Appendix A

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

COVER PAGE

NOAA/JHT

Federal Grant Number Assigned by Agency: NA15OAR4590204

Title: Improvements to Operational Statistical Tropical Cyclone Intensity Forecast Models

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Report Term or Frequency: semi-annual

Final Annual Report? No

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 data was developed and modifications to the model to add the option to use either weekly or daily SST (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 has been implemented in the 2016 version of SHIPS on WCOSS. All changes for this task were incorporated into the 2016 version of SHIPS and retrospective and parallel runs with daily SST and verification have been completed. The code to generate global and regional daily SST data, the modified SHIPS/LGEM, and verification results have been provided to NHC for evaluation. NHC requested additional test runs with daily SST, including testing the updated, 2017 version of SHIPS with daily SST for the 2017 season. Some of the new tests with the 2017 model and sample were motivated by the forecasts for Hurricane Maria, where the weekly SST analysis did not properly represent the cold wake left by Hurricane Jose. This test could help demonstrate that the daily SSTs can be very important for specific forecasts even if the impact on a basin-wide sample is small. Also, statistical tests were performed and demonstrated that DSST is very noisy compared to weekly SST (RSST). It was also found that using temporally averaged DSST has a potential for improving SHIPS and LGEM forecasts. Additional testing using temporal average will be performed using 2017 Atlantic Hurricane Season data.

2) **Add to SHIPS/LGEM a physical mechanism to account for storm-induced SST cooling.** 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 data available in real-time has been developed and incorporated into the SHIPS and LGEM processing scripts. The option to use either SST or DAVT has been added to both SHIPS and LGEM. The final version of the algorithm to use DAVT with variable mixing depth and final regression coefficients will be derived using the 2018 version of SHIPS/LGEM to allow direct comparison of the experimental version with the operational version during 2018 Atlantic and East Pacific hurricane seasons. NHC requested the development of an updated climatology of the ocean heat content and ocean variables, including the depth of 26° and 20° isotherms, and ocean mixed layer depth. This new climatology was needed because much of the developmental database does not include those ocean parameters, and climatological values are used when real time values are missing. It was found that the use of the climatology of the ocean mixing layer depth to estimate DAVT assuming either constant or variable mixing depth for the storm induced mixing significantly improves the performance of SHIPS/LGEM with DAVT. A one-year no-cost extension (NCE) for this project was requested and approved by NOAA, to allow additional testing of the latest 2017 version of SHIPS/LGEM with DAVT.

3) **Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM.** A statistical-dynamical method to predict tropical cyclone wind structure (Decay SHIPS Wind Radii, DSWR) in terms of wind radii has been developed and has been running in real-time 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 results have been provided to NHC and JTWC. Verification for the 2016 season has been completed and provided to NHC. DSWR has been running in real-time at CIRA during 2017 season, and verification results for the 2017 season will be provided to NHC after final 2017 best track data become available.

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 2017	Actual: Sep 2016 – Aug 2017
Modify SHIPS and LGEM to use 0.25° daily Reynolds SST	Evaluate parallel runs from 2016 and make necessary adjustments to SHIPS.	The evaluation of the parallel runs has been completed and the results were provided to NHC and presented at the Interdepartmental Hurricane Conference (IHC). Additional tests demonstrated that using temporally averaged DSST produces improvements relative to single-time DSST for SHIPS/LGEM.
Modify SHIPS and LGEM models to use DAVT	Modify SHIPS/LGEM code to work with DAVT assuming constant and variable mixing depth. Add algorithm to estimate DAVT based on variable storm-induced mixing depth calculated from "ocean age" using new MLD climatology.	The SHIPS/LGEM code was modified to work with DAVT estimated assuming either constant or variable mixing depth. The algorithm to estimate DAVT based on variable storm-induced mixing depth calculated from "ocean age" predictor was added to the models. A NCE was requested and approved to perform additional testing and verification.
Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM	Evaluate parallel runs from 2016 and make necessary adjustments to DSWR	The evaluation of the parallel runs was completed and the results were provided to NHC, presented at IHC, and published. In addition, test runs with including DSWR into the RVCN consensus model were completed. DSWR with updated coefficients was run in real-time at CIRA during 2017 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	85%	Aug 2018	Yes. NCE was requested and approved to perform additional testing and verification.
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)

