Appendix A

FORMAT FOR USE IN SUBMISSION OF INTERIM AND FINAL RESEARCH PERFORMANCE PROGRESS REPORTS

COVER PAGE

NOAA/JHT

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Title: Improvements to Operational Statistical Tropical Cyclone Intensity Forecast Models

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Final Annual Report? Yes

1. ACCOMPLISHMENTS

Summary of the project accomplishments for the 3 main project tasks:

1) **Replace in SHIPS and LGEM weekly 1° resolution SSTs with daily 0.25° resolution SSTs.** These changes were designed to improve forecast performance and set the stage for including upper-ocean data to explicitly account for SST cooling. The software for pre-processing Daily Reynolds SST (DSST) data was developed and modifications to the model to add the option to use either weekly SST (RSST) or DSST were completed. A new module was added to SHIPS/LGEM to handle the selection of SST and ocean heat content (OHC) data and that module was implemented in the 2016 version of SHIPS on WCOSS. Changes for this task were incorporated into the 2016 version of SHIPS and retrospective and parallel runs with daily SST and verification were completed. The code to generate global and regional DSST, the modified SHIPS/LGEM, and verification results have been provided to NHC for evaluation. Statistical tests were performed and demonstrated that DSST is very noisy compared to RSST. It was also found that using temporally or spatially averaged DSST produces better improvement to SHIPS and LGEM forecasts, as compared to DSST. The updated real-time processing for DSST data and the updated database of 1982 - 2017 DSST data were provided to NHC and have been used for operational runs for 2018 season and to include DSST in the SHIPS predictors' database. The spatially-averaged DSST (DSTA) was implemented in the operational versions of SHIPS and LGEM on WCOSS for 2018.

2) **Add to SHIPS/LGEM a physical mechanism to account for storm-induced SST cooling.** Multiple papers, including Lin et al. (2013) and Price (2009), have demonstrated that the use of tropical cyclone- (TC) cooled SST instead of SST to calculate the storm maximum potential intensity (MPI) produces a more realistic upper intensity bound estimate and that the ocean temperature vertically-averaged from the surface to the depth of TC-induced mixing is a more robust metric of the SST cooling effect than the OHC. The algorithm for estimating the depth-averaged temperature (DAVT) assuming constant and variable mixing depth from the OHC and upper-ocean data available in real-time was developed and incorporated into the SHIPS and LGEM processing scripts. The option to use either SST or different versions of DAVT was added to both SHIPS and LGEM. It was found that the available ocean data that include SST, mixed-layer depth (DML), and depths of 26° and 20° isotherms (D26 and D20), do not provide enough information to accurately estimate DAVT. The OHC, the subsurface ocean data, and the corresponding climatologies were completely re-derived from full ocean profiles to obtain an input dataset (the Extended OHC, EOHC) that allows for the accurate calculation of DAVT. The dependent and independent test demonstrated that SHIPS and LGEM forecasts could be significantly improved with using DAVT derived from EOHC dataset. The OHC data from EOHC dataset were also found beneficial for SHIPS, LGEM, and RII, and were used with the operational 2018 version of SHIPS on WCOSS. The final version of the algorithm to use DAVT with variable mixing depth and final regression coefficients should be re-derived for 2019 version of SHIPS/LGEM to account for SST that is planned to be changed for 2019 version of SHIPS/LGEM due to the issues discovered with daily Reynolds SST during 2018 season. NHC is planning to run SHIPS with DAVT in quasi-production on WCOSS for 2019.

3) **Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM.** A statistical-dynamical method to predict TC wind structure (Decay SHIPS Wind Radii, DSWR) in terms of wind radii has been developed and has been running in real-time at CIRA since August 2016. The basis for TC size variations is developed from an infrared satellite-based record of TC size (Knaff et al. 2014), which is homogenously calculated from a 1996-2012 sample. The change in TC size is predicted using a statistical-dynamical approach where predictors are based on environmental diagnostics derived from global model forecasts and observed storm conditions. Once the TC size has been predicted, the forecast intensity and track are used along with a parametric wind model to estimate the resulting wind radii following Knaff et al. (2017). The DSWR code and verification for 2017 was completed and results were provided to NHC and JTWC. DSWR was transitioned to operations at the Joint Typhoon Warning Center (JTWC) in September 2017. NHC is planning to run DSWR in quasi-production at WCOSS for the 2019 Atlantic Hurricane season.

What were the major proposed **goals, objectives, and tasks** of this project, and what was accomplished this period under each task? (a table of planned vs. actuals is recommended as a function of each task identified in the funded proposal)

Goals, Objectives, Tasks	Planned: Sep 2016 – Aug 2018	Actual: Sep 2016 – Aug 2018
Modify SHIPS and LGEM to use 0.25° daily Reynolds SST	Develop version of SHIPS/LGEM with DSST and complete all related testing.	Version SHIPS/LGEM with spatially averaged daily SST (DSTA) was developed and tested. It was transitioned to operations at NHC for 2018 season.
Modify SHIPS and LGEM models to use DAVT	Develop DAVT database and related software, develop version of SHIPS/LGEM with DAVT and complete all related testing.	A comprehensive dataset of OHC, DML, and subsurface ocean data was derived from the full ocean profiles. Version of SHIPS/LGEM with DAVT was developed and tested. Testing demonstrated that SHIPS and LGEM forecasts can be significantly improved with DAVT. NHC is planning to run version of SHIPS/LGEM with DAVT in quasi-prod for 2019 season.
Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM	Develop DSWR model and complete all related testing.	DSWR model was developed and tested. DSWR was transitioned to operations at JTWC in September 2017. NHC is planning to run DSWR in quasi-production on WCOSS from 2019 Atlantic Hurricane season.

Are the proposed project tasks **on schedule**? What is the cumulative percent toward completion of each task and the due dates? (table recommended)

Task	Cumulative percent towards completion and due dates	Due Date	On schedule (yes/no)
Modify SHIPS and LGEM models to use 0.25° daily Reynolds SST	100%	Feb 2017	Yes
Modify SHIPS and LGEM models to use DAVT	100%	Aug 2018	Yes
Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM	100%	Feb 2017	Yes

What were the major completed **milestones** this period, and how do they compare to your proposed milestones? (planned vs. actuals table recommended)

The table provides a brief summary of the work completed for each of the project millstone. Additional milestones were added to reflect additional tasks performed for the project.

Milestone	Completed vs proposed
Create databases of TC size parameters and daily Reynolds SST	Databases were successfully created and provided to NHC
Modify SHIPS code to use daily, 0.25° Reynolds SST	SHIPS code was modified to use daily, 0.25° Reynolds SST
Adapt SHIPS statistical code to predict storm structure	DSWR model was developed
Run SHIPS dependent sample statistics for the years 2005-2013 and complete retrospective SHIPS runs with daily SST	Dependent sample testing for 1982 - 2016 and retrospective runs for 2010 – 2016 were completed for SHIPS/LGEM with daily, 0.25° Reynolds SST
Year 1 semi-annual report	Semi-annual report was submitted and is available online
Present year 1 results at IHC and gather feedback	Results were presented at IHC. Presentation is available online.
Conduct algorithm changes based on feedback and validation results	Spatially averaged version of DSST was added in response to NHC feedback
Develop code to read daily N Shay and NCODA upper ocean datasets and estimate depth-averaged temperature, convert data to input data format used by SHIPS	Code was developed for reading ocean data and calculating depth-averaged temperature (DAVT). Testing of the newly derived DAVT values demonstrated that available data do not provide information needed to derive accurate values of depth-averaged temperature. DAVT was later re-derived from full ocean profiles.
Modify SHIPS to use depth-averaged temperature to account for SST cooling, assuming constant mixing depth	SHIPS/LGEM code was modified to use DAVT assuming constant missing depth
Prepare final updated version of the modified SHIPS code for parallel runs during the 2016 season (to include use of daily SST, use of depth-averaged temperature to account for SST cooling, and TC-size estimates) for Atlantic and East and Central Pacific basins.	Parallel runs of SHIPS/LGEM with daily Reynold SST and of DSWR were conducted at CIRA
Coordinate with JHT and TSB staff to implement updated SHIPS code on NCEP supercomputer (WCOSS) or implement code at CIRA	Parallel runs were implemented at CIRA
Submit Year 1 final report.	Year 1 Final report was submitted and is available online
Begin parallel runs during 2016 season and monitor results during the season	Parallel runs of SHIPS/LGEM with daily Reynold SST and of DSWR were conducted at CIRA

Modify SHIPS to include depth-averaged SST based on the variable mixing depth	SHIPS/LGEM were modified to use multiple versions of DAVT. The final modifications were made to 2018 versions of SHIPS/LGEM and included options to use 14 different versions of DAVT (assuming constant missing depth from 25 m to 200 m, and assuming variable mixing depth) as a replacement for either SST or OHC. In addition that version of the code allows to use different version of SST, DAVT, and/or OHC for each part of the code, including SHIPS, LGEM, and several versions of RII
Extend SHIPS modifications to the global version	'The DSWR model is global, and was transitioned to operations at JTWC in 2017. When the original proposal was written NHC and JTWC were using very similar versions of SHIPS/LGEM. Current operational versions of SHIPS/LGEM differ substantially between NHC and JTWC, and the changes applied to NHC's version of SHIPS and LGEM cannot be directly applied to JTWC's version. The most time-consuming part of this project was to develop databases of DSST and EOHC and the corresponding processing code that includes readers, generating databases in real-time, making climatology, and estimating DSTA and DAVT values, including SST cooling assuming constant or variable mixing depth along the storm track. All developed databases and related software is global. The databases and related software will be made available to NRL/JTWC so they can include it in future versions of their SHIPS/LGEM models.
Evaluate parallel runs from 2016 season and make any necessary adjustments to the modified SHIPS	The results were evaluated for DSWR and SHIPS/LGEM with daily SST. Runs with daily SST demonstrated that there is no improvement. The likely reason is that DSST is very noisy compared to weekly SST. As result, it was decided to use the area-averaged version of DSST to reduce noise. Use of the area-averaged version of DSST (DSTA) shows significant improvement compared to use of weekly SST.
Year 2 semi-annual report	Year 2 semi-annual report was submitted and is available online.
Present year 2 results at IHC and compile feedback from JHT advisors	Results were presented at IH and the presentation is available online.

Complete retrospective runs of modified SHIPS with all improvements and additions included	This milestone was replaced. It was found that exiting datasets do not allow for accurate calculation of DAVT. Thus, the new Extended OHC (EOHC) dataset was developed from full ocean profiles. In addition, the new version of climatology was developed to provide better values for IHC from EOHC dataset and to obtain climatological values for the newly developed variables
Complete SHIPS verification by comparing the intensity forecasts against the final NHC best track, and size parameters against the final wind radii in the best track	Final verification of SHIPS/LGEM results with the DAVT values from EOHC dataset was completed and demonstrated that the use of DAVT could very significantly improve SHIPS/LGEM forecasts. Final verification of SHIPS/LGEm with daily SST and of DSWR was also completed, and results are included in this report.
Finalize updated SHIPS/LGEM/RII code for product enhancements/additions; coordinate with JHT and TSB staff to implement SHIPS/LGEM upgrades approved for operational implementation.	- SHIPS with daily SST was transitioned to operations at NHC in 2018 - DSWR was transitioned to operations at JTWC in 2017, and is currently being tested at NHC. NHC plans to run DSWR in quasi-prod for 2019 and transition it to operations for 2020 - NHC plans to run SHIPS/LGEM with DAVT in quasi-prod for 2019 season
Submit Year 2 final report.	Year 2 final report was submitted and is available online

A detailed description of work completed, and results obtained for each of the 3 main project Tasks is provided below. The 3 main project tasks include: 1) add to SHIPS/LGEM daily Reynolds SST 2) add to SHIPS/LGEM depth-averaged temperature, and 3) Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM.

Task 1: Modify SHIPS and LGEM models to use daily SST with 0.25 deg resolution.

1.1. Importance of using high-resolution daily SST data. The use of high-resolution, 0.25° daily SST instead of low-resolution 1° weekly SST could be very important for tropical cyclone (TC) intensity forecast, especially for the storm moving over sharp SST gradients and/or in the cold wake of the earlier TC. Figure 1 shows an example of 2016 east Pacific hurricane Blas that was moving over the SST cooled by TC Agatha. Figure 2 (left) shows the differences between weekly and daily Reynolds SST along the track of Blas. It could be seen that the differences could be as high as 1°C over some portions of the track. Figure 2 (right) shows the difference in SHIPS/LGEM forecast with using weekly (RSST) or daily (DSST) data. As could be seen from Figure 2, both SHIPS and LGEM are very sensitive to small variations in SST and taking into account SST changes on a daily time scale could significantly affect SHIPS and LGEM forecast accuracy.

