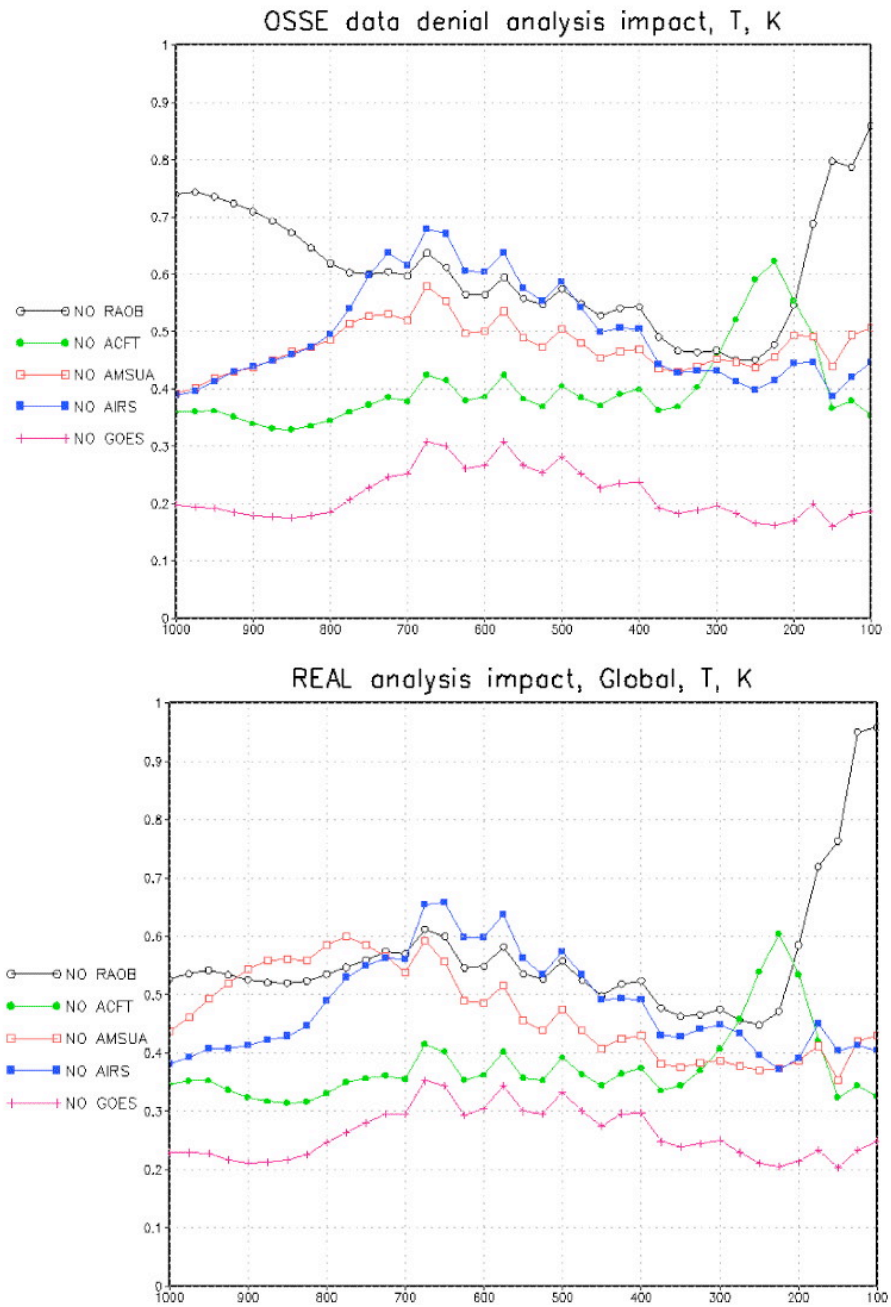

Figure 2. Calibration of synthetic observations: analysis impact of select observation types. Relative impact of observations on temperature - global mean values of RMSE difference between data denial and control analysis. Top: calibrated OSSE system. Bottom: archived real observations.

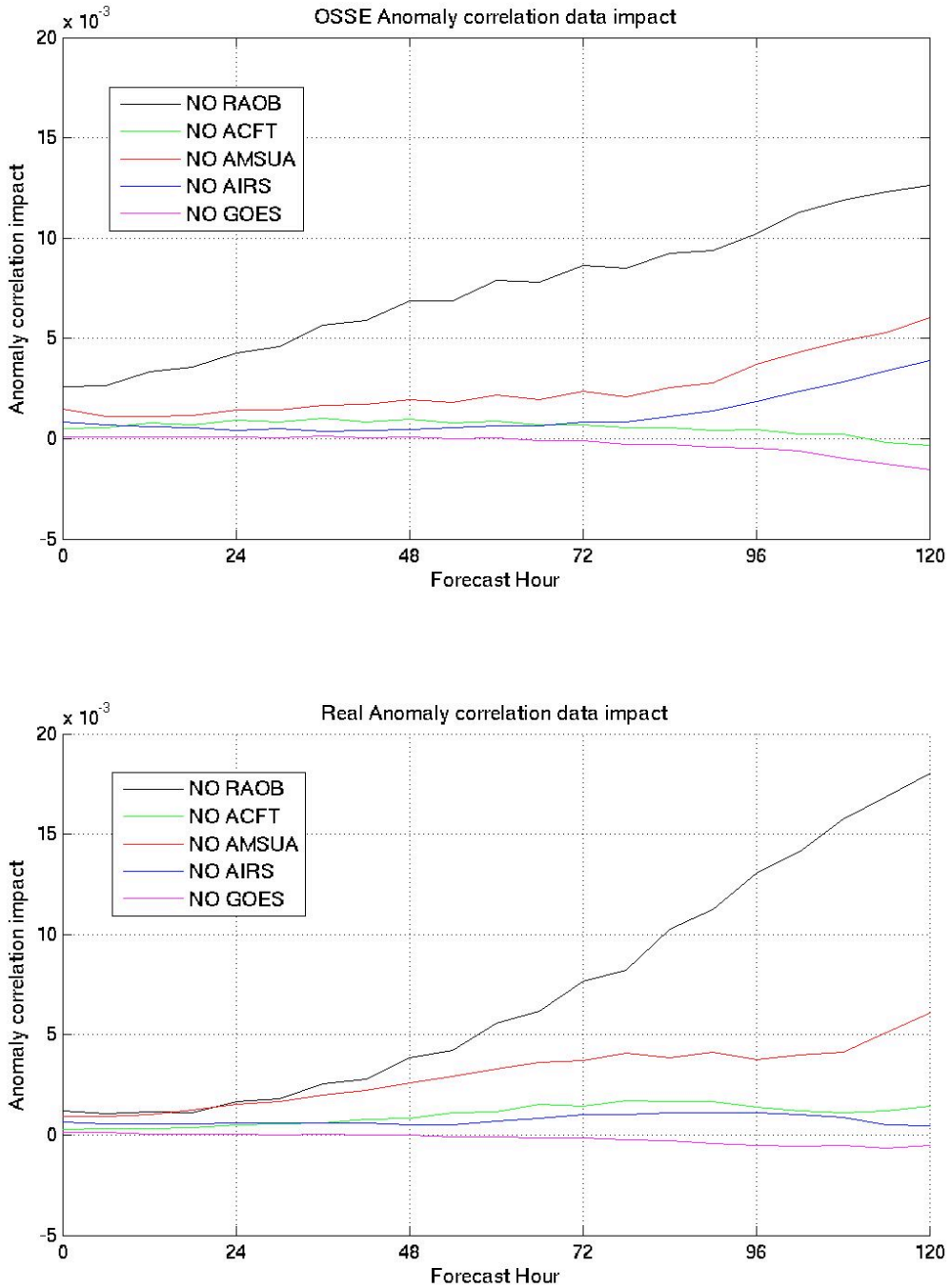

Figure 3. Calibration of synthetic observations: global anomaly correlation impact for geopotential height in 120-hour forecasts. Relative impact of observations on anomaly correlation - data denial minus control analysis. Top: calibrated OSSE system. Bottom: archived real observations.