Milestone	Completed vs proposed
Begin parallel runs during 2016 season and monitor results during the season	Completed as proposed
Modify SHIPS to include DAVT based on the variable mixing depth	Completed as proposed
Extend SHIPS modifications to the global version	Completed as proposed
Evaluate parallel runs from 2016 season and make any necessary adjustments to the modified SHIPS	Completed as proposed
Present year 2 results at IHC and compile feedback from JHT advisors	Completed as proposed
Complete retrospective runs of modified SHIPS with all improvements and additions included	Additional modifications were made to both DSST and DAVT versions of the model based on suggestions from NHC advisors. NCE was requested and approved to perform additional verification to include the latest 2017 version of SHIPS/LGEM and recent 2017 Atlantic storms.
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	NCE was requested and approved to perform additional verification to include the latest 2017 version of SHIPS/LGEM and recent 2017 Atlantic storms.
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.	NCE was requested and approved to perform additional verification to include the latest 2017 version of SHIPS/LGEM and recent 2017 Atlantic storms.

Detailed description of the work completed for each milestone since the last report is presented below.

Milestone: Begin parallel runs during 2016 season and monitor results during the season. Parallel runs of SHIPS/LGEM with daily SST and DAVT assuming constant mixing depth for the Atlantic and East and Central Pacific basins, as well as parallel runs of DSWR for the Atlantic and East and Central Pacific basins have been conducted at CIRA for part of 2016 season and evaluated.

Milestone: Modify SHIPS to include DAVT based on the variable mixing depth. The 2016 version of SHIPS and LGEM has been modified to use RSST, DSST, and/or DAVT with either constant or variable mixing depth. The updated code is written in a way that allow the use of different "SST" variables by different parts of the code. That is necessary since SHIPS includes several modules, such as different versions of the Rapid Intensification Index (RII) that have not been trained to use daily SST or DAVT. The DAVT assuming variable mixing depth has been 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. The mixing depth as a function of storm translational speed (captured by OA) and latitude is estimated from

$$Mixing\ Depth = \mathrm{a} + \mathrm{b} * (\mathrm{OAGE}) + \mathrm{c} * (OAGE)^2, \quad (1)$$

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 (1) 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.

Milestone: Extend SHIPS modifications to the global version. All modifications for SHIPS and LGEM code, as well as DSWR model, are global and can be used in all basins. The database of the global DSST, OHC and subsurface ocean data has been developed. The updated climatology of OHC and other ocean variables is also global. The developmental databases for all basins were updated to include DSST, updated climatology of OHC, D20, D26, OHC20, and MLD. The above variables were added to the latest developmental databases for the Atlantic (1982 - 2016), east Pacific (1982-2016), west Pacific (1998 - 2015), Indian Ocean (1998 - 2015), and Southern Hemisphere (1998 - 2015). The updated databases and related code will be provided to Dr. Kate Musgrave who is working on an HFIP project that incudes updating the global version of SHIPS to include all latest modifications added for the Atlantic and east Pacific basins.

Milestone: Evaluate parallel runs from 2016 season and make any necessary adjustments to the modified SHIPS.

1) Parallel runs of SHIPS/LGEM with DSST have been conducted during September – November 2016, and the results have been made available to NHC via an ftp site, ftp://rammftp.cira.colostate.edu/chirokova/JHT_2015_2017/rt_demo/, and evaluated. Figure 1 shows the MAE and biases for the 2016 season with DSST.