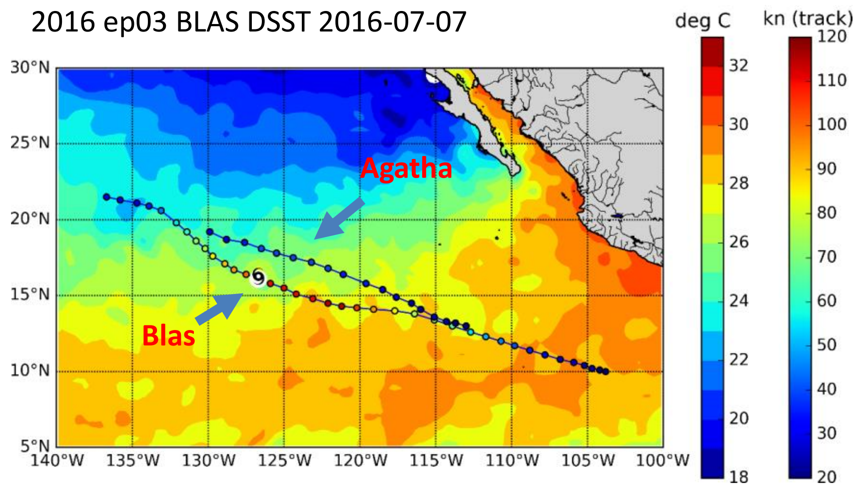

Figure 1. Example of tropical cyclone moving over sharp SST gradient in a cold wake of the previous TC.

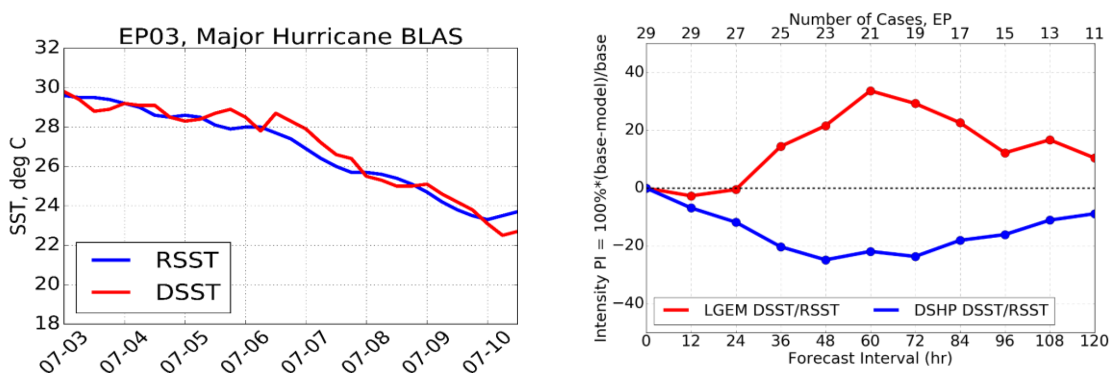

Figure 2. Left: Difference between weekly and daily Reynolds SST along the track of Hurricane Blas. Right: Percent improvement (PI) forecast for Blas for SHIPS (blue line) and LGEM (red line) with RSST and DSST.

1.2 Comparison of daily and weekly Reynolds SST. The database of the daily Reynolds SST for the years 1982 – 2017 was developed. The developed software included the software for automatically downloading and reading daily Reynolds SST in NetCDF format, as well as the software for converting daily Reynolds SST data to standard SHIPS input format, and for adding daily Reynolds SST data to SHIPS diagnostic files.

The format of the DSST data was changed in April 2017 from NetCDF3 to compressed NetCDF4. The software for processing DSST was updated to account for that change. The full 1982 - 2017 database of DSST was updated to ensure that it contains exactly the same data that are available in the updated DSST archive on https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/access/. The updated database and software were provided to NHC. The data were included in SHIPS developmental database and the software has been running at NHC in real-time during 2018 season to generate at NHC DSST in SHIPS format that have been used for the 2018 operational versions of SHIPS and LGEM.

Figure 3 shows the scatter plots of weekly Reynolds SST (RSST) vs daily Reynolds SST (DSST) for the Atlantic (left) and east Pacific (right). The differences between RSST and DSST can be very large, up to about 5°C, which could be very significant for SHIPS/LGEM forecasts. The earlier testing SHIPS/LGEM used DSST and did not show significant forecast improvement. The comparison of DSST with RSST demonstrated that DSST data is very noisy compared to RSST. To reduce the noise, temporally and spatially averaged DSST was tested. Statistical tests with both SHIPS and LGEM showed that the use of DSST averaged over the last 3 days as well as DSST averaged over 50 km around the storm center produces improvements for both SHIPS and LGEM forecasts relative to the use of the most recent DSST.

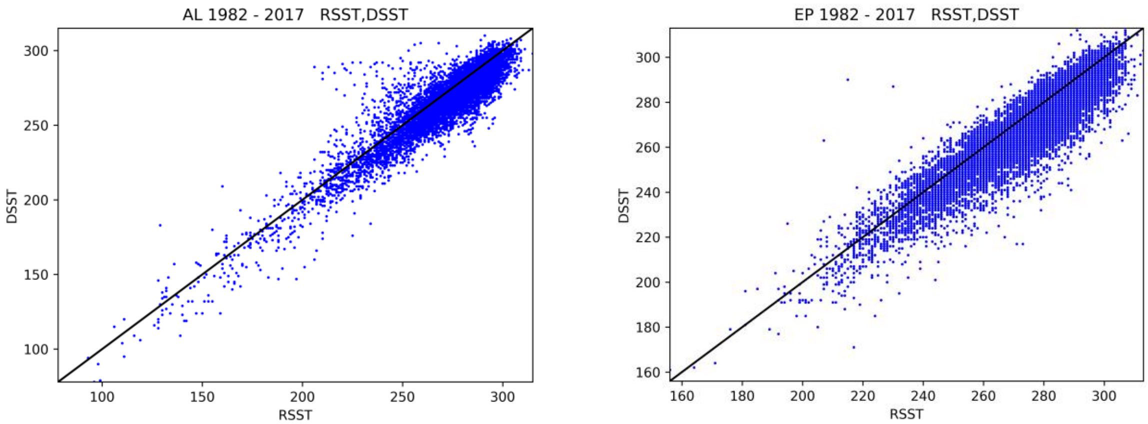

*Figure 3. Scatter plots of weekly (RSST) vs Daily (DSST) Reynolds SST for the Atlantic (Left) and east Pacific (Right). Units are °C *10*

1.3 Modifications to SHIPS and LGEM. Both SHIPS and LGEM were modified to add the option to use either RSST or DSST, including the option to use different SST for different models, including SHIPS, LGEM, and different versions of the RII. Additional module for selecting and processing daily and weekly SST was added to SHIPS. That module was included in the 2016 operational version of SHIPS/LGEM.

1.4 SHIPS/LGEM verification with daily SST. SHIPS/LGEM with RSST replaced by the spatially-averaged version of daily SST, DSTA, was transitioned to operations at NHC for 2018 Hurricane season. Figure 4 shows the comparison of reruns of SHIPS and LGEM with RSST and DSTA for the years 2010 – 2017, and Figure 5 shows independent reruns for 2018.

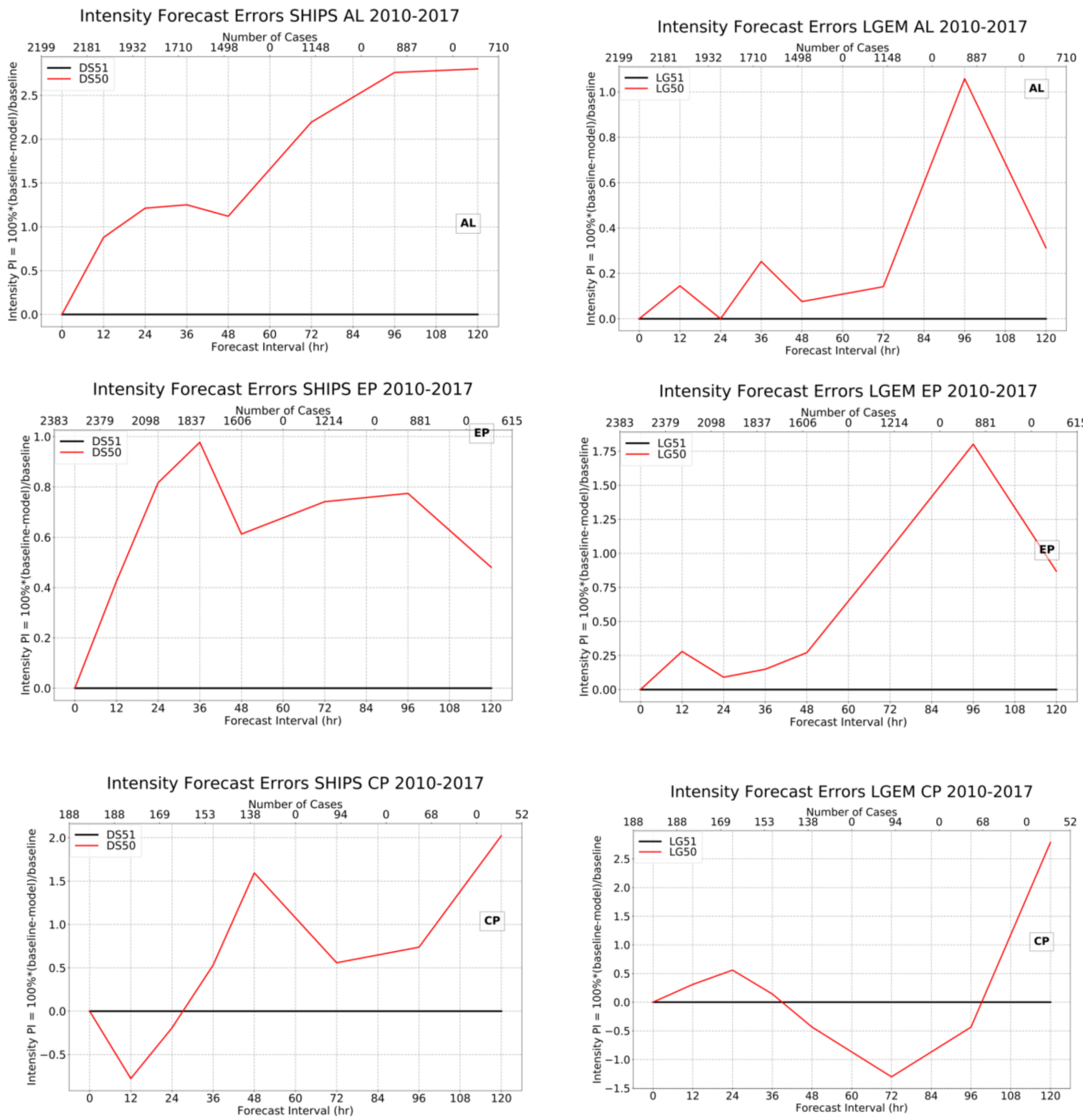

Figure 4: SHIPS (left column) and LGEM (right column) forecast verification for 2010 - 2017 for Atlantic (upper row) and east Pacific (bottom row). Shown is forecast Percent Improvement (PI) with RSST replaced by DSTA. The red line, Run 50 shows forecast PI of DSTA version relative to the baseline Run 51 with RSST (horizontal black line). Use of DSTA shows significant forecast improvement for Atlantic and east Pacific for both SHIPS and LGEM. The results for central Pacifc are more mixed, especially for LGEM.

As can be seen from Figure 4, use of DSTA provides significant forecast improvement for both SHIPS and LGEM for Atlantic and east Pacific. The most improvement is seen for SHIPS in the Atlantic, with up to 2.7 PI for 96 – 120 hr forecast lead time (FLT). The results for central Pacific are not as good, especially for LGEM which shows up to 1.2 % forecast degradation with use of DSTA. That can be possibly explained with a very limited sample size for central Pacific storms. Also, most of the storms in central Pacific sample are from 2015. There were 9 central Pacific systems in 2015, which is rather unusual, suggesting that conditions during these storms, including SST may not be representative of average conditions.

