Final Project Report to OAR

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Project Title: CIMAS Contributions to OAR Disaster Recovery Act Projects
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Research Period: February 1, 2014– January 31, 2016
Lead CIMAS PI: Sang-Ki Lee

1. Goals and objectives

The present project aims to make use of new observation technology to improve the understanding of air-sea interaction for extreme weather events for the ultimate goal of improving tropical Atlantic intensity and track forecasts and seasonal outlooks. Using observations and numerical experiments, the project also aims to assess the value of current observational efforts and to propose improvements in how ocean and atmospheric observations need to be carried out in order to improve forecasts and outlooks. With these goals in mind, this project concentrates on three tasks to be carried out in close collaboration with NOAA AOML scientists.

1) Observing System Experiments (OSE and OSSE) in support of Data Gap Mitigation; Lead PI: Dr. Robert Atlas, NOAA/AOML
2) Sustained and Targeted Ocean Observations for Improving Atlantic Tropical Cyclone Intensity and Hurricane Seasonal Forecasts; Lead PI: Dr. Gustavo Goni, NOAA/AOML
3) The Impact of Emerging Observing Technologies on Future Predictions of Hurricane Structure and Intensity Change; Lead PI: Dr. Joseph Cione, NOAA/AOML

The summary of our research progress made for the project period (of February 1, 2014 – January 31, 2016) is described below for the three tasks.

2. Progress Summary

Task-1: Observing System Experiments (OSE and OSSE) in support of Data Gap Mitigation; Lead PI: Dr. Robert Atlas, NOAA/AOML

The primary goal of this project under the Sandy Supplemental is to develop the next-generation OSSE capability that is needed to support decision making on investments in new observing systems, including engineering trade studies and the development of new data assimilation techniques to optimize the use observations. At the same time as we developed this new capability, we performed preliminary OSSEs with a previously developed OSSE system and also with a newly developed hurricane OSSE system. All of these goals have been met, as described in the following. Key experiments will be repeated with the new OSSE capability in 2016.

Contribution to NOAA's research goals

The OSSE project has contributed the following to advance NOAA's goals:

1. CGOP, the Community Global OSSE Package has been developed, its components validated and tested, and it is now being used to run experiments and to validate the new end-to-end OSSE capability, which is comprised of:
   a. The G5NR, a mesoscale, non-hydrostatic, 7-km resolution NR created by NASA GMAO;
   b. The operational (as of January, 2015) versions of the T1534 GFS and GDAS global forecast and data assimilation systems;
   c. Radiance data simulation based on the current version of the CRTM, which is used in the operational radiance observation operator; and
   d. RO data simulation based on the current version of the operational bending angle observation operator.
2. Conducted preliminary OSSEs with the T511 and HNR1 OSSE systems to study HSS and additional RO alternatives for a potential data gap.
3. Prepared data sets and started experiments with the CGOP to extend the preliminary HSS and RO experiments.
4. Reported our results extensively in the refereed literature and at conferences.

Executive Summary

AOML, CIMAS, and the rest of the OSSE team (hereafter referred to collectively as the OSSE team or more simply as "we") are aiding NOAA by conducting observing system simulation experiments (OSSEs) and other data denial studies to determine the potential value of two strategies to mitigate data-gaps. These strategies supplement satellite observations with new observations from additional Global Navigation Satellite System Radio Occultation (GNSS/RO) satellites and a global system of geostationary hyperspectral sounder instruments. We conducted preliminary OSSEs with previous OSSE systems and built an advanced "next-generation" OSSE capability.

The OSSE team completed preliminary OSSEs to evaluate the potential impact of geostationary hyperspectral sounder instruments on global model forecasts and regional model hurricane forecasts. The results of the global model experiments show a significant improvement in forecast accuracy in the Southern Hemisphere, but did not show significant improvement over North America. The results of the hurricane model experiments are mixed. They indicate some potential to improve hurricane forecasts if the frequency of observations increases. However, these results are not final, and more research is needed to improve the application of these instruments for weather prediction, and to determine if a significant impact over North America is possible. We conducted this research using both global and regional models and will incorporate results into the more advanced and comprehensive OSSEs that we expect to complete by the end of 2016.

The OSSE team performed preliminary experiments to determine the benefits to global weather forecasts by increasing the number of GNSS/RO satellite profiles. Preliminary OSSEs evaluated Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC-2, equatorial and polar components) using previous global OSSE system and assimilating radio occultation refractivity observations. The results of this experiment show that increasing the number of assimilated radio occultation satellites from 6 to 18 improves weather forecasts: 18

satellites is better than 12 satellites; 12 satellites is better than 6 satellites. We also conducted preliminary regional hurricane OSSEs. These experiments showed improved short-range forecasts as the number of satellites increased from 6 to 30. More rigorous OSSEs will be conducted with the advanced next-generation global OSSE system and results will be available by the end of 2016. In addition to these OSSEs, real data Observing System Experiments (OSEs) have been conducted to evaluate the impact of losing the current RO constellation on global weather forecasts. These experiments showed that removing RO observations from the model degrades forecasts

Introduction

Observing System Simulation Experiments (OSSEs)

Observing System Simulation Experiments (OSSEs) provide a rigorous, cost-effective approach to evaluate the potential impact of new observing systems and alternate deployments of existing systems, and to optimize observing strategies. They are also used to prepare for the assimilation of new types of data to accelerate their application to operational prediction, as well as to optimize the assimilation of existing data. OSSEs are an extension of Observing System Experiments (OSEs), which use data denial experiments to determine the impact of existing observing systems. Atmospheric OSSEs determine the impact of new systems by performing data denial experiments that assimilate synthetic observations simulated from a realistic Nature Run (NR) stipulated to represent the "true" atmosphere.

For the OSSEs to produce accurate quantitative results, all of the components of the OSSE system must be realistic. This means that (1) the NR, that is used to represent the atmosphere, should be generated by a state-of-the-art numerical model, (2) there should be realistic differences between the NR model and the model used for assimilation and forecasting, (3) the assimilation methodology must conform to current or future practices, (4) observations should be simulated with realistic coverage and accuracy, and (5) the entire OSSE system must be validated to ensure that the accuracy of analyses and forecasts, and that the impact of existing observing systems in the OSSE are comparable to the accuracies and impacts of the same observing systems in the real world.

Outline of this Report

Following this introduction and a section that provides background and context for the project, we present results organized by the OSSE system used. Each OSSE system is based on and named for a NR. Each OSSE system section describes the experiments and results obtained to date for both global navigation satellite system radio occultation (GNSS/RO) and geostationary hyperspectral sounder (Geo-HSS) gap-fillers. A concluding section provides a summary, discusses implications, and presents an outlook for the future.

End material includes an appendix describing the infrastructure used by the project, a list of acronyms, and the references. Most acronyms are defined when first used in the text as well as in the list of acronyms, but some commonly used acronyms of organizations (e.g., NASA, WMO), satellites (e.g., Aqua, COSMIC), and instruments (e.g., HIRS, ATMS) are only defined in the list of acronyms.

Background

Basic OSSE Description

The methodology currently used for OSSEs (worldwide) was redesigned in the early 1980s by the lead NOAA investigator to increase the realism and usefulness of such experiments (Atlas and Pagano 2014; Atlas 1997). It consists of the following elements (shown schematically in Fig. 1):

(1) A long atmospheric model integration using a very high resolution "state-of-the-art" numerical model to provide a complete record of the assumed "true" state of the atmosphere referred to as the "nature run" or "reference atmosphere." For the OSSE to be meaningful, it is essential that the NR be realistic, i.e., possess a model climatology, patterns of storm tracks, etc., that agrees with observations to within pre-specified limits.

(2) Simulated conventional and remotely-sensed observations from the NR. 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.

(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 NR is used for assimilation and forecasting. Typically this model has less accuracy and resolution than the NR 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 (CTRL) and experimental assimilations. As with OSEs, forecasts are generated at regular intervals to develop an independent sample. The analyses and forecasts are then verified against the NR 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 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. This ensures that the results of the OSSEs will be credible and realistic.

For both realism and relevance, all project experiments make use of versions of operational systems, including the GFS and HWRF forecast models and the GSI, EnKF and hybrid EnKF/GSI analysis systems. These technologies are described in the Appendix. This approach leverages the R2O/O2R resources of the JCSDA. Some experiments also make use of the HEDAS developed at AOML. O2R activities have succeeded at installing the new NCEP system on JIBB and S4 (Kumar et al. 2015, Boukabara et al. 2016d). This system, which went operational in Jan 2015, includes data assimilation (DA) at T574 and forecasts at T1534 resolution. Both the GSI and EnKF run at the same DA resolution. In addition an R&D version of the operational system at reduced resolution with T670 for the GFS and T254 for the DA that allows more efficient (quicker, less storage) experiments is used by the project. Comparison of real data T1534 and T670 experiments show that the main features of the analyses and forecasts are similar, but that the higher resolution system is more accurate. All of these configurations have been tested within our OSSE setting.

An additional OSSE methodology, referred to as "QuickOSSE" can be used as an adjunct to the rigorous OSSE methodology described above. In a QuickOSSE, one or more very accurate numerical model forecasts of up to 5-10 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. However, a QuickOSSE by itself cannot yield the statistical significance that is required.

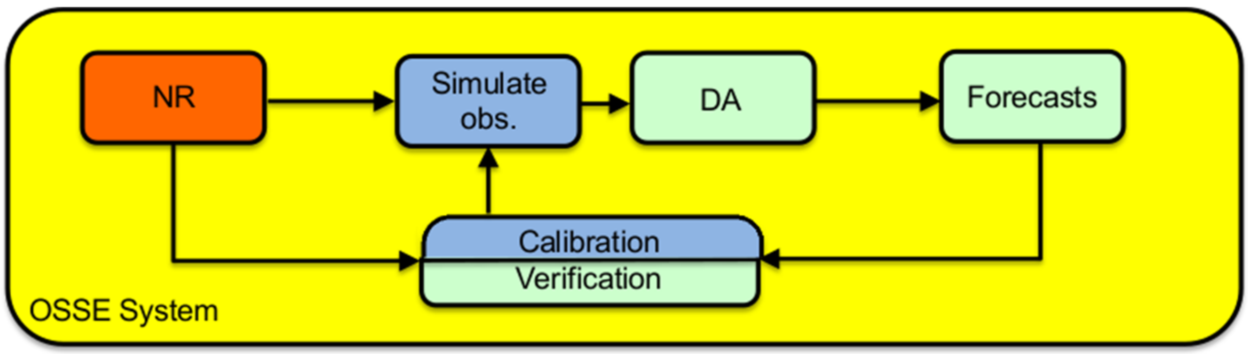

Figure 1. OSSE data flow diagram. Green marks components from the operational system.

<u>Past OSSEs and Value to Decision-makers</u>

OSSEs are extremely useful in answering numerous questions about the impact and optimal use of observing systems before they are developed and deployed. An extensive series of global OSSEs have been conducted by Atlas, the lead NOAA investigator, 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 proposed degradation of the Lidar Atmospheric Wind Sounder (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:

(a) 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 numerical weather prediction, as well as to the assimilation of SSM/I wind speed data.
(b) Determine the specific requirements for space-based lidar winds for the Global Tropospheric Wind Sounder (GTWS) mission.

Context for Gap-Filler OSSEs: Potential and Challenges

Potential of assimilating Global Navigation Satellite System/Radio Occultation (GNSS/RO) observations

NOAA has been assimilating Global Navigation Satellite System/Radio Occultation (GNSS/RO) observations into its operational global data assimilation (DA) system since 01 May 2007. This required the development of new numerical algorithms, quality control procedures, and estimates of observation errors for RO data (Cucurull et al. 2007, 2008). Since then, RO observations have shown a positive impact on global numerical weather prediction worldwide, complementing infrared and microwave observations from satellites (Anthes 2011; Cucurull 2010). A radio occultation occurs when a receiver on a low Earth orbiting (LEO) satellite tracks a GNSS satellite (in medium Earth orbit) that is observed to rise or set relative to Earth. The arrival time of the received radio signal is delayed by the refractive bending and slowing of the signal as it traverses the atmosphere. By measuring the change in phase measurements during the occultation event, vertical profiles of bending angle, atmospheric refractivity, pressure, temperature, and water vapor can be retrieved.

The largest contribution to improving weather forecast skill over the last decade has come from the assimilation of microwave and infrared radiances from passive nadir sounders. However, these observations contain biases that need to be corrected, and thus require the assimilation of additional unbiased measurements to prevent a drift in the bias corrections applied to the radiance measurements. (In the DA community, bias has the specialized technical meaning of errors that occur regularly in similar situations.) Unlike microwave and infrared sounder radiances, RO retrievals are almost insensitive to clouds and are essentially unbiased. RO data reduce the model drift and resulting spurious drift in the bias corrections applied to other observations, thus improving the assimilation of other observations, including radiances (WMO 2012).

Thus, the use of RO observations in operational weather forecasting is beneficial due to *two different effects*: first, from the direct effect of the observations by providing accurate, precise, and independent information on the thermodynamic state of the atmosphere; and second, from the indirect effect of correcting the bias of satellite radiances.

Potential of geostationary hyper-spectral sounder (Geo-HSS) observations

There is great potential for geostationary hyper-spectral sounder (Geo-HSS) in terms of temporal, spatial, and spectral coverage. However, much of the data that Geo-HSS would observe would not be used in current DA systems. This is true for existing instruments: Channels that are impacted by clouds, precipitation or surface conditions are not used. Few channels are used that are sensitive to temperature in the boundary layer or to humidity at any level. As an example, the number of AIRS channels observed by the Aqua satellite is 2378, but only 145 channels are actually assimilated operationally at NCEP. Clearly reaching the full potential of Geo-HSS will require enhancements to the operational DA systems.

An important further potential of Geo-HSS is to leverage its high spatial and temporal resolution to determine atmospheric motion vectors (AMVs). AMVs are an important data set for DA, but are mostly limited to geostationary Earth orbit (GEO) imagery, and high latitude polar orbiting imagers. Designs of proposed Geo-HSS instruments would allow generation of a huge data set of AMVs both from tracking clouds in window channels and from tracking features in water vapor channels. Achieving the potential of these data will require advances in the production and use of AMVs. Geo-HSS instruments also have potential value to monitor surface characteristics (e.g., soil moisture) and air quality (e.g., trace species).

Team Structure

The OSSE activity includes team members across the NOAA OAR labs and cooperative institutions and collaborations with several other organizations, including the JCSDA, ECMWF, and NASA JPL and GMAO. In this project, the Principal Investigator (PI), Dr. Robert Atlas, led the overall effort. The project manager (PM), Dr. Ross Hoffman, assisted the PI in effectively coordinating the project components. Since AOML and CIMAS managed the overall Supplementary Sandy effort, we report here on the work of the entire OSSE team.

There are two supporting factors to the success of this ambitious project. First, collaboration was critically important to provide the skills and knowledge base needed for this complex project. Second, we leveraged other government assets: Second, collaborators (ECMWF and GMAO) created the NRs. Third, we collaborated with GMAO on modeling the errors for the simulated observations. Fourth, detailed knowledge of the GNSS/RO observations came from ESRL and of the Geo-HSS observations from JCSDA and CIMMS. Fifth, JCSDA provided the software infrastructure for radiance modeling through the Community Radiative Transfer Model (CRTM) and for the DA system through their operations to research (O2R) process.

OSSE team components, members, and collaborators include:

- **AOML/CIMAS Hurricane OSSE Team**: Robert Atlas, Ross Hoffman, Sharan Majumdar, Frank Marks, Shirley Murillo, Lisa Bucci, Altug Aksoy, Javier Delgado, Bachir Annane, Kelly Ryan, Kathryn Sellwood, Brian McNoldy, David Nolan;.
- **AOML/RSMAS Ocean OSSE Team**: George Halliwell, Villy Kourafalou.
- **JCSDA and ESSIC-MD OSSE Team**: Sid Boukabura, Kayo Ide, Jim Yoe, Tong Zhu, Sean Casey, Jack Woollen, Michiko Masutani, Isaac Moradi, Narges Shahroudi, Yan Zhou.
- **ESRL OSSE Team**: Lidia Cucurull, Zoltan Toth, Kevin Kelleher, Hongli Wang, Ruifang Li, Yuanfu Xie.
- **CIMMS OSSE Team**: Tim Schmit, Jun Li, Zhenglong Li.
- **NSSL OSSE collaborators:** Steven Koch, Heather Reeves, Thomas Jones.
- **ARL Air Quality OSSE collaborator**: Pius Lee.
- **NASA Goddard OSSE collaborators**: Steven Pawson, Ron Gelaro, Joel Susskind, Bill Putman, Ron Errico, Nikki Privé.
- **NASA JPL OSSE collaborators**: Bjorn Lambrigtsen, Tom Pagano, Jeff Steward, Shannon Brown.

- **ECMWF collaborator**: Lars Isaksen.

To promote collaboration, taking advantage of attendance at the February 2014 AMS annual meeting in Atlanta, the project held a meeting at the end of one day's session. Attendees included Robert Atlas (PI), Ross Hoffman (PM), Sid Boukabara (JCSDA PI), Lidia Cucurull, Kevin Kellehar (ESRL), Jun Li, Zhenglong Li, Tim Schmit (CIMMS PI), Sharan Majumdar, Yuanfu Xie, Zoltan Toth (ESRL PI). This meeting was very successful at promoting a free exchange of ideas and having individuals meet each other in real life. Consequently, at the 2015 and 2016 AMS annual meetings in Phoenix and New Orleans we hosted "OSSE meetings of opportunity" to take advantage of the fact the many team members and collaborators were physically collocated during these meeting. Both of these meetings of opportunity were well attended and were very useful for promoting the exchange of information and enhancing collaboration among the OSSE research community. At the most recent meeting, a number of topics were discussed including new NRs, new approaches to more realistically simulating observations, plans for an OSSE workshop, current status and plans for global, hurricane scale, storm scale, and aerosol OSSEs, new data types, and international collaboration.

Experiments for Other New/Proposed Observing Systems

The project has a focus on Geo-HSS and GNSS/RO, but the team is also actively performing research on several other systems. This work is coordinated with the Geo-HSS and GNSS/RO OSSEs. These other observing systems include:

- **Geo-MW**: a proposed microwave (MW) instrument in GEO (Lambrigtsen 2015). OSSEs studies are underway.
- **Optical Autocovariance Wind Lidar (OAWL)**: a proposed Doppler wind lidar (DWL). OSSEs using both the T511 NR and the HNR1 have been used (Atlas et al. 2015b, Pu et al. 2016).
- **Unmanned aerial systems (UAS)**: OSSEs are being used to compare different sampling strategies for NOAA UAS (Privé et al. 2014; Wang et al. 2015b).
- **Cyclone Global Navigation Satellite System (CYGNSS)**: CYGNSS is a NASA mission that will launch a constellation of micro-satellites that use existing GNSS satellites to retrieve surface wind speed. Preliminary OSSEs using the HWRF OSSE system are reported by Annane et al. (2015) and McNoldy et al. (2016).

T511 OSSE System

ECMWF T511 Global NR

The T511 NR was generated by ECMWF. The T511 NR is described by Andersson and Masutani (2010) and is a free-running forecast from 12 UTC 01 May 2005 to 12 UTC 01 June 2006 that used observed sea surface temperature and sea ice. The T511 spectral truncation corresponds to a horizontal resolution of 26 km and there are 91 vertical levels.

Simulated Observations

For observation types that already exist, observations are simulated according to the types, including both conventional and satellite types, and locations and times as they were actually assimilated in reality. By running a real data assimilation, template files are created. Then the NR is interpolated to the time and position of the real observations and the observed quantities are simulated. The resulting NR values, with errors added, replace the corresponding values in the template files. The data types are:

- Conventional data, principally, surface observations including ships and buoys, radiosondes, and aircraft reports;
- Cloud track winds (CTWs) from geostationary imagery in low to mid latitudes and from polar orbiting instruments (e.g., MODIS) in high latitudes; and
- Radiances for infrared (IR) and microwave (MW) operational observing systems.

Rigorous OSSEs must simulate the various types of errors that exist in the real world. These include random errors, instrumental errors, calibration errors, representativeness errors, and bias errors. Representativeness error accounts for differences between what is measured by the observations and what is represented by the atmospheric model. Examples of phenomena contributing to representativeness error are wind gusts and turbulence. While satellite radiance observations are major contributors to the accuracy of numerical weather prediction (NWP) initial conditions and subsequent forecasts, they contain biases. These biases can be quite significant and can exceed the information content of the observations themselves. Therefore, the assimilation of radiances in operational NWP requires correcting for these biases. Modern DA systems include a variational bias correction (VarBC) to identify and correct bias errors. In our experiments, the bias errors estimated in the real world, and saved in the template files, are added to the simulated observations. It is noteworthy that the VarBC procedure requires some independent unbiased observations to be assimilated in the system that can act as "anchor" points, and thus prevent a drift of the analysis and forecasts to the model climatology. Since RO observations are, for practical purposes, unbiased and occur at times and in regions not well sampled by radiosondes, these data are ideal anchor points (Cucurull et al. 2013).

T511 GNSS/RO Experiments and Results

GNSS/RO are simulated to evaluate the following RO missions: current RO constellation, primarily the COSMIC satellites (6 satellites); the follow-on COSMIC-2 mission, including both the equatorial (6 satellites) and polar components (6 satellites); GeoOptics (12 satellites); and PlanetIQ (12 satellites). GeoOptics and PlanetIQ are both commercial ventures and both plan to launch more than the initial complement of 12 satellites. RO observations from the NRs have been simulated at the geographical locations of all the RO missions listed above. Refractivities have been used in the preliminary OSSEs, while bending angles are being used in the next-generation OSSE capability. The use of bending angle allows the use of RO data at higher levels compared to refractivity—up to 50 km vs. 30 km.

To investigate the benefits of increasing the number of assimilated RO profiles on global weather forecast skill, we conducted preliminary OSSEs using soundings of refractivity. These experiments used the old T511 global OSSE system, which is sub-optimal due to the low resolution NR and DA system, perfect CTRL observations, and profiles of RO refractivity observations. Results from these OSSEs, conducted by Cucurull et al. (2015, 2016) show that overall, increasing the number of assimilated RO satellites from 6 to 18 results in better weather forecast skill: 18 satellites is better than 12 satellites; 12 satellites is better than 6 satellites (Fig. 2). However, there is a lot of room to optimize the assimilation system. In particular, selected cases of large impact are being evaluated in more detail to understand how results can be improved.

