Developing an Inner-Core SST Cooling Predictor for Use in SHIPS

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Principal Investigator: **Joseph Cione**
Hurricane Research Division
NOAA/AOML
Miami, FL 33149

Co- Investigator: **John Kaplan**
Hurricane Research Division
NOAA/AOML
Miami, FL 33149

Co-Investigator: **Chelle Gentemann**
Remote Sensing Systems
Santa Rosa, CA 95401

Co-Investigator: **Mark DeMaria**
NOAA/NESDIS/ORA
Fort Collins, CO 80523

1. Introduction

Results from Cione and Uhlhorn (2003) illustrate a clear link between inner-core sea surface temperature (SST) cooling (relative to ambient SST conditions ahead of the storm) and subsequent TC intensity change (Figure 1).

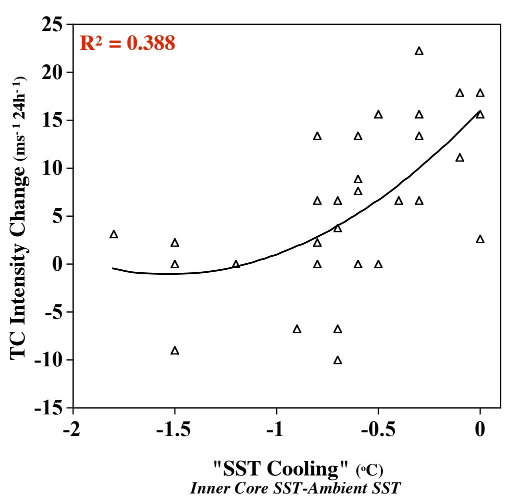

Figure 1. Scatter plot of 24h TC intensity change as a function of SST cooling (inner core - ambient SST) for 23 hurricanes between 1975-2002. The resulting polynomial (2nd order) best-fit is illustrated. Here, 38.8% of the variance with intensity change is explained (i.e. r^2=0.388). The units for intensity change are given as m s^{-1} 24 h^{-1} while SST is measured in ^{o}C. [Figure adapted from Cione and Uhlhorn (2003)].

Simply stated, hurricanes that cooled the least intensified the most. Relatively modest changes in inner-core SST (order 1.0^{o}C) were shown to alter maximum total enthalpy flux (latent plus sensible) by 45% or more. Changes in surface energy flux of this magnitude can be the difference between a system that rapidly intensifies and one that quickly decays. Complicating matters further, inner-core SST cooling patterns often go undetected since it is the most difficult region of the hurricane to accurately and routinely observe. Since operational coupled models have had difficulty simulating and validating inner-core SST cooling patterns (Bender et al 2000), the recent findings from Cione and Uhlhorn (2003) highlight the critical (and immediate) need to accurately account for inner-core SST conditions.

For several years, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria and Kaplan 1999) has shown skill in predicting TC intensity change (DeMaria et al. 2002). The primary goal of this JHT project is to build on SHIPS existing skill by providing improved ambient SSTs as well as new and critically important SST estimates within the difficult to observe high wind inner-core TC environment. It is believed that incorporating a more accurate depiction of the ocean surface boundary condition (SST) into SHIPS will directly result in improved forecasts of TC intensity change, and as such, address the Tropical Prediction Center's (TPC) highest forecast priority (TPC A-1).

2. Accomplishments to date

2a. Algorithm Development

Building upon in-situ inner-core hurricane observations documented in Cione and Uhlhorn (2003), a statistically stable cooling algorithm that utilized along track SST, TC latitude and storm speed as predictors was developed (Figure 2).

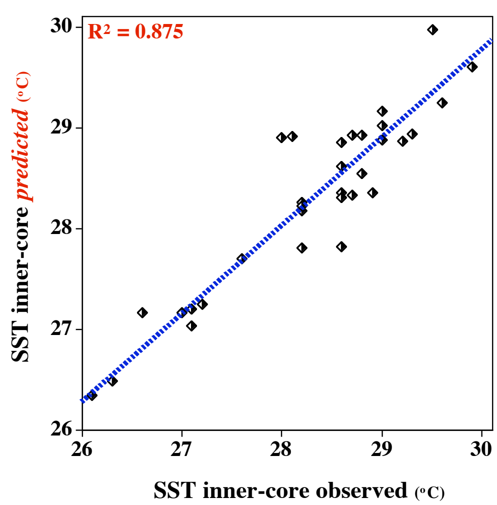

Figure 2. Scatter plot of in-situ SST vs. *predicted* inner-core SST [using the hurricane inner-core SST cooling algorithm developed from the 23-hurricane (1975-2002) sample from Cione and Uhlhorn (2003)]. The linear best-fit shown explains 87.5% of the variance (i.e. r^2=0.875). SST is given in ^{o}C.