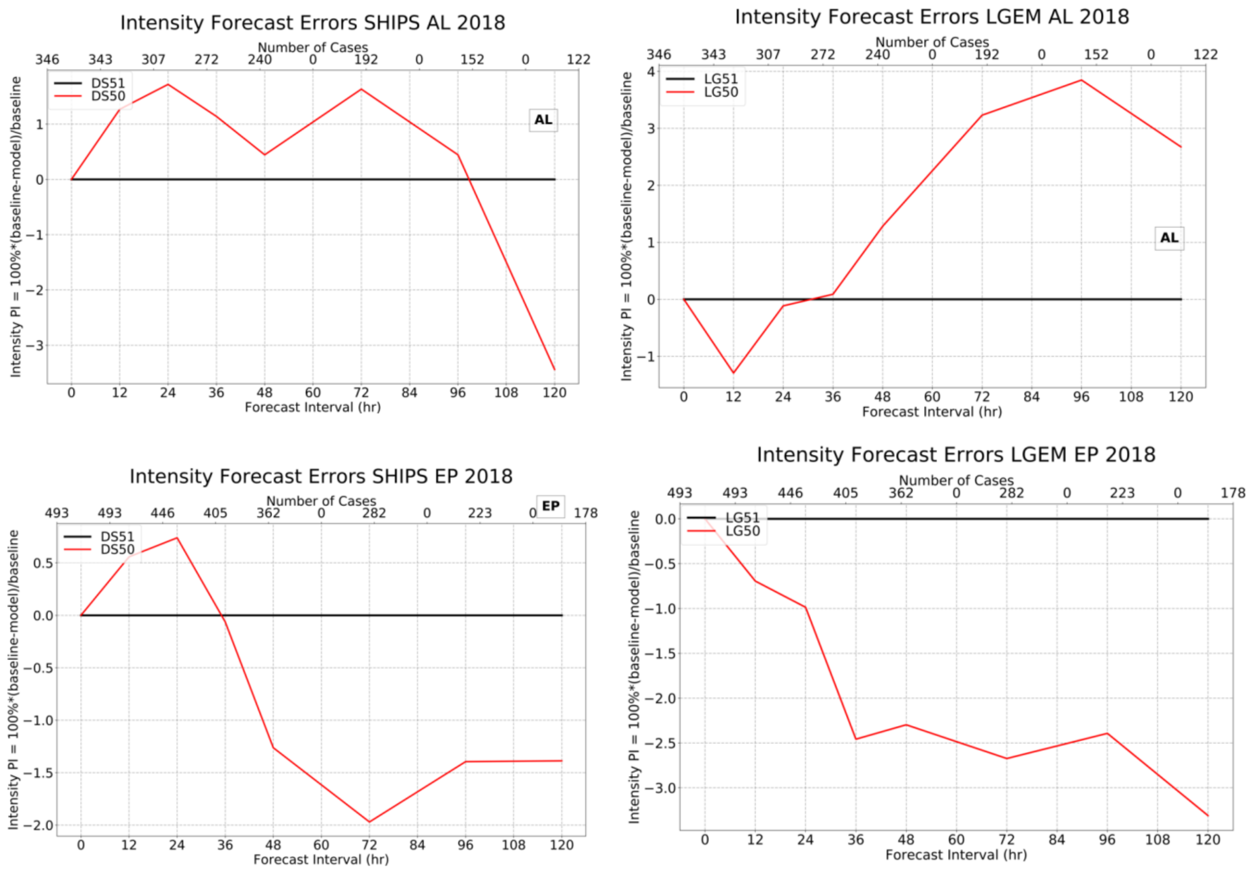

Figure 5. Same as Figure 4 but for 2018. Only data for Atlantic and east Pacific are shown.

As can be seen in Figure 5, the use of DSTA in SHIPS/LGEM did not work well for 2018 season, especially for east Pacific. For east Pacific both SHIPS and LGEM show noticeable forecast degradation while using DSTA. Forecast is also worse with DSTA compared to RSST for long FLT (longer than 96 hours) for SHIPS for the Atlantic. It is likely that the main reason for that, especially for the forecast degradation for east Pacific, can be explained by pour quality of daily Reynolds SST data. Figure 6 shows the daily Reynolds SST compared with ARGO floats in-situ data (upper panel) and GeoPolar Blended SST (lower panel). The Geo Polar Blended SST is currently considered one of the best available SST dataset. As can be seen in Figure 6, during August 2018 there was a very strong artificial cold anomaly in daily Reynolds SST in east Pacific. That cold anomaly was along the track of Hurricanes Hector and Lane. The daily Reynolds SST was originally chosen to be used in SHIPS since these SST data provide the longest record, from 1981 to current, which is important for SHIPS developmental database. Due to the poor quality of Reynolds SST, however, NHC is looking at using different SST data.

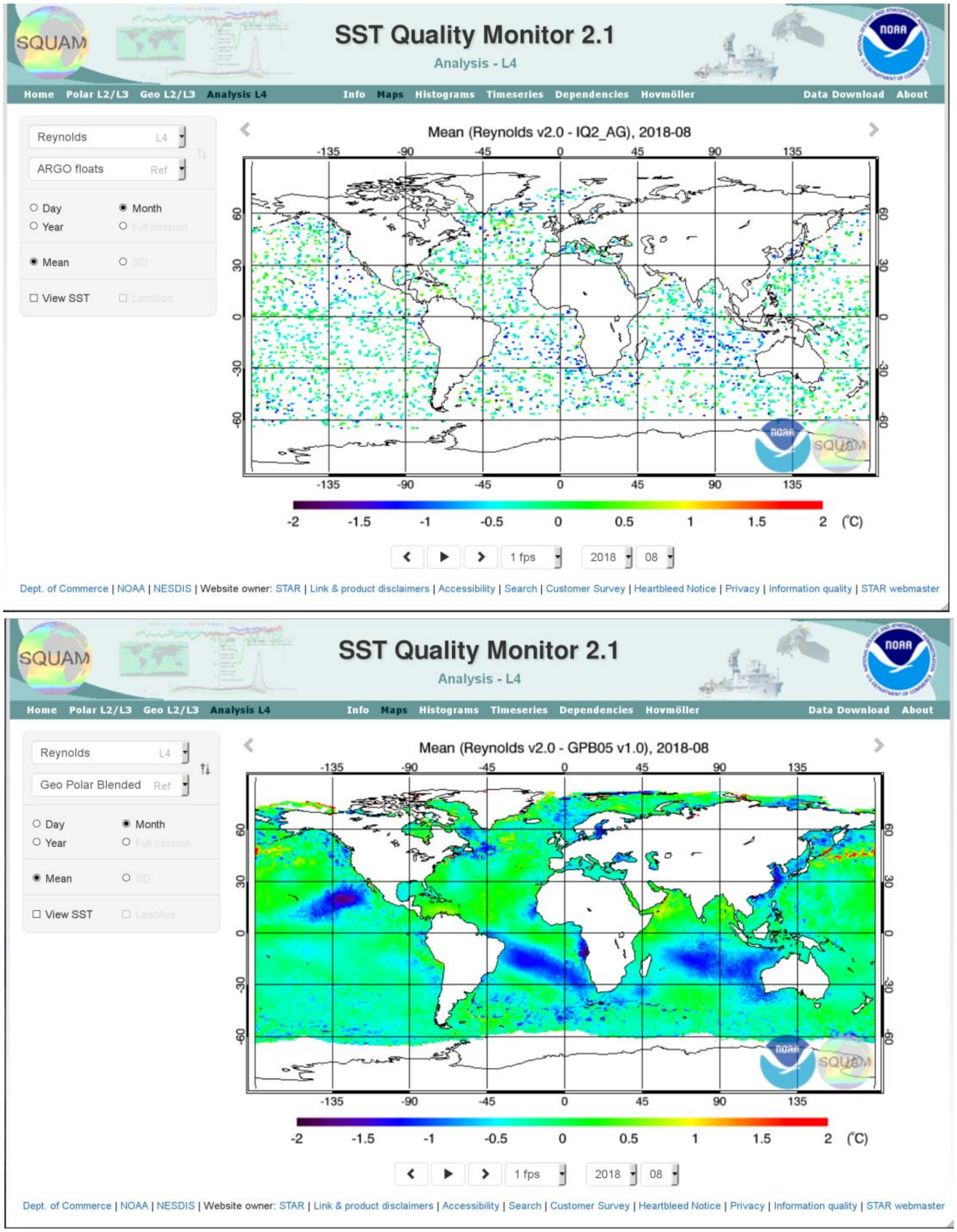

Figure 6. Comparison of daily Reynolds SST with ARGO floats (upper panel) and GeoPolar Blended SST (Loewr Panel). This figure is a snapshot taken from NOAA NESDID SST quality monitor (SQUAM) website, https://www.star.nesdis.noaa.gov/sod/sst/squam/ . Plots show the differences between SSTs for August, 2018. In August, 2018, the Reynolds Daily SST had unrealistically cold anomalies up to 2°C in east Pacific, which significantly affected forecasts for Hector and Lane.

Task 2: Modify SHIPS and LGEM models to use depth-averaged temperature (DAVT)

Lin et al. (2013) and Price (2009) have demonstrated that the use of tropical cyclone- (TC) cooled SST instead of SST to calculate the storm maximum potential intensity (MPI) produces a more realistic upper intensity bound estimate and that the ocean temperature vertically-averaged from the surface to the depth of TC-induced mixing is a more robust metric of the SST cooling effect than the OHC. The goal of this part of the project was to develop software for generating estimates of depth-averaged temperature (DAVT) for both SHIPS developmental database and real-time diagnostic files, and to add to SHIPS and LGEM the capability to use DAVT data.

2.1 Develop database of DAVT data and climatology.

Originally it was planned to estimate DAVT from the ocean data provided by N Shay and/or NCODA datasets. Both datasets provide SST, mixed layer depth (DML), and depth of 26°C and 20°C isotherms. Test of SHIPS and LGEM performed in the beginning of the project did not result in any forecast improvement, suggesting that the available data do not provide sufficient information to obtain accurate estimates of DAVT. Specifically, one of the challenges was with estimating DAVT for mixing depths larger than the depth of 20°C isotherm. That step requires extrapolation of ocean temperature profile that changes non-linearly with depth. After several experiments it was concluded that to obtain reliable DAVT estimate, full ocean temperature profiles were needed.

NHC requested that ocean data be completely re-derived from the full NCODA ocean profiles available at ftp://usgodae.org/pub/outgoing/fnmoc/models/glb_ocn/. The OHC, the subsurface ocean data, and the corresponding climatologies were completely re-derived from full ocean profiles to obtain an input dataset that allows for the accurate calculation of DAVT. The new dataset includes, DML, OHC relative to 26°C isotherm, OHC relative to 20°C isotherm, depth of all isotherms from 16°C to 32°C, as well as the maximum temperature (Tmax) at each point to capture temperature inversions, and the depth of the ocean and the temperature of the lowest available level in each profile. These additional points allow for a very accurate estimation of DAVT. Additional data were added to 2018 version of SHIPS developmental database that includes data for 1982 – 2017 for the Atlantic and east/central Pacific.

As a next step, the software for calculating DAVT assuming constant or varying mixing depth and adding that information to SHIPS developmental database and real-time diagnostic datafiles was developed. The DAVT assuming variable mixing depth was included in SHIPS/LGEM by using the "ocean age" (OA) variable. The OA is a measure of the amount of time that the storm area within R = 60 nmi has been over the same patch of the ocean (Figure 7). The OA is estimated as

$$OA = \int_{-L_{max}}^{0} F dt, \tag{1}$$

where

$$L_{max} = \max T_{lag} \text{ with } D < 2R, \tag{2}$$

where R is the storm radius, and D – distance between storm center at time t = -L and t = 0 .

The mixing depth as a function of storm translational speed (captured by OA) and latitude is estimated from

$$Mixing\ Depth = \mathrm{a} + \mathrm{b} * (\mathrm{OAGE}) + \mathrm{c} * (OAGE)^2, \tag{3}$$

where *OAGE* is the ocean age, and a, b, and c are empirical constants. The form of this equation is based on the idealized numerical simulations of Yablonsky and Ginis (2009) with a coupled hurricane model. The linear term in (3) represents mixing processes and the quadratic term represents upwelling. The upwelling time scale depends on the inertial period, so the ocean age is scaled by that. The mixing does not depend explicitly on the inertial period, so the ocean age in the linear term is scaled by a constant reference inertial period. The intensity of Hurricane Blanca (2015) could be used as an example of the use of OA parameter. Blanca rapidly weakened over warm ocean with high OHC content, likely due the SST cooling caused by the slow storm motion.

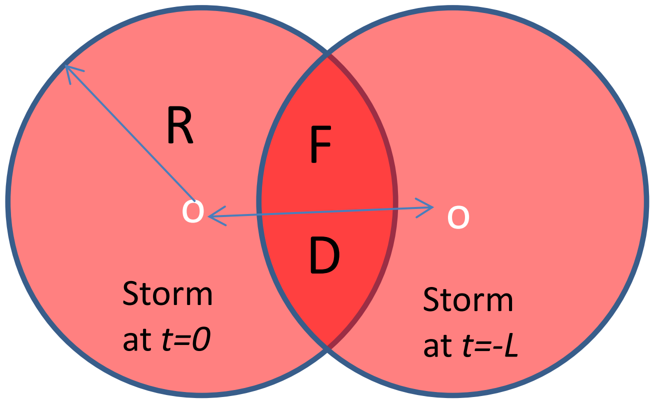

Figure 7. Illustration of how the Ocean Age parameter is estimated. OA is a measure of the time the TC spent over the same area of the ocean.