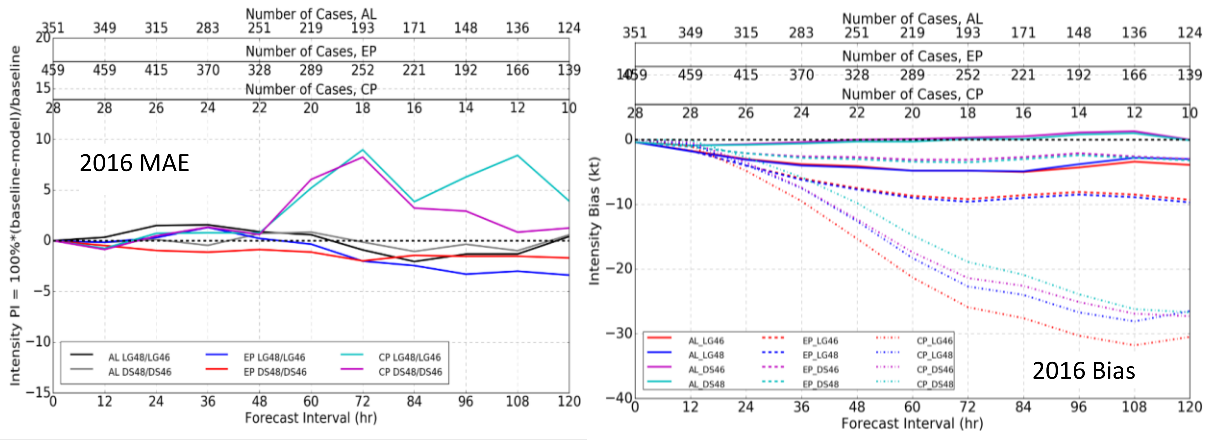

Figure 1. Left: SHIPS/LGEM independent verification for 2016 with daily SST for the 2016 version of the model, with DSST coefficients. Percent improvement relative to the baseline version using weekly SST for the Atlantic (black – LGEM, grey - SHIPS) and East (blue - LGEM; red - SHIPS) and Central Pacific (magenta - LGEM, cyan - SHIPS). Right: intensity bias for the runs shown on the Left. Solid lines show: red – LGEM run for the Atlantic with RSST, blue – LGEM run for the Atlantic with DSST, magenta – SHIPS run for the Atlantic with RSST, cyan - SHIPS run for the Atlantic with DSST. Dashed lines show biases for the corresponding runs for the East Pacific, and dotted line – for the Central Pacific.

Overall, for the 2016 sample the use of DSST instead of RSST resulted in forecasts similar to the version with RSST. The results of parallel runs with DSST during 2016 season were evaluated and presented at IHC in March, 2017.

2) 2016 Parallel runs of SHIPS/LGEM with DAVT for 2016 revealed some issues with the algorithm used to estimate the ocean cooling based on either constant or variable storm-induced mixed depth. To address these issues, the updated climatology of NCODA subsurface data based on 2005 – 2016 data was developed and added to the experimental SHIPS diagnostic files. The new climatology includes the climatology of the ocean mixed layer depth (MLD).

3) Parallel runs of DSWR were conducted for the 2016 season, and the results of these parallel runs were evaluated, provided to NHC, and presented at IHC. It was found that for the Atlantic, the DSWR had rather high MAE and strong positive biases for the 2016 season. Other models, including HWRF, GFDL, and DRCL, also suffered from similar poor performance and had high positive biases, which suggests that 2016 might have been an unusual year in the Atlantic. For the East and West Pacific, DSWR showed a good performance for 2016, with small MAE (compared to DRCL) and almost zero biases in both of those basins. In addition and possibly most importantly, including DSWR into the multi-model consensus (RVCN, Sampson and Knaff, 2015) resulted in either improvements or no degradation to RVCN. RVCN runs included HWRF, GFS, and GFDL in addition to DSWR. The RVCN improvements with DSWR in the consensus included improved forecasts for R64 (from 0% to 28%), R50 (from 0% to 10%), and R34 (from 0% to 9%). DSWR even improved RVCN in the Atlantic, despite its poor performance there. Figure 3 shows the MAE for RVCN with (dashed bars) and without (solid bars) DSWR for Atlantic and East Pacific basins.

