NEAR REAL TIME GLOBAL OPTIMUM INTERPOLATED MICROWAVE SSTS:

APPLICATIONS TO HURRICANE INTENSITY FORECASTING

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1. INTRODUCTION

Knowledge of the sea surface temperature (SST) is important for accurate intensity forecasting. On May 4, 2002, NASA launched the Earth Observing System (EOS) AQUA spacecraft which carries NASDA's Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E), the first polar orbiting microwave radiometer capable of measuring accurate global through-cloud sea surface temperatures (SST). Although microwave SSTs have a lower spatial resolution than the more traditional infrared SSTs, their thru-cloud SST capabilities significantly improve coverage. Global, daily, near real time SSTs at 25 km resolution were calculated using optimum interpolation (OI). The value of the AMSR-E OI SSTs was tested in the Statistical Hurricane Intensity Prediction Scheme (SHIPS) model run operationally by the National Hurricane Center. Overall, the weekly 100 km SSTs used operationally by NHC accurately represented ocean temperatures and substitution of the AMSR-E OI SSTs resulted in only slight forecast improvements (1.3% in the North Atlantic and 6.9% in the East Pacific). However, when oceanic features not resolved by the weekly analysis were present (such as cold wakes), the daily AMSR-E OI SSTs increased forecast accuracy considerably (12% to 60% for Hurricane Genevieve).

2. Background

While prediction of hurricane location (track forecasting) has continually improved in the last several decades, the prediction of storm strength (intensity forecasting) has improved at a much slower rate DeMaria *et al.* (2002); in fact, forecasts of intensity can still have large errors, especially for rapidly intensifying or decaying storms. The consequences of under or over predicting a storm's strength are momentous. On September 16, 1999, Hurricane Floyd hit the US coast, resulting in 57 deaths and estimated total damage of 3 to 6 billion dollars (Pasch *et al.,* 2000) . From September 13th onward, just as the storm was about to make landfall, NHC numerical models consistently underestimated the storm's magnitude. Conversely, during 2002, a rapid weakening of Hurricane Lili just before landfall was unpredicted by the NHC intensity models. Storm preparation is extremely expensive: depending on population density, evacuation of coastline is estimated 1-50 million dollars per mile (Whitehead, 2003). Over-estimates of wind speed can result in avoidable costs as unnecessarily large regions are evacuated or the Naval fleet sent to sea, but under-estimates can lead to avoidable property loss, injury, and death. Better knowledge of the location and strength of winds results in a more precise idea of whom and what will be impacted by the storm. There has been little improvement in intensity prediction in the last decade; therefore, improving intensity prediction has been increasingly prioritized.

Research has demonstrated that the three main controlling factors determining storm intensity are: initial strength, atmospheric structure (specifically vertical shear in the horizontal velocities can disrupt the eye wall), and ocean-atmosphere heat flux under the main core (Emanuel, 1999). Recent research has emphasized the importance of accounting for ocean thermodynamic structure in the prediction of hurricane intensity. For example, the determining factor in Hurricane Lili's rapid de-intensification in

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the Gulf of Mexico was found to be the oceanic heat content, air-sea fluxes in the regions with maximum winds (the Northeast storm quadrant), and entrainment of dry air (Shay *et al.*, 2004). Calculating both oceanic heat content and air-sea heat fluxes requires knowledge of the SST. Additionally, a correlation between changes in storm intensity and the inner core SSTs has been demonstrated (Cione and Uhlhorn, 2003). Since it is widely accepted that SST can be very important in intensity prediction, accurate SSTs are of interest for researchers and as inputs to models. Currently, the NHC utilizes the National Centers for Environmental Prediction (NCEP) optimum interpolated (OI) SSTs, also known as Reynolds SSTs (Reynolds and Smith, 1994).

The NCEP OI SST is a weekly, 100 km, global SST analysis. This product was developed to solve two problems: 1) drifts in the infrared SST retrievals due to aerosol variability and sensor calibration drift, and 2) fill in areas of missing observations due to cloud cover. To accomplish this, in situ SSTs from buoys and ships are used to anchor the infrared satellite SST retrievals and OI is used to construct a weekly map having no data gaps. This has proven to be one of the most successful SST products. However, the price paid for this uninterrupted global coverage is a substantial degradation in temporal and spatial resolution. Since the NCEP SSTs rely on infrared SST retrievals, coverage can be minimal during hurricanes as clouds prevent infrared SST retrieval; therefore, microwave SSTs often provide an exclusive measurement of SST during hurricanes.