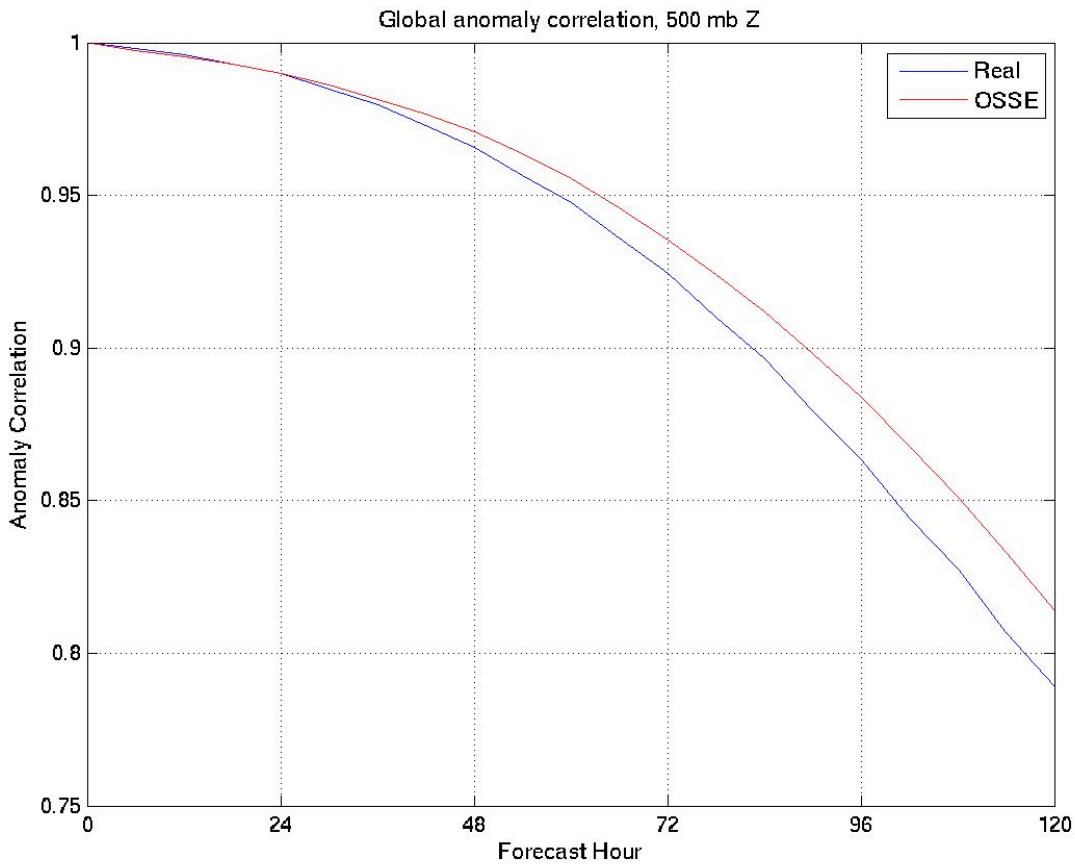

Figure 4. Anomaly correlation for 500 mb geopotential height, global mean. Real data (blue) versus OSSE (red).

2.2 OSSE Experiments

In this OSSE, forecasts with serious deviations from the track of the Nature Run storm were chosen to allow room for improvement when UAS observations are added. Control forecasts were generated using the "standard" set of observations for the entire month of August, and the most promising cases were chosen for experiments.

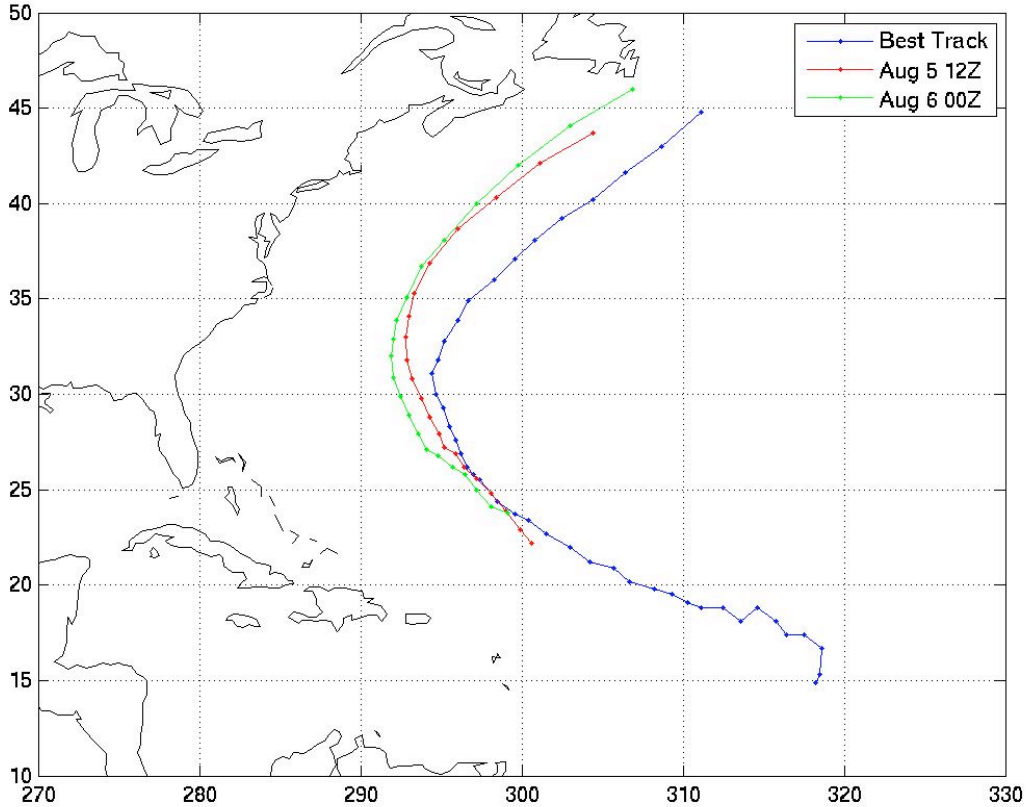

Figure 5. Control track forecasts starting 12Z 5 August (red) and 00Z 6 August (green) vs. Nature Run best track, AL01.

The first Atlantic basin storm, denoted 'AL01', follows a common recurving track, and is generally well forecast in terms of track through its life cycle. However, there are several candidate forecasts that deviate significantly from the true track. The forecasts from 12Z 5 August and 00Z 6 August show a northwestward bias of the storm track in the 3-5 day forecast (Figure 5). By the 120-hour forecast, the track error is approximately 700 km as seen in Figure 6. As is the case with many recurving tropical cyclones (Fogarty and Bowyer 2008), the along-track error is a significant portion of the total track error as the forecast hurricane travels too quickly to the north. Since these two forecasts show the greatest track deviation of any of the forecasts for the first two August Atlantic basin tropical cyclones, they were chosen as the subjects for the initial OSSE.

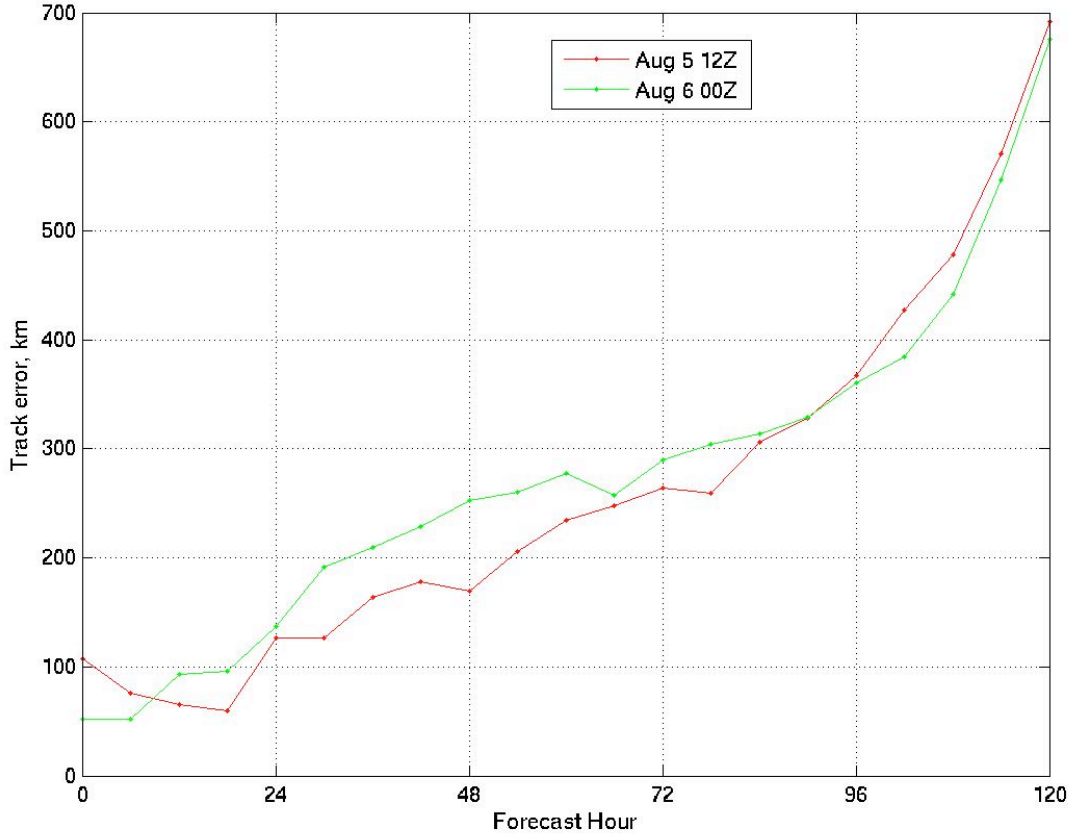

Figure 6. Track error as a function of forecast hour. 12Z 5 August forecast (red) and 00Z 6 August forecast (green).

Two different strategies for observational flight paths are investigated for the 12Z 5 August and 00Z 6 August forecasts. In the first set of experiments, the UAS repeatedly circumnavigates the hurricane to improve initialization of the region near the storm. In the second set of experiments, the area of greatest forecast impact is isolated in a sequence of tests, and flight paths are then chosen within this targeted area.