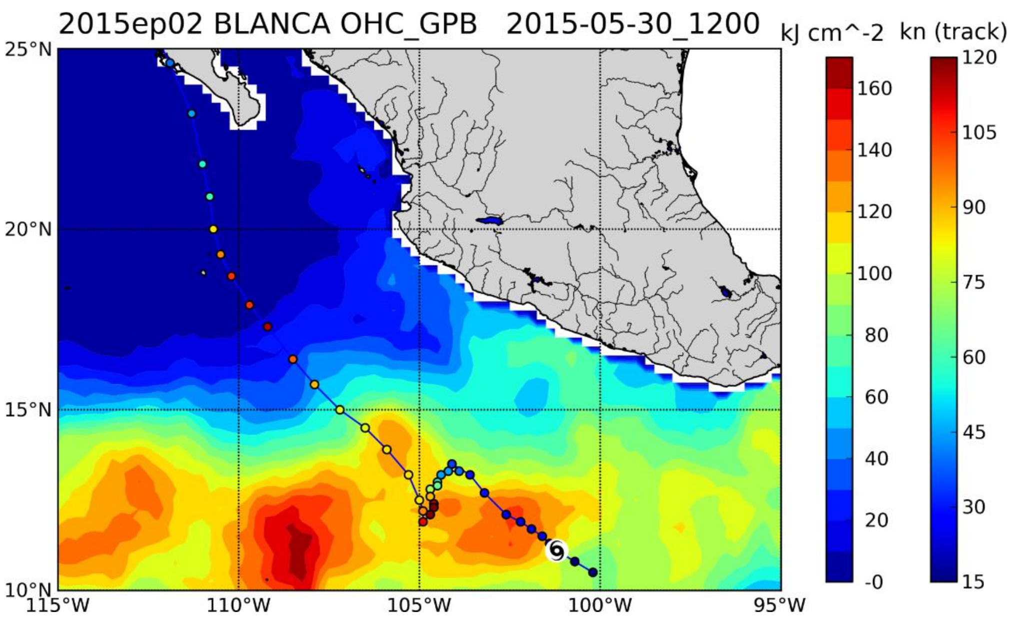

Figure 8. Hurricane Blanca (2015) track. Blanca rapidly weakened over relatively high SST and OHC. One of the possible reasons could be that the SST was cooled since Blanca was moving slowly and spent significant amount of time over the same area of the ocean.

The software for generating past and real-time EOHC data, the 2005 – 2017 EOHC data, the climatology of all EOHC variables, the corresponding readers and writers, the software for generating climatology, and for adding climatological values to the SHIPS diagnostic files was provided to NHC and transitioned to operations for 2018 season.

The DAVT is first calculated assuming either constant mixing depth of 25 m – 100 m or variable mixing depth estimated from the ocean age parameter. As a next step, the area-averaged daily SST is adjusted by the difference between EOHC SST and DAVT calculated in the first step. All variables used for testing are summarized in Table 1. Figure 9 shows several scatter plots of DSTA vs DS16, DSOA, and RTOA. It could be seen that DAVT can show significant variability for the same values of SST. Also, DSOA and RTOA were the two main variables used for testing. As could be seen from Figure 9, DSOA and RTOA are similar in most cases. However, they could differ by as much as 2 – 3 °C in some cases.

DAVT predictor name	DAVT predictor description
DSTA or RDLY	Area-averaged (R = 50 km) daily Reynolds SST
KSST or NDLY	NCODA SST from EOHC dataset
KOHC	NCODA OHC from EOHC dataset
KT05	DAVT assuming constant mixing depth dmix = 25 m
KT10	DAVT assuming constant mixing depth dmix = 50 m
KT16	DAVT assuming constant mixing depth dmix = 80 m
KT20	DAVT assuming constant mixing depth dmix = 100 m
RTOA	DAVT assuming variable dmix = f(OAGE)
DS05	DS05 = DSTA-(KSST-KT05)
DS10	DS10 = DSTA-(KSST-KT10)
DS16	DS16 = DSTA-(KSST-KT16)
DS20	DS20 = DSTA-(KSST-KT20)
DSOA	DSOA = DSTA-(KSST-RTOA)

Table 1. Names and description of variables used for SHIPS dependent sample testing for the Atlantic and east Pacific basins.

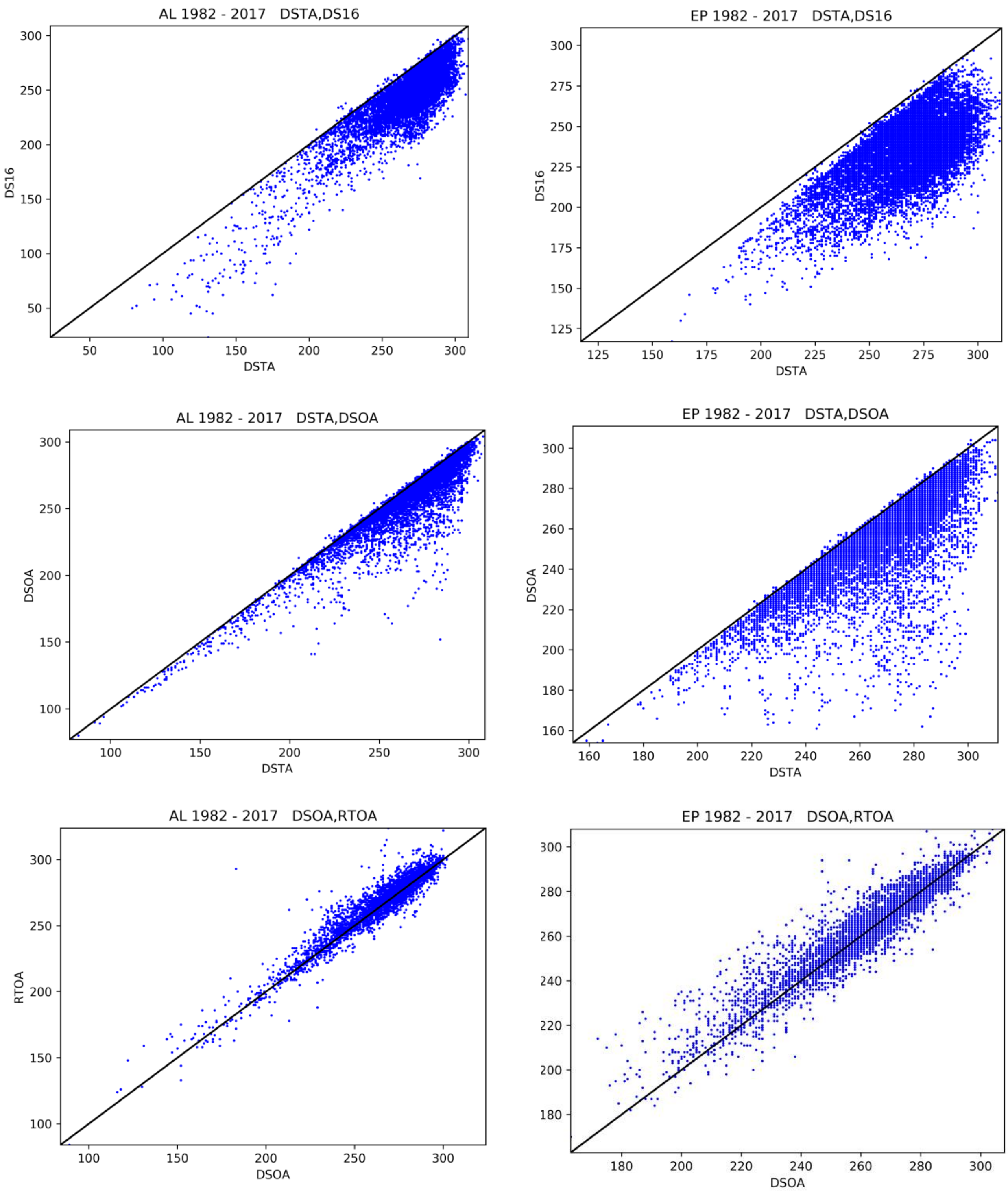

*Figure 9. Scatter plots for the Atlantic (left) and east Pacific (Right) of DSTA vs DS16 (upper row), DSTA vs DSOA (middle row), and DSOA vs RTOA (lower row). Units are °C * 10.*

2.2 Modifications to Rapid Intensification Index (RII). Both SHIPS and LGEM use the RII forecast a predictor. The possibility of adding DAVT to the RII was investigated. As a first step, the value of the minimum potential at which RI, defined as at least 55 kt intensity increase in 48 hours was determined. It was found that for the Atlantic the minimum potential at which RI occurs in the 1982 – 2017 database, is 38.01 kt (max potential is 126.71 kt). For the east Pacific the corresponding numbers are 64.05 kt (min) and 138.29 max. Table 1 summarizes the values of the minimum potential at which RI can occur for DSTA, as well as for different versions of DAVT. Limited testing was conducted with replacing SST and/or OHC by different versions of DAVT in the RII. The results were mixed, and it was decided to use version of RII with DSTA and OHC for further testing. The minimum potential, however, was adjusted in the version of RII used for testing.

	Atlantic	East Pacific
SST Variable	Min Potential at which RI occurs in the database, kt	Min Potential at which RI occurs in the database , kt
DSTA	38.01	64.05
KT05	50.44	57.7
KT10	41,46	42.89
KT16	30.42	16.13
KT20	25.73	2.47
KT25	19.95	2.26
RTOA	37.55	50.03
DS05	35.42	60.92
DS10	30.24	45.52
DS16	23.93	14.6
DS20	19.84	2.67
DS25	12.59	1.43
DSOA	32.3	40.20

Table 2. Values of the minimum potential at which 55 kt/48 hr RI occurs in the 1982 – 2017 SHIPS developmental database.

2.3. Modify SHIPS/LGEM to use DAVT calculated assuming constant and variable mixing depth. Modifications were made to SHIPS/LGEM developmental code as well as to SHIPS and LGEM to use all versions of DAVT listed in Table 1. The code was modified in a way to allow to use different versions of SST, OHC, and DAVT for all different parts of the code, including SHIPS, LGEM, and several versions of RII. Corresponding flags were added to SHIPS code to allow for easy selection of different options. In addition, some common processing blocks were identified and moved to a new OHC and SST processing modules. The updated SHIPS/LGEM code allow to use different SST/OHC/DAVT variables for different parts of the code. It also does all necessary pre-processing for different versions of SST, OHC, and DAVT, which makes it easy to either replace SST or OHC by DAVT, or add a new predictor based on DAVT.

2.4 Dependent sample tests with replacing SST by DAVT. Dependent sample tests using 1982-2017 SHIPS developmental database are shown on Figure 10. For the Atlantic basin three different tests are shown. For the Atlantic basin the operational SHIPS/LGEM use storm-cooled SST, where SST cooling is estimated using J. Cione empirical SST cooling equation. Three different experiments are shown, with J Cione cooling turned either on or off for both experimental and baseline models. Figure 11, the Upper Right panel, shows the improvement of experimental models relative to baseline, where J Cione cooling is not used.

That version shows most improvement for the Atlantic, with overall most improvement at all forecast time with DSTA replaced by DSOA. Figure 10, Upper Left, shows the same results but the baseline model is using J. Cione's ocean cooling parameterization. Since the empirical cooling is trying to account for the same effects that are added by using DAVT, the improvement is more moderate relative to baseline with empirical cooling. Finally, the Lower Left panel on Figure 10 shows the same results where the experimental models do not use empirical cooling, while baseline mode uses empirical cooling. This shows that there is no improvement from adding DAVT, unless empirical J. Cione cooling is used as well. These results suggest that empirical J Cione cooling is still providing very important improvement for the Atlantic, even with DAVT added to the models. The most significant improvement is observed for SHIPS for east Pacific with using DSOA (cyan line) or RTOA (dotted cyan line). Based on the above tests, DSTA was replaced by DSOA for SHIPS and LGEM reruns for 2010 – 2017 and independent reruns for 2018, and J. Cione cooling was turned on for all rerun tests.