3. MW OI SSTs

NASA's Aqua satellite, launched May 4 2002, carries NASDA's AMSR-E microwave radiometer. This is the first polar orbiting microwave radiometer capable of accurate global SSTs since the poorly calibrated Scanning Multi-channel Microwave Radiometer (SMMR) in 1987. The TRMM Microwave Imager (TMI), launched in 1997, had a 10.65 GHz channel capable of accurate SSTs down to 12 C, but was in an equatorial orbit that prevented high-latitude retrievals. Building on this heritage of microwave sensors, AMSR-E is orbiting at an altitude of 705 km, with a 1.6 m antenna that results in a swath width of 1450 km. AMSR-E's twelve channels are used to simultaneously retrieve SST, wind speed, columnar water vapor, cloud liquid water, and rain rate (Wentz and Meissner, 1999). These environmental variables are calculated using a multi-stage linear regression algorithm derived through comprehensive radiative transfer model simulations. SST retrieval is prevented only in regions with sun-glitter, rain, and near land. Since only a small number of retrievals are unsuccessful, almost complete global coverage is achieved

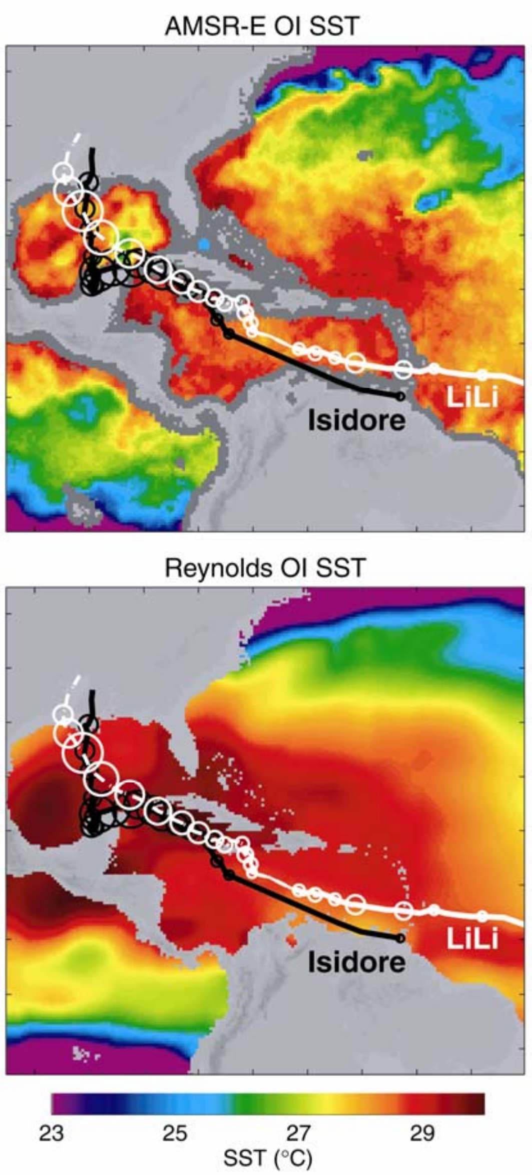

Fig. 1. AMSR-E and NCEP OI SSTs available on September 28, 2002. The AMSR-E OI SSTs show considerably more variability than the smoothed NCEP OI SSTs. The gray areas adjacent to land in the top panel represent areas where microwave SSTs are not retrieved due to side-lobe contamination. In this image, Hurricane Isidore had just passed over the northern Yucatan Peninsula and weakened. The strong winds generated a considerable cold wake seen in the AMSR-E OI SSTs. Hurricane Lili passed over this cold wake, but continued to intensify as it headed towards Louisiana, only weakening just before landfall. These were the two largest storms of the year and both were predicted with less skill than usual.

	Forecast Interval (hr)									
Year Region	**12**	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2002 East Pacific	1.2	3.2	4.5	4.8	5.5	7.4	10.5	11.7	11.4	8.5
2003 East Pacific	3.0	6.1	7.5	8.4		7.7		7.7		1.0
2002 Atlantic	0.3	0.5	-0.2	-1.1	-0.5	-0.2	0.2	0.7	0.8	1.1
2003 Atlantic	0.3	0.7	1.8	1.6		-2.0		-2.6		-1.4

Table 1. North Atlantic and East Pacific average percentage change in forecast errors, substituting AMSR-E for NCEP SSTs in SHIPS, during 2002 and 2003. A positive change indicates a decrease in forecast errors when AMSR-E SSTs were utilized instead of NCEP SSTs, and a negative value indicates an increase in forecast errors.

daily. These SSTs are then used to calculate a daily, 25km OI SST field in near real-time, a considerable improvement from weekly 100 km SSTs. This new high-resolution global SST analysis should find broad utility within the research and operational communities, as SST is one of the most important variables related to the global ocean-atmosphere system. It is a key indicator for climate change and is widely applied to studies of upper ocean processes, to air-sea heat exchange, and as a boundary condition for numerical weather prediction.