2.2.1 Circumnavigational flights

In the circumnavigation flight tests, the UAS flies in circles around the moving center of the hurricane at various radii. Several different configurations were tested, as shown in Figure 7 and described in Table 1:

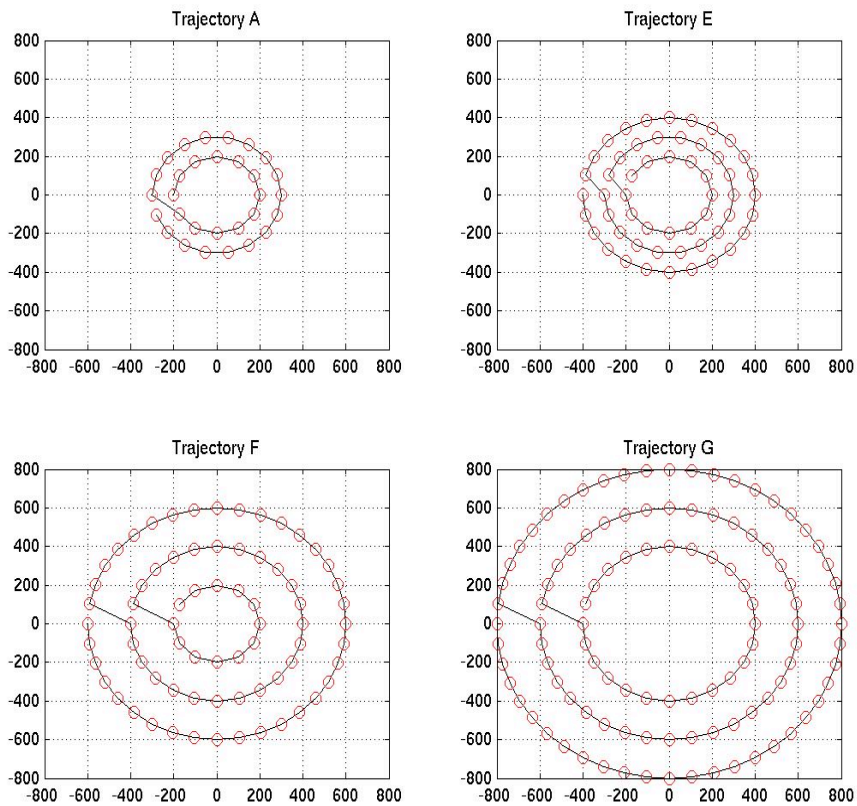

Figure 7. Circumnavigation flight path scenarios. Red circles indicate location of dropsonde releases.

- Trajectory A, in which the UAS flies at 200- and then 300-km radii from the storm.
- Trajectory E, in which the UAS flies at 200-, 300-, and then 400-km radii from the storm
- Trajectory F, in which the UAS flies at 200-, 400-, and then 600-km radii from the storm
- Trajectory G, in which the UAS flies at 400-, 600-, and then 800-km radii from the storm

Trajectory A has an estimated flight time of five hours, which is much shorter than the flight capabilities of the Global Hawk UAS, so the flight path experiments for Trajectory A consist of repetitions of the trajectory – as soon as the first flight of the trajectory is complete, the UAS returns to the first point of the trajectory and repeats the path. The two combinations tested here are 'AA' in which Trajectory A is repeated twice, and 'AAA' in which Trajectory A is repeated three times. Similarly, Trajectory E has an estimated flight time of nine hours, so the combination path 'EE' is tested to make full use of the UAS capabilities. In each trajectory, a dropsonde is released every 105 km along the flight path, indicated by red dots in Figure 7.

Table 1: Flight scenario experiment details.

	First Observation	Observational Flight Time, hr	Number of Sondes
Trajectory AA	06Z 5 Aug	11	60
Trajectory AAA	06Z 5 Aug	16	90
Trajectory EE	03Z 5 Aug	19	108
Trajectory F	06Z 5 Aug	13	72
Trajectory FF	12Z 4 Aug	26	144
Trajectory G	06Z 5 Aug	18	108

The trajectory combinations AA and AAA yield similar forecast results at 12Z 5 August and 00Z 6 August, as seen in Figures 8 and 9 respectively. The impact of the UAS sonde data on the analysis field is primarily seen within a 1000-km radius of the storm center, as evidenced in the streamfunction field in Figure 10. The forecast hurricane tracks show slight improvement in the along-path track error, but little improvement in the cross-track error – the main effect of the UAS observations is to slow the northward progression of the storm during the first few days of the forecast. The 12Z 5 August forecast shows decreased error (Table 2) at all forecast times, but the 00Z 6 August forecast shows increased error after 72 hours for all flights.

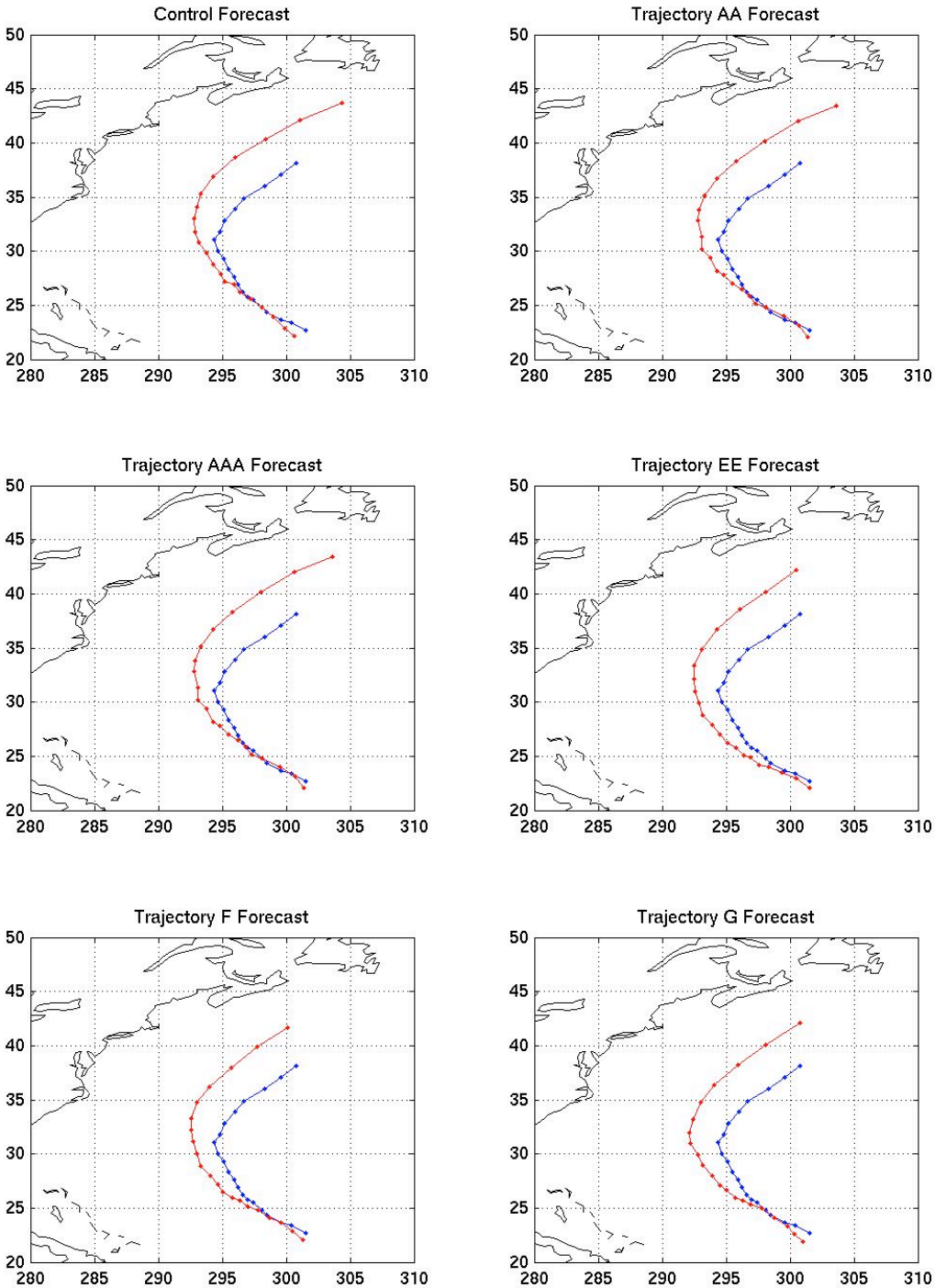

Figure 8: Forecast tracks for circumnavigation scenarios (red) vs Nature Run best track (blue). 12Z 5 August forecast initial time.