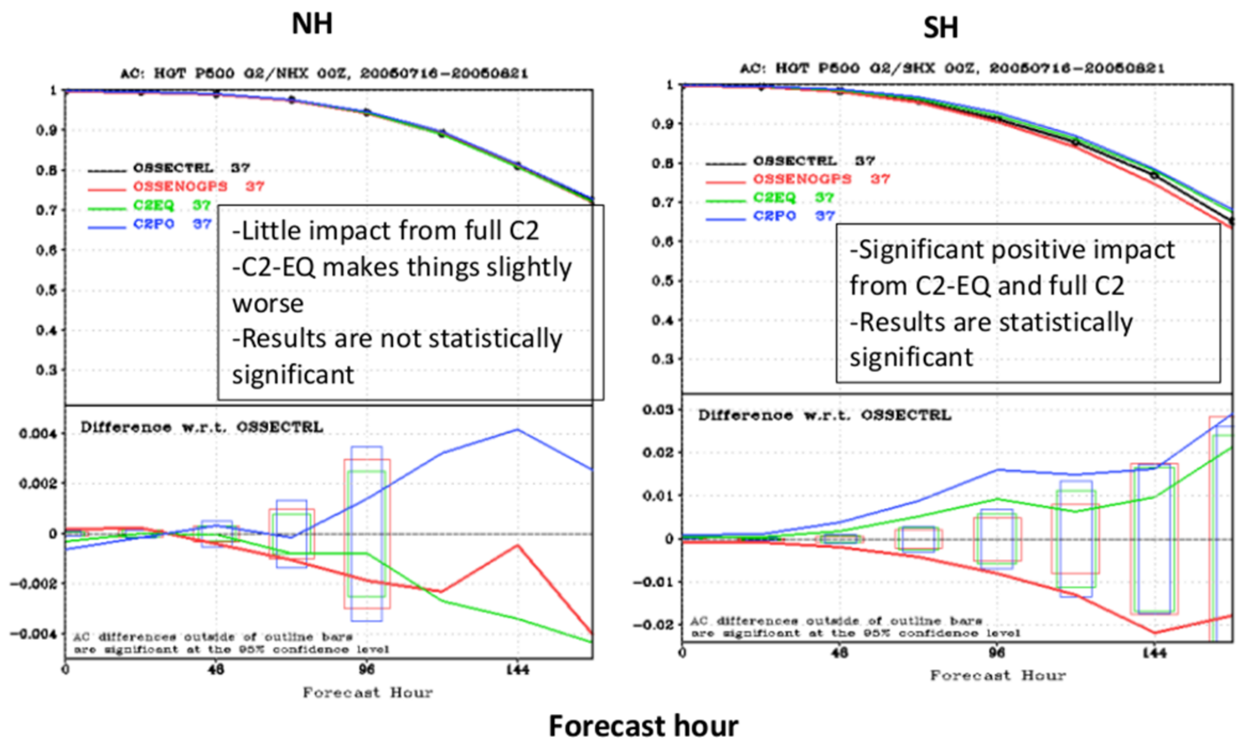

Figure 2. The anomaly correlation coefficient (ACC, unitless) for the preliminary RO OSSEs for Northern Hemisphere (NR, left) and Southern Hemisphere (SH, right) extratropics (20–80°N and S) 500 hPa geopotential height forecasts. In this type of plot the upper panels compare the statistics from the two experiments, and lower panel plots the difference of the statistics of the experiments. In the lower panels, the error bars correspond to differences that are significant at the 95% confidence level.

GNSS/RO OSEs

In addition to the preliminary OSSEs, we conducted OSEs to evaluate the impact of the loss of either MW or RO observations in the operational NCEP Global Data Assimilation System (GDAS) in support of the U.S. data gap mitigation activities (Cucurull and Anthes 2014, 2015). These potential scenarios are important because adjoint-based observation sensitivity techniques consistently show that MW radiances are the number one observing system and that RO soundings are typically among the top five observing systems contributing to short-range NWP forecast accuracy (cf., Cardinali and Healy 2012). Note that the impact of the loss of RO observations on the MW bias corrections is included in the second scenario.

We considered two extreme scenarios. First, we assumed the loss of all MW instruments on NOAA-15, NOAA-18, NOAA-19, and Aqua. Second, we assumed the loss of all RO observations. Because all of the MW and RO systems in our study are not likely to fail before there are at least some replacements, these are worst-case scenarios.

There is a slight loss of accuracy in the Northern Hemisphere (NH) extratropics forecasts when all U.S. MW data are withheld, and this loss is not mitigated by including RO observations (Fig. 3). On the other hand, in the SH extratropics, the loss of RO data produces a much larger negative impact on the forecasts than does the loss of the U.S. MW observations (Fig. 3). The role of ATMS in mitigating the loss of the other microwave sounders is mixed, but generally neutral. Thus the potential “gap” in RO may be a more serious risk to global forecast accuracy than potential gaps in the U.S. MW observations. In addition, the global biases in analyses and forecasts seem to increase as the number of microwave observations increases, particularly in the stratosphere. The modest amount of unbiased RO only partially reduces these biases. Finally, an increase of RO observations should further anchor the model, resulting in improved bias corrections of the satellite radiances.

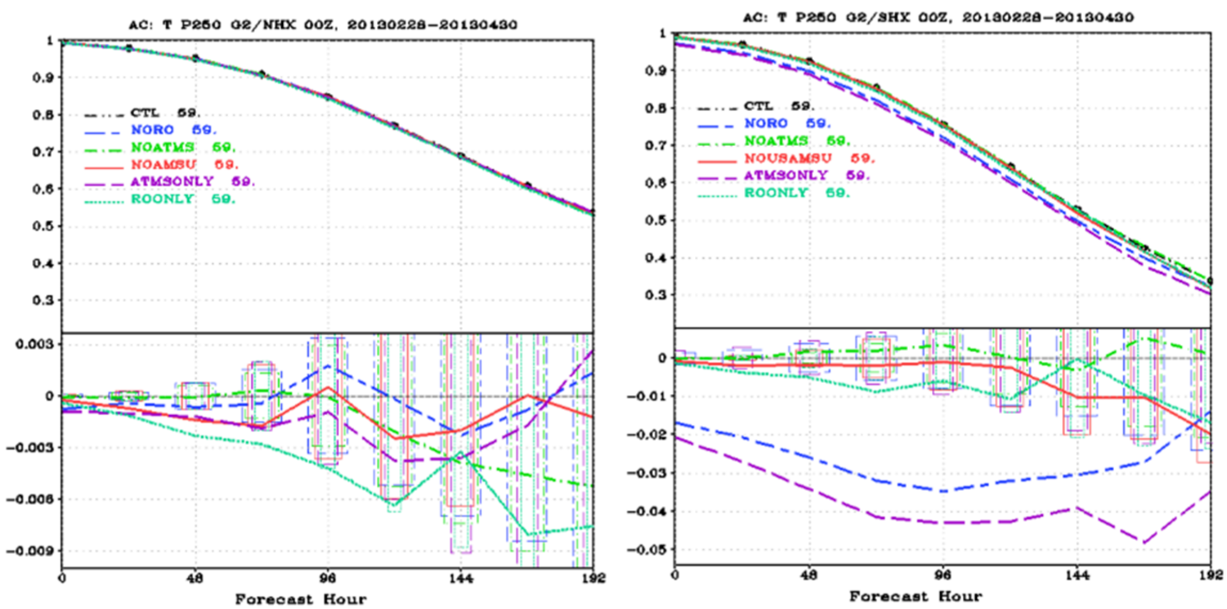

Figure 3. The ACC (unitless) for RO and MW OSEs for NH (left) and SH (right) extratropics (20–80N and S) 250 hPa temperature forecasts. As in Fig. 2.

<u>T511 Geo-HSS Experiments and Results</u>

A series of experiments were conducted to examine the impact of Geo-HSS (Casey et al. 2014). Our preliminary Geo-HSS experiments are for a Geo-AIRS instrument, for which radiance observations were simulated for an AIRS-type instrument in GEO at 75°W, the current location of GOES-13. All of the T511 Geo-HSS experiments used the:

- CRTM, to generate all satellite radiances (Zhu et al. 2012);
- CTRL data that included all observations assimilated operationally in 2012 during two one-month experiment periods;
- T382 Grid point Statistical Interpolation (GSI) or the hybrid T382/T190 GSI/ ensemble Kalman filter (EnKF) DA system to assimilate the observations; and
- T382 Global Forecast System (GFS) to make the forecasts.

Experiments were conducted with or without simulated Geo-AIRS data. In addition, experiments were conducted with or without random errors for the Geo-AIRS, and with four different treatments for the CTRL data: no errors, random errors, bias errors, and random plus bias errors.

All of the T382 GSI experiments (Casey et al. 2014) show that adding Geo-AIRS to the GOES-13 position yields a small but statistically significant impact on short-range forecasts of upper-level winds over the GOES-13 region. Experiments with different treatments of errors yielded mixed results.

More recent experiments with the hybrid DA system show a neutral result for most metrics, and more significant improvements than significant degradations (Fig. 4), suggesting that a single Geo-HSS instrument could have a beneficial impact on global forecasts. Based on Fig. 4, the NH 7 metrics (6%) show significant positive impact and 5 metrics (4%) show significant negative impact, while the SH 35 metrics (28%) show significant positive impact and 0 metrics show significant negative impact. This is consistent with our understanding that adding a new observing system has greater positive impacts when the CTRL observing system is limited, as it is in the SH. In addition, in the tropics, 17 metrics (24%) show significant positive impact and only a single metric (1%) shows significant negative impact.

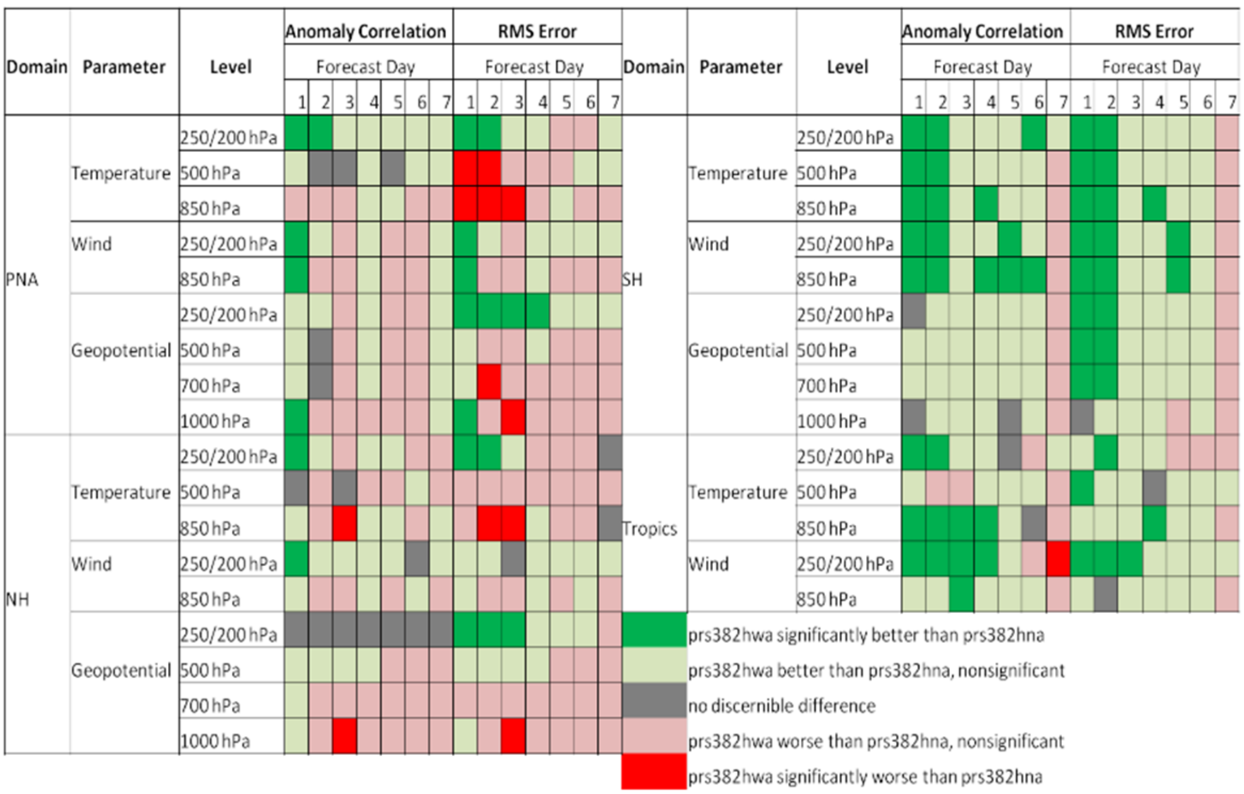

Figure 4. Scorecard for T382-hybrid assessment of Geo-AIRS impacts. The experiment names prs382hwa and prs382hna are the CTRL and CTRL+Geo-AIRS cases respectively. The four regions shown are the Pacific-North American (PNA; 80E-320E, 20N-75N), the northern hemisphere (NH, 20N-80N), the southern hemisphere (SH, 20S-80S), and the tropics (20°S-20°N).

HWRF OSSE System

The Hurricane WRF (HWRF) forecast model is NOAA's operational hurricane prediction capability (Atlas et al. 2015a). A unique OSSE capability—the HWRF OSSE system—was developed at NOAA-AOML. Work is now underway developing an advanced aircraft observation simulator. This will enable observations to be simulated in a very realistic fashion for arbitrary flight paths and for several instruments carried on the P-3 and G-4 aircraft.

Regional Hurricane NR Embedded in the T511 NR

We employ a regional hurricane NR (denoted HNR1) developed by Nolan et al. (2013) in the HWRF OSSE system. The HNR1 depicts the life cycle over 13 days of a rapidly-intensifying hurricane over the North Atlantic with 1-km spatial resolution. A high resolution NR is required for hurricane OSSEs, because hurricanes are not well represented in the T511 NR. The HNR1 is generated by the regional ARW model—the advanced research weather research and forecasting (WRF) model. To create the HNR1, the outermost domain of the ARW model is configured to use initial conditions, boundary conditions, and a nudging target from the T511 NR. The HNR1 is used to simulate observations to be assimilated in the regional DA systems. This coupled global-regional OSSE system allows us to run experiments to determine what observations, assimilated at global or regional scales, will improve the forecasts of hurricane track and intensity.

HWRF Predictability Experiments

A well-known issue in regional hurricane modeling is the decrease of forecast skill at the start of the forecast period, termed spin-down, that is commonly observed for strong hurricanes. This impacts the short-term evolution of the hurricane and limits the predictability of intensity. In our OSSE framework we are investigating whether there exists a necessary minimum complement of observations that would eliminate the spin-down. In the first of our experiments, we investigated whether spin-down would occur if a sufficiently accurate initial state could be provided to the HWRF model. The hurricane in HNR1 intensifies rapidly over the 6-h period from 12 to 18 UTC 04 Aug 2005. Providing “near perfect” temperature, wind, and moisture profiles to the HWRF model by interpolating directly from the nature run was found to not result in spin-down (Atlas et al. 2015c). Running the HWRF model with initial conditions from the GSI analysis of a dense, error-free set of observations results in a weaker hurricane over the 6-h period but no spin-down occurs. We have performed a number of experiments to determine the minimum data set required to eliminate the spin-down error and thereby improve hurricane prediction significantly. For example, in Fig. 5, we see that with excellent data GSI produces a weaker vortex at the surface, but after 6-h, the storm has regained its surface characteristics.

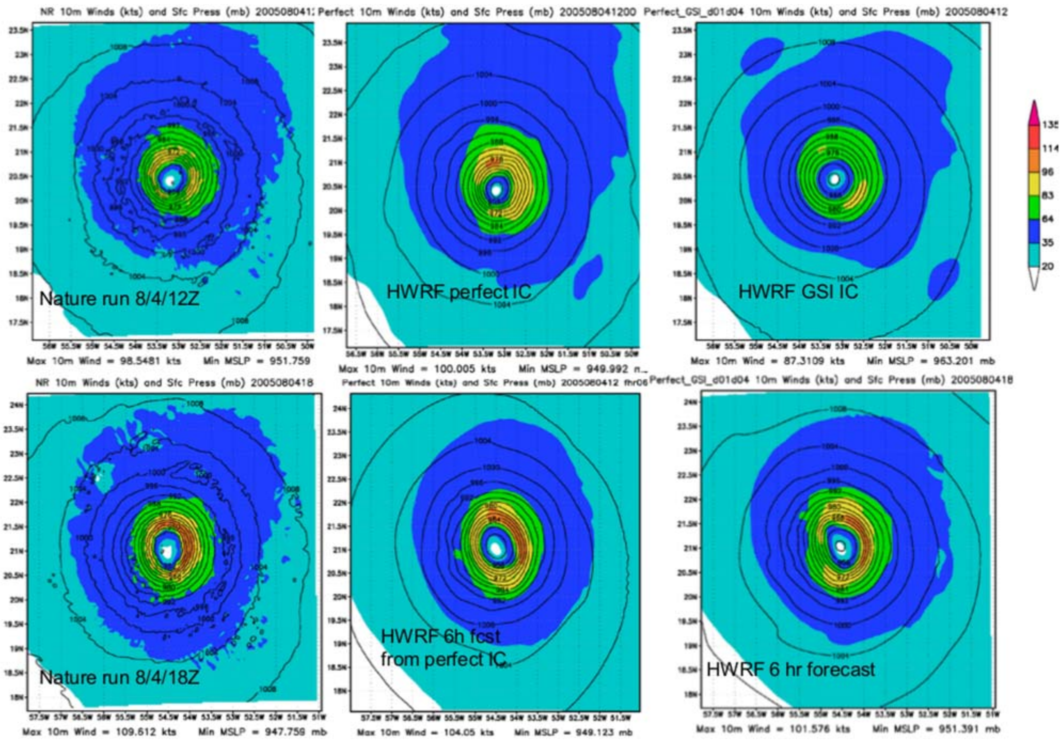

Figure 5. 10m winds (kts) shaded and MSLP (mb) contoured. Sample analysis and 6 hour forecast from 12 UTC Aug 04. Left column shows the 3 km domain from HNR1; center column shows 3 km domain from HWRF cold start run that used HNR1 as initial and boundary conditions; right column shows HWRF cycled run with analysis provided by GSI assimilating perfect data from HNR1 27 km and 1 km domains and GFS background and boundary condition.

<u>HWRF GNSS/RO Experiments and Results</u>

HWRF OSSEs were conducted in which GNSS/RO data from 6, 12, 18, or 30 satellites were added to a Control experimental configuration in which no GNSS/RO data were assimilated. Five-day forecasts were then generated for each of the experiments. The impact of GNSS/RO data on 200 hPa and 500 hPa analyses and short-range (up to 24 hour) forecasts for temperature and relative humidity was found to increase as the number of satellites increased. Figure 6 depicts the root mean square error (RMSE) of atmospheric temperature at 200 hPa in the upper atmosphere. The curves represent the different experiments each with additional satellites, with 30 satellites yielding the highest accuracy. In addition, the assimilation of GNSS/RO, in the GFS-provided initial and boundary conditions, improved storm track forecasts after 80 h. Impacts on forecast storm intensity (minimum surface pressure or maximum surface wind speed) were found to be neutral.

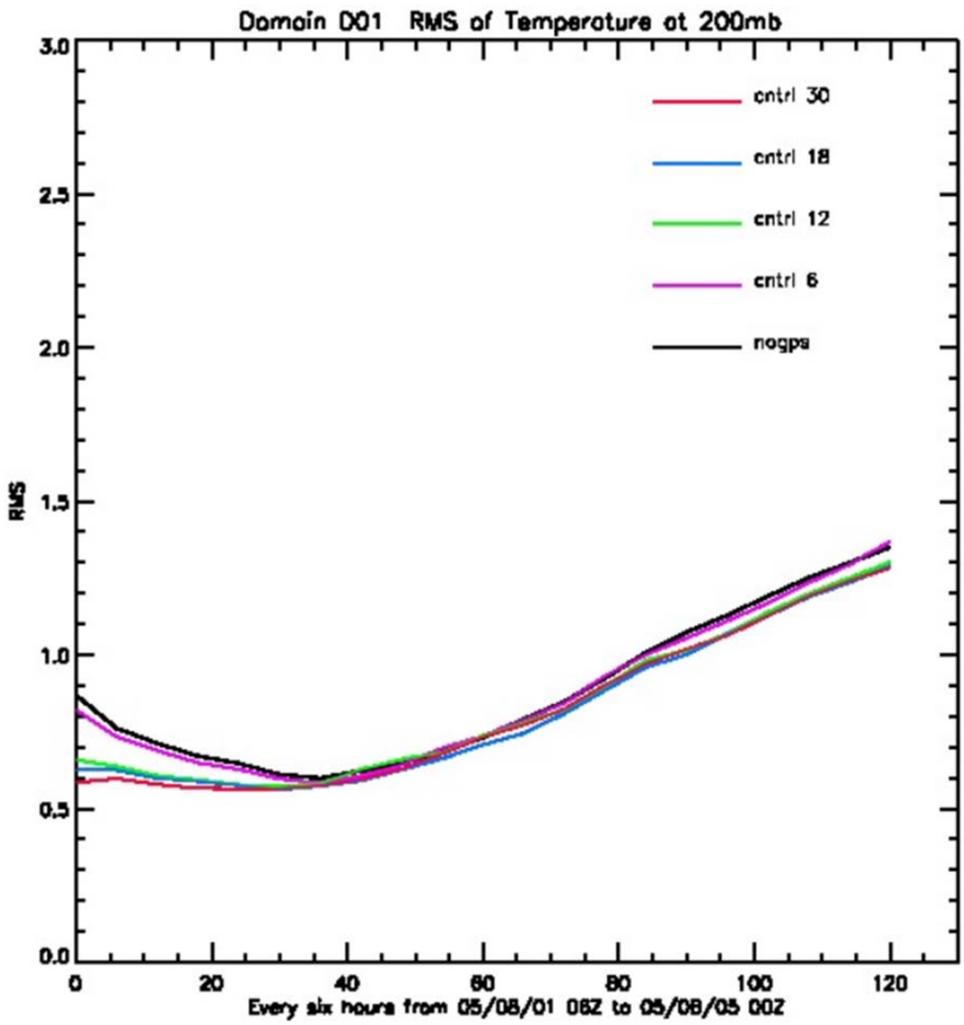

Figure 6. RMSE of atmospheric temperature at 200 hPa for the GNSS/RO OSSEs. Curves are drawn for 0, 6, 12, 18, and 30 receiving satellites.

HWRF Geo-HSS Experiments and Results

Two separate sets of experiments were conducted to examine the impact on tropical cyclone prediction of assimilating simulated hyperspectral observations, either as radiances or retrievals. For the first set (Atlas et al. 2014), CIMSS/University of Wisconsin simulated radiance observations and retrieved profiles of temperature and humidity by using the methodology of Li et al. (2015b and summarized below in the QuickOSSE section). For the second set, Pagano and Mathews (2015) simulated retrievals from HNR1 for the Airborne Research Interferometer Evaluation System (ARIES), a proposed hyperspectral sensor observing system. The observations were simulated in a variety of ways, testing polar LEO versus GEO orbits at different observation intervals and resolutions to demonstrate the sensitivity of the different sets of observations in our regional hurricane HWRF/GSI OSSE system (Atlas and Pagano 2014). Table 1 lists the experiments performed for each set of experiments.