A unique feature of this new analysis is an improved handling of diurnal warming effects on the satellite SSTs. The sun synchronous satellite orbit yields retrievals at a local time of 1:30. During the daytime overpass, solar heating of the ocean surface can cause warming of 3 K (Price *et al.*, 1986). Currently, many researchers and OI SST schemes either ignore daytime retrievals or assign them a higher error than nighttime retrievals. The AMSR-E OI SSTs include both day and night SSTs. To optimally utilize daytime retrievals a simple empirical model of diurnal warming was developed: it depends only on solar insolation, wind speed, and local time of observation (*Gentemann et al.*, 2003). Solar insolation is calculated as a function of latitude and day of year while wind speed is simultaneously retrieved by AMSR-E. Using this model, SSTs are 'normalized' to a daily minimum SST, which occurs at approximately 8 AM. The Global Ocean Data Assimilation Experiment (GODAE) High-resolution SST pilot project (GHRSST-PP) has suggested that calculating a daily minimum temperature is likely the most useful 'bulk' temperature for both research and climate needs (Wick, 2003).

After correcting for diurnal effects and carefully screening rain contamination, daily, 25 km, global OI SSTs are calculated using five day, 100 km, isotropic, homogenous, stationary, decorrelation scales. The previous day's OI SST is used to calculate a difference field with all SSTs to be used in the interpolation. This increment field is multiplied by weights determined by the OI method (Gandin, 1963). OI is a widely utilized method in oceanography and meteorology that makes use of the statistical properties of irregularly spaced data to interpolate onto a regularly sampled (in time and space) grid. If no valid retrievals are present, the increment field is zero, and the value at that grid point will be equal to the previous day's value. When compared to the NCEP OI SSTs, the AMSR-E OI SSTs have a standard deviation of 0.67 C and mean bias of -0.01 C.

Further comparison of the NCEP and AMSR-E OI SSTs show that important temporal and spatial variability is not represented well by the low resolution NCEP data. An example of this is shown in Fig. 1, where both NCEP and AMSR-E SSTs are plotted on September 26, 2002. Hurricane Isidore had just passed through the Gulf of Mexico with Hurricane Lili following close behind. The NCEP OI SSTs do not show the cooling North of the Yucatan Peninsula seen in the AMSR-E OI SSTs. With Lili following closely, timely knowledge of the oceanic thermodynamic structure was needed for forecasts. In this case, the NCEP OI SSTs were unable to provide this information to the intensity models.

4. Hurricane Intensity Models

Three intensity models are utilized by the NHC for intensity prediction: the Statistical Hurricane Intensity FORecast (SHIFOR), SHIPS, and the Geophysical Fluid Dynamics Laboratory model (GFDL) (which predicts track and intensity). The SHIFOR is a simple statistical model, which uses climatological and persistence predictors to forecast intensity change (Jarvinen and Neumann, 1979). Since 1997, the GFDL model has generally been less skillful than SHIFOR and SHIPS (DeMaria and Gross, 2003). Therefore, we have focused on the SHIPS model, which uses climatological, persistence and synoptic predictors (DeMaria and Kaplan, 1994). Intensity is predicted using primarily: the difference between the maximum possible intensity (MPI) and current intensity, vertical shear in the atmosphere, persistence, and 200 hPa temperature within 1000 km of the storm center. MPI is estimated from an empirical relationship between SST and intensity.