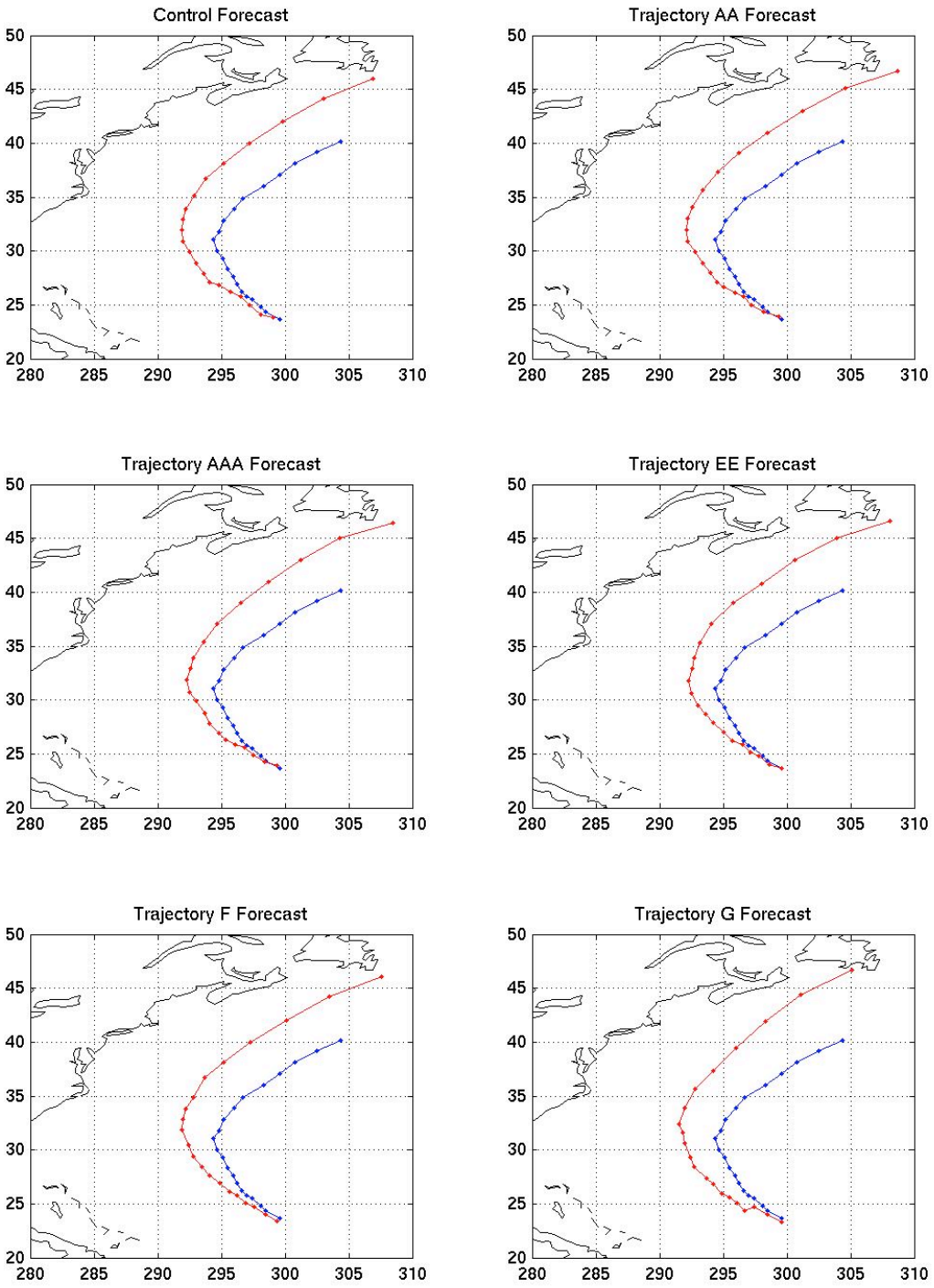

Figure 9: Forecast tracks for circumnavigation scenarios (red) vs Nature Run best track (blue). 00Z 6 August forecast initial time.

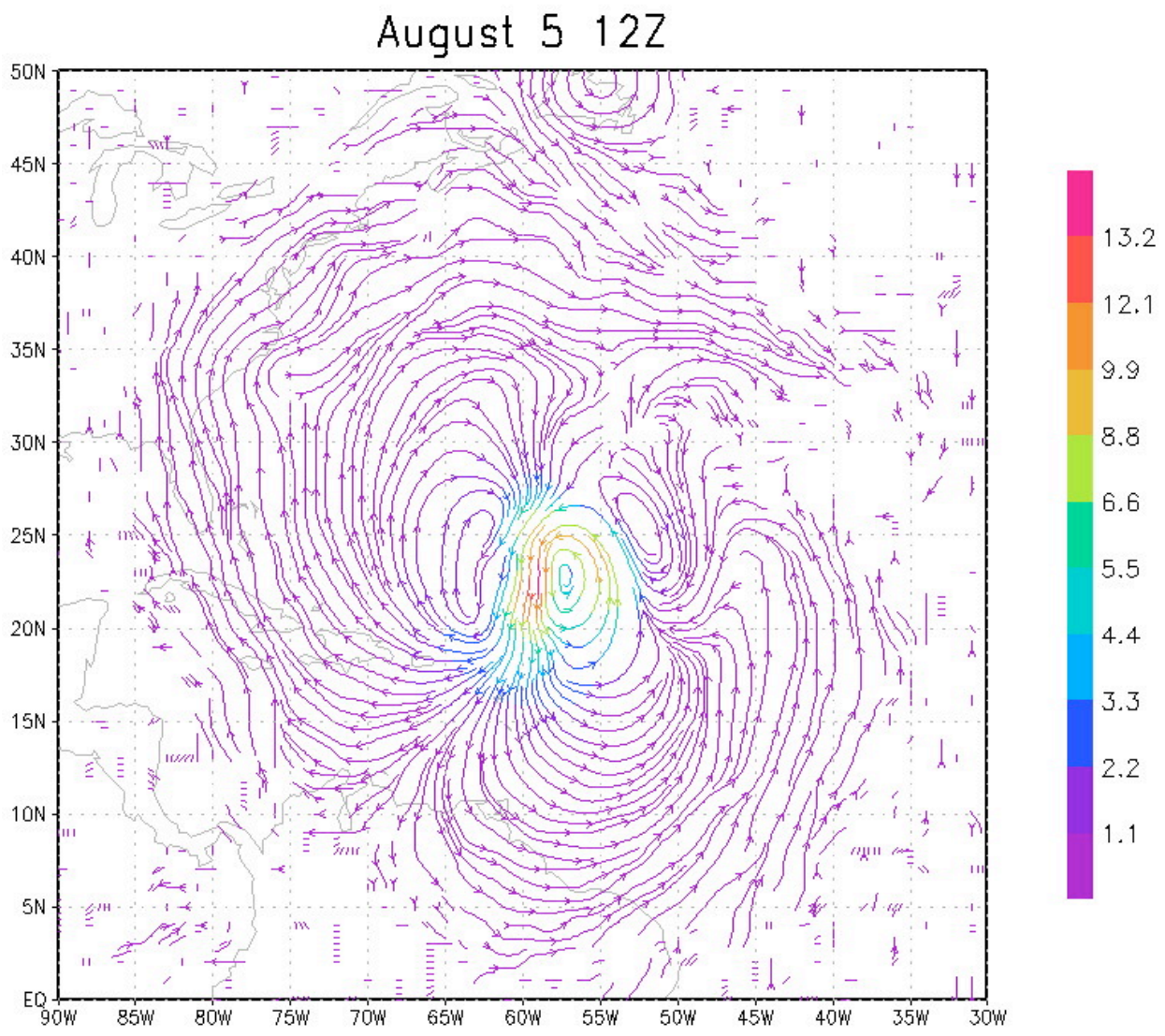

Figure 10. 500 mb streamfunction difference, Trajectory AA versus control analysis, 12Z 5 August. Color indicates windspeed difference, m/s.

Table 2. 12Z 5 August track forecast errors for various trajectory scenarios and control, km.

	Analysis	*24 hr*	*48 hr*	*72 hr*	*96 hr*	*120 hr*
Control	108	127	170	264	367	692
Trajectory AA	67	92	171	210	347	635
Trajectory AAA	67	92	171	210	347	635
Trajectory EE	67	84	134	174	288	456
Trajectory F	70	30	127	164	293	405
Trajectory FF	24	52	169	186	285	571
Trajectory G	103	38	121	183	293	445

Table 3. 00Z 6 August track forecast errors for various trajectory scenarios and control, km.

	Analysis	*24 hr*	*48 hr*	*72 hr*	*96 hr*	*120 hr*
Control	52	137	253	290	361	676
Trajectory AA	30	115	216	278	391	801
Trajectory AAA	30	91	184	240	369	765
Trajectory EE	0	51	191	240	400	772
Trajectory F	39	80	196	286	361	705
Trajectory G	44	119	203	285	393	725

The trajectories with larger radii of observations (EE, F, FF, and G) show greater forecast improvement for 12Z 5 August than the flight paths with smaller radii (AA, AAA). The 00Z 6 August forecast has mixed results, as seen in Table 3. Again, the track forecast improvement is primarily due to reduction in along-track error as the northward translation of the hurricane is slowed during the initial forecast period. In the F and G scenarios, the hurricane vortex is weaker than in the AA and AAA scenarios, presumably due to lack of observations of the inner storm. However, in all of the EE, F, and G scenarios, the 500 mb poleward flow to the north of the storm in the analysis is weaker than in the control, AA, and AAA cases. This difference in the steering flow in the analysis may be related to the improvement in the track forecast. The F scenario has the greatest reduction in track errors for the 12Z 5 August forecast of all of the circumnavigation scenarios tested, as well as the most improvement in the mean sea level pressure of the hurricane environment in comparison to the Nature Run (Table 4). Trajectory FF

was designed to test whether continuous observation improves forecast accuracy, but extending the observation period to 24 hours did not reduce the forecast errors.

Table 4. RMSE for mean sea level pressure over 15—30N, 50—65W, comparison with Nature Run, for various trajectory scenarios and control.