Experiment Set 1	DA Algorithm	Observations	Obs Resolution	Label
Cold Start	None	None	None	Cold
Control	GSI	Conventional and radiances	Based on T511 NR	Control
All-Sky Radiance	GSI	Control + Geo AIRS	HNR1 27 km	ASRad
All Sky Retrievals	GSI	Control + Quick Retrievals from All-Sky Radiances	HNR1 27 km	ASRet
Clear Retrievals	GSI	Control + Quick Retrievals from Clear Radiances	HNR1 27 km	CRetReal
Clear Retrievals (Temp Only)	GSI	Control + Quick Retrievals from Clear Radiances	HNR1 27 km	CRetRealTemp
Clear Retrievals (Moisture Only)	GSI	Control + Quick Retrievals from Clear Radiances	HNR1 27 km	CRetRealMoist
Experiment Set 2	**DA/Cycling**	**Observations**	**Obs Resolution**	**Label**
Control	GSI/6 hours	Conventional and radiances	Based on T511 NR	Control
ARIES	GSI/6 hours	Control + Temp Only Retrievals	2km from 1km HNR1	ARIES_2km_d04
GEO	GSI/6 hours	Control + Temp Only Retrievals	5km from 1km HNR1	GEO_5km_d04
GEO	GSI/3 hours	Control + Temp Only Retrievals	5km from 1km HNR1	GEO_5km_d04_3hrly

Table1. Geo-HSS experiments conducted with the HWRF regional OSSE system.

In the second set of experiments, short term forecast improvements were observed when high-resolution temperature retrievals were added over the hurricane. Adding observations over the larger basin-scale domain yielded improvements that last longer into the forecast period. A 3-h instead of 6-h DA cycle time improves the intensity forecast but degrades the track forecast and vortex structure (Bucci et al. 2015). Impacts of the hyperspectral observations were neutral on the synoptic scale.

In addition, Joel Susskind and Lena Iredell of NASA Goddard provided retrievals from polar and GEO AIRS sounders at several horizontal resolutions, which were tested in the HWRF OSSE system. Initial experiments were conducted in which perfect (i.e, error free) high resolution observations of various quantities were made over the innermost domain. Results were verified in terms of tropical cyclone track and intensity errors and outer domain wide RMS errors. In the context of a GEO AIRS temperature and humidity information together outperformed temperature alone, but it was noted in these idealized experiments that wind data were very valuable and further work on simulating atmospheric motion vectors (AMVs) from GEO AIRS is warranted. Sample results are presented in Fig. 7, which shows the domain wide RMS error of 200 hPa wind and hurricane track error. Note the consistency of the results from these two metrics which is anticipated since upper level winds are important for steering tropical cyclones.

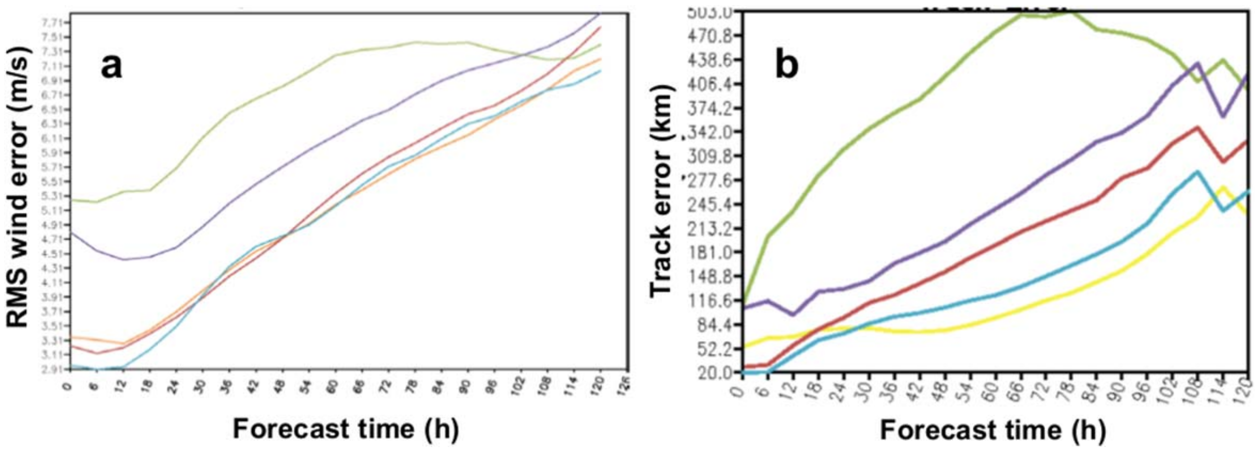

Figure 7. Results for (a) RMS error of 200 hPa wind and (b) track error for the idealized experiments assimilating different variables as described in the text. The experiments are color coded with green for temperature only, purple for humidity only, orange or yellow for temperature and humidty, red for winds, and aqua for all.

T1279 Hurricane Sandy QuickOSSE

T1279 Hurricane Sandy ECMWF Sample NR

We had an informal agreement with ECMWF to produce a new NR with the T1279L91 (10 km horizontal resolution, 91 vertical layers) version of the model that was operational as of 26 January 2010. However, due to legal issues concerning intellectual property, ECMWF only provided only a sample run, which is a 6-day forecast for the Hurricane Sandy case with initial conditions at 00 UTC 27 Oct 2012. The T1279 Hurricane Sandy sample NR is used in the CIMSS QuickOSSE experiments.

Geo-HSS Data Simulation

Geo-HSS simulated radiance data were created by CIMSS (Li et al. 2015a, 2015b) using the Stand-alone AIRS Radiative Transfer Algorithm (SARTA) coupled with a fast cloud model for cloud scattering and absorption. To validate these data, simulations performed with the ECMWF T1279 sample NR (Fig. 8, left panel) are compared with GOES-13 Imager radiance observations (Fig. 8, right panel) to examine the quality of the simulation, including channels consistency, diurnal variations, and cloud coverage.

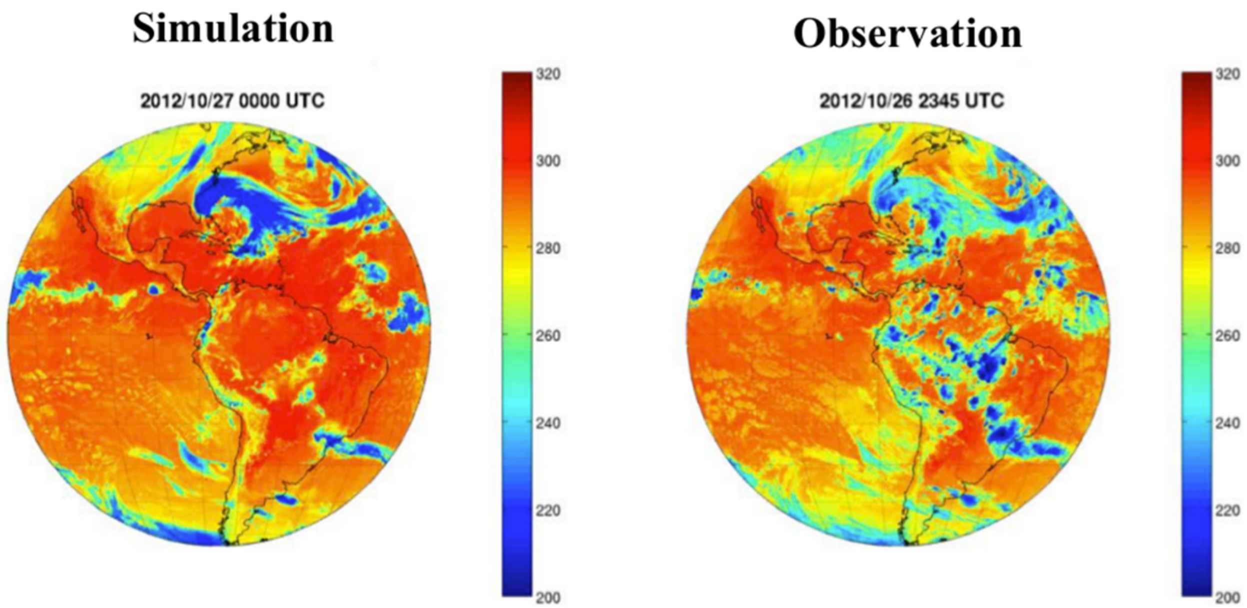

Figure 8. Simulated (left) and observed (right) 10.8 micron window channel radiances. Simulated radiances are from the start of the ECMWF T1279 sample NR valid 00 UTC 27 Oct 2012 and observed radiances are from the GOES-13 Imager 15 minutes earlier.

QuickOSSE Geo-HSS Experiments and Results

The following steps were taken by Li et al. (2015b) to simulate Geo-AIRS and LEO AIRS temperature and moisture profiles from Geo-AIRS radiance data simulated from the ECMWF T1279 sample NR:

(1) A satellite orbit simulator was developed to simulate LEO satellites.

(2) Quick regression retrievals of temperature and moisture profiles were determined from the simulated Geo-AIRS radiances.

(3) LEO AIRS retrievals were also generated using the method of step 2 from Geo-AIRS radiances interpolated to the times and locations determined in step 1.

(4) All retrievals (as well as the simulated radiosonde observations) were encoded to PREPBUFR format, a file format used by GSI.

Limited QuickOSSEs were carried out to evaluate the value-added impacts of high temporal sounding information from GEO AIRS on Hurricane Sandy analyses and forecasts, as well as investigate the impacts of cycling and specification of the background error covariance matrix (Li et al. 2016). The DA system for these experiments used the WRF model coupled with the GSI. Two observation configurations were compared. Both included radiosonde observations. One treatment (LEO) added polar orbiting AIRS data and the second (GEO) added Geo-AIRS data. A three-hour update cycle was used. The main experiment findings are that:

- GEO AIRS soundings have positive impact on hurricane track forecast after 30 hours (Fig. 9); and
- Giving additional weight to the moisture soundings also improves the hurricane track forecast.

CIMSS Quick OSSEs were extended to better understand the impact of different methods of assimilating GEO AIRS data. Also, a new Lagrangian inspired hurricane relocation technique, called parcel displacement method, was developed and tested.

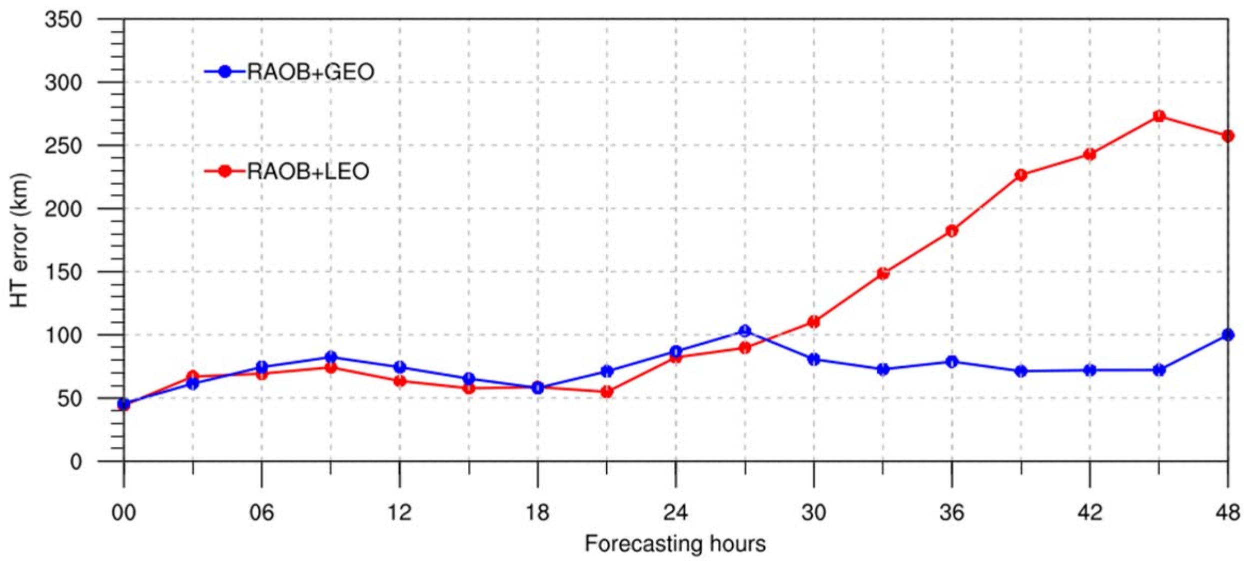

Figure 9. Hurricane track error vs. forecast hour.

G5NR OSSE System

Table 2 provides a summary of the old (T511) and the new (G5NR) global OSSE systems. This table shows comprehensive improvements to the NOAA OSSE capability that the project is implementing. The following sections describe progress in developing the G5NR OSSE system.

	System component	T511 system	New OSSE system
NR	Nature Run (NR)	ECMWF T511	GMAO 7-km (ECMWF T1279)
Obs	Conventional obs errors	Perfect obs	Random error + bias
	Radiance obs errors	Random error	Random error + bias
	GPSRO obs type	Refractivity	Bending-angle
	GPSRO obs errors	None	Random error + bias
	Geo-HSS obs simulation	SARTA (U. Wisconsin)	CRTM (JCSDA)
GDAS	GDAS version	2012	2014
	GDAS analysis	Hybrid GSI/EnKF (T382/T190)	Hybrid GSI/EnKF (T574/T574)
	GDAS forecast	T382 GFS	T1534 GFS
	Radiance bias correction	Two part Slow convergence	Unified Fast convergence
	CRTM version	2.0.5	2.1.3
	VSDB (verification S/W)	Version 16	Version 17

Table 2. Component by component comparison of the T511 OSSE system and the new global OSSE system.

<u>**GMAO 7-km Resolution NR (G5NR)**</u>

The GMAO 7-km resolution NR (know as the G5NR) is a two-year, 7-km-resolution, non-hydrostatic global mesoscale simulation produced with the Goddard Earth Observing System (GEOS-5) atmospheric general circulation model (Putnam et al. 2015). The geometry of G5NR is the cubed sphere, in which the earth is projected onto a cube. This allows great computational speed through parallelization. Each face of the cube has 1440 x 1440 grid points, approximately 2 million points per face. With 6 faces and 72 layers at each location, the G5NR divides the global atmosphere into almost 900 million computational volumes (voxels). Access to data and documentation are all at http://gmao.gsfc.nasa.gov/projects/G5NR/

Figure 10 shows a snapshot of the very realistic simulated weather in G5NR. A comprehensive validation study by GMAO (Gelaro et al. 2014) shows that the G5NR performs well as measured by a majority of metrics considered. Particular benefits derived from the 7-km resolution of G5NR include realistic representations of extreme weather events in both the tropics and extratropics.

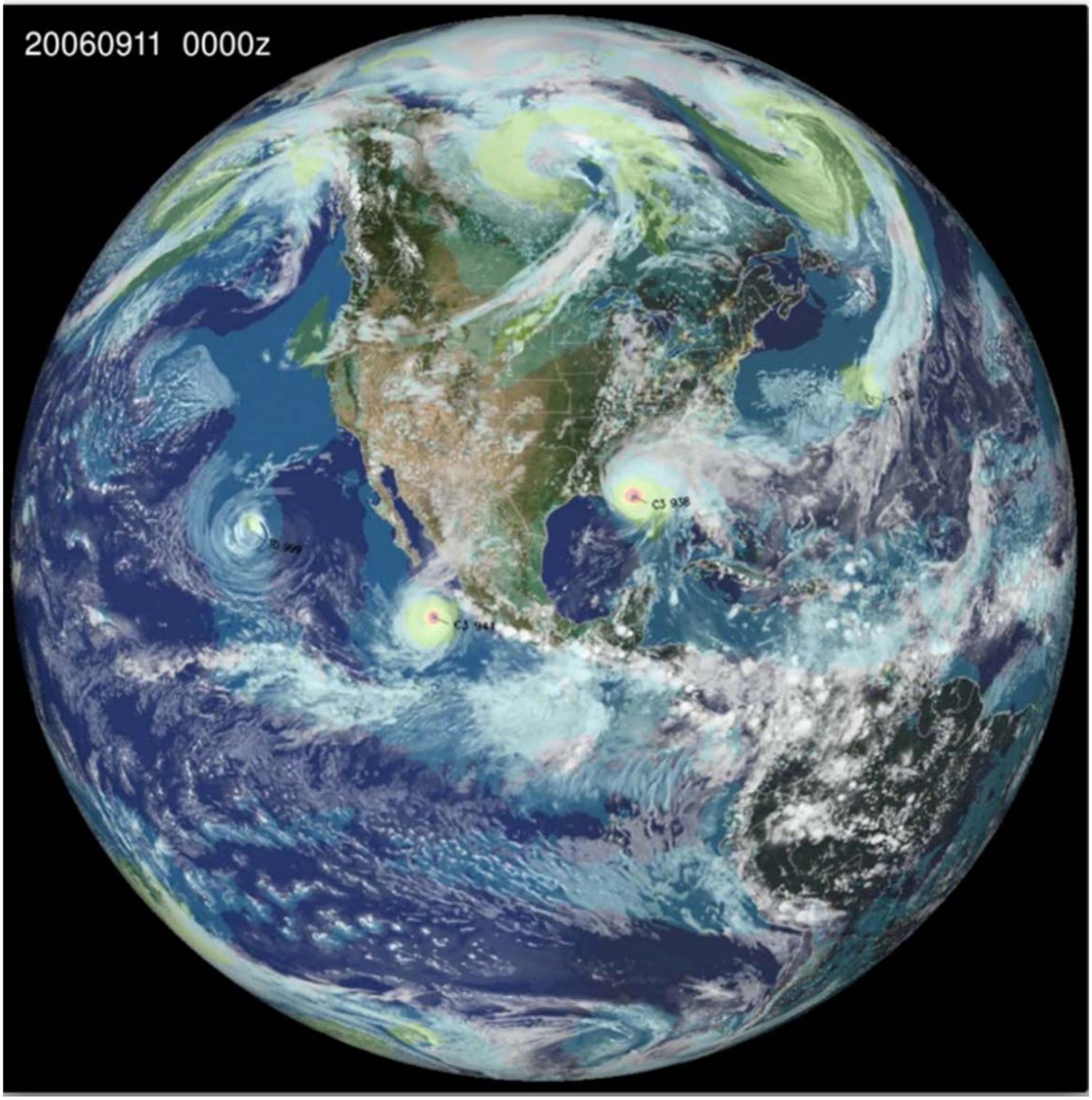

Figure10. A top down view in the visible (i.e., as seen from space) of the G5NR at 00 UTC 11 Sep 2006. An additional color overlay indicates wind speed. At this time two major hurricane are present. One is making landfall on the Gulf Coast *landfall about 30 miles west of Mobile Bay as a Cat 3, borderline Cat 4 storm* with a central pressure of 938 hPa and the second south of Baja California is also Cat 3, with a central pressure of 941 hPa.

Note that we are developing the new OSSE capability with the G5NR, but our design is modular and we anticipate that there will be alternative NRs in the new OSSE capability as we progress.

<u>Case Selection</u>

We have chosen two study periods from 2006. In both cases the last month and a half (15 Aug-30 Sep, 15 Apr-30 May) is the focus of our experiments, allowing us to use the first two weeks to spin-up the DA system. We will focus first on the Aug-Sep case. There are 8 Atlantic hurricanes in the G5NR in Sep 2006. From a societal-economic viewpoint, the eighth Atlantic Hurricane (AL08) of 2006 is the most interesting, making landfall about 30 miles west of Mobile Bay as a Cat 3, borderline Cat 4 storm (Fig. 10). At 2130 UTC 10 Sep 2006, AL08 is centered at 28.8750°W, 271.312°E, near the southeast tip of the Mississippi Delta (Pass A Loutre State Wildlife Management Area) and is at peak strength with a central pressure of 936.398 hPa, and with 10 m winds of 131.609 mph. Landfall occurs 0500 UTC 11 Sep 2006 at 30.2500°W, 271.500°N near Pascagoula with a central pressure of 944.099 hPa and 10 meter winds of 116.103 mph. The Apr-May case is of interest for severe storms and includes a very vigorous mesoscale convective complex (MCC) outbreak on 17-20 May 2006.

Validation of the G5NR

We have conducted additional validation studies of the G5NR: On all time scales, G5NR and NCEP reanalysis are consistent in terms of jet stream level Transient Eddy Kinetic Energy (TEKE). Slight differences exist for the 2-6 day time scale in the north Pacific jet region; 6-30 day time scale in the Atlantic sector (where G5NR is weaker); and the 30-90 day time scales in the tropical and North Pacific sector.

Wang et al. (2015a) compared cyclone track statistics between the G5NR and the analyses from NCEP GDAS. The number of cyclone genesis and lysis, cyclone speed and direction in extratropical regions are diagnosed using sea level pressure with the algorithm of Terry and Atlas (1996). It is found that the averaged minimum of sea level center pressure, cyclone direction, and speed are well simulated in the G5NR. However, G5NR produces a greater number of cyclones than are observed in the GDAS analysis.

Predictability Experiments

The forecast model used to generate the NR and used in the DA system should be realistically different. To demonstrate that this is true for the G5NR and GFS, the GFS was initialized with G5NR initial conditions (Casey et al. 2015). The forecast skill of the GFS to predict the real atmosphere and the G5NR was compared. Differences exist in the sense that GFS is better at predicting the NR than the real world, but these differences in how fast forecast errors grow are small enough to conclude that there is no identical twin problem. For example, Fig. 11 shows that the growth of error in temperature for these two situations is quite similar.

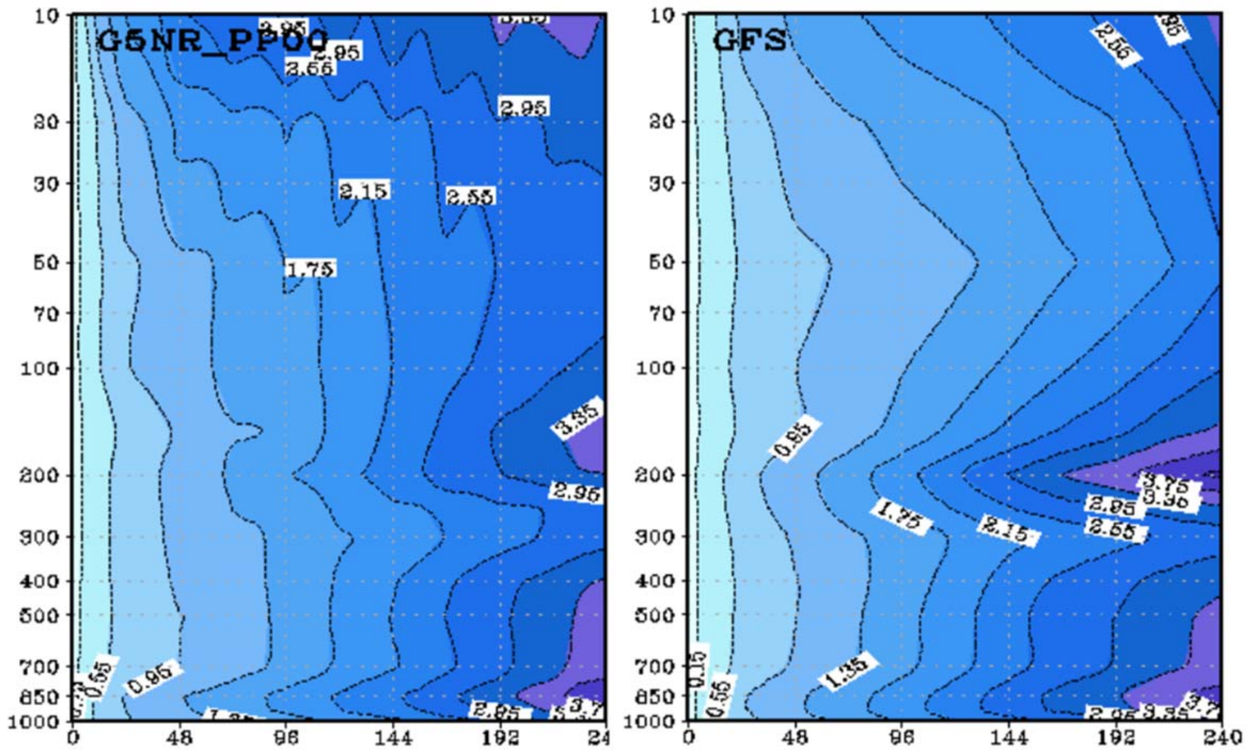

Figure 11. Global RMSE for temperature forecasts in the predictability experiments in simulation (left) and in real life (right). The RMSE is plotted versus forecast time (hours, x-axis) and pressure (hPa, y-axis).