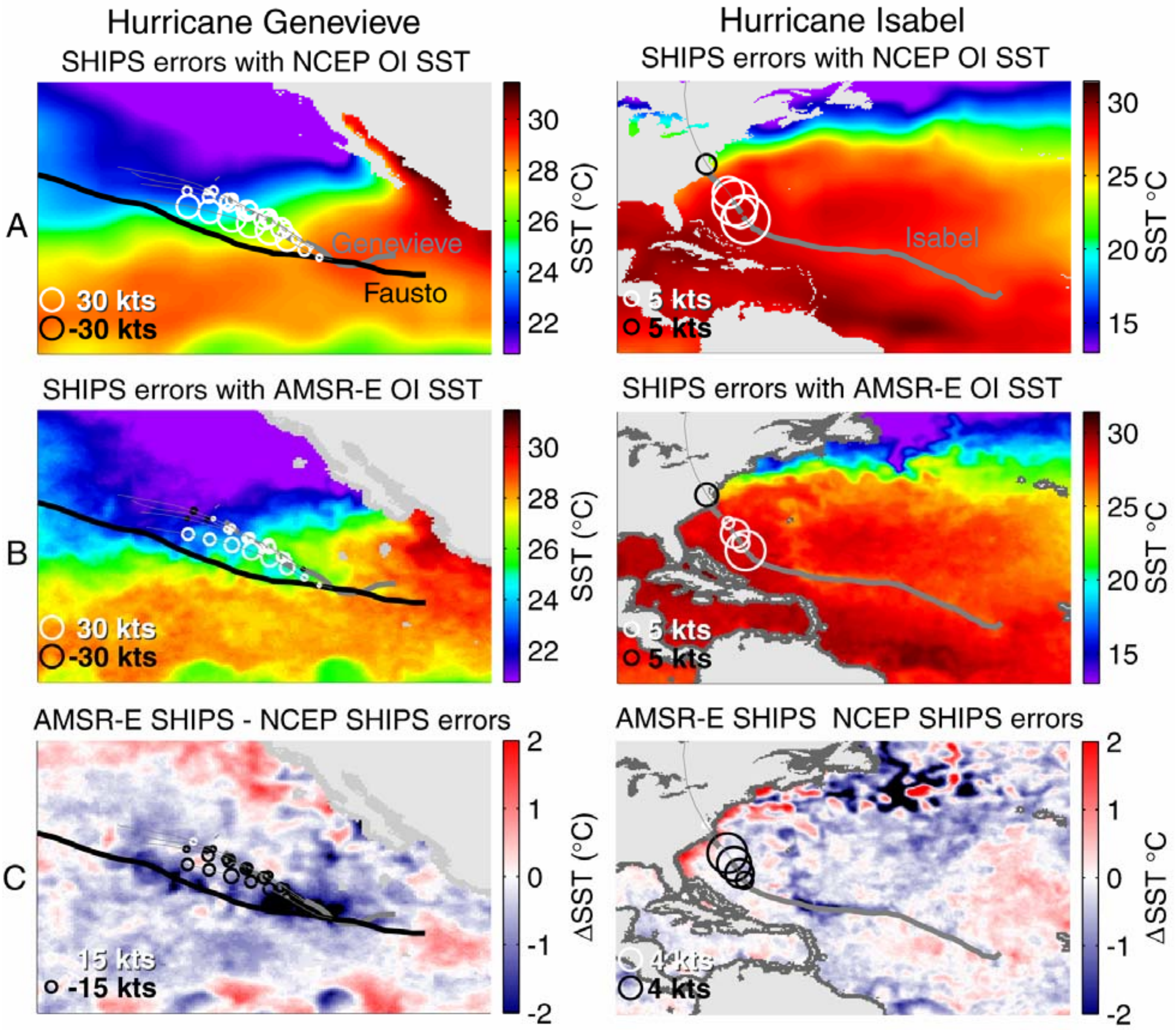

Fig. 2. Forecast errors for Hurricane Genevieve and Hurricane Isabel. The right column shows August 28, 2002 forecast intensity errors for Hurricane Genevieve while the left column shows errors for Hurricane Isabel on September 16, 2003. Errors are indicated by circle color (sign of error) and size (magnitude of error) for NCEP SHIPS (Row A), and AMSR-E SHIPS (Row B). Row C shows AMSR-E SHIPS minus NCEP SHIPS errors. The background color map in row A shows NCEP OI SST, row B shows AMSR-E OI SSTs, and row C shows the difference, AMSR-E minus NCEP OI SST. In row A and B, the white circles indicate that all forecasts over predicted storm strength. In row C, black circles indicate that AMSR-E SHIPS had smaller errors than NCEP SHIPS and white circles indicate larger errors.

5. Results

Operationally, the SSTs used by SHIPS are obtained from the NCEP OI SSTs described above. Here, we tested the effect of substituting the AMSR-E OI SSTs for the NCEP OI SSTs in the SHIPS model. The model was run with both SSTs for all 2002 and 2003 North Atlantic and East Pacific storms where the storm was classified as a tropical cyclone by NHC. Extra-tropical cases were excluded from the verification sample.