	12Z 5 August	*00Z 6 August*
Control	169.3	144.5
Trajectory AA	100.8	117.1
Trajectory AAA	100.8	109.4
Trajectory EE	86.7	106.0
Trajectory F	89.9	112.7
Trajectory G	129.1	119.6

2.2.2 Targeted observations

Adaptive or targeted observations are taken in regions in which the assimilation of these observations is expected to curtail forecast errors. In practice, there is no clear consensus on the optimal methods to determine regions and times for adaptive sampling. In the OSSE, we can determine regions for adaptive sampling using a network of perfect soundings spaced regularly around the globe, in addition to the 'standard' suite of synthetic observations. The ingestion of these perfect soundings is gradually reduced in space and time in a series of cycling runs, and examination of the forecasts allows the regions of influential observations to be located. A control case is performed in which the global net of perfect soundings is ingested, along with the usual conventional and radiance observations, for several days prior to the forecast period of interest. The results of this control case give an indication of the best possible forecast that could be generated by improving the analysis field, versus the influence of model error on the forecasts.

The network of additional soundings is shown in Figure 11; the inclusion of these observations into the model cycling begins at 00Z 1 August. The track errors for forecasts initialized at 12Z 5 August are listed in Table 5. There is a significant reduction in the track error in comparison to the control forecast, with errors of less than 50 km for the first 72 hours of forecast for 12Z 5 August; the 00Z 6 August forecast also shows improvement in comparison to the control forecast, but not to the same extent as the 12Z 5 August forecast. After 72 hours, the forecast track shows signs of the same northward bias seen in the control forecast.

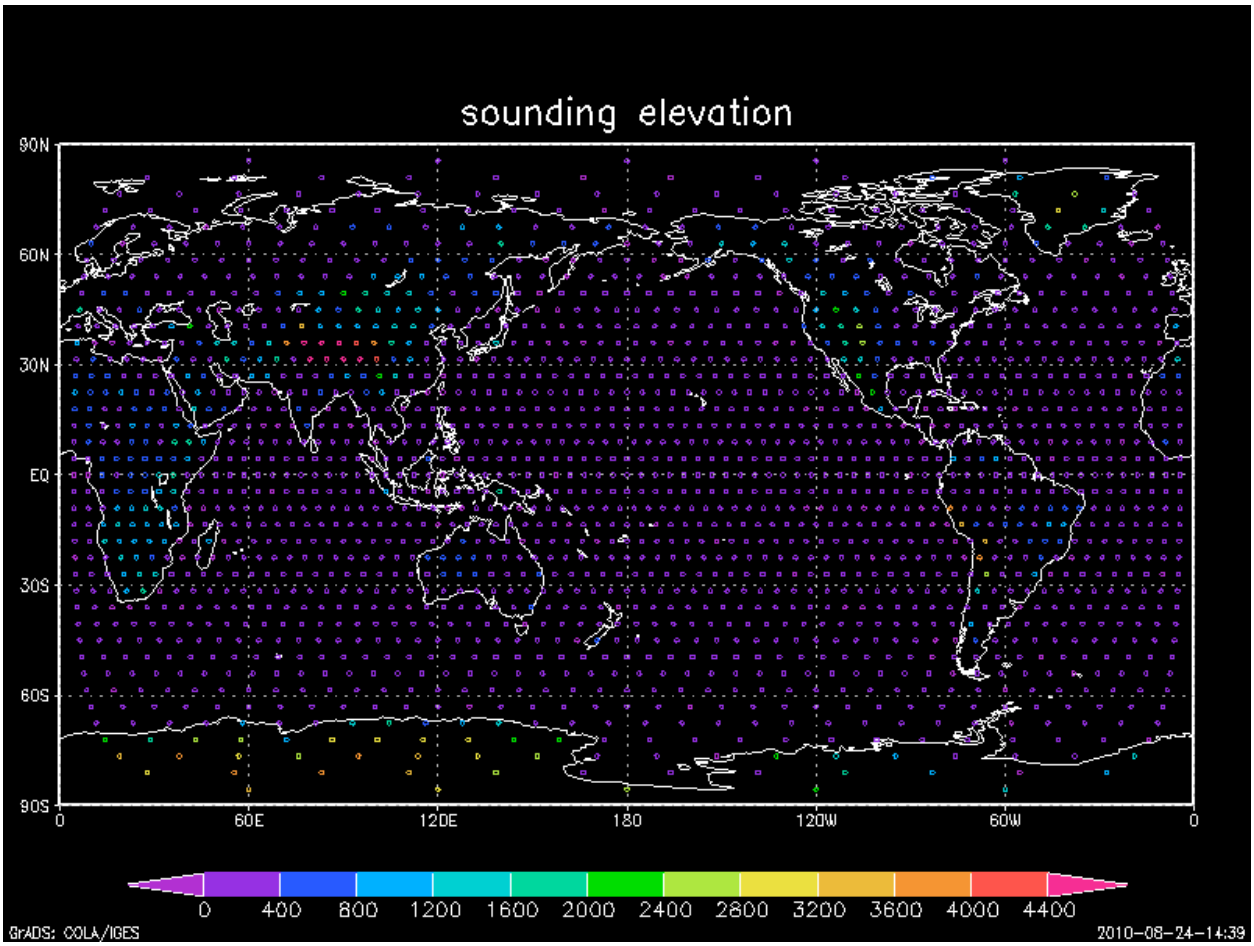

Figure 11. Location of additional soundings used in targeting experiments. Image courtesy of Jack Woollen.

The duration of cycling needed to achieve comparably low forecast track errors is evaluated first. In the control case, cycling begins with a 108-hr lead time prior to the launch of the 12Z 5 August forecast; 36-hr, 24-hr, and 12-hr lead times are tested. The forecast hurricane tracks are shown in Figure 13. With a 36-hr lead time, forecast errors are on a par with the control case (Table 5), but the track errors begin to increase for 24-hr and 12-hr lead times. While a 36-hr observing period is not possible for a single HALE UAS platform, it would be possible for two platforms flying in series. A 36-hr lead cycling time is chosen for the remainder of the targeting experiments, with the focus solely on the 12Z 5 August forecast.

Table 5. 12Z 5 August track forecast errors for targeting scenarios and control, km.

	Analysis	*24 hr*	*48 hr*	*72 hr*	*96 hr*	*120 hr*
Control	24	24	35	35	162	530
36 hours	24	15	39	19	119	375
24 hours	35	57	73	62	166	420
12 hours	46	84	104	53	193	440
180W-0E, 0-50N	24	20	52	29	130	375
0E-360W, 0-50N	24	15	56	22	87	341
90W-0E, 0-50N	24	30	87	67	107	442
90-45W, 0-50N	22	64	100	89	101	225
80-35W, 0-50N	22	42	100	110	228	681
90-45W,10-40N	24	73	116	89	160	337

The region of additional observations is then progressively reduced in area as shown in Figure 12 to determine the location of sensitive regions for the track forecasts. The track forecast for each experiment is illustrated in Figure 13. The Southern Hemisphere and polar region north of 50N are excluded first, with relatively small change in forecast error (Table 5). The Eastern Hemisphere is then excluded with little impact on the forecast, but an increase in track error at all forecast times is seen when the observation region is trimmed to 90W-0E. As the observation region is further reduced to a box from 90W—45W, the 24—72-hr forecast track error increases significantly while there is no increase in error at 72—96 hours. Shifting this observation region 10 degrees to the east results in large error increases after 72 hours.

The large increase in the extended forecast error that occurs when the observation region is shifted from 90—45W to 80—35W implies that there may be a region of sensitivity between 80—90W over central North America. The gradual increase in the track error from 24—72 hours as the observation region progressively shrinks implies that there may not be such a sensitive area for the shorter range forecast. However, attribution is difficult to determine with only single forecast members, as much of the variation between forecasts could simply be due to nonlinear behavior of the forecast system. Ideally, this sort of experiment would be performed using an ensemble rather than a single forecast for each test case, which would give an indication of forecast spread. Had the results of these tests led to a clear indication of a potential targeting region for UAS, this could be explored using reasonable flight paths in the OSSE

system.