OSE/OSSE Transition Experiments

There should be a smooth transition at the start of the NR when switching from OSE to OSSE mode. This experiment also is used to calibrate observation errors, comparing added radiosonde variances in simulation to real observations. A single iteration to correct the random errors used in the simulated observations was sufficient to bring RMSE values to a point where the differences between real and simulated radiosonde RMS errors were not statistically significant (Casey et al. 2015). Figure 12 demonstrates this for radiosonde temperatures in which the right panel shows the good match of these statistics after adding additional random errors to the simulated radiosondes.

Additionally, a methodology to simulate TCVitals observations for the G5NR, including realistic errors was developed. TCVitals are real time estimates by analysts of key tropical cyclone (TC) parameters in real time using all available data. TCVitals position and minimum SLP estimates are used in the GDAS for bogus vortex generation if none already exists in the background or otherwise to relocate the vortex in the background and as ordinary SLP observations.

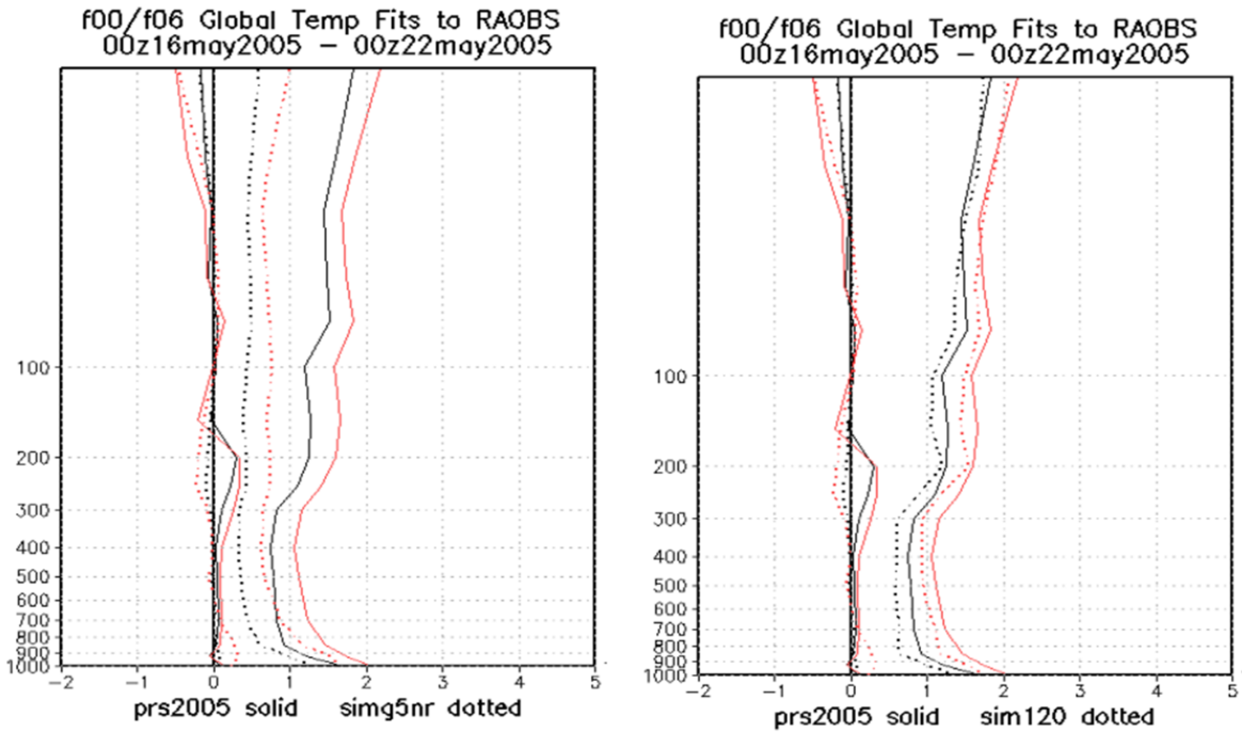

Figure 12. Global mean and RMS differences for temperature innovations (O-B, observation minus background plotted in red) and analysis departures (O-A, observations minus analysis plotted in black). Solid lines are results for the OSE and dotted lines are results for the OSSE. The OSE results are the same in both panels. The OSSE results are for (left) perfect simulated observations (i.e., no error) and (right) simulated observations with calibrated errors.

Real Data Experiments with the New T1534 NCEP Operational System

A T1534/T574 experiment using the 2014 model and real data was performed to produce the templates needed to simulate observations. In addition, the low-resolution T670/T254 version of the DA system was successfully run on the JIBB computer (JCSDA's supercomputer located at NASA/GSFC), providing the real-data counterpart for low-resolution OSSE runs. An additional real-data experiment at T670/T254 resolution assimilates only the suite of observations expected during the data gap. Using this information, mean and standard deviation of variances for all observation types for a given period were computed. The simulated counterpart of this experiment quantifies differences between real and simulated variances and is used to calibrate the observation errors for the new OSSE system.

Observation Simulation

Tests in which a simulated data for a single data type is assimilated at the start of the G5NR serves as a consistency check and partial verification of simulated observations. Simulated samples of all observation types near the start of the G5NR were tested in this way.

Progress in simulating observations includes the following. CIMSS has produced Geo-AIRS data for a GOES east satellite location on the 7-km grid for the two-month Aug-Sep 2006 study period from the G5NR. The new bending angle GNSS/RO software has been integrated into the observation simulation software and is expected to be implemented in the future versions of GSI. All existing observations have been simulated for parts of the Aug-Sep 2006 study period, based on the 2014 actual observations (Boukabara et al. 2016a). Because we are interested in a potential data gap, observations from U.S. afternoon polar orbiters are not included. Software has been developed to simulate a constellation of 5 Geo-HSS instruments with IASI characteristics (Casey et al. 2016).

JCSDA has been tuning the simulated observation errors using a calibration approach that compares (O-B) (i.e, 6-h forecast errors or innovations) statistics in real data experiments and in the OSSE.

Development of the Community Global OSSE Package (CGOP)

In response to the challenges of creating, maintaining, and validating a state of the art OSSE system a modular extensible framework for conducting OSSEs has been developed with the goals of (1) supporting decision-makers with quantitative assessments of proposed observing systems investments, (2) supporting readiness for new sensors, (3) enhancing collaboration across the community by making the most up-to-date OSSE components accessible, and (4) advancing the theory and practical application of OSSEs. Towards these goals, the Community Global OSSE Package (CGOP) is designed to be highly flexible, user friendly (i.e., relatively easy to install and use), well documented, and regularly synchronized with the operational versions of the global DA system, the Community Radiative Transfer Model (CRTM), and other OSSE system components that are adopted from operations and the research community, thereby enhancing the credibility of results from OSSEs made using the CGOP. The current release of the CGOP is based on a new mesoscale global nature run produced by NASA using the 7-km cubed sphere version of the Goddard Earth Observing System Model, version 5 (GEOS-5) Atmospheric General Circulation Model and the latest (January 2015) operational version of the NOAA global data assimilation (DA) system. CGOP includes procedures to simulate the full suite of observing systems used operationally in the global DA system, including conventional in situ, satellite-based radiance, and radio occultation observations (Boukabara 2016b). The CGOP is designed to evolve, both to improve its realism and to keep pace with the advance of operational systems (Boukabara 2016c).

An important component of the CGOP activities is the validation of the simulated observations. As an example of the activities involved in this validation, we compare real to "perfect" simulated radiances and use the ATMS as an example for microwave (MW) instruments and the Cross-track Infrared Sounder (CrIS) for infrared (IR) instruments. ATMS is a 22 channel microwave instrument operating at a frequency range of 23.8 GHz to 190 GHz. ATMS Channels 1, 2, and 16 are known as surface channels because the measured radiances are mostly emitted by the surface. ATMS Channels 3-15 are temperature sounding channels centered around the oxygen absorption band at 57 GHz. The rest of ATMS channels (17-22) are humidity sounding channels and sensitive to the tropospheric humidity. Thus, we present results from three ATMS channels: Channel 1 (23.8 GHz), a surface channel; Channel 11 (57.3 GHz), a temperature sounding channel; and Channel 22 (183.3 GHz), a humidity sounding channel, to demonstrate that the observation simulation in the MW is properly handling variations in temperature, humidity, and surface properties.

Figure 13 shows maps of real (Fig. 13a) and simulated (Fig. 13b) observations (as well as the difference, simulated minus real in Fig. 13c) for ATMS Channel 1. First, note that, by construction, the data coverages match. The real observations are valid within 3 h of 00 UTC 1 Aug 2014 but the simulated observations are for 2006. Therefore, an identical match is not expected. However, the general response pattern of microwave surface channels is seen in both real and simulated observations. Low brightness temperature (BT) values occur over clear sky ocean since ocean emissivity is typically 0.5–0.7 and high BT values occur over land where emissivity is generally close to 1.0. Also Tb values increase over the ocean with increasing water vapor. This occurs because, as water vapor absorbs and emits in the MW, increasing water vapor elevates the weighting function for MW channels and partially replaces the very cold signal from the ocean surface (due to its low emissivity) with a warm atmospheric signal. Compared to the ocean, larger differences are observed between real and simulated observations over land as well as over ice/snow covered areas. The mean difference (simulated minus real) BT values over land is about 10.5 K compared to only 0.24 K over ocean. The large differences over land are attributed to the uncertainty in the land surface emissivity calculations.

The same maps are shown for ATMS channel 11 in Fig. 13.d-f. Since Channel 11 is sensitive to the upper troposphere and lower stratosphere temperature and is not affected by the surface, the differences between real and simulated observations over land for Channel 11 are considerably smaller than those for Channel 1. The mean difference is 0.47 over land and 1.53 K over ocean. Figure 13 also shows the real (Fig. 13.g) and simulated (Fig. 13.h) observations for ATMS Channel 22. This channel is more sensitive to clouds than other channels but not sensitive to surface emissivity, except in very dry conditions. However, since this channel is very sensitive to tropospheric humidity, differences will reflect differences between meteorological systems in reality and in simulation. Also differences between the real and simulated zonal mean humidity are apparent in these maps. For example in the latitude band from the equator to 30◦S brightness temperatures are generally higher in reality than in the G5NR, reflecting a dryer atmosphere in reality. The mean difference is 0.76 over land and 2.51 K over ocean.

The histograms for the distribution of BT for the three ATMS channels are shown in Fig. 14. These distributions agree well in reality and in simulation for the water vapor channel (Channel 22) and especially for the stratospheric temperature sounding channel (Channels 11). Larger differences that are observed for the surface channel (Channel 1) are attributed to the differences in the surface emissivity in reality and in simulation.

CrIS is a Fourier transform interferometer operating from the shortwave to longwave spectrum, covering three bands including the far IR (655-1095 cm^{-1}), near IR (1210-1750 cm^{-1}), and shortwave (2155-2550 cm^{-1}) regions. CrIS channels are sensitive to the surface temperature, surface emissivity, atmospheric temperature, humidity, and many other atmospheric constituents such as CO_2, N_2O, CO, SO_2, CH_4, etc. The operational DA system only uses a subset (399 out of 1305) of the CrIS channels (Gambacorta and Barnet 2011). For example, since there is no provision to use atmospheric trace gases as Community Radiative Transfer Model (CRTM) inputs, those channels sensitive to these atmospheric constituents are not well simulated by CRTM and therefore not used for NWP. Similar to ATMS, we present results from selected CrIS channels: Channel 73 (number 18 of the CrIS subset at 695 cm^{-1} or 14.38849 μm), a CO2 temperature sounding channel; Channel 198 (number 79 of the CrIS subset at 773.125 cm^{-1} or 12.93452 μm), a surface channel; and Channel 945 (number 300 of the CrIS subset at 1498.75 cm−1 or 6.67223 μm), a humidity sounding channel.

Figure 15.a-c shows the maps for CrIS channel 73, a temperature sounding channel, which is not sensitive to the surface. The real and simulated observations show similar patterns (Fig. 15.a-b). The mean difference (simulated minus real, Fig. 15.c) is 0.15 K over land and 0.60 K over ocean. The histogram of the differences between simulated and real observations shows that most of the differences are less than 5 K (Fig. 5.c). In the IR, unlike the MW, surface channels see opaque cloud as an elevated and cold surface. This is clearly seen in CrIS channel 198 in reality (Fig. 15.d) where a number of cold cloudy regions are evident. These are entirely absent in the simulation (Fig. 15.e) since clouds are not included. The absence of cloud in the simulation is also evident in the difference map (Fig. 15.f) and the histograms (Fig. 5.d-f) for this channel. The real and simulated observations for CrIS Channel 945, the water vapor channel, are shown in Fig. 15.g-h. Due to the opacity of water vapor there is an anti-correlation between water vapor and measured radiance—that is, the source of the observed radiance moves higher in the atmosphere as water vapor increases. Thus high values of radiances correspond to dry regions in both the simulated and real observations. The mean difference (simulated minus real, Fig. 15.i) over the ocean is -0.24 K and -0.73 K over land. Figure 16.i, the histogram of these differences, shows that most of the differences between simulated and real observations are less than 15 K. Substantial differences are expected for this water vapor channel since the meteorological patterns in reality and simulation are independent.

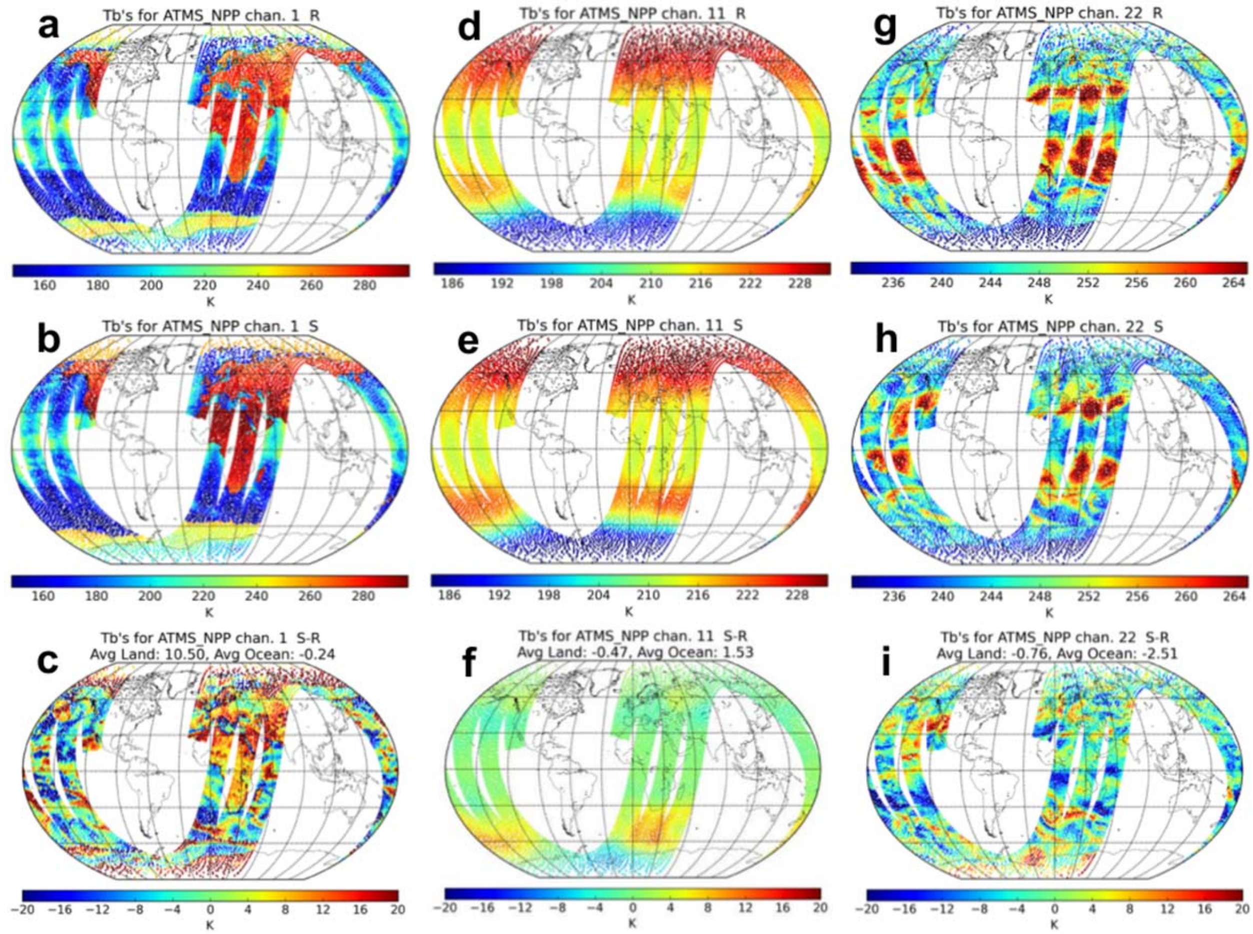

Figure 13. Maps of BT (K) for ATMS Channels 1, 11, and 22 (from left to right) for a single cycle at 00UTC 1 Aug from reality (top), as simulated from the NR (middle) and of the differences (simulated minus reality). Color scales (K) vary from panel to panel.

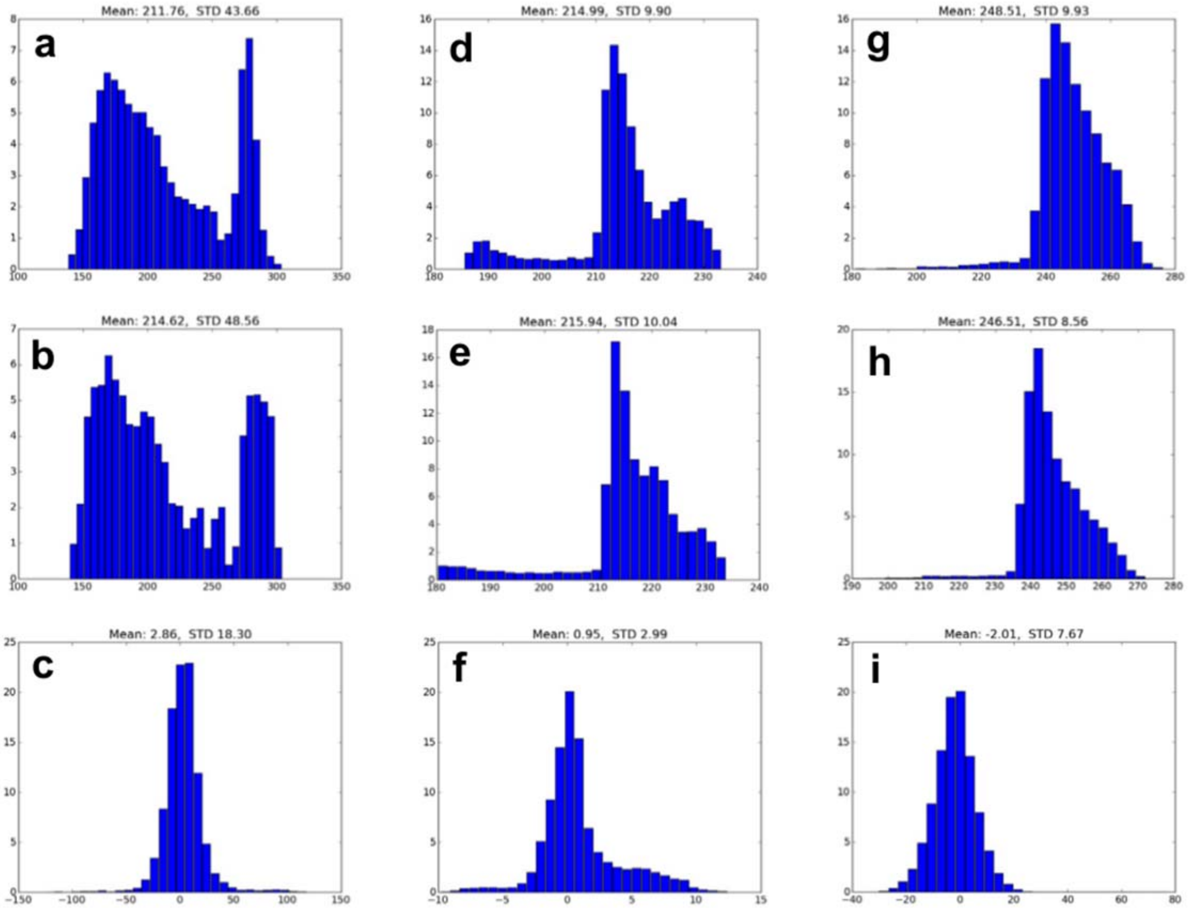

Figure 14. Histograms of BT (K) for ATMS Channels 1, 11, and 22 (from left to right) for a single cycle at 00 UTC 1 Aug from reality (top), as simulated from the NR (middle) and of the differences (simulated minus reality). The scaling of the x-axis (%) and y-axis (K) vary from panel to panel. The mean and standard deviation of each distribution are given above each panel.