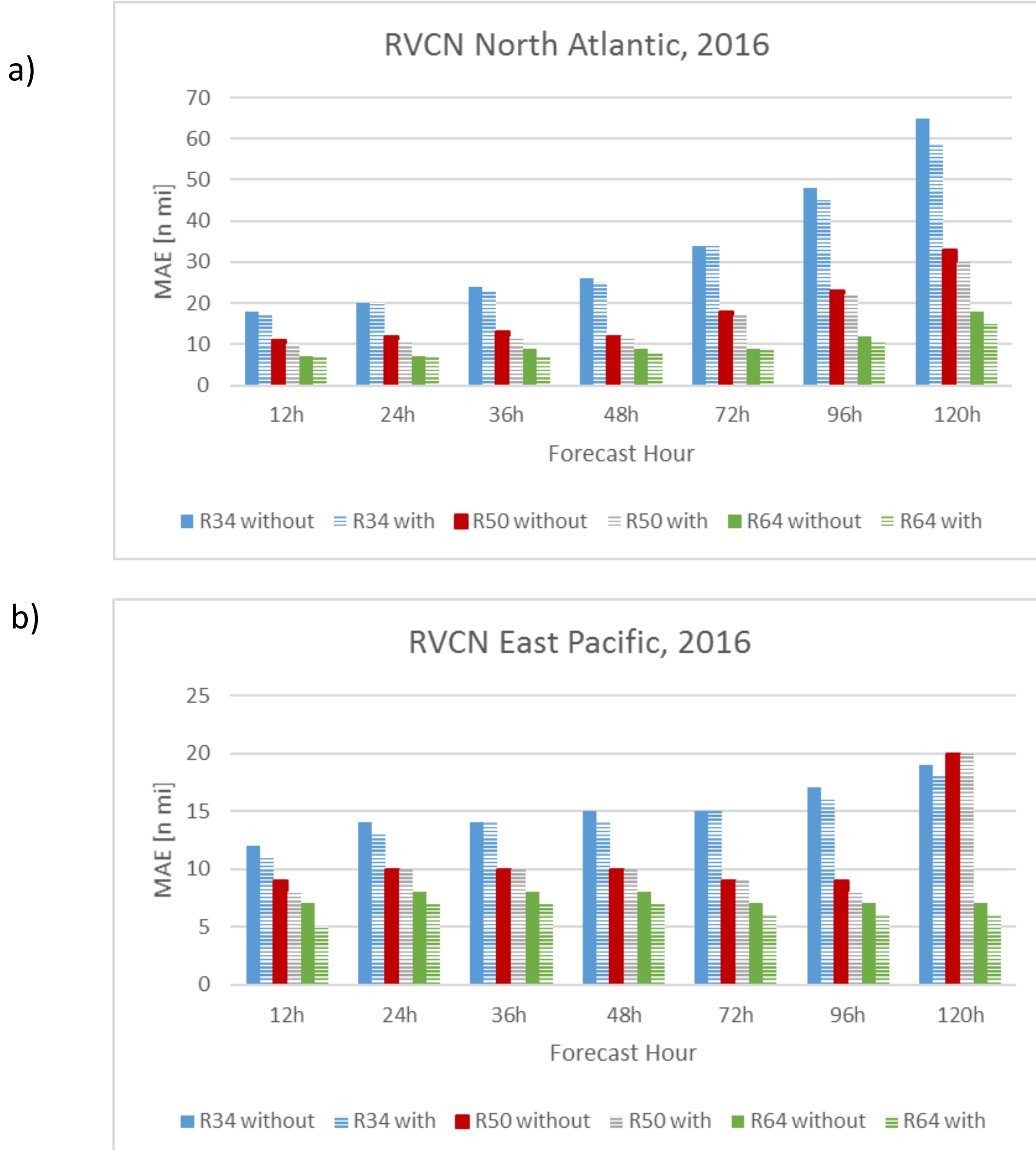

Figure 3: RVCN MAE (a) for the Atlantic and (b) East Pacific basin. RVCN included HWRF, GFS, and GFDL. Solid bars show runs without DSWR and dashed bars show runs with DSWR.

Milestone: Present Year 2 results at IHC and compile feedback from JHT advisors. The results from the Year 2 of the project were presented at 2017 Tropical Cyclone Operations and Research Forum (71st Interdepartmental Hurricane Conference), 13-16 March, 2017, Miami FL. The presentation is available online at http://www.nhc.noaa.gov/jht/15-17_proj.php

Milestone: Complete retrospective runs of modified SHIPS with all improvements and additions included.

Additional modifications were made to both DSST and DAVT versions of the model based on suggestions from NHC advisors.

Additional testing with DSST was performed after reviewing the results of the retrospective and parallel runs for the 2016 season. Specifically, the comparison of DSST with RSST demonstrated that DSST data is very noisy compared to RSST. To reduce the noise, temporally averaged DSST was tested. Statistical tests with both SHIPS and LGEM showed that the use of DSST averaged over the last 3 days produces improvements for both SHIPS and LGEM forecasts relative to the use of the most recent DSST. Additional testing will be performed using data from the 2017 Atlantic Hurricane season, and the updated databases and software will be provided to NHC.