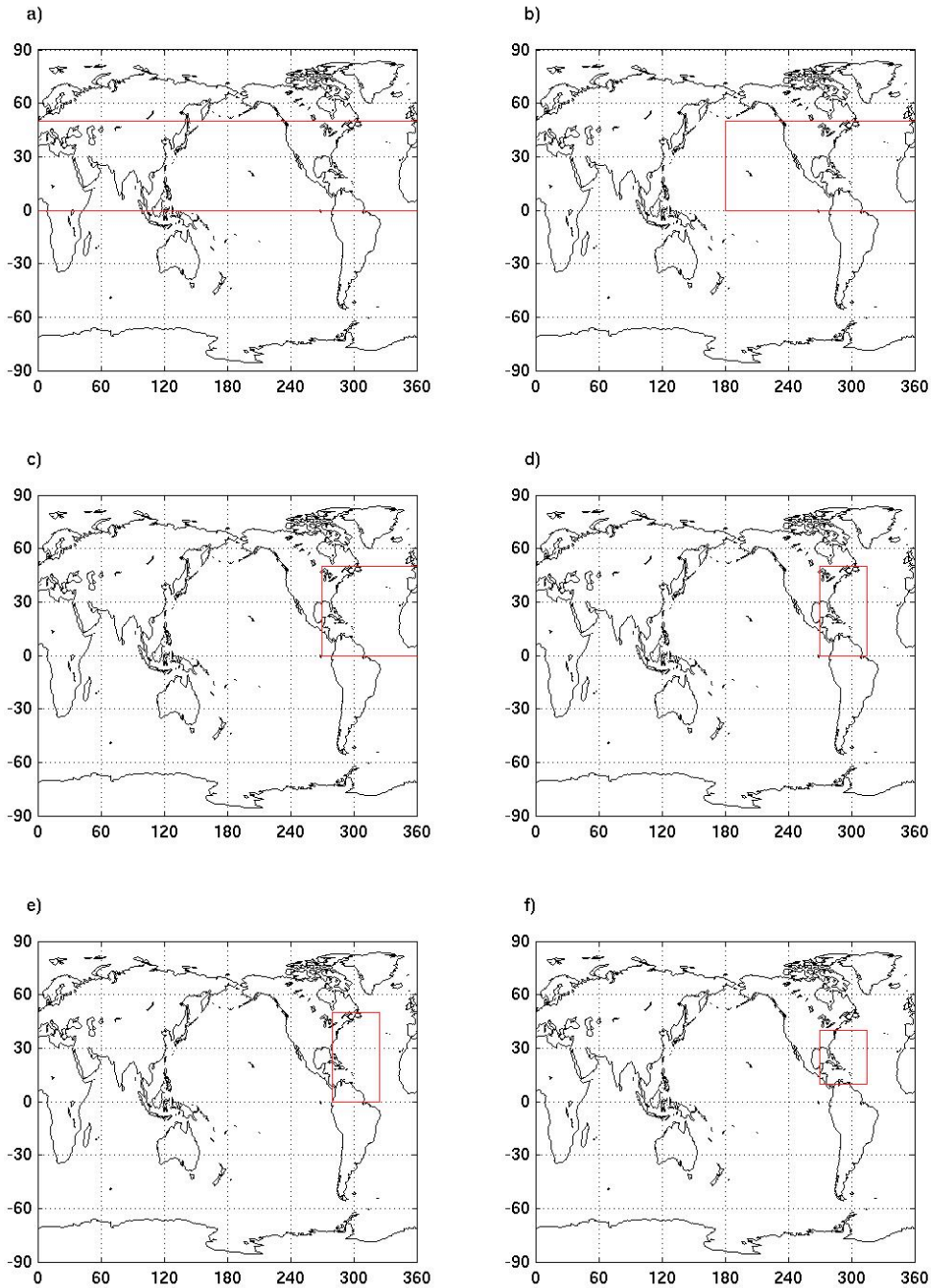

Figure 12. Regions of additional sounding observations for targeting experiments. a) 0—360W, 0—50N b) 180W—0E, 0—50N c) 90W—0E, 0—50N d) 90W—45W, 0—50N e) 80W—35W, 0—50N f) 90W—45W, 10—40N.

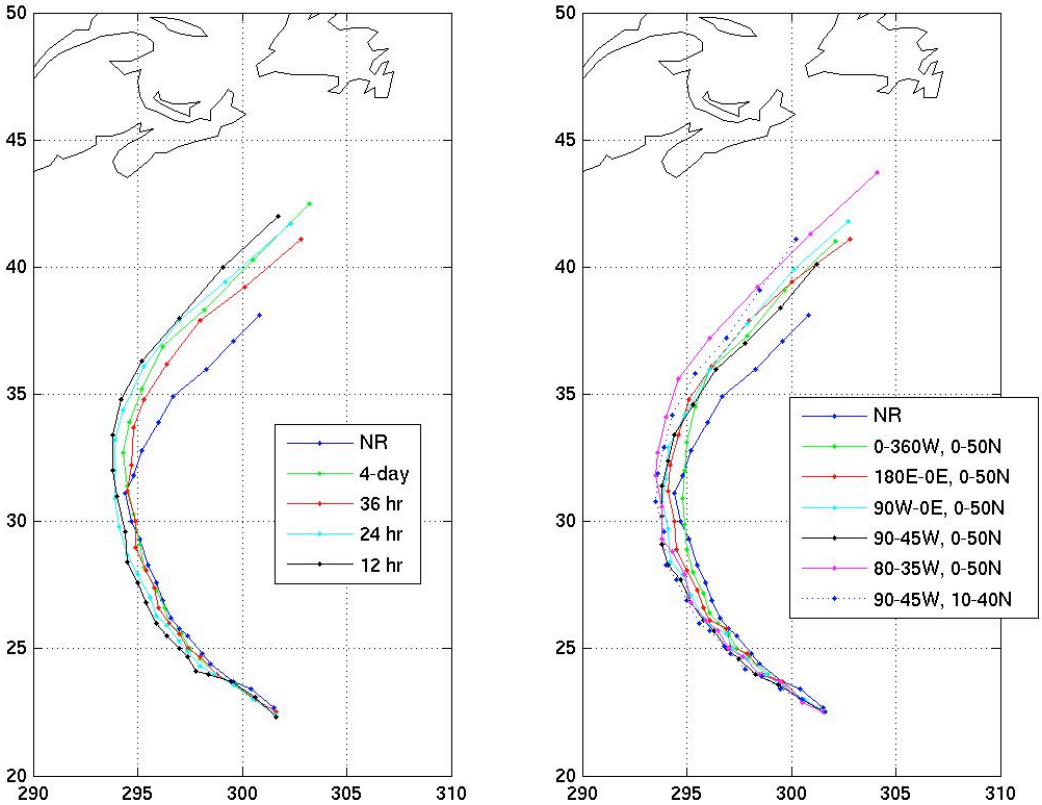

Figure 13. Track forecasts for targeted observation experiments, 12Z 5 August analysis. Left, global observations with various spinup cycling periods. Right, 36-hr spinup with reduced observation area.

2.3 Discussion

The circumnavigation scenarios were chosen as likely possible flight paths that could be planned well in advance of a UAS mission to provide sampling of the storm environment. Sampling both the outer and inner storm regions yielded greater track improvement in comparison to repeatedly sampling only the inner storm environment. This result indicates that observing a larger area can be effective even when locations are not subject to repeat sampling. In addition, an extended observing period of greater than 24 hours was found to result in the greatest reduction of forecast errors. This indicates that continuous observation by multiple platforms or by platforms with multi-day flight capabilities are needed.

The UAS sonde observations provided information that significantly improved the track forecast. However, the sampling area required to achieve the best possible track forecast was too large to be realistically observed by one UAS. One region that might be sensitive to

additional observations (80—90W) was located over land in an area not suitable for UAS operations.

The results presented here are confined to a single case study, and as such should not be broadly applied to general cases. The synoptic situation and source of forecast errors is different for every tropical cyclone and each forecast per storm. Evaluation of additional hurricanes from the Nature Run will give a broader view of the potential impact of UAS observations on track forecasts, and may give guidance on the best choice of a set of 'standard' UAS mission strategies. The attempt at 'targeting' used in this report is not suitable for operational use; a real-time objective targeting strategy would be required for live attempts at customizing flight paths to sample sensitive regions for a particular hurricane.

3. Regional OSSE

While the skill of tropical cyclone track forecasts has advanced significantly over the past twenty years, intensity forecasts have not improved over this period. This section presents a regional OSSE system built for the evaluation of UAS observation impact on hurricane intensity forecasts. This OSSE can help NOAA evaluate the value of a UAS observation system for improving hurricane intensity and also potentially provide guidance on how to fly UAS platforms in order to maximize their impact. Unlike the global OSSE, the regional OSSE is run at very high resolution, and is capable of producing mesoscale structures within tropical cyclones.

3.1 Regional OSSE Framework

The development of this regional “Quick” OSSE has been a collaborative effort between NOAA/GSD, the NOAA Atlantic Oceanographic and Atmospheric Laboratory (AOML), NOAA/UAS, University of Miami, NASA and the NCAR/NOAA Developmental Testbed Center (DTC). Details of the regional OSSE are described below.

3.1.1 Nature Run

A WRF-ARW (Advanced Research Weather Research and Forecast) model is used to generate a Nature Run from 2—5 September 2008, based on Hurricane Ike. The Nature Run

has:

a) 2-km resolution with 51 vertical levels

b) No cumulus parameterization

c) Thompson micro-physics

d) Yonsel University boundary layer scheme

e) 5-layer land surface model

f) spatial range from 11.9N to 28.1N and 68.2W to 35.8W

The forecast is output every 15 minutes in general and 5 minutes during rapid intensification of the hurricane. Such high frequency Nature Run output allows for investigation of the rapid changes in hurricane structure, intensification and weakening and are critical to severe weather events.