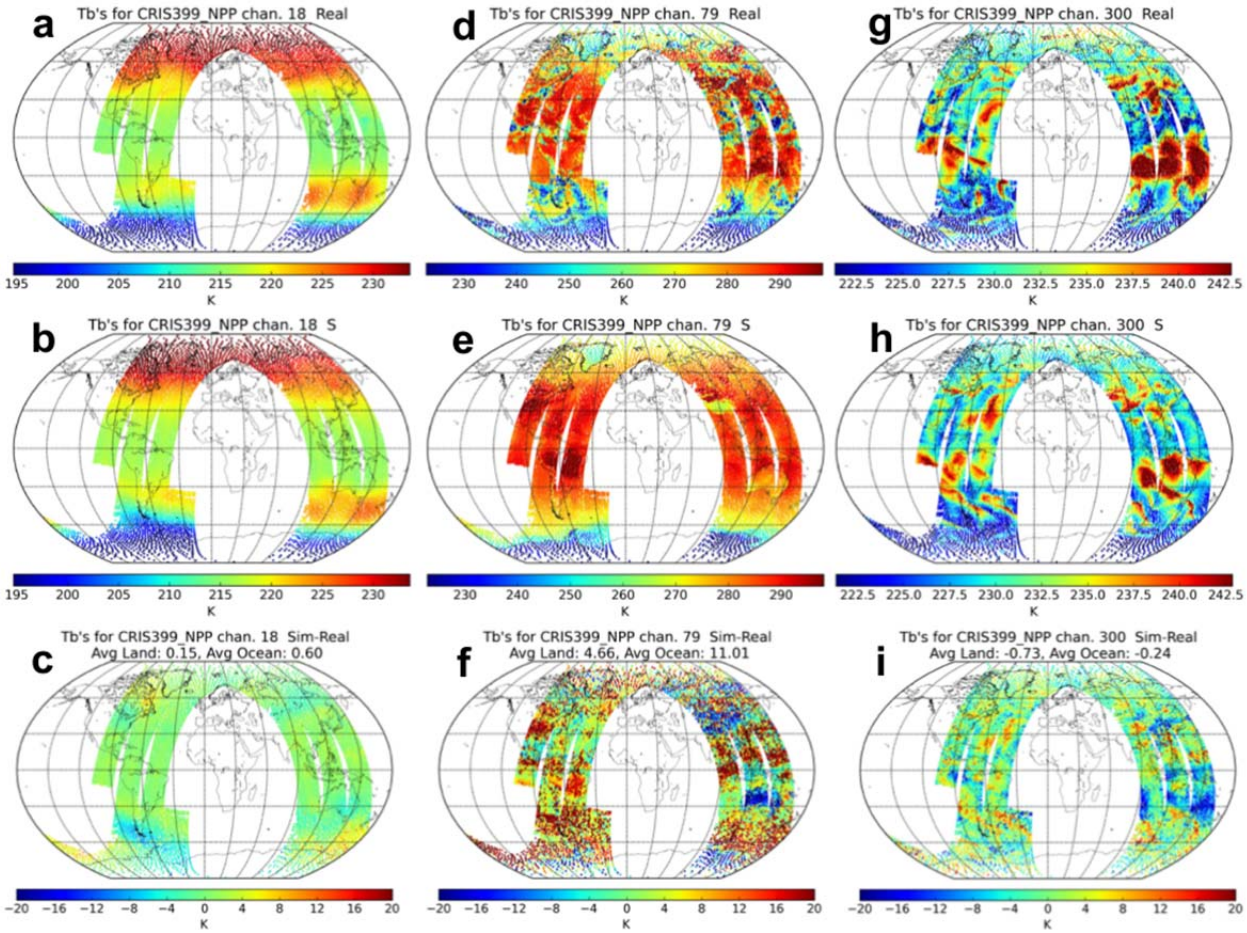

Figure 15. Maps of BT for CrIS Channels 73, 198, and 300 (from left to right) for a single cycle at 06UTC 1 Aug from reality (top), as simulated from the NR (middle) and of the differences (simulated minus reality). Color scales (K) vary from panel to panel.

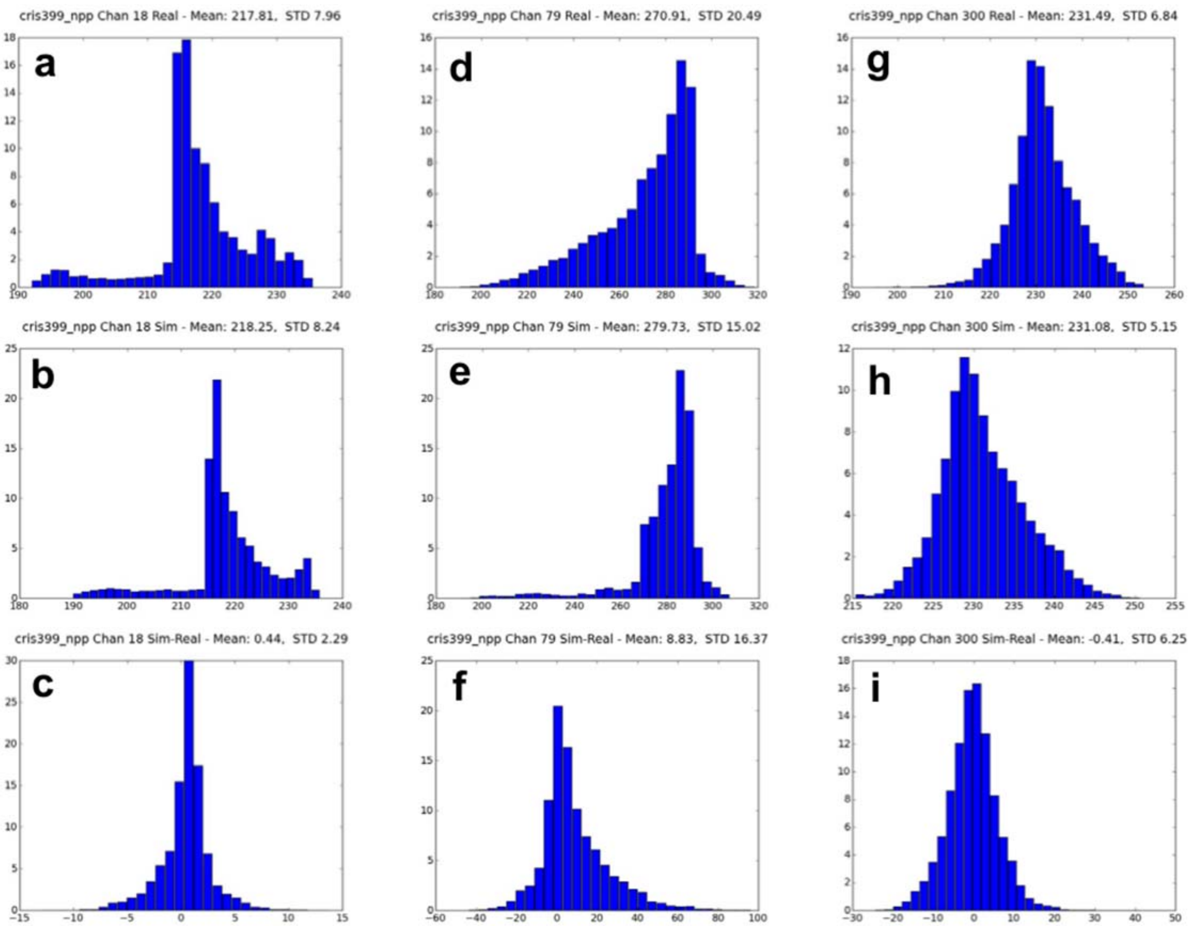

Figure 16. Histograms of the data plotted in Fig. 15, i.e., of BT for CrIS Channels 73, 198, and 300 (from left to right) for a single cycle at 06 UTC 1 Aug from reality (top), as simulated from the NR (middle) and of the differences (simulated minus reality). The scaling of the x-axis (%) and y-axis (K) vary from panel to panel. The mean and standard deviation of each distribution are given above each panel.

Conclusions

We have met the project goals, which are to:

1. Develop a new state-of-the-art OSSE capability.
2. Conduct experiments for Geo-HSS and GNSS RO (gap fillers) and other proposed instruments using the
   - Previous OSSE system for preliminary results;
   - Coupled global regional OSSE system for hurricane forecasting; and
   - To begin experiments with the new OSSE capability for results applicable to the current operational system. (These experiments are scheduled to be completed during 2016.)

Preliminary experiment results

Preliminary OSSEs to evaluate the potential impact of Geo-HSS instruments on global model forecasts and regional model hurricane forecasts show a significant improvement in forecast accuracy in the Southern Hemisphere, but did not show significant improvement in the Northern

Hemisphere. The results of the hurricane experiments have been mixed. They indicate some potential to improve hurricane predictions, particularly as the frequency of observations increases. However, these results are not yet definitive, and more research will be required to optimize the impact of these data for numerical weather prediction and to determine if a significant impact over North America will occur. This research is currently being performed using both global and regional models and will be incorporated into the more advanced and comprehensive OSSEs that we expect to complete in December 2016.

We performed preliminary experiments to determine the benefits of increasing the number of GNSS/RO profiles on global weather forecast skill. Preliminary OSSEs have evaluated COSMIC-2 (equatorial and polar components) using NOAA's T511 global OSSE system configuration and assimilating a retrieved type of RO observations. The results of this experiment indicate that increasing the number of assimilated RO satellites from 6 to 18 improves weather forecast skill: 18 satellites is better than 12 satellites; 12 satellites is better than 6 satellites. A preliminary regional hurricane OSSE was also conducted. This experiment showed improved analyses and short-range (up to 24 hour) forecasts as the number of satellites was increased from 6 to 30. More rigorous OSSEs will be conducted with the advanced, next-generation global OSSE system during 2016. In addition to these OSSEs, real data Observing System Experiments (OSEs) have been conducted to evaluate the impact of losing the current RO constellation on global weather forecast skill. These experiments showed that forecast skill is degraded when RO observations are removed from the model.

The Outlook for Future OSSEs

The new OSSE capability will be applied in a number of experiments to get results compatible with today's operational systems. These OSSEs will quantify the impact and optimize the use of various proposed and operational instruments, including Geo-HSS and GNSS RO, as described in this report, but also MW sounders in GEO, UAS, CYGNSS, DWL (Baker et al. 2014), and others.

Additionally, we anticipate a number of enhancements to the G5NR OSSE system, including:

- Increased resolution to 3.5 km for selected periods in the G5NR;
- A new hurricane basin scale WRF NR embedded in the G5NR is in development at AOML and is currently undergoing testing using a uniform 3 km grid, but plans are to try to create this NR using a finer, perhaps 1 km grid;
- New DA components from the O2R process to keep pace with NCEP advances, including hybrid 4d DA, which is expected to become operational in 2016; and
- New applications of OSSEs to models of other components of the earth system that interact with the atmosphere, including, for example, Severe Storms, Ecosystems, and Air Quality OSSEs.

Looking further ahead and motivated by the developments documented in this report of a new advanced OSSE system Hoffman and Atlas (2016b) see many opportunities for further improvements and anticipate that some of these potential improvements will become requirements in the future as the OSSE technique is applied in new settings—in diverse and coupled domains and with the use of increasingly advanced and sophisticated simulations of nature and observations. For example, Halliwell et al. (2014, 2015) are now conducting OSSEs for the ocean. In addition, opportunities for further improvements are also challenges to current OSSEs and in general correspond to important considerations when interpreting the experimental results of any particular OSSE in support of decision-making. Thus, the list of opportunities/challenges as well as our list of requirements for current OSSEs constitutes an "OSSE checklist", which is provided as a web page at AOML (www.aoml.noaa.gov/qosap/osse-checklist/).

Due to considerations of realism and relevance, it is clear that as operational forecast and data assimilation (DA) systems evolve, OSSE systems must evolve in parallel. Expected development of operational systems will greatly challenge our ability to construct more realistic OSSE systems. An additional set of challenges will arise when future DA systems strongly couple the different earth system components. A connection between these two types of challenges is evident in the continuing advance toward using more and more data that entangle signals from different components of the earth system, such as surface-affected microwave radiances. In response, future OSSE systems will require coupled models to simulate nature and coupled observation simulators. The requirements for future evolving OSSE systems and potential solutions to satisfy these requirements is discussed by Hoffman and Atlas (2016a, 2016b).

Appendix: Infrastructure

Forecast models

Global Forecast System (GFS)

The T511 OSSE system uses the T382L64 (35 kilometer horizontal resolution, 64 vertical layers) version of the Global Forecast System (GFS) that was operational as of 31 May 2005.
The new OSSE system uses the T1534L64 (9 kilometer horizontal resolution, 64 vertical layers) semi-Lagrangian version of the GFS that became operational on 14 January 2015. Optionally, the new OSSE system also uses the T670L64 (20 kilometer horizontal resolution, 64 vertical layers) semi-Lagrangian research version of the GFS.

Hurricane Weather Research and Forecasting (HWRF) model

Versions of Hurricane Weather Research and Forecasting (HWRF) model from 2012 and 2014 have been used for the project. The outer domain has 61 vertical levels and a 9-km horizontal grid. The inner storm-following domain has a 3-km horizontal grid.

Data Assimilation Systems

Data assimilation systems are constantly evolving. To maximize relevance, OSSEs should be conducted with up-to-date versions of operational DA systems. For our experiments, three different analysis methodologies are employed:

Gridpoint Statistical Interpolation (GSI)

The Gridpoint Statistical Interpolation (GSI) is a three dimensional (3d) variational analysis system that assimilates a wide range of data types. The GSI assimilates satellite radiances and includes a variational bias correction for radiances. The action of the GSI is to combine a background estimate of the atmospheric state, which is normally a 6-h forecast, and all available recently observed data, usually within 3 hours of the analysis time. The GSI analysis is optimal provided the background and observational error statistics are correct. However, the traditional static (or climatological) background error statistics are not correct for any particular day. This issue has led to the development of several ensemble and hybrid DA methods that use the variability in the forecast ensemble to estimate the background error covariances.

In the global experiments, the GFS/GSI use a spectral resolution of T382/T382 in the T511 OSSE system, T1534/T574 in the new OSSE system and T670/T254 in the new research and development system. For the regional experiments, the GSI analysis is computed on the outer (9-km) domain and analysis increments are interpolated to and added to the inner (3-km) domain.

Ensemble Kalman Filter (EnKF)

The ensemble Kalman filter (EnKF) is a data assimilation scheme based on the traditional Kalman filter update equation. The pure EnKF has been used in some regional OSSEs, but not in any global OSSEs. The EnKF uses an ensemble of short-term forecasts to estimate background-error covariances. The forecasts are then adjusted to newly available observations. In the systems described here, the size of the ensemble is 80. The EnKF generally produces more accurate analyses and forecasts than a 3d-Var approach with static covariances like the GSI. Additionally, the EnKF automatically provides a random sample of the estimated analysis-error distribution, which can then be used as initial conditions for an ensemble prediction system (Whitaker and Hamill 2002).

Hybrid GSI/EnKF

Recent and planned global OSSEs will use a combination of the GSI and an EnKF. In this hybrid method, the EnKF provides an estimate of the background error covariances that depends on the synoptic weather situation. For the GSI component, the estimate from the EnKF and from the static climatological background error covariances are combined. The GSI solution is then used to recenter the EnKF ensemble before advancing to the next analysis time.

In the global experiments, the GFS/GSI/EnKF use a spectral resolution of T382/T382/T190 in the T511 OSSE system, T1534/T574/T574 in the new OSSE system and T670/T254/T254 in the new R&D system. The hybrid GSI/EnKF is being developed for regional OSSEs.

Computational Infrastructure

A major expansion to the CIMSS supercomputer S4 under the NOAA Sandy Supplemental Grant was completed in late July 2014 and the system is now available to researchers (Kumar et al. 2015). The JIBB supercomputer also went through an expansion in March 2014.

OSSE Acronyms

ACC	anomaly correlation coefficient
AIRS	Atmospheric Infrared Sounder
AL08	Atlantic hurricane 8
AMS	American Meteorological Society (Boston)
AMSU	Advanced Microwave Sounding Unit
AMV	atmospheric motion vector
AOML	Atlantic Oceanographic and Meteorological Laboratory (Miami FL)

ARIES	Airborne Research Interferometer Evaluation System
ARL	Air Resources Laboratory
ARW	Advanced Research WRF
ATMS	Advanced Technology Microwave Sounder
BUFR	Binary Universal Form for the Representation of Meteorological Data
CGOP	Community Global OSSE Package
CIMAS	Cooperative Institute for Marine and Atmospheric Studies (Miami FL)
CIMMS	Cooperative Institute for Mesoscale Meteorological Studies (Norman OK)
CIMSS	Cooperative Institute for Meteorological Satellite Studies (Madison WI)
COSMIC	Constellation Observing Satellites for Meteorology, Ionosphere, and Climate
CrIS	Cross-track Infraed Sounder
CRTM	Community Radiative Transfer Model
CTRL	Control experiment
CTW	cloud track wind
CYGNSS	Cyclone Global Navigation Satellite System
DA	data assimilation
DWL	Doppler wind lidar
ECMWF	European Center for Medium-Range Weather Forecasting
EnKF	ensemble Kalman filter
ERS	European Remote Sensing
ESRL	Earth System Research Laboratory (Boulder CO)
ESSIC	Earth System Science Interdisciplinary Center (Univ. of Maryland, College Park)
G5NR	GMAO 7-km resolution NR
GDAS	Global Data Assimilation System
GEO	geostationary Earth orbit
Geo-AIRS	geostationary instrument with AIRS characteristics
Geo-HSS	geostationary hyper-spectral sounder
Geo-MW	geostationary microwave instrument
GEOS	Goddard Earth Observing System
GFS	Global Forecast System
GHz	giga Hertz
GMAO	Goddard Modeling and Assimilation Office
GNSS	global navigation satellite system
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center (NASA)
GSI	Gridpoint Statistical Interpolation
GTWS	Global Tropospheric Wind Sounder
HEDAS	Hurricane Ensemble Data Assimilation System
HIRS	High Resolution Infraed Radiation Sounder
HNR1	first hurricane NR
HSS	hyper-spectral sounder
HWRF	Hurricane Weather Research and Forecasting (model)
IASI	Infrared Atmospheric Sounding Interferometer
IR	infrared
JCSDA	Joint Center for Satellite Data Assimilation
JIBB	JCSDA in a Big Box (NASA Goddard Space Flight Center)

JPL	Jet Propulsion Lab (NASA)
LAWS	Lidar Atmospheric Wind Sounder
LEO	low Earth orbit
MCC	mesoscale convective complex
Metop	Meteorological Operational Satellite Programme (European)
MHS	Microwave Humidity Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MSLP	mean sea level pressure
MW	microwave
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration
NR	nature run
NSCAT	NASA Scatterometer
NSSL	National Severe Storms Laboratory (NOAA)
NWP	National Weather Prediction
O2R	operations to research
OAR	Office of Oceanic and Atmospheric Research
OAWL	optical autocovariance wind lidar
OSE	observing system experiments
OSSE	observing system simulation experiments
P-3	Lockheed P-3 Orion aircraft
PI	principal investigator
PM	program manager
PNA	Pacific-North American
PREPBUFR	quality controlled data in BUFR format
QuickOSSE	Quick OSSE
R&D	research and development
RMS	root mean square
RMSE	root mean square error
RO	radio occultation
RSMAS	Rosenstiel School for Marine and Atmospheric Science
S4	Supercomputer for Satellite Simulations and Data Assimilation Studies (Space Science and Engineering Center at the University of Wisconsin-Madison)
SARTA	Stand-alone AIRS Radiative Transfer Algorithm
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SH	Southern Hemisphere
SLP	sea level pressure
SSM/I	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
TC	tropical cyclone
TCVitals	Tropical Cyclone Vital Database
TEKE	transient eddy kinetic energy
TxxxLyy	xxx triangular spectral truncation with yy layers
UAS	unmanned aerial systems

UTC	Universal Time Coordinated
VarBC	variational bias correction
WMO	World Meteorological Organization (Geneva)
WRF	Weather Research and Forecasting (model)

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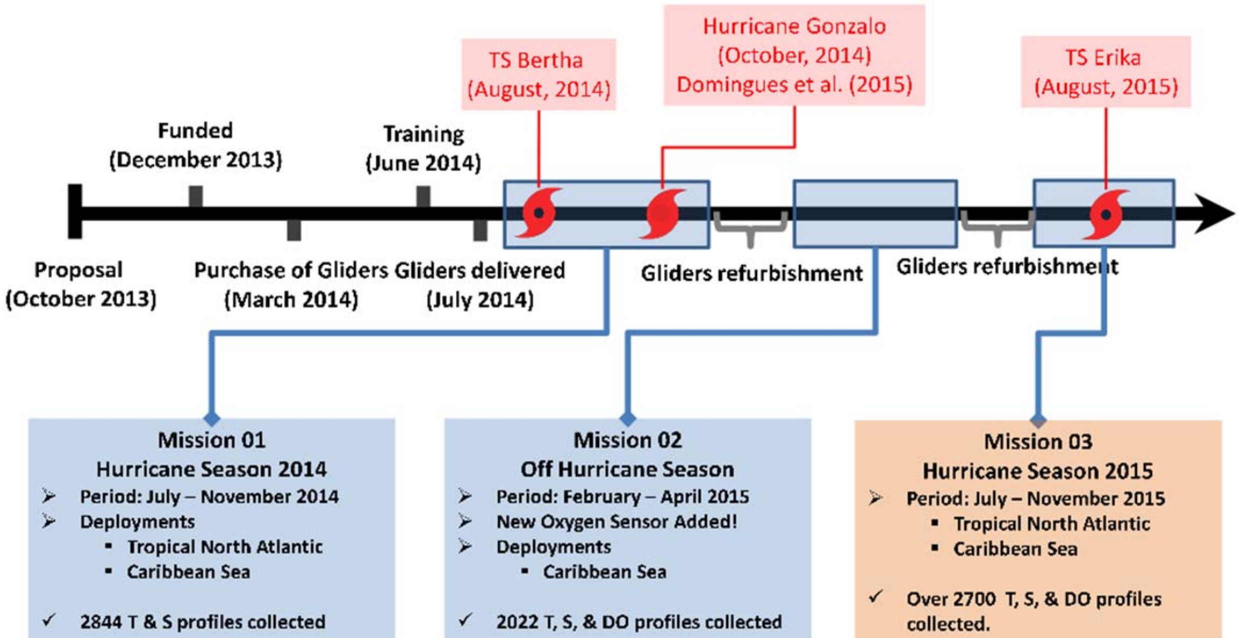
Task-2: Sustained and Targeted Ocean Observations for Improving Atlantic Tropical Cyclone Intensity and Hurricane Seasonal Forecasts; Lead PI: Dr. Gustavo Goni, NOAA/AOML

Through this proposed task, we have successfully carried out four underwater glider missions of sustained and targeted upper-ocean profiling of temperature, salinity, dissolved oxygen and depth-averaged current velocities in the Caribbean Sea and Tropical North Atlantic Ocean. During the two years of this project, over 8,000 profiles were collected in waters off Puerto Rico in the Caribbean Sea and Tropical North Atlantic. Data collected by the underwater gliders were made available in real-time through AOML website (http://www.aoml.noaa.gov/phod/gliders) and through the Global Telecommunications System (GTS). Data were also distributed through NOAA Integrated Ocean Observing System - IOOS (http://www.ioos.noaa.gov/). The underwater glider obserations during hurricane Gonzalo (2014) were assimilated into a hurricane forecast model (HYCOM-HWRF). Preliminary model simulations indicate that the underwater glider data significantly improve ocean initial conditions when they are assimilated into HYCOM-HWRF model. Key results and findings from the four glider missions and the hurricane forcast model experierments are summarized in this report.

(1) Summary of Research Conducted

(1.1) ***The underwater gliders deployment and operations in the Caribbean Sea and North Atlantic Ocean***

Timeline of underwater glider operations:



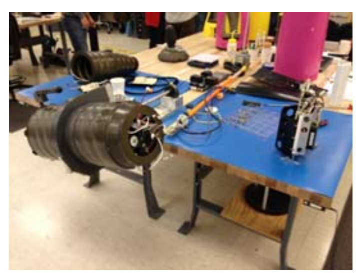
Seaglider planning meeting (March 25, 2014):
Project partners from AOML, NDBC, CIMAS, UPRM, ANAMAR, and NCEP participated this meeting (at AOML) to discuss various logistical, operational, and data management issues.