2b. Dependent Sample Results (1989-2004)

Working closely with J. Kaplan and M. Demaria, the newly developed TC Inner-Core SST Cooling Algorithm was tested in a dependent mode using 1000s of individual forecasts taken from the SHIPS 1989-2004 Atlantic basin storm database. Analyses incorporating observations from tropical depression strength or greater systems resulted in improved SHIPS intensity forecasts over all time periods between 12-120h. These results are encouraging since no mean degradation was found at any forecast interval even though many weak systems were included in the analysis. When results were stratified by initial storm intensity and observed intensity change, the positive impact of utilizing inner-core SSTs on SHIPS forecasts was found to be even more significant (see Figures 3-4).

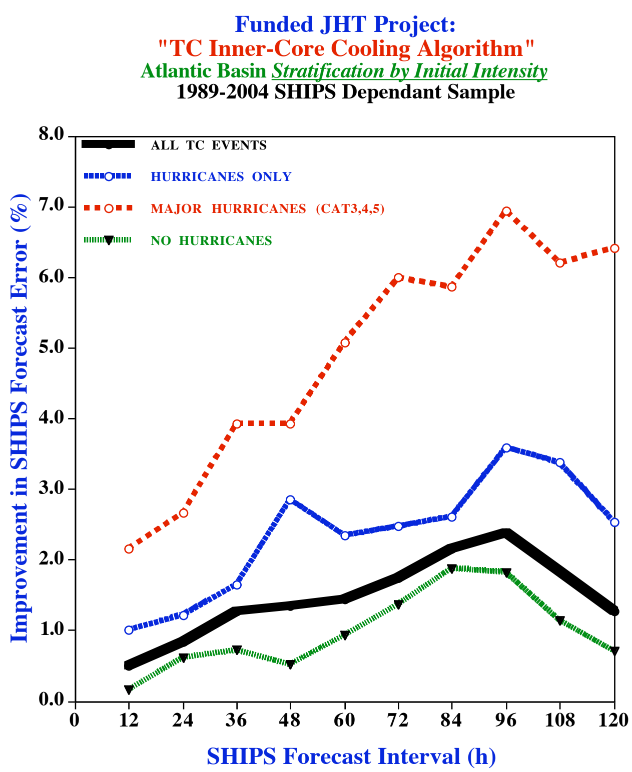

Figure 3. Improvement in SHIPS forecast error (in %) as a function of forecast interval (from 12h-120h) when inner core SST was used in lieu Reynolds SST. The four lines shown are: all forecasts of tropical depression strength or greater (BLACK); all forecasts of tropical depressions and tropical storms (GREEN); all forecasts of hurricanes (BLUE); and forecasts of major (Category 3, 4 and 5) hurricanes (RED).