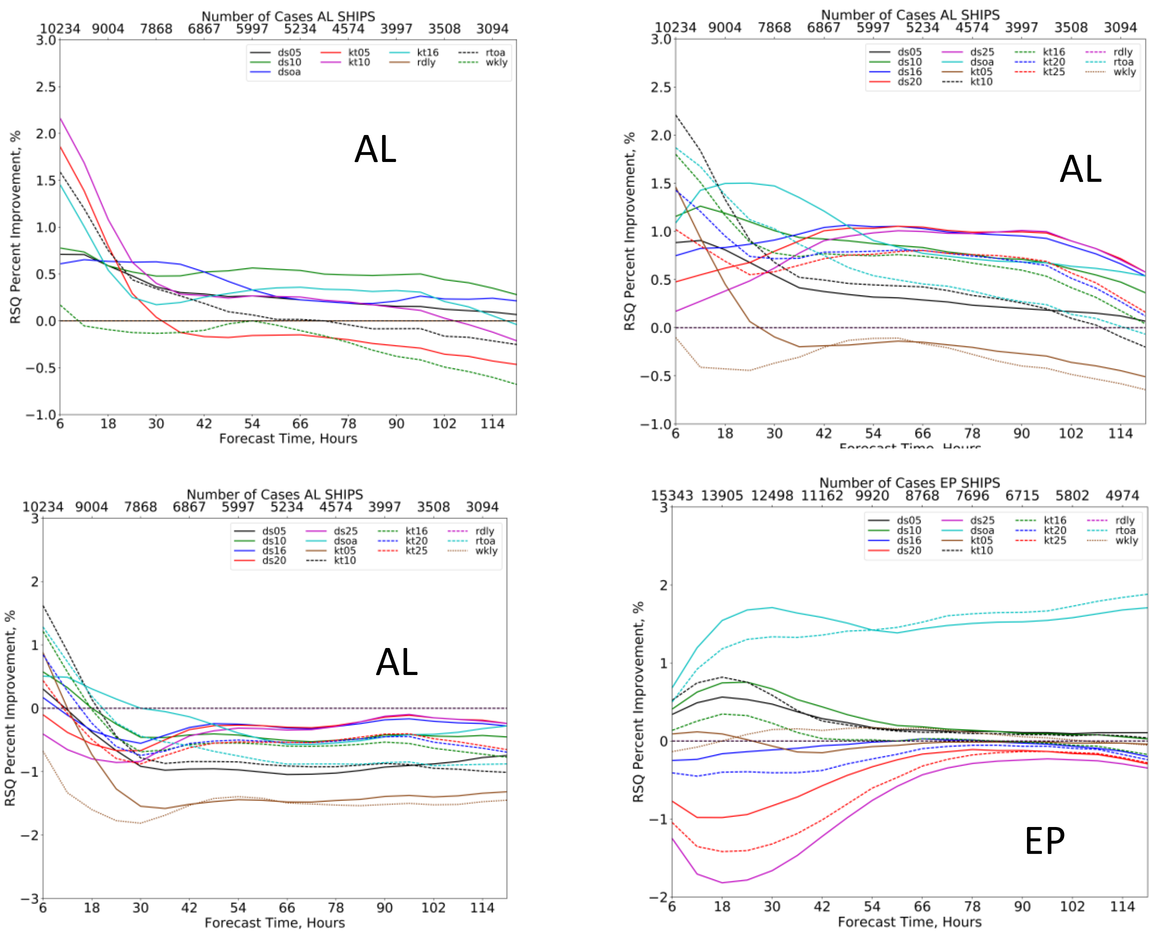

Figure 10. Upper left: R^2 percent improvement for SHIPS dependent tests for the Atlantic with DSTA replaced by different versions of DAVT. Black horizontal line is the baseline daily SST (DSTA). Shown are: Upper Left: forecast percent improvement for the Atlantic basin with J Cione cooling turned on for both baseline model and experimental models. Upper Right: same but with J Cione cooling turned off for both experimental and baseline models. Lower Left: same, but with J. Cione cooling turned off for experimental models, and J Cione cooling turned on for the baseline model. Lower Right: east Pacific. The most significant improvement is observed for SHIPS for east Pacific with using DSOA (cyan line) or RTOA (dotted cyan line).

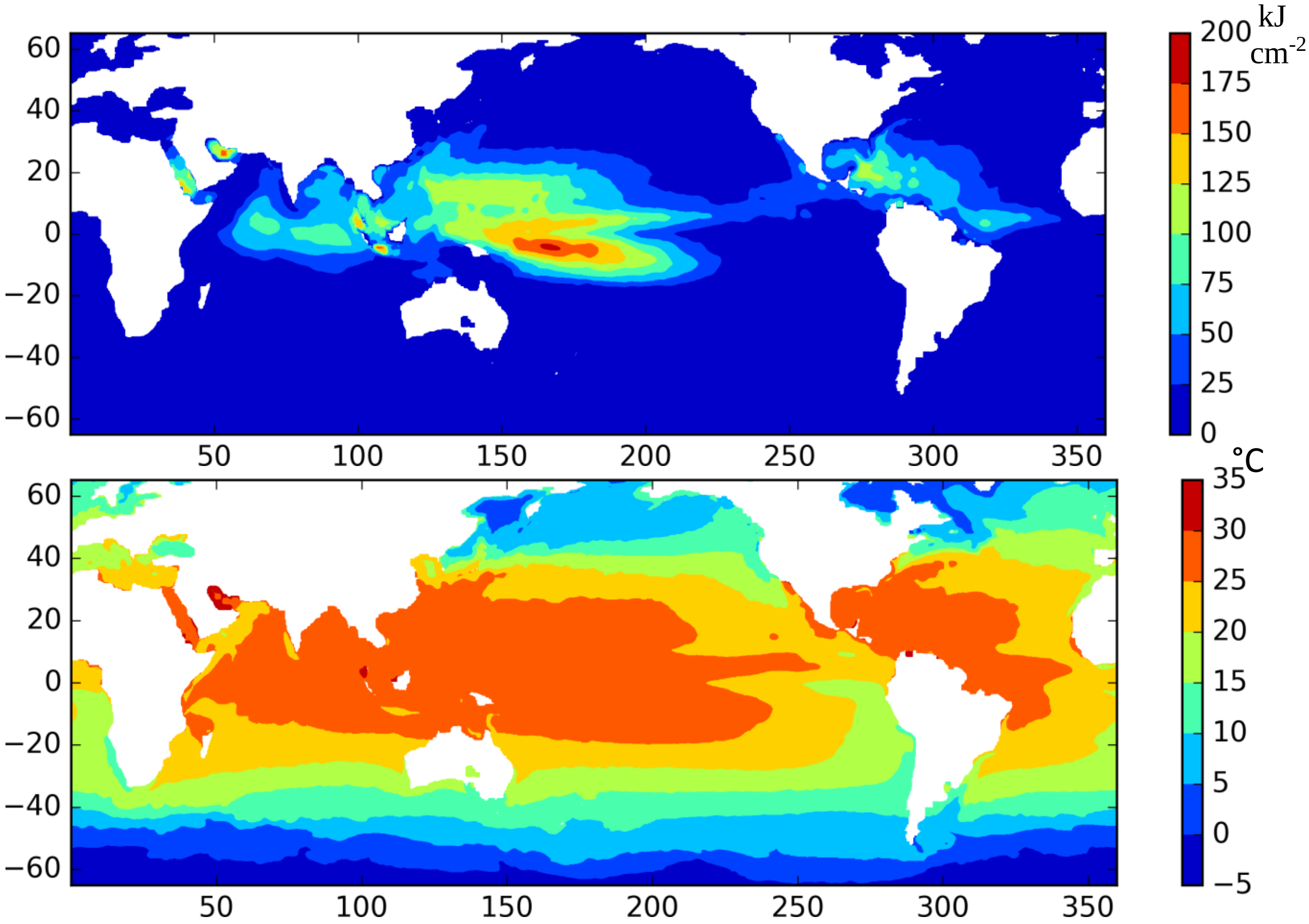

Figure 11. Upper panel. OHC climatology for September. Lower panel: DAVT assuming dmix = 80 m. 80m is typical mixing depth for Cat 3 Hurricane.

2.5. *Dependent sample tests with replacing OHC by DAVT.*

In addition to replacing SST used to calculate the Maximum Potential Intensity (MPI) by different versions of DAVT, tests were conducted with using different versions of DAVT as a replacement for the OHC predictor. According to Price (2009), OHC and DAVT assuming dmix = 100 m are well correlated over the deep ocean when OHC is 75 kJ cm^{-2} or higher. OHC and DAVT are poorly correlated for low OHC values below 50 kJ cm^{-2}. The most significant differences between DAVT and OHC are observed over the cold water (SST < 26ºC) and over shallow continental shelf where OHC tends to be low even for high SST values. (Price, 2009). That is consistent with the results shown on Figures 11 and 12. Figure 11 shows OHC (Upper panel) and KT16 (Lower panel) climatology for September. The climatology is based on 2007 – 2017 data. It could be noted that there are two situations where DAVT is poorly correlated with OHC. DAVT shows a lot of variation at higher latitudes, where OHC is zero because the SST is below 26°C. Also, DAVT shows high values in the Gulf of Mexico where OHC is rather low. That reflects the limited usefulness of OHC in shallow water conditions and is consistent with Price (2009) results.

Figure 12 shows higher correlation between OHC and RTOA in the east Pacific and lower correlation in the Atlantic where many regions have a wide continental shelf and shallow ocean conditions. Note that for the Atlantic there are (a) OHC values equal 0 while RTOA changes from 8°C to 27ºC. The colder part of that corresponds to cold water (SST < 26 ºC), and the warmer part of that likely correspond to shallow shelf, where RTOA is increasing as SST is increasing, but OHC remains rather low. These are the two situations where OHC and DAVT are poorly correlated. Figure 12 only uses the data along TC tracks from 1982 – 2017 SHIPS developmental database, thus these situations when OHC and DAVT are poorly correlated are often encountered along TC tracks, especially in the Atlantic basin.

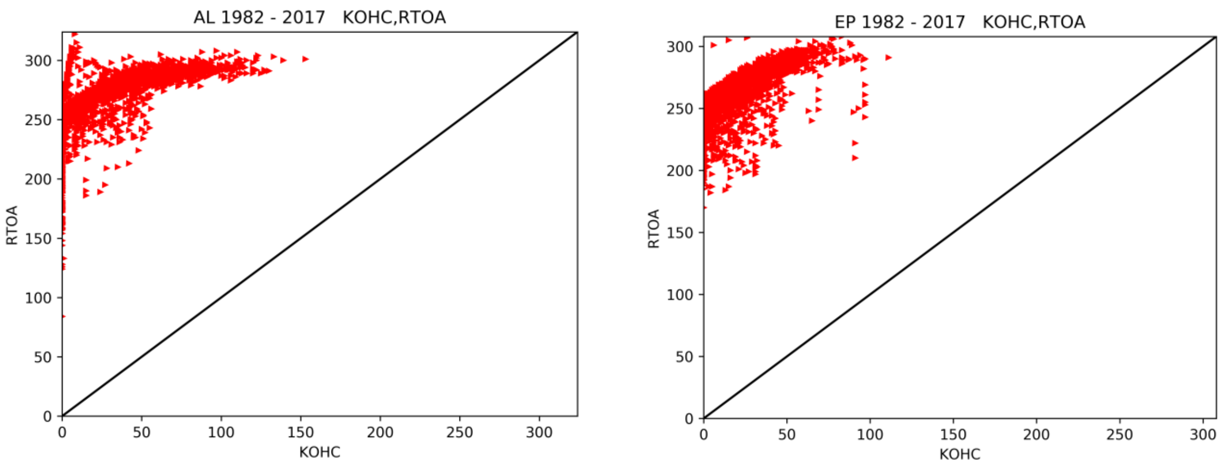

*Figure 12. Scatter plot of RTOA (units ºC * 10) vs KOHC (kJ cm $^{-2}$) for the points long the TC tracks from 1982 – 2017 SHIPS developmental database. The correlation between RTOA and KOHC is higher for the east/central Pacific than for the Atlantic basin.*

Dependent sample tests using 1982-2017 SHIPS developmental database are shown on Figure 13. For the Atlantic the most improvement is observed with replacing OHC by RTOA at 6 hr FLT. For the east Pacific replacing OHC by either DSOA or RTOA shows forecast improvement at all FLTs, with the most improvement at 120 hr FLT, up to 2.0 PI, with replacing OHC by RTOA. Based on these results an experimental model with OHC replaced by RTOA was used for dependent 2010-2017 reruns and independent 2018 reruns.