At-sea-test of underwater gliders (March 26, 2014):
An at-sea-test of underwater gliders took place near the cape Florida Channel using a small charter boat.


Refurbishment training: (June 2014):
CIMAS team members, Grant Rawson and Kyle Seaton participated training offered by Kongsberg Underwater Technology on tear down, sensor exchange, rebuild, test and trim glider.

Pilot training: (June 2014):
Grant Rawson, Kyle Seaton and Francis Bringas participated training offered by Kongsberg Underwater Technology on piloting system, glider data plotting, glider deployment, overnight glider piloting and glider recovery.





First mission (July - November, 2014):
Two underwater gliders were purchased in March 2014 and delivered to CIMAS in July 2014. We successfully carried out the first deployment of the two underwater gliders. The first glider was deployed south of La Parguera, Puerto Rico on July/15/2014 from the R/V La Sultana of the University of Puerto Rico at Mayaguez (UPRM). The second glider was deployed 14nmi off the coast of San Juan, Puerto Rico on July/19/2014. The deployment of the second glider was done after one day delay to change a faulty modem. Data from the two gliders were widely distributed (including GTS) in real time. NCEP/CPC, NRL and NCEP/EMC started to assimilate the data to

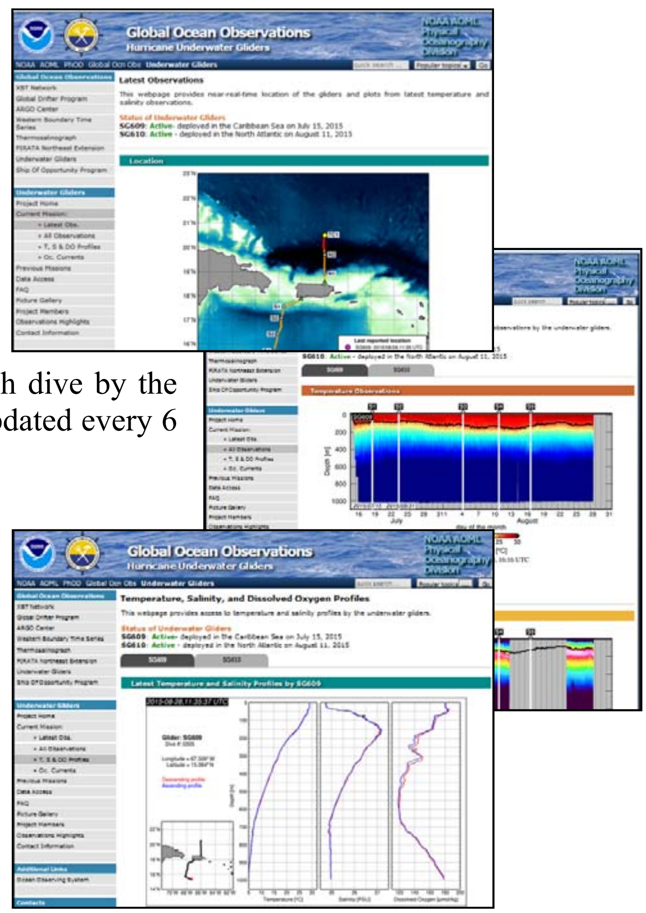
initialize their operational forecast models (CFSv2; HWRF-HYCOM; Global HYCOM). The two gliders collected 2844 temperature and salinity profiles until recovery on November, 2014.

Second mission (February - April, 2015):
Two underwater gliders were deployed in the Caribbean Sea on February, 2015. During this second mission, the two gliders collected 2022 temperature, salinity, and dissolved oxygen profiles until recovery on April, 2015.

Third mission (July - November, 2015)
Two underwater gliders were deployed on July, 2014, one in the Caribbean Sea, and one in the North Atlantic Ocean. Together, both gliders collected over 2,700 temperature and salinity and until dissolved oxygen until their recovery on November, 2015.

Fourth mission: (March – June, 2016)
Two underwater gliders were deployed on March, 2016 in the Caribbean Sea and currently scheduled to be recovered in June 2016.

Underwater glider data distributions:
Data collected by the underwater gliders are made available through the Global Telecommunications System (GTS).

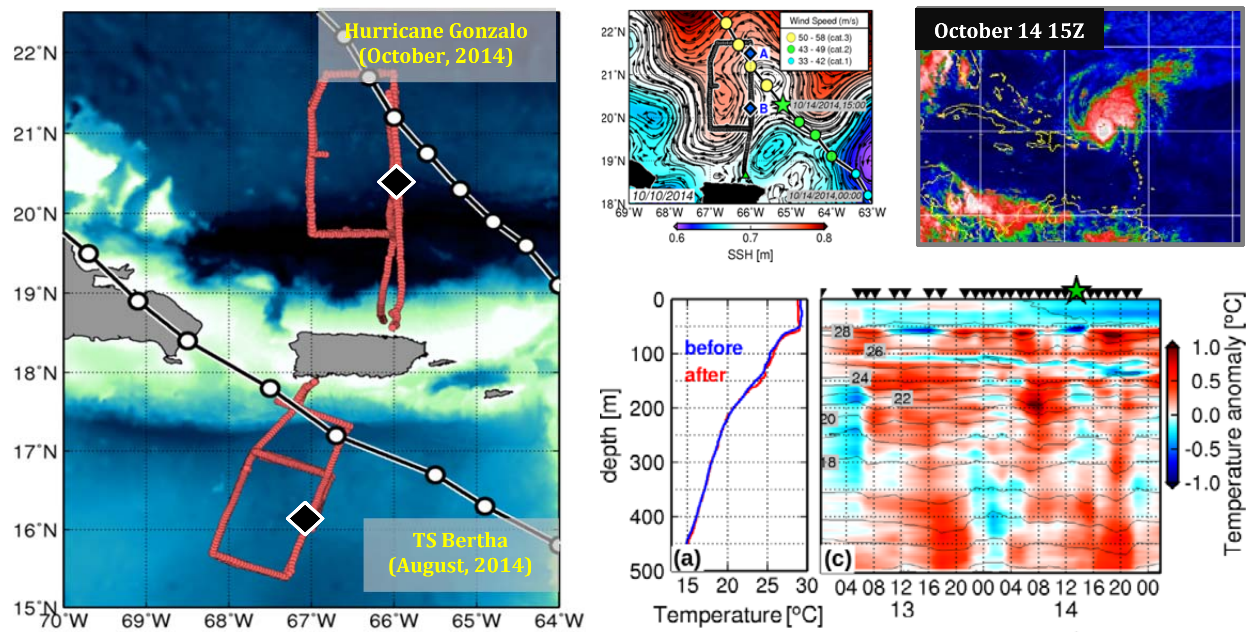


After the first deployment, a data website (http://www.aoml.noaa.gov/phod/gliders) was launched to provide near-real time location of the two gliders, and latest temperature and salinity profile observations. This webpage also provides access to near-real time data from the two underwater gliders. Data for each dive by the underwater gliders is in NetCDF format and updated every 6 hours.

Information and plots on the current location of the gliders and observations are also made available in real-time through AOML/PhOD website. These plots include temperature, salinity, and dissolved oxygen profile observations, as well as estimates of surface and depth-averaged current velocity provided by the underwater gliders. Data are also distributed through NOAA Integrated Ocean Observing System, also known as IOOS (http://www.ioos.noaa.gov/). During the two years of this project, over 8,000 profiles were collected in waters off Puerto Rico in the Caribbean Sea and Tropical North Atlantic.

Upper ocean observations during tropical storms

During our first mission in the 2014 hurricane season, tropical storm Bertha (Aug 2014) and hurricane Gonzalo (Oct 2014) passed near the underwater gliders. During Oct 8-13, we were able to pilot one glider on the projected path of the hurricane Gonzalo to obtain a unique data set of pre-storm, on-storm and post-storm temperature-salinity profiles.



A manuscript entitled "***Upper-ocean response to Hurricane Gonzalo (2014): salinity effects revealed by sustained and targeted observations from underwater gliders***" by Ricardo Domingues, Gustavo Goni, Francis Bringas, Sang-Ki Lee, Hyun-Sook Kim, George Halliwell, Jili Dong, Julio Morell, and Luis Pomales was published in Geophysical Research Letters (Domingues et al., 2015).

The study presented a comprehensive assessment of the upper-ocean response to winds of Hurricane Gonzalo (2014) using sustained and targeted ocean observations sampled by one underwater glider during the 2014 hurricane season. The main finding this study is that salinity has potentially played an important role in modulating the upper-ocean response to Hurricane Gonzalo: a near-surface barrier layer (Figure 1a) linked with low salinity has potentially suppressed the wind-driven turbulent mixing cooling due to strong stratification. Conditions favorable for turbulent mixing were only marginally reached after the Hurricane Gonzalo travelled the closest from the location of the underwater glider. As a result, maximum surface cooling observed during Hurricane Gonzalo caused anomalies of -0.4°C (Figure 2), which is much smaller than the surface cooling reported during other Atlantic hurricanes.

Salinity effects were also identified as one of the main sources for discrepancies in ocean simulations by a coupled ocean-hurricane model used for hurricane intensity forecasts. Results reported by this study have important implications for hurricane research, and may potentially lead to improvements in ocean simulations on a coupled ocean-hurricane model used for hurricane forecasts.

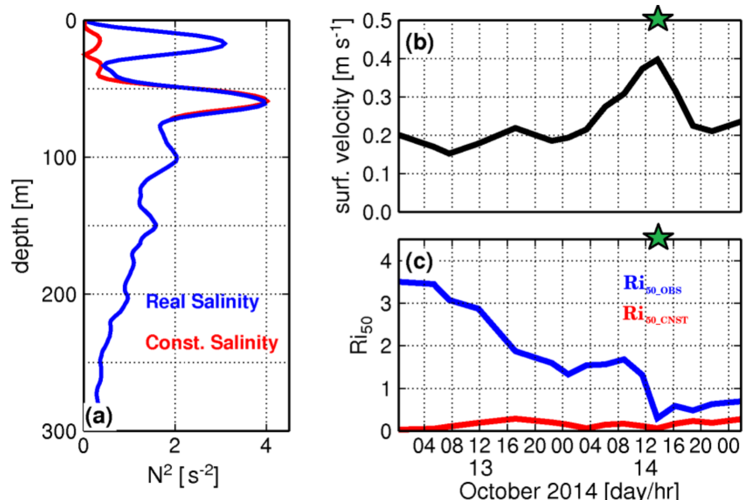


Figure 1. (a) Squared buoyancy frequency (N^2) profile based on initial glider observations at site B (blue line) and based on the real salinity profile but with constant salinity above 50m (red line). (b) Surface velocity magnitude at site B based on the surface drift of the glider. (c) Averaged Richardson Number above 50m (Ri_{50}) during the two-day record at site B computed using real glider observations (Ri_{50_OBS}) and real observations but with constant salinity above 50m (Ri_{50_CNST}).

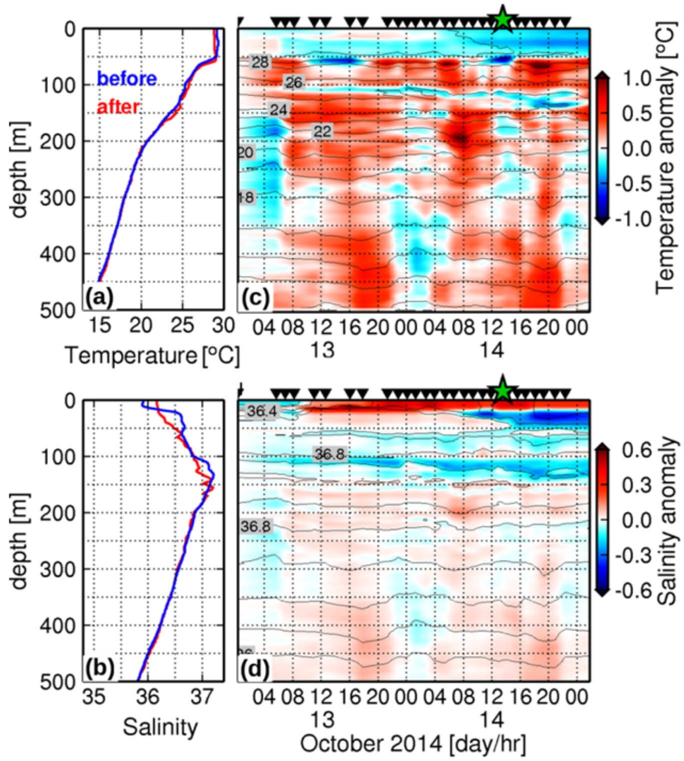


Figure 2. (a) Pre-storm (blue line) and post-storm (red line) temperature profiles at site B. (b) same as Figure 2a, but for salinity. (c) Depth-time diagram of temperature anomalies during the two-day record at site B. (d) same as Figure 2c, but for salinity.

(1.2) ***Impact of assimilating upper ocean observations on hurricane intensity forecasts***
This project aims to investigate the impact of assimilating ocean observations, especially those from underwater gliders, on hurricane forecast using a high resolution coupled atmospheric-ocean numerical model system. In this project, we first set out to examine whether the ocean conditions are able to affect hurricane intensity and track forecasts. Then temperature and salinity data extracted from real underwater gliders, along with other conventional ocean observations, are assimilated into the ocean model to drive the coupled forecast for a particular hurricane. The impact of assimilating temperature and salinity profiles from underwater gliders on the hurricane's forecast is examined. Finally, to investigate the potential impact of a future glider network, simulated glider observations are assimilated within the framework of Observing System Simulation Experiments (OSSE). A "picket fence" of 6 gliders along the storm's path is created and assimilated in OSSE. The impact of these simulated observations is also evaluated.

Impact of ocean initial conditions on Hurricane Gonzalo's forecast
Hurricane Gonzalo (2014) is simulated with a high resolution Hurricane Weather and Research Forecast (HWRF)-Hybrid Coordinate ocean model (HYCOM) coupled forecast system. The multi-nesting atmospheric HWRF model has a horizontal resolution of 27-9-3 km and 61 vertical sigma levels, with the two inner domains moving with the storm. Physical parameterization schemes include RRTMG long- and short-wave radiation, HWRF-specified surface layer parameterization, modified GFS planetary boundary layer (PBL) parameterization, Ferrier microphysics scheme and SAS cumulus scheme for two outer domains. The HYCOM ocean model has a 1/12° resolution and 32 hybrid vertical levels. The ocean mixing layer is parameterized with K-profile parameterization (KPP) scheme. The HWRF model sends wind stress, long- and short-wave radiation, precipitation, surface pressure to HYCOM, the ocean model, while the HYCOM model sends sea surface temperature (SST) back to HWRF as an exchange.

The HWRF model is initialized from the GFS analysis at 1800 UTC, October 12, 2014. The ocean is initialized from the Real-Time Ocean Forecast System (RTOFS) forecast of EMC in the control experiment. Another two different ocean initial conditions from the same time and date but different years (2012 and 2013) are also used to drive the forecast as sensitivity experiments to examine the impact of ocean conditions on Gonzalo's forecasts. The three experiments are denoted as RTOFS2014, RTOFS2013 and RTOFS2012 according to the ocean ICs they are initialized.

The control experiment or RTOFS2014 is first verified with the best track. The predicted track forecast of RTOFS2014 follows closely to the best track in general during the 126 hours forecast, with southward bias from 24-60 hours and a faster moving speed during the last 24 hours (Figure 3). The simulation predicts the intensification of Gonzalo generally well in terms of minimum sea level pressure (Figure 3). The predicted maximum wind is weak compared to the best track estimate (Figure 3). When compared against the underwater glider observations, the pre-storm ocean from the model simulation has a shallower mixed layer, a cold bias above 60 m and a warm bias from 60-110 m (not shown). SST and ocean heat content (OHC) from the model and the observation are almost identical. The simulated pre-storm upper level ocean water is saltier than the observation. After the storm passed, the simulated mixed layer depth is close to the glider observation with SST 0.3^{o}C cooler than observed.

The experiments using different ocean initial conditions show little sensitivity in the track forecast with the predicted TC paths similar to each other (Figure 3). The impact on intensity forecasts is much larger. The vortex in RTOFS2012 intensifies earlier and is stronger than the other two experiments from 24-96 forecast hours (Figure 3). RTOFS2013 predicts the weakest storm with a minimum sea level pressure barely reaching to 955 hPa. The intensity forecasts from these experiments are consistent with the initial ocean SST and OHC (Figures 4 and 5). In the first 48 hours, RTOFS2012 has the highest OHC and the second highest SST along the storm path (Figure 4 and 5), leading an earlier intensification and a stronger storm. From 48 to 96 hours, SST and OHC of RTOFS2013 are always lower than the other two, suggesting a larger SST cooling effect and a much weaker storm predicted (Figures 4 and 5).

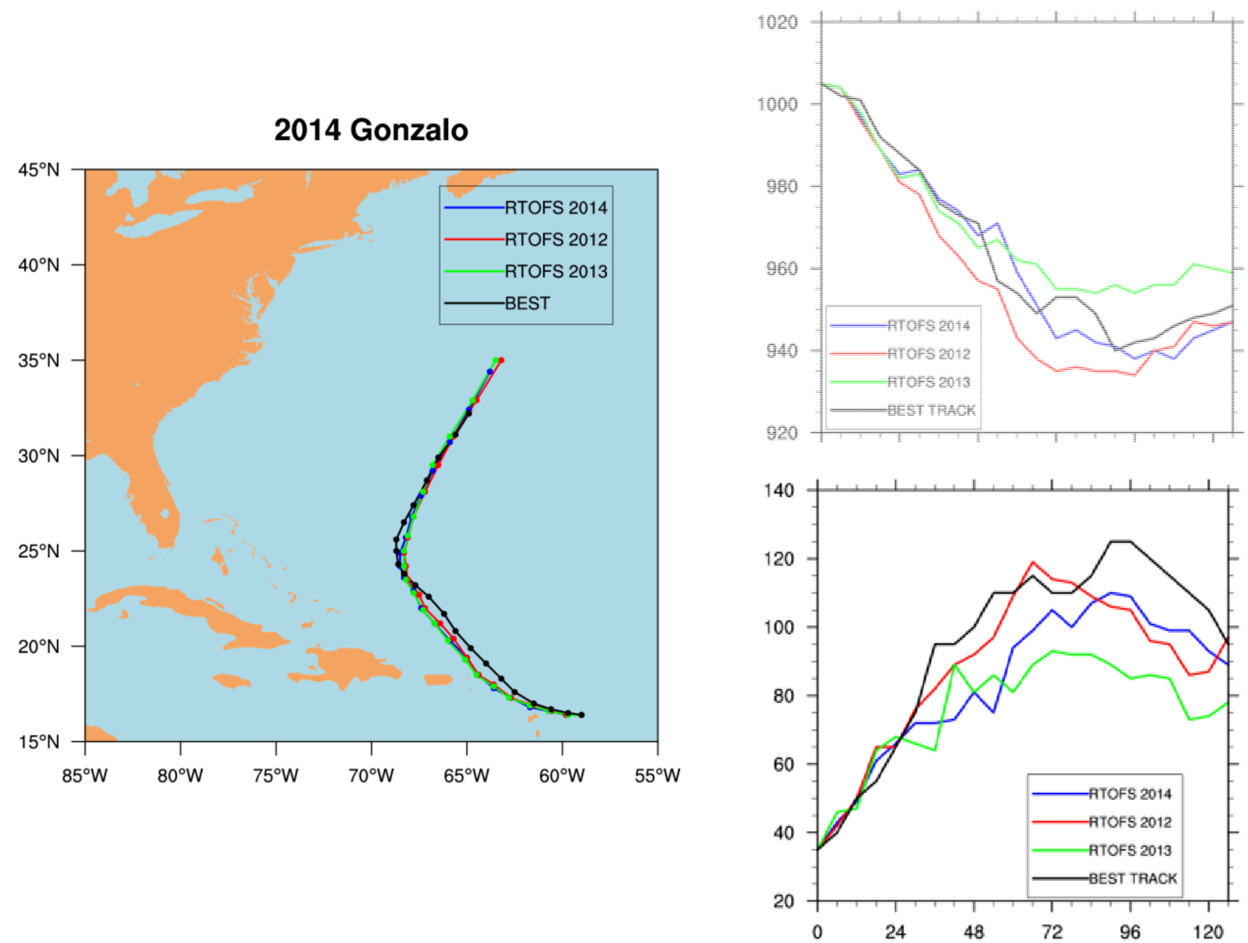


Figure 3. Left panel: Hurricane Gonzalo's track forecasts from three experiments, starting from 1800 UTC Oct. 12 2014 and plotted every 6 hours, along with the best track. Right upper panel: predicted Gonzalo's minimum sea level pressures (hPa) with time, along with the best track; right lower panel: predicted Gonzalo's maximum winds (kts) with time, along with the best track.

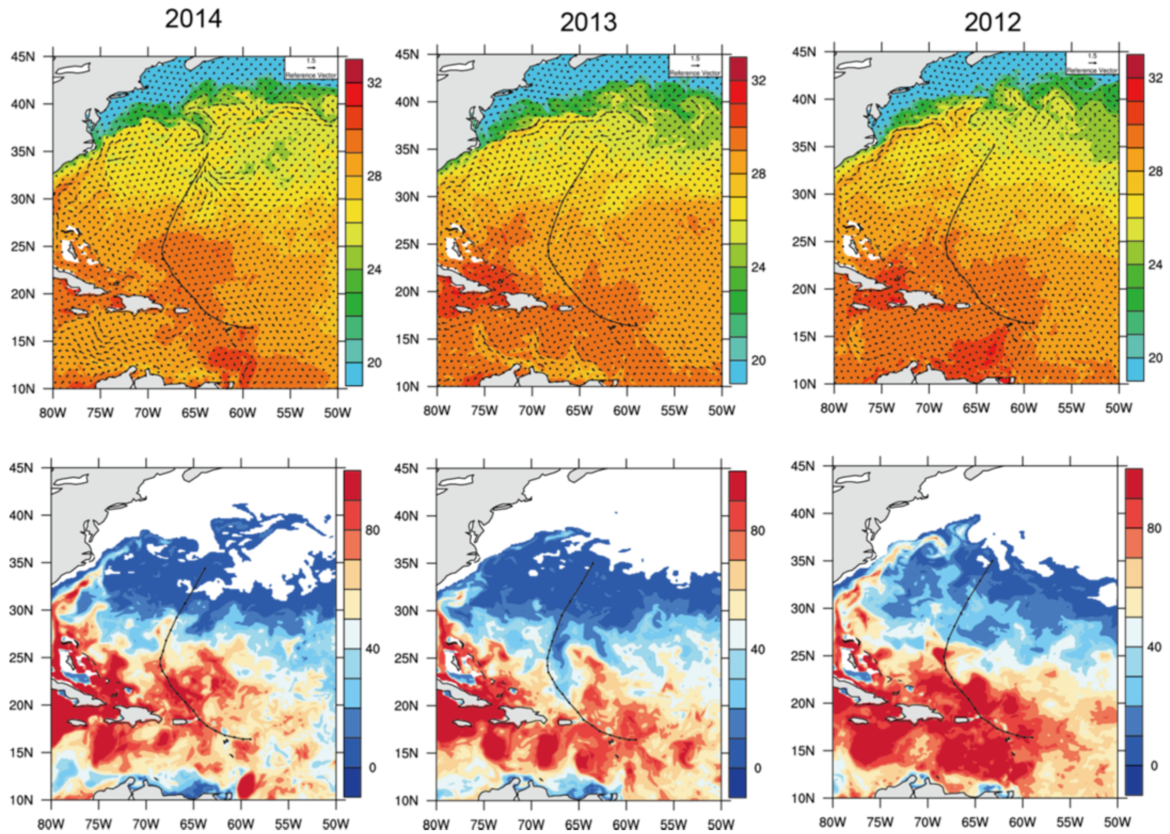


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Figure 4. Upper panel: Initial SST from three experiments; Lower panel: Initial OHC from three experiments.