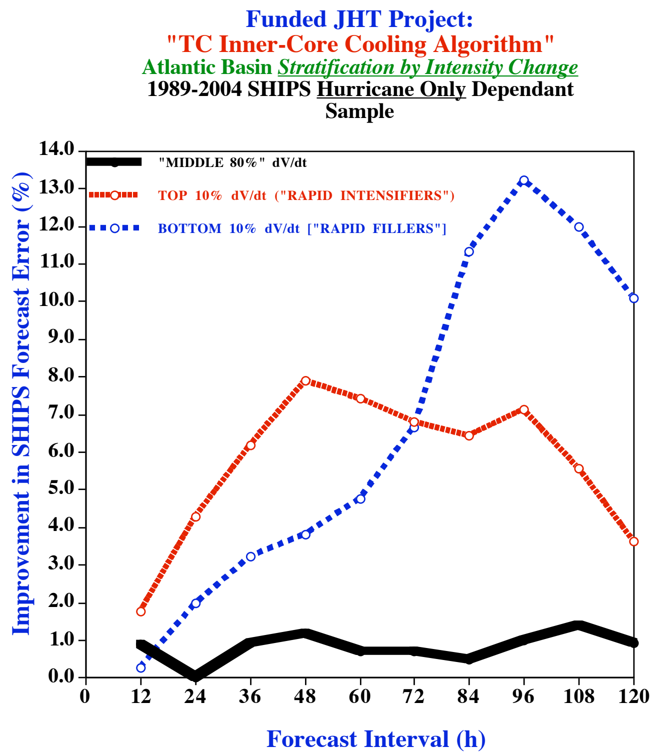

Figure 4. Improvement in SHIPS forecast error (in %) as a function of forecast interval (from 12h-120h) when inner core SST was used in lieu Reynolds SST. The three lines shown are: all forecasts of hurricanes EXCLUDING rapid intensifiers (top 10% of the sample) and rapid fillers (bottom 10% of the sample) (BLACK); ONLY forecasts of rapid intensifiers (top 10% of the sample) (RED); ONLY forecasts of rapid fillers (bottom 10% of the sample) (BLUE). For this analysis, "intensity change" is defined as the observed change in hurricane intensity over the t=0 to t=24 forecast period.

Figures 3 and 4 illustrate that intensity forecasts involving major (Category 3 4 and 5) hurricanes and forecasts associated with rapid intensity change (top and bottom 10% of the hurricane sample) netted the largest forecast improvements (7-13.5%) when estimated inner-core SST was used in lieu of Reynolds SSTs (used operationally in SHIPS prior to 2005). These very encouraging results were recently presented in detail at the 2005 IHC held in Jacksonville Florida (March, 2005).

2c. Independent Sample Results and Testing of High Temporal and Spatial Resolution SSTs in SHIPS (2003 Atlantic hurricane season)

Given the inherent difficulties associated with accurately predicting TC intensity change and the obvious public concern associated with a major hurricane landfall event, it is very encouraging that using inner-core SSTs in SHIPS appears to work best when forecasters potentially need it the most.

While these dependent sample results are very significant, the next step was to test the impact of using the inner-core SST cooling algorithm on an independent storm sample. Once again, working closely with M. DeMaria and C. Gentemann, SHIPS forecast using inner-core SST estimates as well additional microwave-derived ambient SST values were tested in the SHIPS model using data from the 2003 Atlantic Hurricane season. Baseline SHIPS 2003 forecasts (that use Reynolds weekly SSTS) were compared with re-run SHIPS forecasts using inner-core SST estimates derive from the algorithm as well as and microwave SSTs. In addition, 50km resolution NCEP "real-time global" (RTG) daily SSTs were tested. The summary results from these SHIPS model re-runs for the 2003 season are shown in Table 1.

Table 1. SHIPS Forecast Sensitivity to SST (2003 North Atlantic Hurricane Season)

SHIPS Average Intensity Forecast Skill (relative to SHIFOR) Using Alternate SSTs (%)							
	Forecast Interval (hr)						
Model	12	24	36	48	72	96	120
SHIPS w/Reynolds ***(SST: weekly-100km-IR-operational)***	16.3	30.2	31.1	35.3	31.7	13.9	-10.0
SHIPS w/inner-core SSTs ***(SST: predicted-inner-core)***	15.3	28.9	32.5	38.2	36.4	22.4	-1.3
SHIPS w/ AMSR-E ***(SST: daily-25km-microwave)***	16.3	30.2	33.7	36.7	29.7	12.8	-10.6
SHIPS w/NCEP RTG ***(SST: daily-50km-IR)***	14.9	27.8	30.8	34.1	27.2	10.2	-12.3
SHIPS w/Inner-core SSST ***minus*** **SHIPS w/Reynolds**	**-1.0**	**-1.3**	**1.4**	**2.9**	**4.7**	**8.5**	**8.7**
No. Cases	*318*	*289*	*260*	*232*	*183*	*146*	*121*

Table 1. SHIPS average forecast sensitivity using various SST estimates for the 2003 North Atlantic hurricane season. SSTs tested include Reynolds (operationally used in SHIPS), inner-core SST algorithm-derived SSTs, daily microwave AMSR-E derived SSTs and IR daily SSTs (NCEP RTG). The skill shown is calculated as the fractional increase/decrease in forecast error from the baseline SHIFOR intensity forecast. Positive (negative) values denote forecast improvement (degradation) over SHIFOR. Shown in blue (red), SHIPS w/ inner-core SSTs minus SHIPS w/Reynolds depicts the forecast skill improvement (degradation) found when SHIPS forecasts using inner-core estimates of SST are compared with SHIPS forecasts using Reynolds SSTs.