The model forecasts are evaluated by comparison with NHC best track intensities, which are the post storm estimates of these parameters based upon all available information. The intensity error is the absolute value of the forecast and observed maximum surface wind. Table 1 shows the percent change in intensity forecast error when SHIPS was run with AMSR-E SSTs (AMSR-E SHIPS) rather than NCEP SSTs (NCEP SHIPS), for North Atlantic and East Pacific storms in 2002 and 2003. A positive change indicates that forecast errors were smaller for AMSR-E SHIPS than NCEP SHIPS. The intensity forecast improvement obtained by substituting AMSR-E for NCEP OI SSTs, ranges from –2.0 to 1.8%, in the North Atlantic and 1 to 11.7% in the East Pacific. Using a standard statistical test, the 2002 differences between the NCEP and AMSR-E were statistically significant (at the 95% level) only at 120 h. However, for the East Pacific, the differences were statistically significant at all times except 60 h. These results are somewhat surprising, since the SHIPS model was not ‘tuned’ to the AMSR-E OI SSTs (the statistical relationships used in the prediction were developed from the NCEP SST analyses). The very small bias between NCEP and AMSR-E OI SSTs is likely helping to SHIPS use AMSR-E OI SSTs. It is possible that tuning the model to AMSR-E SSTs would further improve the intensity forecasting. The larger improvement in the East Pacific is due to changes in SST that were not resolved by the weekly NCEP OI SST.

The difference between the AMSR-E and NCEP SHIPS model forecast errors was examined for individual North Atlantic and East Pacific storms. For many storms the AMSR-E SHIPS outperformed the NCEP SHIPS and SHIFOR model, but there was considerable variability in the results. This is expected, as SST is not the only factor influencing intensity changes. While improving the SST will help in storms where it was a major factor and was in error, storms are influenced by other forcings - when these are dominate, changing the SST will not necessarily result in an improved forecast. In the North Atlantic, the forecasts for the two strongest storms of the season, Lili and Isidore, were both improved by the addition of AMSR-E OI SSTs. For several other North Atlantic storms, such as Cristobal and Edouard, the forecast error actually increased in the AMSR-E SHIPS. For these two storms, the track error was large and improving the SSTs at the wrong location clearly does not improve skill.

The largest improvement in the 2002 East Pacific storms was seen for Genevieve. Genevieve ran over a cold wake left by Fausto, the magnitude of the cold wake was not well-represented in the NCEP OI SSTs and therefore not accounted for in the NCEP SHIPS, resulting in a much more accurate forecast from the AMSR-E SHIPS. In Fig. 2, the forecasts made on August 28, 2002 for Hurricane Genevieve, just before it crossed Fauto’s cold track, are shown. The heavy gray line indicates the hurricane’s actual track while thin gray lines show the forecasted tracks. Along each forecasted track, the intensity error is indicated by the color and size of the circle. A white (black) circle indicates an over (under) prediction of storm intensity.

Fig. 2A shows no cold track present in the SST, while the AMSR-E OI SSTs shown in Fig. 2B show a strong cold wake. The SST anomaly, Fig. 2C, shows a 2 difference in temperatures given by NCEP and AMSR-E OI SST. The white circles in Fig. 2A-B indicate that all forecasts over predicted storm strength. The black circles in Fig. 2C show that AMSR-E SHIPS has smaller errors than NCEP SHIPS. In fact, the errors decrease from 31 kts (NCEP SHIPS) to 14 kts (AMSR-E SHIPS) for the 108-hr forecast. For this storm, AMSR-E SHIPS had errors 12% to 60% less than NCEP SHIPS errors.

Another example is shown in the right column of Fig. 2, which shows the September 16, 2003 00Z forecast for Hurricane Isabel, as it approaches the East Coast. Using the AMSR-E SSTs in SHIPS decreased forecast errors for the 12-hr through 48-hr forecast by 18% to 64% (the 72-hr forecast errors increased by 14%).

6. Conclusions

These new global microwave SSTs have great potential for increasing current understanding of the relationship between how upper ocean heat content can affect hurricane intensity as well as how mixing and upwelling cools the SSTs after storm passage. The advent of microwave SSTs allow for accurate analysis in regions where traditional infrared SSTs have lacked coverage due to cloud cover. The NCEP OI SSTs successfully represents SSTs for storm forecasting in most situations, but where there is major change not captured by the weekly average, such as cold wakes from previous storms, the daily AMSR-E SSTs appreciably improve accuracy of the forecasts by providing more accurate SSTs. The inclusion of this dataset in hurricane intensity forecasting demonstrates a decrease forecast errors up to 11.7%. This could likely be improved with additional research into the spatial distribution of air-sea heat fluxes and development of a SHIPS intensity model ‘tuned’ to AMSR-E SSTs.

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