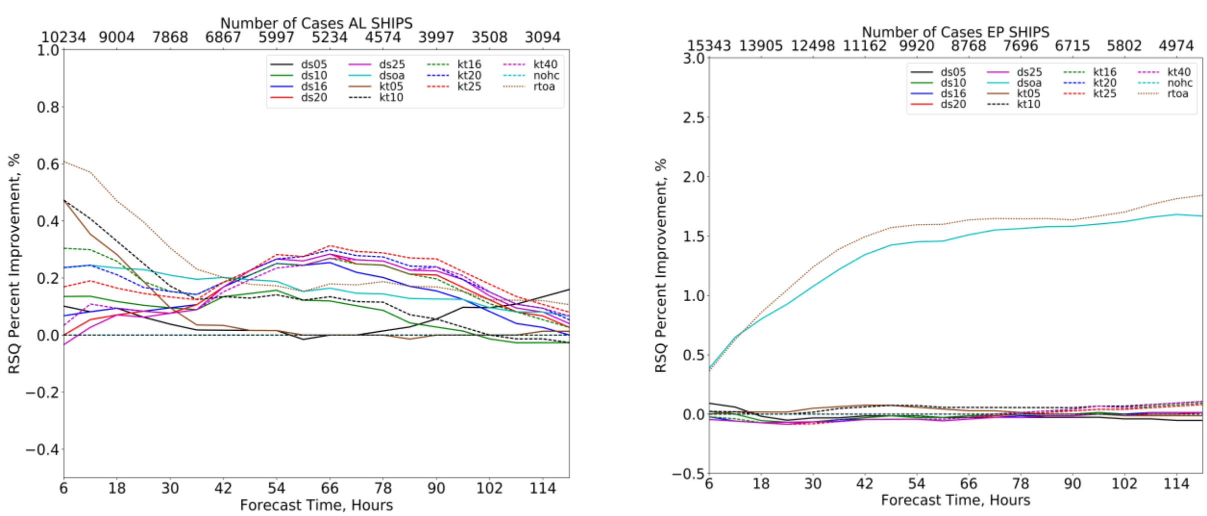

Figure 13. R^2 percent improvement for SHIPS dependent tests for the Atlantic (left) and east Pacific (right) with OHC replaced by different versions of DAVT. The most significant improvement is observed for SHIPS for east Pacific with using DSOA (cyan line) or RTOA (dotted brown line).

2.6. SHIPS/LGEM verification with SST or OHC replaced by DAVT.

Figure 14 shows verification results for the experimental 2018 version of SHIPS with (a) DSTA replaced by DSOA (Run 63) and (b) OHC replaced by RTOA (Run 65) for the years 2010 - 2017 and Figure 15 shows the independent verification of the same versions of SHIPS/LGEM for 2018. The improvement is shown reliable to a baseline version with are-averaged daily SST (DSTA) used as SST (Run 50). The baseline version is the rerun of SHIPS/LGEM conducted at CIRA using the 2018 operational version of SHIPS LGEM with DSTA and OHC. The results show the most improvement for the LGEM forecast for the East Pacific, and overall are consistent with the previous results. In the Atlantic SHIPS forecast is improved by up to 1.3 PI at 36 hr FLT for Run 63 and up to 0.8 PI at 36 hr FLT for Run 65. For east Pacific SHIPS forecast shows most improvement at 48 hr FLT, with most significant improvement, up to 4 PI for Run 63. At long FLT, longer that 84 – 96 hr, the SHIPS east Pacific forecast in experimental models gets significantly worse than baseline version. For LGEM, the most significant and stable improvement is observed for east Pacific, with up to 8 PI at 72 hr FLT for Run 63. For the Atlantic most improvement for LGEM is observed with using RTOA instead of OHC (Run 65), with most improvement (up to 2.4 PI) at 120 hr FLT.

The independent verification for 2018 (Figure 15) shows most improvement for the Atlantic, with up to 8 PI in SHIPS at FLT of 120 hr for Run 63, and up to 6.8 PI for 72 hr FLT for LGEM for Run 63. Run 63 also works best for SHIPS for east Pacific, with up to 5 PI for SHIPS at 48 hr FLT. It's interesting that for east Pacific LGEM shows the least forecast improvement for 2018, while the experimental models performance was best for LGEM for east Pacific for 2010 – 2017 sample. It should be also noted that for 2018 for most FLTs Run 65 shows more improvement compared to Run 63. One possible explanation could be differences in SST and the sensitivity of the experimental models, especially Run 63 to quality of SST data. As was discussed earlier, the daily Reynolds SST had very large and unrealistic cold anomalies in east Pacific in 2018 that significantly affected SHIPS and LGEM performance. That could possibly explain better performance of experimental model Run 65 that replaces OHC by RTOA which is independent for daily Reynolds SST. Verification of experimental Run 63 and Run 65 for 2010 – 2017 was also conducted for central Pacific, and it was found that the central Pacific forecast does not improve, and can get significantly worse with the experimental models.

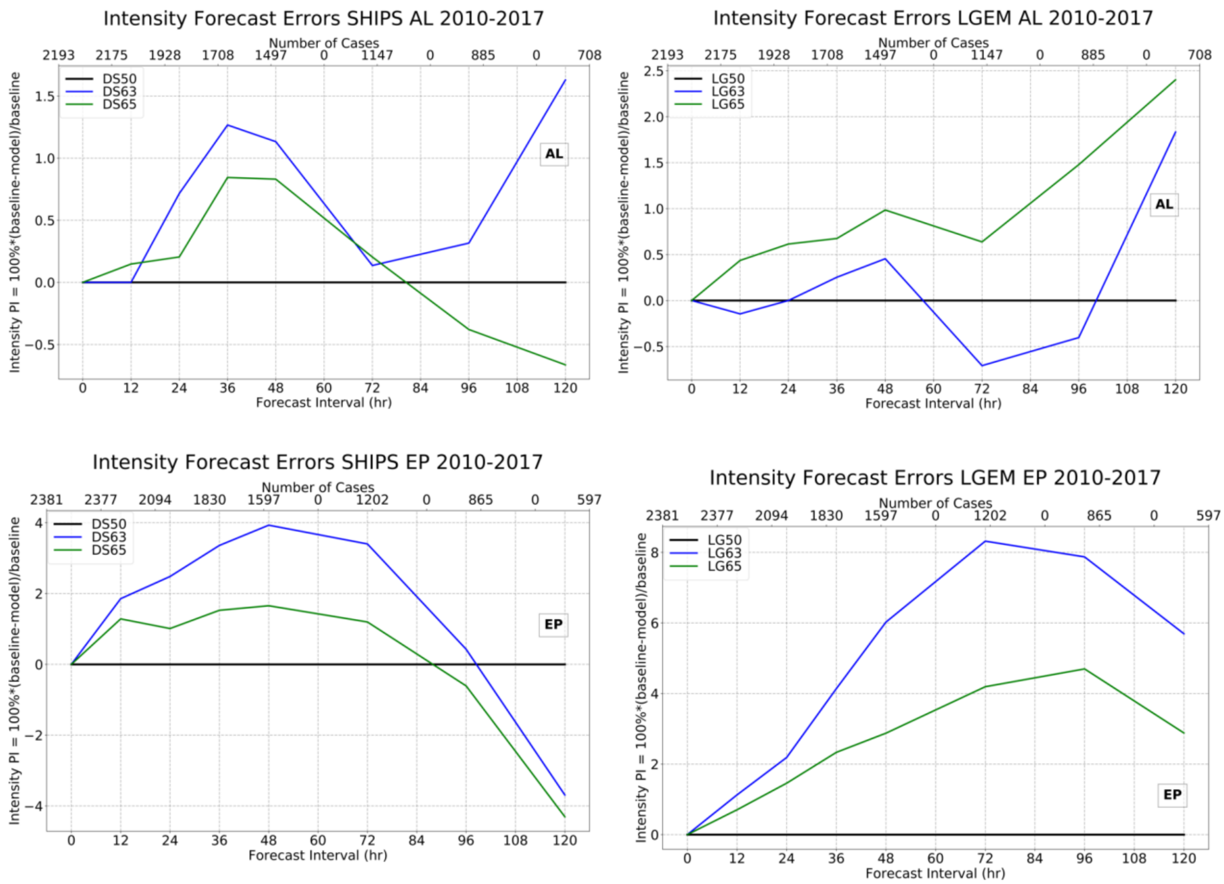

Figure 14: SHIPS (left column) and LGEM (right column) forecast verification for 2010 - 2017 for Atlantic (upper row) and east Pacific (bottom row). Shown is forecast Percent Improvement (PI) with SST replaced by DSOA (blue line, Run 63), and forecast PI with OHC replaced by RTOA (green line, Run 65) relative to the baseline model that uses DSTA and OHC (Run 50, horizontal black line). The most significant improvement for all forecast lead times is seen in the east Pacific for LGEM (blue line, Run 63, replaces DSTA by DSOA).

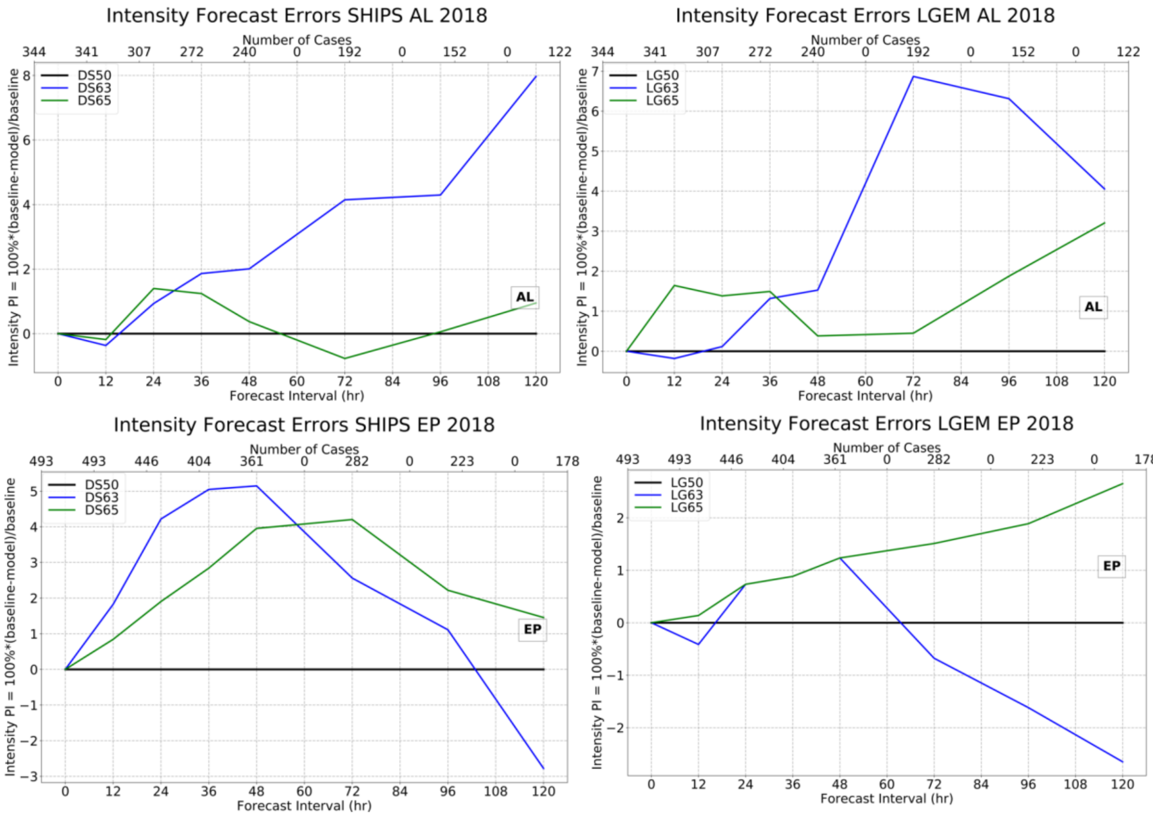

Figure 15: Same as Figure 2, but shows independent verification for 2018.

Overall, experiments with Run 63 and Run 65 shows that using DAVT in SHIPS and LGEM could result in a very significant intensity forecast improvement, especially for middle (36 – 48 hr) and long (72 – 120 hr) FLTs. The most improvement is found with using DSOA or RTOA which are estimated assuming variable mixing depth estimated using the OA parameter. The experiments were conducted with replacing either SST or OHC by DAVT. Another possible way to use additional information provided by DAVT would be to add a new DAVT-based predictor to SHIPS and LGEM, instead of replacing existing predictors. That way the information provided by SST and OHC will be preserved in the models, and DAVT would be adding a correction term. Also, the DAVT estimates might not be accurate enough for calculating MPI, which might be especially important for the Atlantic where empirical MPI function in non-linear. Possible options include using the SST cooling, (DSTA-DSOA) or (DSTA-RTOA), or DSOA or RTOA as new predictors. Because of the issues with daily Reynolds SST that were revealed during the 2018 season, NHC is looking at using different SST dataset instead of Reynolds SST for 2019 season. Since SST is a very important variable and SST quality could significantly affect forecast, the final tests with selecting the best option of DAVT to use should be conducted with the version of SST that will be used for 2019 season.

Task3 : Develop Decay SHIPS Wind-Radii (DSWR) forecast model.