From Table 1, we see that SHIPS w/Reynolds SSTs, AMSR-E microwave SSTs and SHIPS w/ NCEP daily IR SSTs improve upon SHIFOR for forecast intervals less than 120 hours. However only the SHIPS forecasts that used inner-core SSTs approached no degradation at 120h. Table 1 also shows that AMSR E SST improvements relative to SHIFOR over the 12-48h period are greater than or equal to SHIPS w/Reynolds improvements over that same timeframe. Additionally, significant average skill improvements were found (over SHIPS w/Reynolds) between 72-120h when Inner-core SST estimates were used. Over the 72-120h forecast interval, average forecast average skill improvement (relative to SHIPS w/Reynolds) was found to be 7% (450 forecasts) and 8.6% between 96-120h (267 forecasts).

In addition to the mean 2003 seasonal improvements shown above, Table 2a and 2b illustrate results for the (only) two storms (Fabian and Isabel) that were observed to rapidly intensify (dV/dt $\geq$30kts/24h) during the 2003 Atlantic hurricane season. Similar to findings shown in

Table 1, SHIPS forecasts using the TC inner-core algorithm derived SST estimates outperformed the corresponding 'baseline' SHIPS forecasts using 100km weekly Reynolds SST. These results are also consistent with key findings illustrated in the dependent sample analysis shown in Section 1, where the magnitude of the forecast improvement (relative to SHIPS w/Reynolds) when inner-core SSTs were used was maximized during cases of significant intensity change. It should also be noted that when average forecasts are combined for both Fabian and Isabel an overall 1.5% skill improvement was found when daily AMSR-E microwave SST were used in SHIPS (relative to weekly Reynolds values).

Table 2a. SHIPS Forecast Sensitivity to SST (HURRICANE FABIAN 2003)

SHIPS Average Intensity Forecast Skill (relative to SHIFOR) Using Alternate SSTs (%)							
	Forecast Interval (hr)						
Model	12	24	36	48	72	96	120
SHIPS w/Reynolds ***(SST: weekly-100km-IR-operational)***	4.3	7.1	7.9	13.5	19.3	0.0	-24.6
SHIPS w/Inner-core SSTs ***(SST: predicted-inner-core)***	1.7	12.0	16.1	20.2	41.3	34.2	1.3
SHIPS w/ AMSR-E ***(SST: daily-25km-microwave)***	9.0	12.3	11.5	15.3	21.2	4.5	-20.2
SHIPS w/NCEP RTG ***(SST: daily-50km-IR)***	4.7	7.4	8.1	14.7	21.5	4.3	-21.2
SHIPS w/Inner-core SSTs ***minus*** **SHIPS w/Reynolds**	**-2.9**	**4.9**	**8.2**	**6.7**	**22.0**	**34.2**	**25.9**
No. Cases	*45*	*43*	*41*	*39*	*35*	*31*	*27*

Table 2a. SHIPS average forecast sensitivity using various SST estimates for Hurricane Fabian (2003). SSTs tested include Reynolds (operationally used in SHIPS), inner-core SST algorithm-derived SSTs, daily microwave AMSR-E derived SSTs and IR daily SSTs (NCEP RTG). The skill shown is calculated as the fractional increase/decrease in forecast error from the baseline SHIFOR intensity forecast. Positive (negative) values denote forecast improvement (degradation) over SHIFOR. Shown in blue (red), SHIPS w/inner-core SSTs minus SHIPS w/Reynolds depicts the forecast skill improvement (degradation) found when SHIPS forecasts using inner-core SSTs are compared with SHIPS forecasts using Reynolds SSTs.