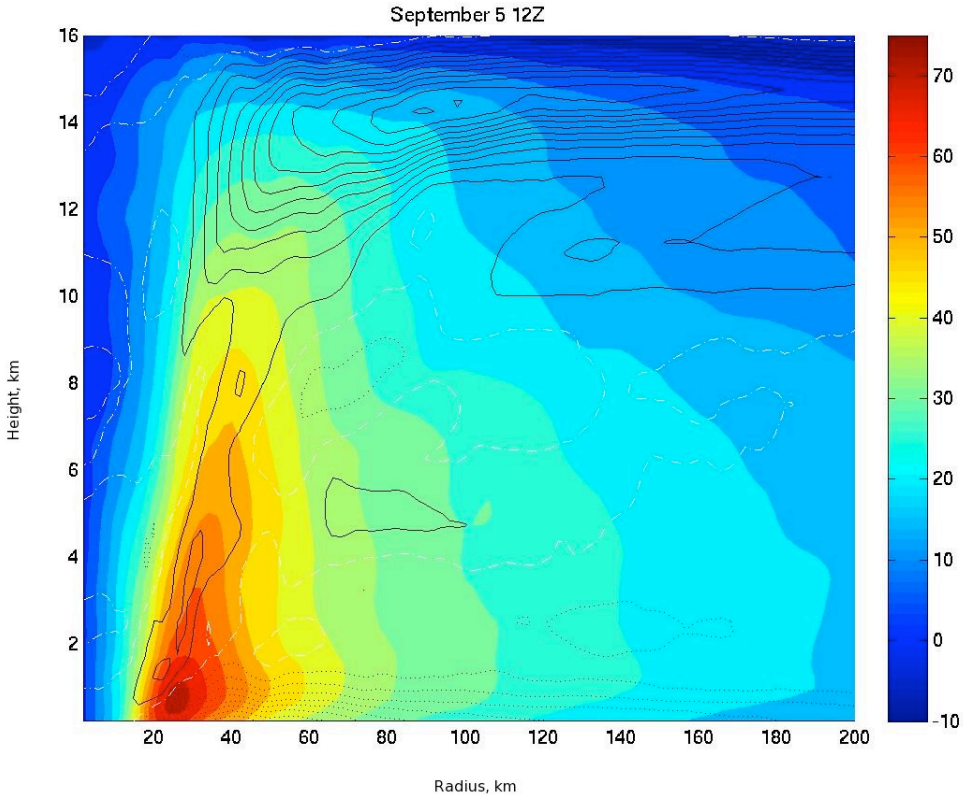

Figure 14. Tangential mean winds (color, m/s) and radial mean winds (black contours) for the Nature Run hurricane on 12Z 5 September. Dash-dot line indicates zero winds, dotted contours are inward flow, solid contours are outward flow.

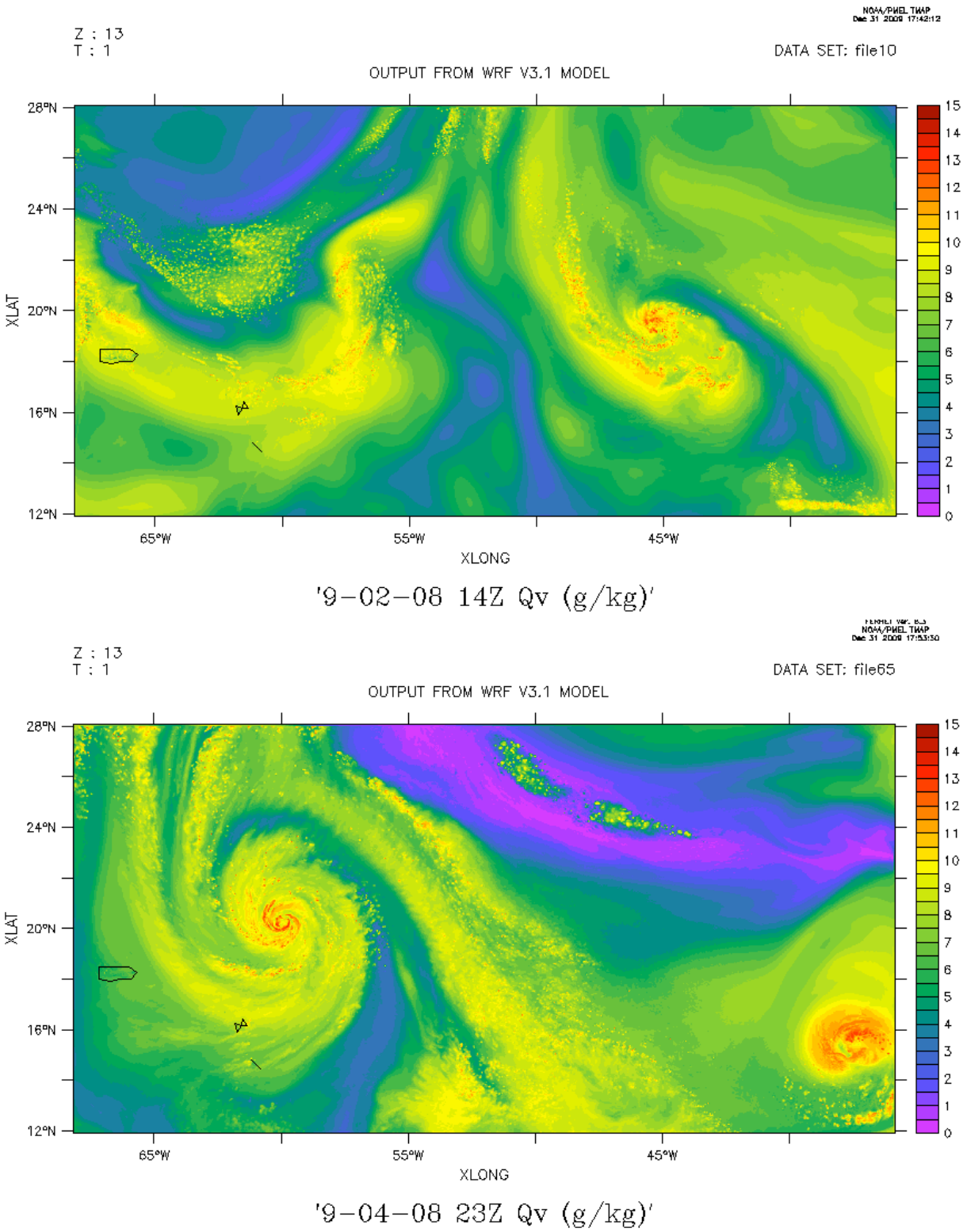

Figure 15. 700 mb specific humidity in the Nature Run, g/kg. Top, early formation period, 12Z 2 September. Bottom, during rapid intensification, 23Z 4 September.

The Regional OSSE team examined the Nature Run for hurricane intensity, hurricane wind structure and rapid intensification and weakening. It was found that the Nature Run exhibits the gross characteristics of an intensifying hurricane (Figures 14 and 15). The track of the Nature Run hurricane is south of that of the actual Ike (Figure 16), and the period of rapid intensification occurs 24 hours later in the Nature Run (Figure 17).

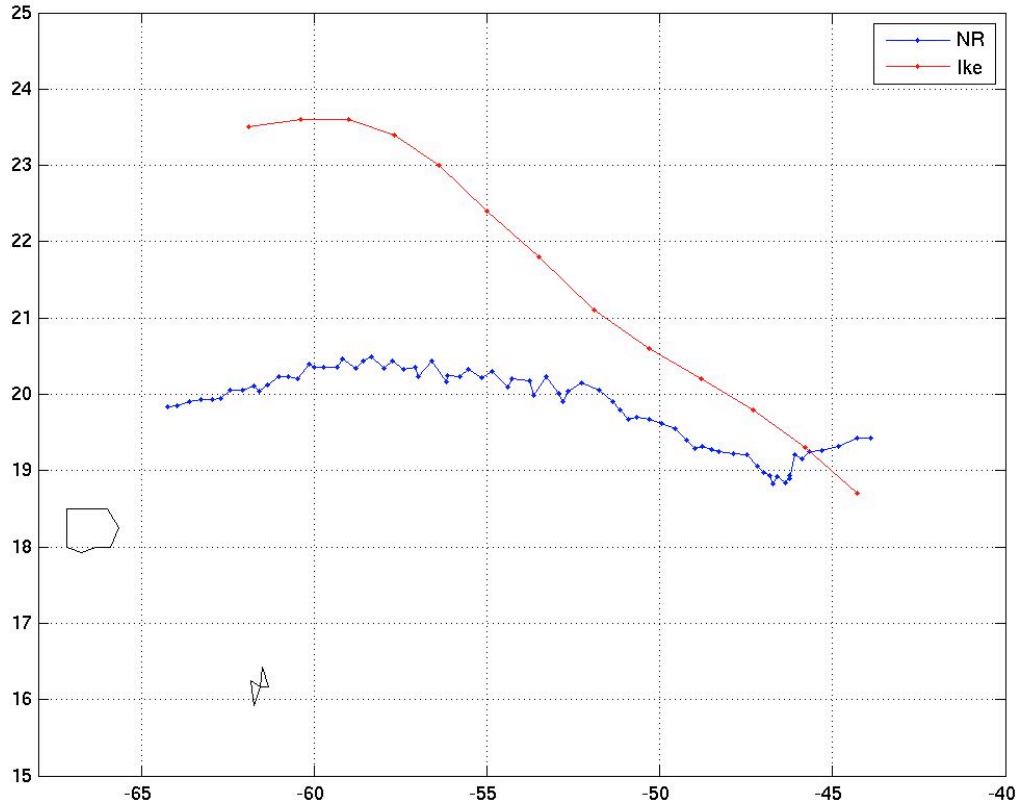

Figure 16. Track of the hurricane in the Nature Run (blue) and Hurricane Ike (red), from 12Z 2 September to 12Z 5 September.