The DSWR model was developed and transitioned to operations at JTWC in 2017. NHC is planning to run DSWR in quasi-prod for 2019 season and transition it to operations for 2020 season. The details about DSWR model can be found in the following paper:

Knaff, J., C. Sampson, and G. Chirokova, 2017: A global statistical–dynamical tropical cyclone wind radii forecast scheme. *Wea. Forecasting*, **32**, 629–644, doi: 10.1175/WAF-D-16-0168.1.

Highlights of that paper suggest:

1. This method (DSWR) is a competitive method for predicting the wind radii, even if the SHIPS forecasts of intensity and track are used for wind radii estimates.
2. That its inclusion in a simple wind radii consensus (RVCN), results in no degradation, and, in most cases, improves the consensus forecasts.
3. That the predictors related to mid-level moisture (+), initial size (-), storm latitude (+), 200 hPa divergence (+) are best related to changes in TC size, the sign of the relationships is shown in parentheses.

Verification of DSWR for 2017 was completed and provided to NHC and JTWC. It was found that in the Atlantic DSWP performs similar to other methods and is high-biased. In the east Pacific DSWR is skillful relative to DRCL for 2017. The biases in both east and west Pacific are very low. In addition, it was found that DSWR improves the multi-model wind radii consensus, RVCN that includes GFS (AHNI), HWRF (HHFI), and ECMWF (EMXI). DSWR provided either improvements or no degradation to RVCN when added as a member for all basins and all wind radii thresholds. Figure 2 shows MAE for 2017 RVCN consensus wind radii forecasts with and without using DSWR. Verification of DSWR for west Pacific was also conducted and showed that it's inclusion in RVCN is beneficial and reduces biases caused by the global NWP.

The DSWR was transitioned to operations at JTWC in September 2017. It is planned to run DSWR in quasi-production at NHC on WCOSS for the 2019 Atlantic Hurricane season.

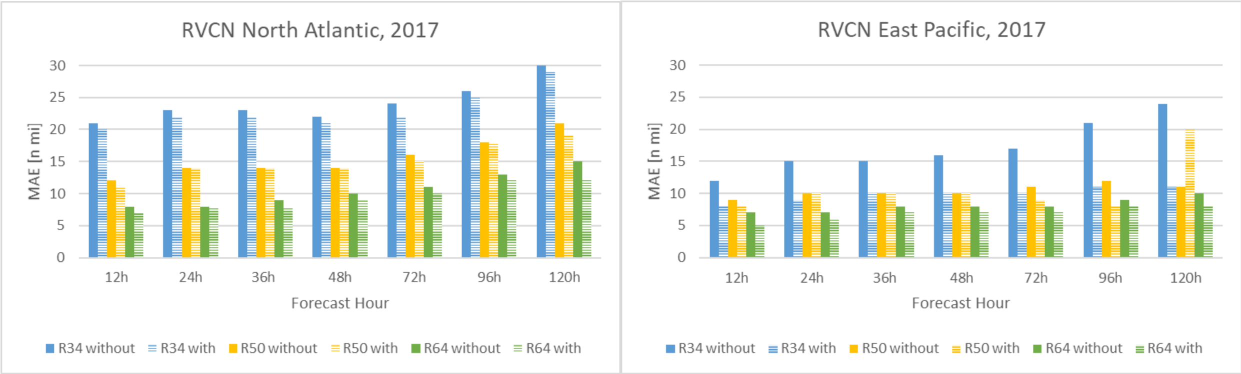

Figure 16: RVCN MAE (Left) for the Atlantic and (Right) East Pacific basin. RVCN included HWRF, GFS, and ECMWF. Solid bars show runs without DSWR and dashed bars show runs with DSWR.

What opportunities for training and professional development has the project provided?

People working on the project obtained increased knowledge and skills in the development of statistical models. Project PIs, Galina Chirokova (in 2016, 2017, and 2018), Andrea Schumacher (in 2017) and Collaborator, John Knaff (in 2016) participated in the TCORF/IHC conferences. There were no training activities during the reporting period.

How were the results disseminated to communities of interest?

1) The project results were presented at the IHC in 2016, 2017, and 2018) The IHC presentations and previous project reports are available online at http://www.nhc.noaa.gov/jht/15-17_proj.php?large. Additional details about the project were communicated to NHC points of contact, Dan Brown, Lixion Avila, and Chris Landsea.

2) Real-time DSWR (2016 and 2017) and SHIPS/LGEM with DSST (2016) forecasts were also provided to NHC POCs via an ftp server per NHC's request.

3) Verification of 2016 retrospective runs with DSST and dependent test with DAVT were provided to NHC.

3) The DSWR code has been provided to NHC and Naval Research Laboratory (NRL), Monterey for implementation at JTWC. The DSWR was transitioned to operations at JTWC in September, 2017.

4) The 2017 SHIPS/LGEM code updated to use RSST, DSST, or DAVT was provided to NHC. The changes will be implemented in the 2018 operational version of SHIPS.

5) The global and regional DSST and the new EOHC ocean data together with the software for creating and reading historical and real-time DSST and EOHC data were provided to NHC. The updated database of DSST, OHC, and ocean data will be included in the SHIPS developmental database, and should eventually replace the RSST and the old OHC data. The software for generating real-time DSST and OHC data will be used to generate data for the operational 2018 SHIPS and LGEM.

6) The updated climatology of DSST, OHC, D20, D26, DML, and all other variables included in the EOHC dataset, as well as the software for updating, reading, and including that climatology into SHIPS developmental database was provided to NHC.

What do you plan to do during the next reporting period to accomplish the goals and objectives?

This is the final report for this project. However, we plan to work with NHC and NRL/JTWC to provide to them the most updated software and databases developed for this project. We will also further work with JHT and NHC TSB staff to implement experimental versions of SHIPS/LGEM and DSWR on quasi-production on WCOSS for the 2019 season.

2. PRODUCTS

What were the major completed **products or deliverables** this period, and how do they compare to your proposed deliverables? (planned vs. actuals table recommended)

Product/Deliverable	Actual
2017 SHIPS/LGEM code modified to work with RSST, DSST, and DAVT	Provided to NHC as planned
Updated DSST database in SHIPS format for global and regional files for 1982 - 2017	Provided to NHC as planned. Will be provided to NRL/JTWC.

Verification of SHIPS/LGEM dependent tests with the re-derived DAVT	Provided to NHC as planned
New dataset of the OHC and subsurface ocean data for 2006 - 2017	Provided to NHC as planned. Will be provided to NRL/JTWC.
Updated climatology for DSST, OHC, MLD, and depths of 16° (D16) - d32° (D20) isotherms	Provided to NHC as planned
Updated software for processing DSST and EOHC climatology	Provided to NHC as planned
Software for real-time processing of DSST and EOHC data	Provided to NHC as planned. Will be provided to NRL/JTWC.
Verification of DSWR runs	Provided to NHC/JTWC as planned
Software for estimating DAVT from variables saved in SHIPS diagnostic files	Final version will be provided to NHC and NRL/JTWC
Software for adding position for the last 5 days to SHIPS diagnostic files, that is required to calculate OA parameter in real-time.	Final version will be provided to NHC and NRL/JTWC
Software for adding EOHC data to both developmental and real-time diagnostic files.	Final version will be provided to NHC and NRL/JTWC
Software for adding DSOA and RTOA to both developmental and real-time diagnostic files.	Final version will be provided to NHC and NRL/JTWC
SHIPS developmental code with options to use multiple versions of SST and DAVT as a replacement for SST or OHC, or as an additional predictor	Final version will be provided to NHC
2018 version of SHIPS/LGEM modified to include DAVT, and options to use different versions of SST and DAVT. DAVT can be used as a replacement for OHC and/or SST, or as an additional predcitor, and different versions can be selected for different parts of SHIPS code, including SHIPS, LGEM, and different versions of RII.	Final version will be provided to NHC
Verification results for dependent and independent SHIPS/LGEM reruns with DAVT	Included in this report

What has the project produced?
-publications, conference papers, and presentations*;

Presentations:

Chirokova G., J. Kaplan, and J. Knaff, 2018: Improvements to Operational Statistical Tropical Cyclone Intensity Forecast Models Using Wind Structure and Eye Predictors. *2018 Tropical Cyclone Operations and Research Forum (TCORF)/71th Interdepartmental Hurricane Conference (IHC), 13-15 March, 2018, Miami, Florida.* The presentation will be available online at http://www.nhc.noaa.gov/jht/15-17_proj.php?large.

Schumacher A., G. Chirokova, J. Knaff, and M. DeMaria, 2018: Improvements to Operational Statistical Tropical Cyclone Intensity Forecast Models. 98th AMS Annual Meeting / 22nd Conference on Satellite Meteorology and Oceanography, 7 - 11 January 2018, Austin Texas

Chirokova G., J. Knaff, and A. Schumacher, 2017: Improvements to operational statistical tropical cyclone intensity forecast models. *2017 Tropical Cyclone Operations and Research Forum (TCORF)/70th Interdepartmental Hurricane Conference (IHC), 13-16 March, 2017, Miami, Florida.* The presentation will be available online at http://www.nhc.noaa.gov/jht/15-17_proj.php?large.

Chirokova G., J. Knaff, and A. Schumacher, 2016: Improvements to operational statistical tropical cyclone intensity forecast models. *2016 Tropical Cyclone Operations and Research Forum (TCORF)/70th Interdepartmental Hurricane Conference (IHC), 14-17 March, 2016, Miami, Florida.* The presentation is available online at http://docs.google.com/viewer?url=http://www.nhc.noaa.gov/jht/ihc_16/ihc16chirokova-s04-04.pdf?time=0

Knaff, J. A., G. Chirokova, C. R. Sampson, and M. DeMaria, 2016: Development of Global Statistical-Dynamical Tropical Cyclone Wind Radii and MSLP Guidance. *32nd AMS Conference on Hurricanes and Tropical Meteorology, 18-20 April 2016, San Juan, Puerto Rico.*

Publication: A manuscript detailing the statistical-dynamical method to predict tropical cyclone wind structure in terms of wind radii method, its independent performance in 2014 and 2015, and how it may contribute to the wind radii consensus has been published in Weather and Forecasting.

Knaff, J., C. Sampson, and G. Chirokova, 2017: A global statistical–dynamical tropical cyclone wind radii forecast scheme. *Wea. Forecasting*, **32**, 629–644, doi: 10.1175/WAF-D-16-0168.1.

Highlights of that paper suggest:

4. This method (DSWR) is a competitive method for predicting the wind radii, even if the SHIPS forecasts of intensity and track are used for wind radii estimates.
5. That its inclusion in a simple wind radii consensus (RVCN), results in no degradation, and, in most cases, improves the consensus forecasts.
6. That the predictors related to mid-level moisture (+), initial size (-), storm latitude (+), 200 hPa divergence (+) are best related to changes in TC size, the sign of the relationships is shown in parentheses.

-website(s) or other Internet site(s);

- The real-time DSRW forecasts are available at ftp://rammftp.cira.colostate.edu/knaff/DSWR/

-technologies or techniques;

- Improved (lower biased) TC vortex model for wind radii.
- Method to estimate DAVT from limited ocean parameters.
- Method to estimate the Ocean Age parameter to account for storm translational speed and the corresponding varying mixing depth

-inventions, patent applications, and/or licenses; and

None

-other products, such as data or databases, physical collections, audio or video products, software, models, educational aids or curricula, instruments or equipment, research material, interventions (e.g., clinical or educational), or new business creation.

- New improved EOHC dataset that includes OHC and other subsurface ocean data. EOHC dataset includes both global and regional files.
- Database of DSST data converted to SHIPS input format. The database includes both global and regional files.
- Updated climatology of DSST, OHC, MDL, D16 - D32, based on the EOHC data for 2005 - 2017
- Database of NCODA OHC, D16 - D32, OHC20, and MLD converted to SHIPS input format. The database includes both global and regional files.

*For **publications**, please include a full reference and digital object identifier (DOI; http://www.apastyle.org/learn/faqs/what-is-doi.aspx) and attach all publications and presentations on this project from this reporting period to the progress report, or include web links to on-line versions. Within your publications and presentations, please include language crediting the appropriate NOAA/OAR organization and program (e.g., NOAA/OAR/OWAQ and the U.S. Weather Research Program; or NOAA/OAR/NSSL and the VORTEX-SE program) for financially supporting your project. Suggested language is as follows:
"This material is based upon work supported by the U.S. Weather Research Program within NOAA/OAR Office of Weather and Air Quality under Grant No. XXXXXXX."

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on this project?

Galina Chirokova, John Knaff, Andrea Schumacher, Robert DeMaria, Jack Dostalek

Has there been a change in the PD/PI(s) or senior/key personnel since the last reporting period?