Table 2b. SHIPS Forecast Sensitivity to SST (HURRICANE ISABEL 2003)

SHIPS Average Intensity Forecast Skill (relative to SHIFOR) Using Alternate SSTs (%)							
	Forecast Interval (hr)						
Model	12	24	36	48	72	96	120
SHIPS w/Reynolds ***(SST: weekly-100km-IR-operational)***	25.4	26.2	26.2	31.3	21.3	6.5	-17.1
SHIPS w/inner-core SSTs ***(SST: predicted-inner-core)***	28.7	28.4	28.2	36.4	32.2	22.4	0.1
SHIPS w/ AMSR-E ***(SST: daily-25km-microwave)***	23.6	25.7	28.8	31.9	17.7	2.7	-19.8
SHIPS w/NCEP RTG ***(SST: daily-50km-IR)***	24.1	23.3	23.6	26.2	14.3	0.2	-21.5
SHIPS w/Inner-core SSTs ***minus*** **SHIPS w/Reynolds**	**2.7**	**2.2**	**2.0**	**5.1**	**10.9**	**15.9**	**17.2**
No. Cases	*49*	*47*	*45*	*43*	*39*	*35*	*31*

Table 2b. SHIPS average forecast sensitivity using various SST estimates for the Isabel (2003). SSTs tested include Reynolds (operationally used in SHIPS), inner-core SST algorithm-derived SSTs, daily microwave AMSR-E derived SSTs and IR daily SSTs (NCEP RTG). The skill shown is calculated as the fractional increase/decrease in forecast error from the baseline SHIFOR intensity forecast. Positive (negative) values denote forecast improvement (degradation) over SHIFOR. Shown in blue, SHIPS w/inner-core SSTs minus SHIPS w/Reynolds depicts the forecast skill improvement found when SHIPS forecasts using inner-core SSTs are compared with SHIPS forecasts using Reynolds SSTs.

2d. Additional Independent Sample Results (2004 Atlantic hurricane season)

Table 3. SHIPS Forecast Sensitivity to SST (2004 North Atlantic Hurricane Season)

Average Intensity Error (knots) and % Skill Improvement/Degradation to SHIPS							
	Forecast Interval (hr)						
Model	12	24	36	48	72	96	120
SHIPS w/Reynolds ***(SST: weekly-100km-IR-operational)***	7.8	10.7	12.7	13.6	16.9	22.5	26.2
SHIPS w/inner-core SSTs ***(SST: predicted-inner-core)***	7.7	10.6	12.6	13.5	16.5	21.6	25.1
% Improvement/Degradation (when Inner-core SSTs were used)	**0.9**	**0.7**	**0.3**	**0.7**	**2.4**	**4.3**	**3.8**

Table 3. SHIPS average intensity error (kts) and % change in skill for the 2004 North Atlantic hurricane season. SSTs tested include Reynolds (operationally used in SHIPS) and inner-core derived SSTs. The improvement in skill shown (in blue) is calculated as the fractional decrease in forecast error from the baseline SHIPS intensity forecast.

From Table 3, we see that average SHIPS forecasts for the 2004 Atlantic hurricane season improved at every forecast interval between 12-120h. Over the 72-120h forecast interval, average forecast average skill improvement (relative to SHIPS w/Reynolds) was found to be 3.5%.

3. Final Comments/Summary of Work

Prior to the onset of the 2005 Atlantic hurricane season it was decided that the inner-core SST cooling algorithm would be used operationally within SHIPS due to the strong dependent sample (1982-2004) and independent sample (2003 and 2004) results already shown. The PIs are very pleased with these findings and decision to use the algorithm operationally in 2005 and as such, believe we have successfully met the responsibilities we initially proposed in this JHT proposal. It is our hope that NHC/TPC decides to permanently use the algorithm in SHIPS for years to come. Future (currently unfunded) work that is planned includes testing of a next generation inner-core SST algorithm that will be basin independent (E and W Pacific as well as Atlantic). This version of the algorithm would also incorporate new data (2000-2005) and most likely utilize information on storm intensity and subsurface ocean structure. This work, while preliminary, shows great promise.

Another unfunded effort will be to see if a surface flux predictor can be developed for use in SHIPS. The inner-core SST predictor is only "one half of the puzzle" with regard to estimating surfaces fluxes in within the high wind TC environment. Successfully estimating inner-core surface air temperature and moisture, will in turn enable testing of 'bulk' heat flux parameters for possible future use in SHIPS. This work is set to begin in the near future.

In closing, the PIs feel fortunate that they were given the opportunity to assist the operational forecast community. We hope for a similar opportunity to continue this important collaboration in the future. We are confident that we can build upon the progress we have already made by significantly improving the inner-core SST algorithm as well as potentially deriving new inner-core air-sea predictors for future use in SHIPS.

References

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