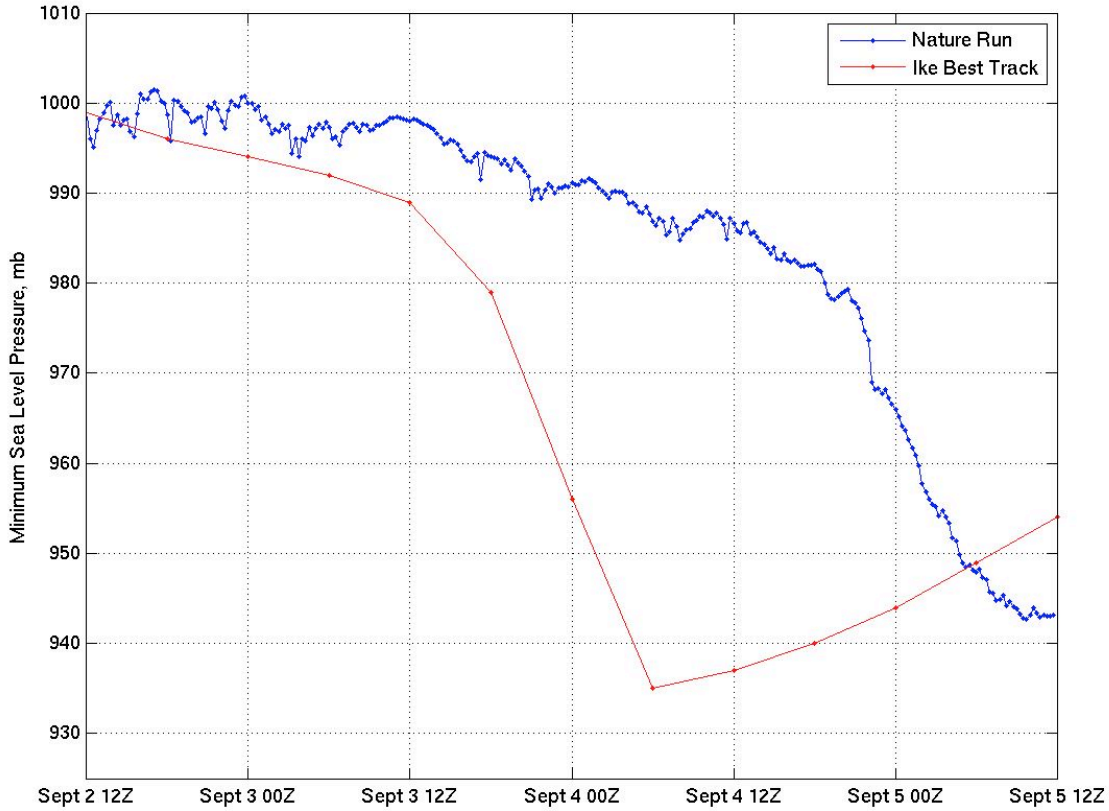

Figure 17. Minimum central mean sea level pressure for the Nature Run (blue) and Hurrcane Ike (red) best track.

3.1.2 Data Assimilation Scheme

To avoid identical twin experiments, the NOAA Hurricane WRF (HWRF) model at 5km resolution is used for the experiment forecasts. A Developmental Testbed Center version of GSI (Gridpoint Statistical Interpolation) is used to assimilate all conventional (*in-situ*) observations, including the future synthetic UAS observation data. To ingest these *in-situ* observations into GSI, the Local Analysis and Prediction System (LAPS) is used to convert the raw data into intermediate files and then into BUFR format. Working with DTC, a cycling system was built for this OSSE system, i.e., a GSI-HWRF data assimilation and forecast system.

3.1.3 Synthetic Observations

Synthetic observations from existing *in-situ* and future UAS observations are derived from the

Nature Run. The existing observation systems include RAOB, profiler, ACARS, radiometer, mesonet, surface and marine data, and POES soundings. Radiance data such as AIRS, AMSU, GOES, and HIRS were omitted from this preliminary OSSE. A set of future UAS observation data is also generated from this nature run, using realistic simulation of aircraft flight through the Nature Run wind field. By varying the UAS flight patterns and observation frequency and location, the UAS data impact will be investigated.

3.2 Regional OSSE Status

Currently, the regional OSSE system is undergoing testing with synthetic observations in preparation for initial experiments. The Nature Run is complete, a workflow manager has been created for the forecast model, and synthetic observations have been generated for conventional data types within the Nature Run domain. Due to recent computer system upgrades, some adjustments to the OSSE are required before experimentation can begin. Once testing and debugging are complete, a set of control forecasts will be generated, and candidate cases will be selected for experiments. At that point, mission scenarios will be designed based on the synoptic situation of the chosen analysis period, and synthetic UAS observations will be generated and tested in the OSSE. The “Quick regional OSSE” results will be reported later in a supplement to this OSSE report.

4. Future Work

The experimental results discussed in this report are preliminary findings that will be greatly expanded in future work.

4.1 Global OSSE

In addition to the hurricane “AL01” already investigated, the other hurricanes occurring later in the season, in addition to numerous tropical cyclones in the eastern Pacific, western Pacific, and Indian Ocean basins are candidates for examination. The Atlantic basin storms will be evaluated first, given their bearing on likely NOAA UAS missions. There may be better

candidate forecasts for these hurricanes than the forecasts tested in the preliminary studies – of particular interest is the early October storm, AL11, which circumnavigated the Yucatan peninsula and struck the Mexican coast as a strong hurricane.

Scenarios of interest that should be investigated with the global OSSE system include:

- combining HALE UAS with manned reconnaissance missions
- continuous observation of the hurricane eye by Coyote UAS
- extended forecasts to 240 hours
- tropical cyclone genesis
- spacing of sonde observations
- monitoring by multiple UAS platforms
- testing with more recent versions of the GFS/GSI forecast models

These scenarios will provide a more thorough evaluation of the potential benefits of UAS observations as well as an analysis of the most effective methods of employing UAS to improve hurricane track forecasts.

The majority of the investment in an OSSE system is in the setup and calibration; once the OSSE system is complete, it may be used for a wide range of observing systems and test scenarios. In addition to the *in situ* instrumentation considered in this OSSE, remote sensing instruments can be tested in future experiments. The main constraint on testing of instrumentation with this OSSE system is a result of the resolution of the Nature Run – at roughly 40km grid spacing. This OSSE is not suited for simulation of very high resolution remote sensing instruments. Other types of observing systems could also be evaluated using the current OSSE framework.

This Global OSSE is also suitable for the investigation of different atmospheric phenomena aside from tropical cyclones. Many aspects of the Nature Run have been evaluated under the Joint OSSE collaborative effort, and the performance of the Nature Run is well understood. Midlatitude baroclinic systems and cyclones are well represented in the Nature Run, as are atmospheric rivers, which can result in high-impact weather events. The extended time period of the Nature Run also lends itself well to statistical studies in addition to case studies, so the OSSE system would be able to evaluate the regular operational use of observing networks.

In the longer term, the OSSE system may be “revamped” with more sophisticated synthetic observations and newer versions of forecast models and data assimilation packages. While the OSSE would need to be re-calibrated after any improvements are made, this process would be streamlined due to previous efforts. One of the potential uses of the OSSE system is to evaluate

the relative performance of different data assimilation methods in a controlled environment.

4.2 Regional OSSE

The regional OSSE is currently at an early stage of development, and there are many potential areas of growth for future endeavors. The immediate plans are to complete a set of experiments with the preliminary setup currently under development. The results from these first tests will help guide future developments for the regional OSSE as well as informing the UAS Program about potential hurricane intensity missions for HALE UAS.

Many of the choices for the Nature Run and forecast models for the regional OSSE have been based upon expediency rather than the best possible setup. The forecast model and data assimilation suite were chosen because they were the only available working system, but are far from ideal. As new models and data assimilation systems such as ensemble Kalman filter and STMAS become operational in the future, the regional OSSE can switch to more suitable systems. Radiance data should also be generated for the regional Nature Run and included in the data assimilation, and the OSSE should be properly calibrated to lend more credence to the results.

The high spatial and temporal resolution of the regional OSSE are suited to observing systems such as airborne Doppler radar and lidar. Simulation code for these and other new observing systems that might be deployed on UAS should be generated for testing in the OSSE system; collaboration with NASA and other NOAA laboratories would expedite this process. In order to test these new instruments in the OSSE, the data assimilation system must be expanded to include ingestion of these challenging observation types.

The regional OSSE described in this report is a ‘quick’ OSSE, rather than a full regional OSSE. In a full regional OSSE, which is being developed by AOML and the University of Miami in collaboration with GSD, the regional Nature Run is itself embedded within a global Nature Run, which supplies the boundary conditions. The regional forecast model similarly receives boundary conditions from a second global forecast model that is run with synthetic observations from the global Nature Run, as in the global OSSE. This type of regional OSSE is very complicated and difficult to develop. With the advanced state of the global Joint OSSE, however, it may be possible to use the ECMWF Nature Run and GFS/GSI system from the global OSSE as a basis for developing a full regional OSSE for future use.

5. Appendix: Joint OSSE Organizations

European Centre for Medium-Range Weather Forecasts (ECMWF)

Joint Center for Satellite Data Assimilation (JCSDA)

National Aeronautics and Space Administration Global Modeling and Assimilation Office (NASA/GMAO)

National Centers for Environmental Prediction Environmental Modeling Center (NCEP/EMC)

National Oceanic and Atmospheric Administration Earth Systems Research Laboratory (NOAA/ESRL)

National Environmental Satellite, Data, and Information Service (NESDIS)

Simpson Weather Associates (SWA)

NASA Software Integration and Visualization Office (NASA/SIVO)

Royal Netherlands Meteorological Institute (KNMI)

Geosystems Research Institute at Mississippi State University

Meteo France

Japan Meteorological Agency (JMA)

United Kingdom Met Office.

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