No

What other organizations have been involved as partners? Have other collaborators or contacts been involved?

NHC points of contact have been involved. Also, work for this project has been coordinated with NHC TSB branch.

4. IMPACT

What was the impact on the development of the principal discipline(s) of the project?
The project addresses program priorities NHC-1/JTWC- 1, NHC-13/JTWC- 10, and NHC-17/JTWC-13. The results of this project will first provide improved statistical-dynamical guidance for TC intensity. These intensity guidance techniques are routinely used operationally at NHC and JTWC to forecast TC intensity. Secondly this project developed a new statistical-dynamical forecast guidance for TC structure (i.e., wind radii) that appears somewhat independent to NWP guidance, making it a nice addition to wind radii consensus methods.

What was the impact on other disciplines?

The results of this project should allow for improved operational TC intensity and structure forecasts that are important for other agencies and general public. Improvements in these capabilities may also lead to other high priority forecasts (e.g., storm surge watch/warnings, wave forecasts) and decisions (e.g., evacuations, ship routing).

What was the impact on the development of human resources?
Nothing to report

What was the impact on teaching and educational experiences?
Nothing to report

What was the impact on physical, institutional, and information resources that form infrastructure?
Nothing to report

What was the impact on technology transfer?
Methods developed at CIRA, if approved by the JHT, will transition to NHC operations. Two parts of this project, SHIPS/LGEM with daily SST and DSWR were already transitioned to operations. In addition, the new EOHC dataset has been used operationally AT NHC for 2018 season. The technologies that were already transferred include the method for calculating DAVT calculations assuming constant or variable storm-induced mixing depth and a simple vortex model.

What was the impact on society beyond science and technology?
The results of this project should allow for improved operational TC intensity forecasts that are important for other governmental agencies, industry, and general public. These efforts significantly contribute to NOAA's goal of a *Weather-Ready Nation*.

What percentage of the award's budget was spent in a foreign country(ies)?
None

5. CHANGES/PROBLEMS

Describe the following:

-Changes in approach and reasons for the change.

It was found that the available ocean data that include SST, mixed-layer depth (DML), and depths of 26° and 20° isotherms (D26 and D20), do not provide enough information to accurately estimate DAVT. NHC requested that ocean data be completely re-derived from the full NCODA ocean profiles available at ftp://usgodae.org/pub/outgoing/fnmoc/models/glb_ocn/. The ocean data were re-derived, and the new EOHC dataset was developed using subsurface ocean data from full ocean profiles. The DAVT estimated from re-derived data provides improvement to the SHIPS/LGEM forecasts. In addition, OHC data from the EOHC dataset will be implemented in the 2018 operational version of SHIPS, LGEM, and RII.

-Actual or anticipated problems or delays and actions or plans to resolve them.

A one-year NCE for the project was requested and approved by NOAA. The extension was used to complete additional testing and provide to NHC the final updated version of the developed software and databases, as well as final verification results. Additional milestones required to produce new datasets and conduct additional testing were completed. The newly developed EOHC dataset allowed to obtain DAVT estimates that produce a very significant improvement in SHIPS/LGEM intensity forecasts.

-Changes that had a significant impact on expenditures.
None
-Change of primary performance site location from that originally proposed.
None

6. SPECIAL REPORTING REQUIREMENTS

Report on any special reporting requirements here (see previous instruction #3). If there are none, state so.

- Your assessment of the project's Readiness Level (current and at the start of project; see definitions in Appendix B)

Start of the project: RL3
Current: RL7 - 9

-If not already reported on in Section 1, please discuss:
-- Transition to operations activities
1) SHIPS/LGEM with daily SST was transitioned to operations at NHC for 2018 season

2) DSWR was transitioned to operations at JTWC in September, 2017.

3) Fixes to some minor computer bugs in the SHIPS/LGEM/RII processing that were identified in the course of this work were implemented in the 2016 operational version of the NHC guidance suite on WCOSS.

4) Spatially-averaged DSST data and OHC data from the new EOHC dataset produced by this project were used at NHC operationally for 2018 season

The transition to operations of the remaining products generated by this project, including DSWR and SHIPS/LGEM with DAVT was scheduled in the spring of 2019, if accepted by NHC. The timing of the final transition will depend on the availability of NHC Technology and Science Branch (TSB) resources. However, due to NCO code moratorium, the DSWR and SHIPS/LGEM with DAVT cannot be transitioned to operations for 2019. Instead, NHC now plans to run those in quasi-prod for 2019 and transition to operations at NCO for 2020.

-- Summary of testbed-related collaborations, activities, and outcomes (if it's a testbed project)

1) Real-time forecasts of the TC-size estimates were made available via the CIRA ftp server, server at ftp://rammftp.cira.colostate.edu/knaff/DSWR/ starting on the 18th of August. Past forecasts made in 2016 were also provided at this time.

2) Real-time SHIPS forecasts with DSST were made available via CIRA ftp server at
ftp://rammftp.cira.colostate.edu/chirokova/JHT_2015_2017/rt_demo/
during 2016 Atlantic and East Pacific Hurricane seasons.

3) Verification of the retrospective SHIPS runs with DSST and parallel runs from 2016 season were provided to NHC

4) 2017 version of SHIPS modified to use DSST and DAVT was provided to NHC.

5) DSWR model was provided and tested on WCOSS for potential 2017 or 2018 quasi-prod production.

6) Updated database of DSST global and regional data from 1982 – 2017 in SHIPS format was provided to NHC

7) Re-derived EOHC global and regional datasets for 2005 - 2017 were provided to NHC

8) Updated NCODA-based climatology of DSST, OHC, MLD, D26, and D20 and all ocean variables included in the EOHC dataset was provided to NHC together with the software for creating and reading that climatology and adding climatological data to the SHIPS diagnostic files

9) Software for generating DSST and EOHC data in SHIPS format in real-time was provided to NHC and will be used to generate data for the operational 2018 versions of SHIPS and LGEM.

10) Software for estimating DSOA and RTOA in real-time will be provided to NHC and NRL/LTWC

11) Software for adding EOHC and DAVT data to the developmental database and real-time SHIPS diagnostic files was developed and will be provided to NHC and NRL/JTWC

12) Updated versions of SHIPS, LGEM, and developmental code with the option to use different versions of SST, OHC, and DAVT for different models, including SHIPS, LGEM, and versions of RII was developed and will be provided to NHC.

13) The possibility of including Decay SHIPS Wind Radii (DSWR) and MSLP estimates in operational Automated Tropical Cyclone Forecast System (ATCF) A-decks has been discussed with NHC points of contact (POCs). The implementation of DSWR in the operational A-decks for 2019 season will depend on the availability of NHC resources. Transition to operations of DSWR is delayed to 2020 beacus of NCO code moratorium.

14) The possibility of implementing SHIPS with DAVT in the quasi-production version of SHIPS on WCOSS for 2019 seasons has been discussed with NHC POCs and NHC TSB staff. The implementation of SHIPS with DAVT in the quasi-production for 2019 season will depend on the availability of NHC TSB resources. Transition to operations of SHIPS/LGEM with DAVT is delayed to 2020 because of NCO code moratorium.

-- Has the project been approved for testbed testing yet (if it's a testbed project)?

SHIPS/LGEM with daily SST was already transitioned to operations at NHC for 2018 season. NHC plans to implement SHIPS/LGEM with DAVT and DSWR in quasi-production version of the NHC Guidance Suite on WCOSS during 2019 season. The implementation of the new products in the quasi-production for 2019 season will depend on the availability of NHC TSB resources.

-- What was transitioned to NOAA?

The following software was transitioned to NOAA:

1) Some minor computer bugs in the SHIPS/LGEM/RII processing were identified in the course of this work, and were corrected in the 2016 operational version of the NHC guidance suite on WCOSS.

2) Software necessary for DSWR forecasts with updated coefficients were provided to NHC. The implementation of DSWR is planned (personal communication, Mark DeMaria) on quasi production for forecasting during the 2018 season, depending on the availability of NHC TSB resources

3) 2017 version of SHIPS model with the option to use both DSST and DAVT was provided to NHC. The new modifications will be implemented in the 2018 operational version of SHIPS and LGEM.

4) Updated database of DSST data (1982 - 2017) and newly derived EOHC data (2005 - 2017) were provided to NHC and will be included in the SHIPS developmental database

5) Updated climatology of DSST and ocean data, including IHC, D26, D20, and MLD climatology, as well as climatology of other variables included in the EOHC dataset and related software.

6) Software for generating real-time DSST and EOHC data that will be used to run 2018 operational versions of SHIPS, LGEM, and RII

7) DSWR model was transitioned to operations at JTWC in September, 2017

8) Updated version of DSWR was transitioned to NHC and tested at NHC in October, 2017.

Test Plans for USWRP-supported Testbed Projects

I. *What* ***concepts/techniques*** *will be tested? What is the scope of testing (what will be tested, what won't be tested)?*

The following models will be tested:

- SHIPS/LGEM with DAVT assuming constant mixing depth
- SHIPS/LGEM with DAVT assuming variable mixing depth
- DSWR

II. ***How*** *will they be tested? What* ***tasks*** *(processes and procedures) and activities will be performed, what preparatory work has to happen to make it ready for testing, and what will occur during the experimental testing?*

1) Tasks that will be performed during testing at CIRA:
- run scripts to receive operational SHIPS diagnostic files in real-time
- run scripts to add DAVT to the operational diagnostic files
- run the models
- save the model output and make it available to NHC and JTWC via ftp

2) Preparatory work:
- complete retrospective runs using 2018 version of SHIPS/LGEM
- derive updated coefficients for different version of SHIPS

3) During the testing:
- monitor model performance
- conduct post-season verification

III. ***When** will it be tested? What are **schedules and milestones** for all tasks described in section II that need to occur leading up to testing, during testing, and after testing?*

1) When it will be tested:
- During the 2018 Atlantic and East Pacific Hurricane seasons

2) Schedules and Milestones:
- Complete retrospective runs of modified SHIPS/LGEM (Oct 2017 - June 2018)
- Coordinate with TSB staff to implement parallel runs on quasi-production on WCOSS or implement them at CIRA (Jun 2018 - Aug 2018)
- Complete post-season verification (Dec 2018 - Jan 2019)

IV. ***Where** will it be tested? Will it be done at the PI location or a NOAA location?*

1) If possible, the updated models will tested on quasi-production on WCOSS, depending on the availability of TSB resources.
2) If parallel runs of experimental SHIPS/LGEM and DSWR cannot be implemented on quasi-production, they will be implemented at CIRA.

V. *Who are the key **stakeholders** involved in testing (PIs, testbed support staff, testbed manager, forecasters, etc.)? Briefly what are their **roles and responsibilities**?*

Stakeholders and Roles:
- PIs: prepare model: provide code and data to NHC, conduct parallel runs at CIRA if needed
- TSB staff and JHT support staff: if possible, implement updated models on quasi-production on WCOSS. Evaluate the new products and provide feedback.
- JHT POCs: monitor the model performance and provide feedback to PIs

VI. *What **testing resources** will be needed from each participant (hardware, software, data flow, internet connectivity, office space, video teleconferencing, etc.), and who will provide them?*

- The updates models require resources similar to the operational versions. Existing hardware and software will be used for testing on quasi-production on WCOSS and/or at CIRA.

VII. *What are the **test goals, performance measures, and success criteria** that will need to be achieved at the end of testing to measure and demonstrate success and to advance Readiness Levels?*

1) Test goals:
- Evaluate the performance of the updated and new models
- Compare experimental parallel runs with operational runs
- Provide testing results to NHC and JTWC and respond to feedback

2) Performance measures:
- Model verification with the algorithms that are used to evaluate the performance of the operational models

3) Success criteria:
- Performance of the experimental models compared to the performance of the operational models

VIII. *How will testing **results** be documented? Describe what information will be included in the **test results final report**.*

Test results will be provided to NHC and JHT in the final project report and test results final report.
1) The documentation of the test results will include:
- the results of retrospective model verification
- the results of the post season verification of real-time runs.

2) The test results final report will include the result of the retrospective model verification. The post season verification cannot be completed until the end of the hurricane season, therefore these results might not be available in time to be included in the test results final report.

7. BUDGETARY INFORMATION

Is the project on budget? Much of the quantitative budget information is submitted separately in the Federal Financial Report. However, describe here any major budget anomalies or deviations from the original planned budget expenditure plan and why.

The project is on budget

8. PROJECT OUTCOMES

What are the outcomes of the award?

The improved version of the operational statistical-dynamical models for forecasting TC intensity is being developed. The new statistical dynamical model for forecasting TC wind radii has been developed.

Are performance measures defined in the proposal being achieved and to what extent?

The performance measures defined in the proposal (the milestones) are being achieved as planned.

9. REFERENCES

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