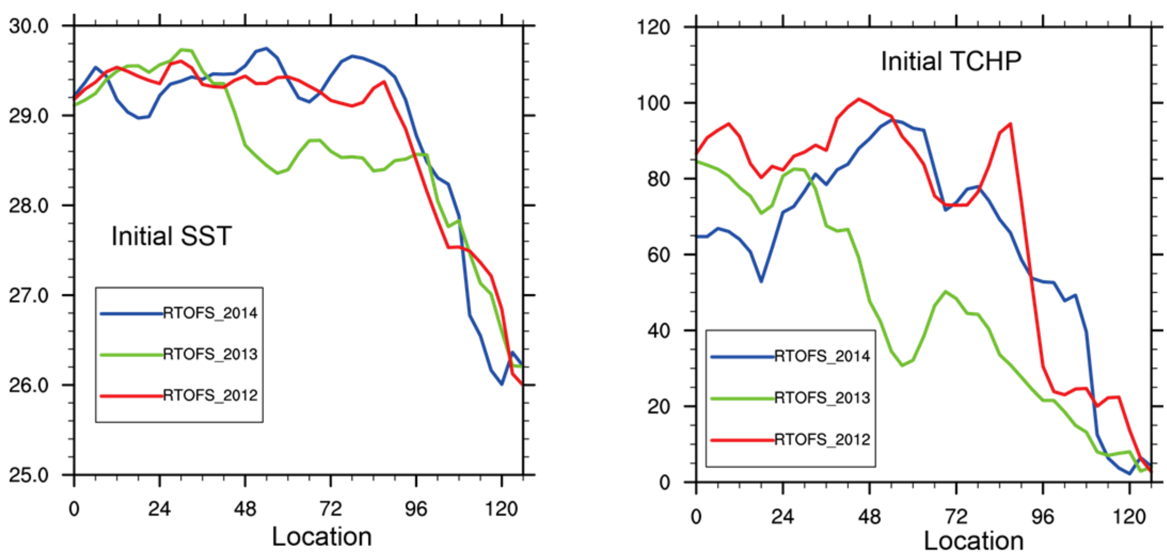

Figure 5. Initial SST (left) and OHC (right) of three experiments along the predicted storm track, averaged over a circle along the storm path with a radius of 86 km (~ twice of Gonzalo's radius of maximum wind).

Impact of real underwater glider ocean observations on Hurricane Gonzalo's forecast

The ocean initial conditions are from the forecast-data assimilation system maintained by Atlantic Oceanographic and Meteorological Laboratory/Physical Oceanography Division (AOML/PHOD). The ocean data assimilation system used in this study is the Tendral Statistical Interpolation System (T-SIS). T-SIS essentially uses a statistical interpolation method and users can specify forecast/background error covariance flexibly. In this study, an ensemble of model states sampled at different times are used to represent the forecast error covariance. More detailed introduction of T-SIS can be found in Halliwell et al. (2014).

The ocean observations assimilated include along-track measurements of sea surface height anomaly (SSHA) from three satellite altimeters (Jason-1, Jason-2 and Environmental Satellite), sea surface temperature (SST) from the satellite-derived multichannel SST (MCSST) product, in-situ measurements collected by ship and surface buoys and surface drifters, temperature profiles from expendable bathythermograph (XBT) collected both from ships and airborne (AXBT), airborne conductivity temperature depth probe (AXCTD), airborne current profiles (AXCP). The observation errors for each of the above types are the same as in Halliwell et al. (2014). All of the above observations are denoted as conventional observations, as compared to underwater gliders. The localization or cutoff radii for each type are also consistent with Table 3 of Halliwell et al. (2014). The conventional observations are assimilated daily from 00 UTC March 15 of 2014 throughout 00 UTC October 13 2014. The T/S data from two underwater gliders were assimilated from 00 UTC July 15 to 00 UTC October 13 2014. Only the glider T/S data collected close to 00 UTC of each day were assimilated. All the ocean data assimilation is performed with the ocean forecast only.

An ocean forecast from 2009 to 2014 without any observation assimilated is denoted as NODA as the benchmark experiment. Three data assimilation experiments were designed to examine the impact of assimilating underwater glider T/S data and conventional observations, denoted as GLID, CTRL and ALL (
Table).

After the initialization of both atmospheric and ocean models, the 126 hours coupled forecast started from 00 UTC October 13 to 06 UTC October 18, covering most of the life cycle of Gonzalo as a hurricane.

The pre-storm ocean profile has a mixed layer with around 55 m depth and an SST of 29°C (Figure 6a). The temperature profile of NODA has a shallow mixed layer of 10 m deep and shows negative bias across the upper 150m depth of the ocean. SST is 0.2°C colder than observed. There is a local maxima bias of -1.5°C at the observed mixed layer base of 55 m (Figure 6a). The negative bias continues to increase from 65 m to deeper ocean and reach beyond -1.5°C down from 100 m. The assimilation of glider observations in GLID improves the thermal structure by reducing the bias throughout most of the upper 150 m depth (Figure 6a). The SST of GLID is warmer than observed by 0.3°C. Similar local maximum is found at the MLD base with a smaller value of -0.9°C than NODA. The bias is always below 0.4°C between 60 to 120 m and increased to 1°C down to 150 m. The temperature profile of CTRL is similar to GLID above the MLD base but has bias always higher than 0.5°C from 60 m to 150 m, which suggests the assimilation of conventional observations also improves the pre-storm thermal structure of this region but not as much as assimilating the glider observation. The assimilation of additional glider observation data based on conventional observations further improves the initial thermal structure: the mixed layer depth of ALL is around 30 m, deeper than CTRL but still 25 m shallower than observed (Figure 6a). The bias is further reduced over most of the upper 150 m depth compared to CTRL. There is 0.3°C degradation at 55 m of ALL over CTRL, which is possibly caused by inaccurate background/forecast error covariance.

The observed subsurface salinity quickly increases from the surface to a local maximum at 20 m (Figure 6b). NODA underestimates the salinity with negative bias over 0.5 from 20 m down to 150 m depth. The assimilation of glider T/S data in either GLID or ALL limits the negative bias down to 0.2 (Figure 6b). The conventional observations also help to reduce the error but not as much as the assimilation of glider observation. The salinity of ALL is very close to the observation from 20 to 105 m with near-zero errors (Figure 6b).

The impact of assimilating underwater glider observations is not only limited to the exact location of the observations. The error covariance and local radii combined together determine how far the observation's impact will reach during the assimilation. The following forecast cycles will spread the impact of data assimilation even further. The initial large scale ocean environment around Gonzalo's path is plotted to briefly examine how far and how large the impact is. SST and TCHP in the vicinity of Gonzalo's future path are particularly focused.

Figure 7 shows initial SSTs of three experiments at 00 UTC October 13 2014 overlapped with each individual storm's 126 hours predicted tracks. Along with them is the Remote Sensing Systems (RSS) SST retrieved from satellite microwave and IR products and optimally interpolated (OI) at 9 km resolution, overlapped with the best track. In the pre-storm ocean, a large body of warm water region with SST over 28.5°C dominated the Carribean sea and southern branch of the North Atlantic subtropical gyre. This warm water region is known as Atlantic warm pool and closely correlated with Atlantic hurricane activity (Wang and Lee 2007). Gonzalo crossed over the warm pool regions with SST above 29°C before and around the recurvature, coinciding with the rapid intensification of Gonzalo. When there is no observations assimilated, the warm pool of NODA is weaker and smaller compared to the satellite retrieved SST. Around and along the storm track, SST never exceeds 29°C (Figure 7). The assimilation of glider observation enhances the warm pool around glider's location and over the storm path. With conventional observations assimilated in CTRL, the warm pool structure is much better retrieved in a much larger area: the warm pool structure of the environment and along the storm path is close to the SST observations in terms of both strength and location (Figure 7). The additional assimilation of glider data in ALL has little further impact (not shown) given the limited space for further improvement of CTRL.

During the 126 hours forecast, the predicted track is close to the best track and shows little sensitivity to different ocean initial conditions. On the other hand, the assimilation of conventional ocean observations significantly improves Gonzalo's intensity forecasts (Figure 8) by reducing the averaged absolute error of minimum sea level pressure and maximum surface wind 47% and 46% respectively. The predicted storms initialized from ocean conditions with conventional ocean observations assimilated (CTRL) are category 3 and closer to the best track, compared to a category 2 storm predicted in NODA. The assimilation of underwater glider observations shows marginal impact (Figure 8). The improvement on Gonzalo 's intensity forecast is partly from a stronger surface enthalpy heat flux induced by the warmer upper ocean condition, especially after 36 hours (Figure 9).

Experiment	Obs assimilated/Remark
NODA	No obs
GLID	Two underwater gliders
CTRL	Conventional ocean obs (Jason altimeter, MCSST, AXBT, AXCTD etc.)
ALL	Gliders+conventional ocean obs

Table 1. Experiment assimilating different ocean observations.

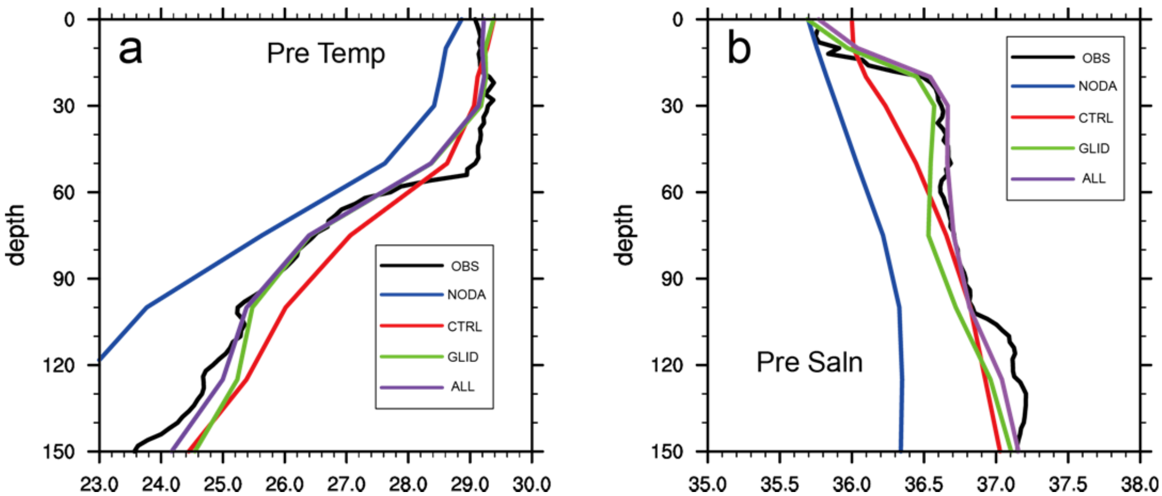

Figure 6. (a) Temperature and (b) salinity profiles at 00 UTC October 13 2014 from four experiments, compared to the glider observation.

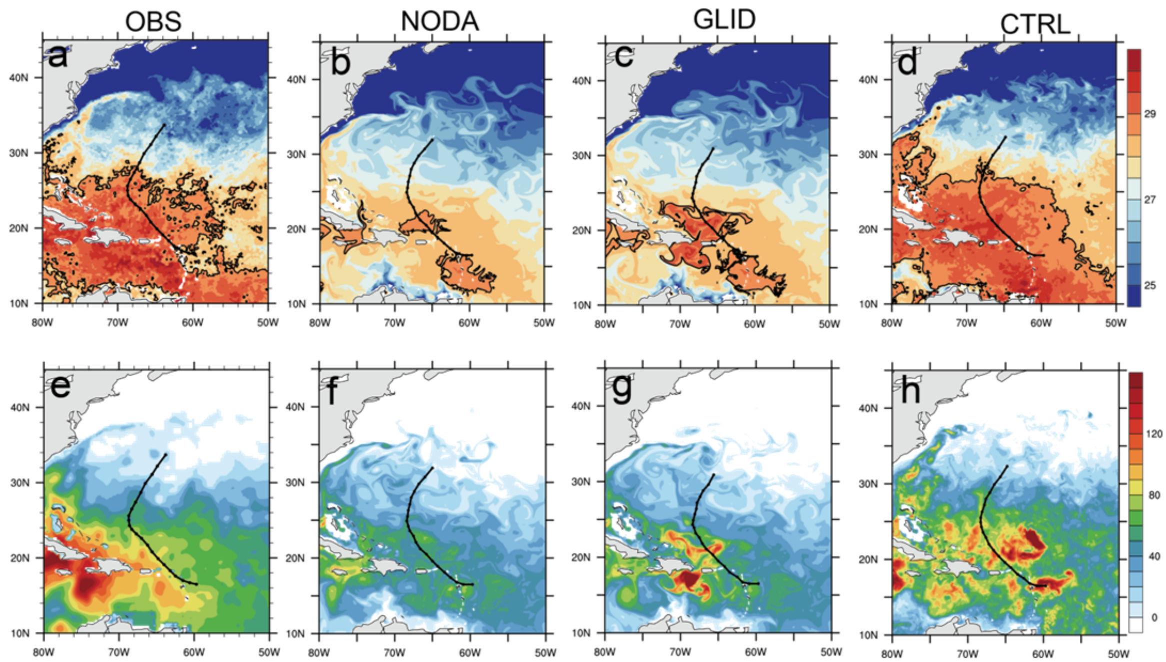

Figure 7. SST (upper panel) and TCHP (lower panel) of NODA (b and f), GLID (c and g) and CTRL (d and h), along with the observation (a and e) at 0000 UTC October 13, overlapped with the best track (a and e) or the predicted track of each individual experiment (b-d, f-h). 28.5°C isotherms are highlighted in SST plots to denote north Atlantic warm pool (see section 4.2).

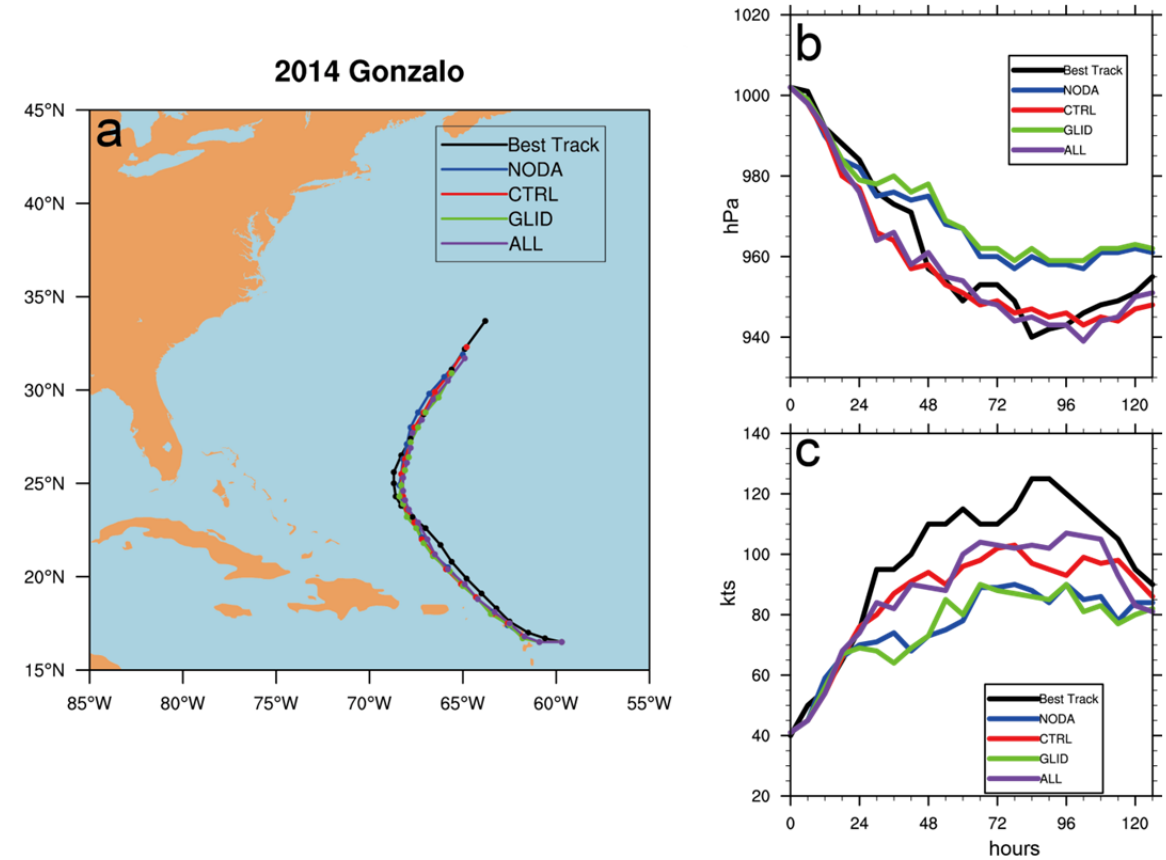

Figure 8. Hurricane Gonzalo's track forecast (a), minimum sea level pressure (center pressure) (b) and maximum wind forecasts (c), along with the best track.

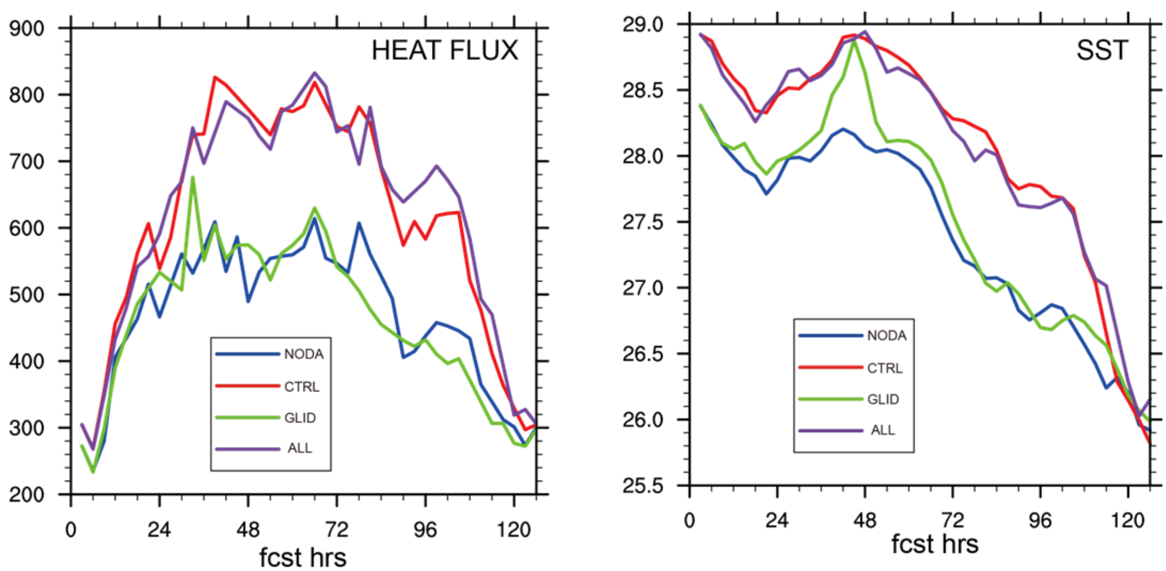

Figure 9. Evolution of in-storm surface enthalpy flux and SST (moving with storms).

Impact of simulated underwater glider ocean observations on Hurricane Gonzalo's forecast in OSSE framework

OSSE experiments is designed to evaluate the potential impact of "new observing systems and alternate deployments of existing systems, and to optimize observing strategies" (Hoffman and Atlas, 2016). This part of the project investigates a possible deployment strategy by adding more underwater gliders along the hurricane's track and assesses the impact of assimilating these simulated observations in the framework of ocean OSSE. A nature ocean run (NR) is first created to simulate the true ocean and another run denoted NODA is performed to mimic the trajectory of current forecast ocean model without any observations assimilated. These two ocean model simulation is carefully calibrated to make their climatological difference realistic to the difference between the real observation and the current forecast model. The major differences between these two model realizations include physical parameterizations and vertical resolutions. The philosophy of OSSE framework design is extensively described in Halliwell et al. (2014). The simulated observations used in OSSE are extracted from the nature run (NR) and are assimilated on the base of NODA. The ocean data assimilation and forecast cycles are summarized in Table 2 and denoted as CTRL, GLID6 and ALL respectively. In our OSSE study, the number of underwater gliders increases to six and arranged along the storm path as a picket fence pattern. Other deployment strategy with more underwater gliders (e.g. 18) and different distribution of these glider observations are under further investigation. After the ocean assimilation-forecast cycles ends, the ocean fields are used to drive the 126 hours coupled forecast for Hurricane Gonzalo, starting from 0000 UTC October 13 2014.

SST and OHC from assimilating different or no ocean observations, along with the nature run, are plotted in Figures 10 and 11. A large warm pool dominates the Carribean sea and southwest part of Atlantic subtropical gyre in the nature run, which is the "true" ocean in the OSSE framework. Along the storm path, SST is always above 28.5°C and reaches to 29 °C between 36-66 hours into the forecast. The warm pool area in NODA is much smaller and weaker with reduced SST along Gonzalo's track. The assimilation of 6 gliders helps to increase warm pool's coverage extending more to the east but not to the north. As a result, SST and OHC along the storm track changes little in GLID6. The assimilation of conventional ocean observations greatly improves the representation of warm pool in the ocean initial condition of CTRL. The coverage of warm pool of CTRL is much closer to the nature run. The SST and OHC patterns of CTRL are also similar to NR. The additional assimilation of 6 underwater gliders in ALL doesn't show further benefit to CTRL with both SST and OHC similar to CTRL.

The track forecasts of Gonzalo are not largely affected by the assimilation of ocean observations (not shown). Center surface pressures and surface maximum winds are plotted in Figure 12. The simulated storm of NR or truth reaches to 946 hPa and 100 knots at 78 hour forecast. NODA fails to simulate the strong vortex as NR and only predict a storm of 956 hPa and 87 knots. The assimilation of 6 underwater gliders shows almost no improvement over CTRL. There is even slight degradation in some forecast hours. When conventional ocean observations are assimilated in CTRL, the better retrieval of ocean features, such as the warm pool, improve the forecast solidly. CTRL predicts the storm intensity as almost exactly the same as the nature run. After 84-120 hours, the intensity of CTRL is stronger than the nature run. The additional assimilation of 6 underwater gliders in ALL weakens the storm during 72-96 hours in terms of center surface pressure or during 60-84 hours in terms of maximum surface winds. After 102 hours, the weaker intensity forecast of ALL than CTRL is actually closer to the "truth".

Experiments	Obs assimilated/Remark
NODA	No obs
GLID6	Six underwater gliders
CTRL	Conventional ocean obs (Jason altimeter, MCSST, AXBT, AXCTD etc.)
ALL	Gliders+conventional ocean obs

Table 2. Experiment assimilating different ocean observations in the OSSE framework.

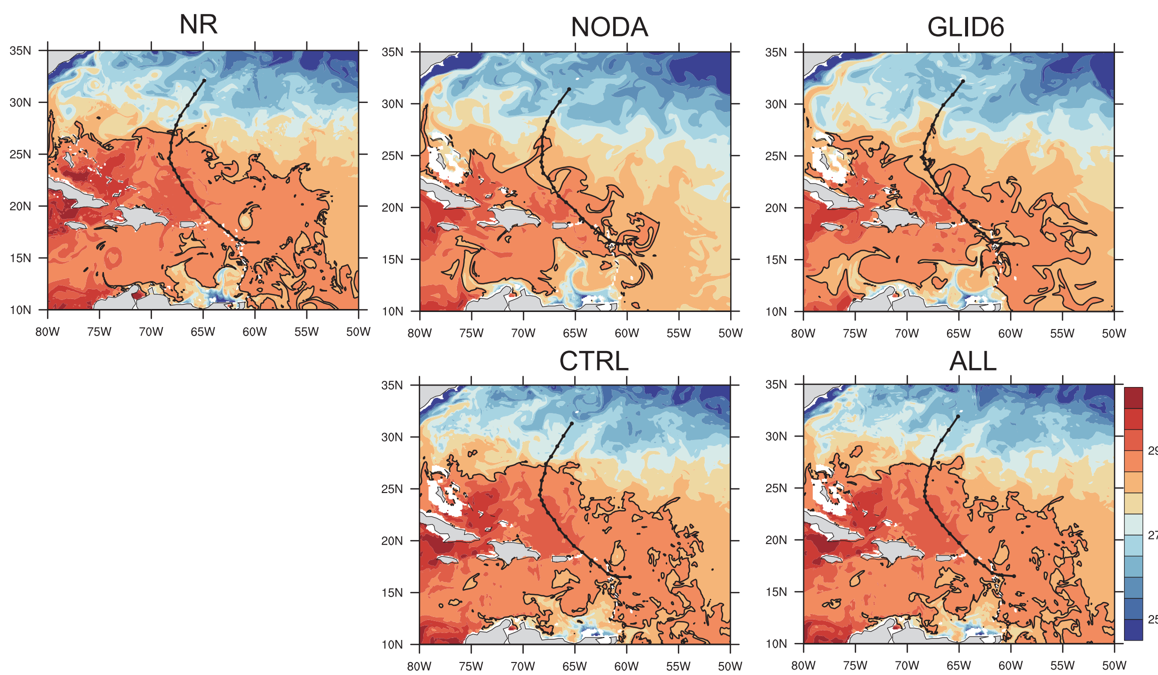

Figure 10. SST of NR (nature run), NODA, GLID6, CTRL and ALL at 0000 UTC October 13, overlapped with the predicted track of each individual experiment. 28.5 ^{0}C isotherms are highlighted in SST plots to denote north Atlantic warm pool.

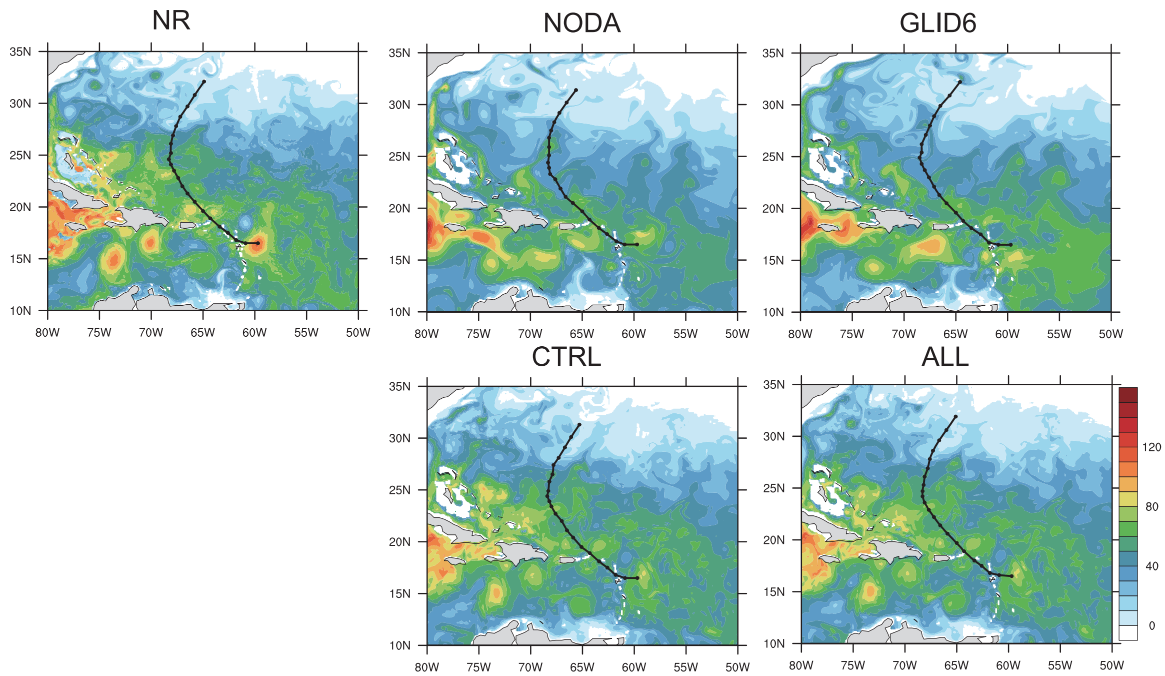

Figure 11. TCHP of NR (nature run), NODA, GLID6, CTRL and ALL at 0000 UTC October 13, overlapped with the predicted track of each individual experiment.

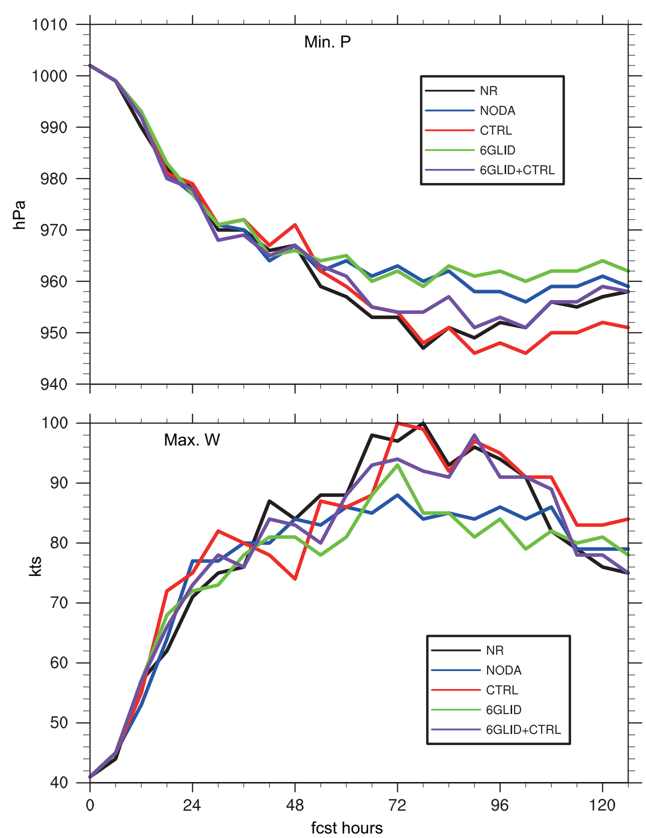

Figure 12. Hurricane Gonzalo's minimum sea level pressure (center pressure) (upper panel) and maximum wind forecasts (lower panel).

Task-3: The Impact of Emerging Observing Technologies on Future Predictions of Hurricane Structure and Intensity Change; Lead PI: Dr. Joseph Cione, NOAA/AOML

The primary objective of this project is to evaluate and assess the benefits of using new and emerging technologies consisting of aircraft-deployed low altitude unmanned aircraft systems (UAS) and Doppler wind lidar (DWL) profiling systems to better predict tropical cyclone intensity change through evaluation of and improvements to the physical routines used within NOAA's operational Hurricane Weather Research Forecast (HWRF) model based on these novel observations. Currently, detailed analyses of temperature, moisture and wind below 500m are very limited due to the fact that the primary source of data in this region of the storm is from point-source GPS dropsonde measurements. Improvements to observing this area is critical since it's where energy is exchanged with the ocean and where the winds directly impact lives and property. Moreover, recent analyses from modeling and observational studies have shown a strong sensitivity to initial conditions, especially for atmospheric moisture at low levels within the storm environment. In order to address this critical data void, this project will test and evaluate UAS and DWL emerging technologies to assess how observations from each platform may complement and enhance existing data coverage within the tropical cyclone boundary layer and ultimately lead to improved forecasts of intensity change.

This funded effort will extend and leverage existing OAR and Hurricane Forecast Improvement Project (HFIP) sponsored observing programs to evaluate novel technologies, instruments and observing platforms that provide improved kinematic and thermodynamic observations within the atmospheric boundary layer of tropical cyclones. Focus will be directed toward collecting data capable of evaluating and improving tropical cyclone predictions through better defining of the initial atmosphere and ocean, removal of model biases, and improved atmospheric physics characterization and parameterization. The primary scientific objectives to achieve them are listed below:

- Significantly Enhance Atmosphere/Ocean Boundary Layer Observations
- Evaluate HWRF and POM Hurricane Structure
- Improve HWRF and POM Model Physics (Part I)
- Improve HWRF and POM Model Physics (Part II)
- Establish an 'Optimal Mix' for Hurricane Boundary Layer Observations

(1) Project Summary

- Eric Uhlhorn and Joe Cione traveled to Mississippi to secure pre-season deployment of AXBTs to St Croix, in partnership with the 53rd Air Force Reserve Unit (Biloxi, MS). Travel was supported using project SS funds.

- In mid May 2014, funds were allocated to purchase 5 Coyote UAS with integrated metoc payload. These UAS are currently under construction by Sensintel and Itri Corp.

- Funds were allocated to purchase GPS sondes in support of the SS project. A portion of these resources was used to buy sensors and related equipment to modify 250 units replete with IR sensors to enable measurement of SST.

- Co-PI, Jun Zhang participated the Doppler wind Lidar (DWL) ground test and operational training at the Aircraft Operational Center (AOC) in Tampa. After it was fully tested in early August 2014, the DWL was installed on the P3 (N42) aircraft and evaluated against dropsonde data in missions into hurricanes. These results were presented at the 32nd Conference on Hurricanes and Tropical Meteorology. The DWL wind data will be used to evaluate the model physics of the HWRF model. These data can also be assimilated into HWRF for real-time hurricane forecasts.

- For the first time, the DWL on NOAA P3 aircraft has collected wind data in tropical cyclone conditions. DWL wind data were successfully collected in Hurricanes Danny and Erika in the 2015 hurricane season. The DWL wind data were quality-controlled and then were assimilated in the Hurricane Weather and Research Forecast (HWRF) model to study the impact of DWL winds on hurricane track and intensity forecasts. CIMAS scientist, Lisa Bucci, led this effort. Co-PI, Jun Zhang, led the analyses of the DWL data together with dropsonde and flight-level data to study the boundary layer structure and dynamics in TCs.

- Presented Coyote UAS Hurricane Edouard (2014) analyses at The Interdepartmental Hurricane Conference held in Jacksonville, FL (February 2015)

- Performed preliminary comparison of Coyote UAS pressure, wind temperature data collected in Hurricane Edouard with measuremtns collected by NOAA P-3 aircraft (GPS sondes and Tail Doppler Radar winds) (March 2015)

- PI Cione, Co-Is Uhlhorn and Jaimes began preliminary analysis of atmospheric and oceanic data collected in Hurricane Edouard during 11-19 September 2014. In addition to these observational analyses, preliminary comparisons were also made between the emerging technology data that was collected in Edouard (UAS, drifters) and NOAA operational model output (POM and HWRF). Initial findings from these analyses were presented at the Hurricane Forecast Improvement Project's annual meeting held in Miami (November 2014). A key finding from this work is that both the NOAA operational ocean model (POM) and atmospheric model (HWRF) appeared to exhibit evidence of possible physical biases. This work is preliminary but it is encouraging nonetheless. With additional work from EMC and other operational entities it is hoped that the biases identified as a direct result of this funded project will ultimate help improve the physical performance of the operational modeling system currently used by NOAA to forecast hurricanes.

2. Publications resulted from the three tasks:

Atlas, R., L. Bucci, B. Annane, R. Hoffman, and S. Murillo, 2015a: Observing system simulation experiments to assess the potential impact of new observing systems on hurricane forecasting. Marine Technology Society Journal, 49 (6), 140–148, doi:10.4031/MTSJ.49.6.3. Special issue, Evolution of Marine Technologies: Commemorating the 50th Anniversary of the MTS Journal, guest edited by Donna Kocak.

Atlas, R. and T. S. Pagano, 2014: Observing system simulation experiments to assess the potential impact of proposed satellite instruments on hurricane prediction. Imaging Spectrometry XIX, P. Mouroulis and T. S. Pagano, Eds., Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, Proceed. SPIE, Vol. 9222, 9 pp. doi:10.1117/12.2063648.

Atlas, R., V. Tallapragada, and S. Gopalakrishnan, 2015b: Advances in tropical cyclone intensity forecasts. Marine Technology Society Journal, 49 (6), 149–160, doi:10.4031/MTSJ.49.6.2. Special issue, Evolution of Marine Technologies: Commemorating the 50th Anniversary of the MTS Journal, guest edited by Donna Kocak.

Atlas, R., T. Vukicevic, L. Bucci, B. Annane, A. Aksoy, J. Delgado, X. Zhang, and S. Gopalakrishnan, 2014: Observing system simulation experiments to evaluate the impact of remotely sensed data on hurricane prediction. 31st Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, Boston, MA, San Diego, CA, available online at https://ams.confex.com/ams/31Hurr/webprogram/Paper243409.html, paper 7A.5.

Atlas, R., et al., 2015c: Observing system simulation experiments (OSSEs) to evaluate the potential impact of an optical autocovariance wind lidar (OAWL) on numerical weather prediction. J. Atmos. Oceanic Technol., 32 (9), 1593–1613, doi:10.1175/JTECH-D-15-0038.1.

Boukabara, S. A., R. Atlas, and R. N. Hoffman, 2016a: Observing system simulation experiments (OSSEs) to assess the potential impact of proposed observing systems on global NWP and hurricane prediction. 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorological Society, Boston, MA, New Orleans, LA, paper J5.2. Recorded presentation: Available online at https://ams.confex.com/ams/96Annual/webprogram/Paper290959.html.

Boukabara, S.-A., et al., 2016b: Community global observing system simulation experiment (OSSE) package :: Cgop. description and usage. J. Atmos. Oceanic Technol., 33, revised. doi:10.1175/JTECH-D-16-0012.1.2

Boukabara, S. A., et al., 2016c: Community global OSSE package (CGOP). 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorological Society, Boston, MA, New Orleans, LA, paper J7.2. Recorded presentation: Available online at https://ams.confex.com/ams/96Annual/webprogram/Paper283679.html.

Casey, S. P. F., L. P. Riishojgaard, M. Masutani, T. Zhu, J. S. Woollen, R. Atlas, Z. Li, and T. J. Schmit, 2014: Impact assessments of adding errors to simulated radiance data in observing system simulation experiments. Second Symposium on the Joint Center for Satellite Data Assimilation, American Meteorological Society, Boston, MA, Atlanta, GA, available online at https://ams.confex.com/ams/94Annual/webprogram/Paper241890.html.

Casey, S. P. F., et al., 2016: Geostationary hyperspectral infrared constellation: Global observing system simulation experiments for five Geo-HSS instruments. 20th Conference on Integrated

Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorological Society, Boston, MA, New Orleans, LA, paper J7.4. Recorded presentation: Available online at https://ams.confex.com/ams/96Annual/webprogram/Paper283540.html.

Cucurull, L., R. Li, S. P. F. Casey, T. Peevey, R. Atlas, R. N. Hoffman, and J. S. Woollen, 2016: Observing system simulation experiments with several combinations of radio occultation constellations. 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorological Society, Boston, MA, New Orleans, LA, paper J7.3. Recorded presentation: Available online at https://ams.confex.com/ams/96Annual/webprogram/Paper286702.html.

Domingues, R., G. Goni, F. Bringas, S.-K. Lee, H.-S. Kim, G. Halliwell, J. Dong, J. Morell and L. Pomales, 2015: Upper-ocean response to Hurricane Gonzalo (2014): salinity effects revealed by sustained and targeted observations from underwater gliders. Geophys. Res. Lett., 42, 7131-7138, doi:10.1002/2015GL065378.

Hoffman, R. N., 2015: Evolving topics in data assimilation. Eugenia Kalnay Symposium, American Meteorological Society, Boston, MA, Phoenix, AZ, paper 2.1. Recorded presentation, manuscript, and handout: Available online at https://ams.confex.com/ams/95Annual/webprogram/Paper267956.html.

Hoffman, R. N. and R. Atlas, 2016a: Future advances in observing system simulation experiments. 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorological Society, Boston, MA, New Orleans, LA, paper 1.2. Recorded presentation: Available online at https://ams.confex.com/ams/96Annual/webprogram/Paper286098.html.

Hoffman, R. N. and R. Atlas, 2016b: Future observing system simulation experiments. Bull. Amer. Meteor. Soc., 97 (9), in press. doi:10.1175/BAMS-D-15-00200.1.

Jones, T. A., S. Koch, and Z. Li, 2015: Assimilating synthetic hyperspectral sounder temperature and humidity retrievals to improve severe weather forecasts. Tellus A, submitted.

Lee, P., et al., 2016: Observing system simulation experiments (OSSEs) using a regional air quality application for evaluation. Air Pollution Modeling and its Application XXIV, 599–605, Springer Proceedings in Complexity, doi:10.1007/978-3-319-24478-5 97.

Li, J., Z. Li, T. J. Schmit, F. Zhu, P. Wang, A. Lim, R. Atlas, and R. Hoffman, 2015a: Value-added impact from future geostationary hyperspectral infrared sounder observations on hurricane forecasts. 2015 Fall Meeting, American Geophysical Union, San Francisco, CA, session A33P: Improving Clouds and Water Vapor Simulations in Climate Models and Observing System Simulation Experiments I.

Li, Wang, Han, Li, and Zheng] Li, J., P. Wang, H. Han, J. Li, and J. Zheng, 2016a: On the assimilation of satellite sounder data in cloudy skies in the numerical weather prediction models. J. Meteor. Res., 30, in press. doi:10.1007/s13351-016-5114-2.

Li, Z., J. Li, T. J. Schmit, P. Wang, A. Lim, R. Atlas, and R. N. Hoffman, 2015b: Geostationary advanced infrared sounder radiance simulation and validation for Sandy Supplemental OSSE. 19th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorological Society, Boston, MA, Phoenix, AZ, paper 2.4. Recorded presentation: Available online at https://ams.confex.com/ams/95Annual/webprogram/Paper266492.html.

Li, Z., T. Schmit, and J. Li, 2014: Simulate Geo AIRS radiance from T1279 NR sample. Tech. rep., CIMSS.

Li, Z., et al., 2016b: A quick regional OSSE impact study on geostationary hyperspectral infrared sounder for hurricane forecasts. 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorological Society, Boston, MA, New Orleans, LA, paper J6.5. Recorded presentation: Available online at https://ams.confex.com/ams/96Annual/webprogram/Paper287367.html.

Masutani, M., J. S. Woollen, L. P. Riishojgaard, S. P. F. Casey, Z. Ma, T. Zhu, and L. Cucurull, 2014: Observation system simulation experiment. Donald R. Johnson Symposium, American Meteorological Society, Boston, MA, Atlanta, GA, poster 882. Available online at https://ams.confex.com/ams/94Annual/webprogram/Paper240199.html.4

Masutani, M., et al., 2015: Building OSSE system at JCSDA. 20th Conference on Satellite Meteorology and Oceanography, American Meteorological Society, Boston, MA, Phoenix, AZ, poster 142. Manuscript: Available online at https://ams.confex.com/ams/95Annual/webprogram/Paper269243.html.

McNoldy, B. D., B. Annane, J. Delgado, L. Bucci, R. Atlas, S. J. Majumdar, M. Leidner, and R. N. Hoffman, 2016: Impact of CYGNSS data on tropical cyclone analyses and forecasts in a regional OSSE framework. 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), American Meteorol gical Society, Boston, MA, New Orleans, LA, paper J6.6. Recorded presentation: Available online at https://ams.confex.com/ams/96Annual/webprogram/Paper285158.html.

Privé, N. C., Y. Xie, S. Koch, R. Atlas, S. J. Majumdar, and R. Hoffman, 2014: An observation system simulation experiment for the unmanned aircraft system data impact on tropical cyclone track forecasts. Mon. Wea. Rev., 142 (11), 4357–4363, doi:10.1175/mwr-d-14-00197.1.

Pu,Z., L. Zhang, S. Zhang, B. Gentry, D. Emmitt, B. Demoz, and R. Atlas, 2016: The impact of Doppler wind lidar measurements on high-impact weather forecasting: Regional OSSE and data assimilation studies. Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications,Volume III, S. K. Park and L. Xu, Eds., Springer, in press.

Schmit, T., Z. Li, J. Li, F. Zhu, P. Wang, and A. Lim, 2014: CIMSS quick rOSSE preliminary results with EC nature run. Tech. rep., University of Wisconsin.

Wang, P., J. Li, J. Li, Z. Li, T. J. Schmit, and W. Bai, 2014: Advanced infrared sounder subpixel cloud detection with imagers and its impact on radiance assimilation in NWP. Geophys. Res. Lett., 41 (5), 1773–1780, doi:10.1002/2013gl059067.

Wang, P., et al., 2015: Assimilation of thermodynamic information from advanced infrared sounders under partially cloudy skies for regional NWP. J. Geophys. Res. Atmos., 120 (11), 5469–5484, doi:10.1002/2014JD022976.

Xie, Y., H. Wang, Z. Toth, and Y. Zhang, 2014: GSD 2013 UAS project report. Tech. rep., ESRL/OAR/NOAA, Boulder, CO.

4. Publciation Categories

Category	Number
Total count of publications for the reporting period	31
NOAA lead author	12
CIMAS lead author	5
Other CIs lead authors	12
Other lead authors	2
Peer-reviewed	14
non peer-reviewed (including presentations)	17

5. Employee Support (CIMAS only)

Category	Number	BS	MS	Ph.D
Total number of employees that receive at least 50% support from NOAA, postdocs and visiting scientists, by job title and terminal degree	7	0	3	4
Total number of undergraduate and graduate students receiving any level of support	0	0	0	0
Number of employees (including postdocs and visiting scientists) that received less than 50% annual salary support	11	5	2	4
Number of supported postdocs and students from subawards	1	0	0	1
Number of employees/students that receive 100% of their funding from an OAR laboratory and/or are located within that laboratory	64	N/A	N/A	N/A
Number of employees/students that were hired by NOAA within the last year	N/A	N/A	N/A	N/A