The new climatology of ocean data, including OHC, D26, D20, and MLD, was updated to include 2016 data. In addition, the 2017 version of the developmental databases for all global basins, including Atlantic, east Pacific, west Pacific, Indian Ocean, and Southern Hemisphere were updated to include new climatology. The corresponding modification were made to the software for estimating ocean cooling based on constant and variable mixing depth to include the use of the updated climatology. The most significant modification included the use of MLD climatology for the years 1982 - 2004, for which subsurface ocean data are not available. The previous version of the code was estimating mixed layer depth from D26, D20, SST, and OHC when MLD data were not available. It was found that the use of MLD climatology significantly improves the statistical fit for both SHIPS and LGEM compared to the previous version that was estimating MLD from other ocean data. Statistical testing with the 2017 version of SHIPS and LGEM provided the best results for SHIPS using

$$Mixing\ Depth = 40 + 1.5625 * (\mathrm{OAGE}) + 0.0651 * (OAGE)^2, \qquad (2)$$

And for LGEM using

$$Mixing\ Depth = 50 + 1.5625 * (\mathrm{OAGE}) + 0.0651 * (OAGE)^2, \qquad (3)$$

It was also found that the constant mixing depth that produces most overall forecast improvement is 80 m for SHIPS and 120 m for LGEM. Figure 3 shows dependent test results for SHIPS for Atlantic and east Pacific. Shown are the R^2 values for all forecast times for different versions of DAVT relative to weekly SST (RSST), based on 1982 - 2016 sample. For both Atlantic and east Pacific, the use of DAVT estimated assuming variable mixing depth shows improved results relative to the baseline RSST version at all forecast times. For the Atlantic the use of DAVT assuming variable mixing depth and a = 40 provides the best overall improvement, with maximum improvement of 0.7 % for 12 hour forecast. For the east Pacific the best results are obtained with DAVT assuming variable mixing depth and a = 50 with maximum improvement of 2.1 % at 30 hr forecast time.

A one-year NCE has been requested and approved to perform additional testing with the updated climatology and estimates of constant and variable storm-induced ocean mixing depth. Additional testing will include the most updated 2017 versions of SHIPS and LGEM, as well as evaluation of performance for the 2017 Atlantic Hurricane Season, which was requested by NHC.

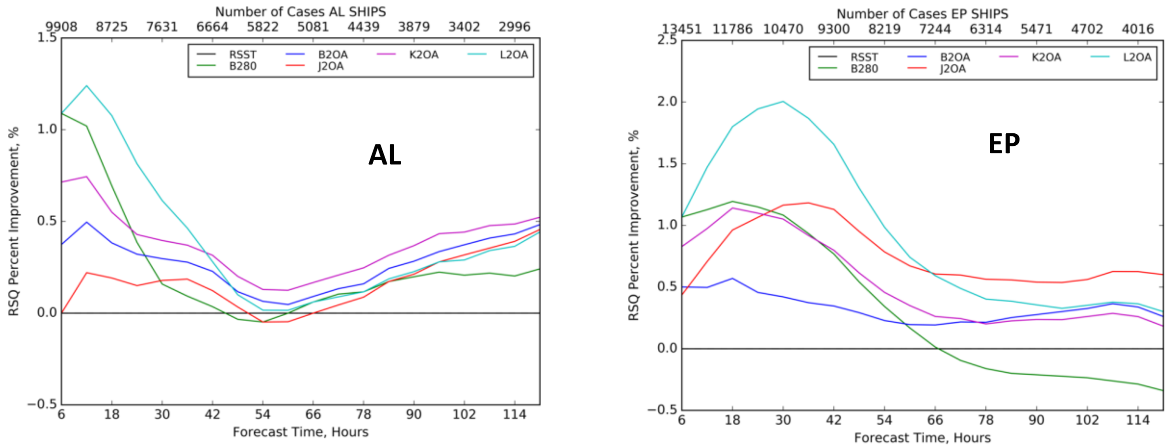

Figure 2. RMS error percent improvement for the Atlantic (left) and East Pacific (right) basins as obtained by SHIPS dependent test based on 1982 - 2016 developmental data. The plots show percent error change relative to the baseline version using RSST. Shown are: RSST (black) - operational version using weekly SST; B280 (green) - version with DAVT calculated assuming constant mixing depth 80 m; B2OA (blue) version with DAVT calculated assuming variable mixing depth with constant a = 25; J20A (red) - same as B20A, using a = 10; K2OA - same as B20A, using a = 40; and L2OA - same as B20A, using a = 50.

Milestone: 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

NCE was requested and approved to perform additional verification to include the latest 2017 version of SHIPS/LGEM and recent 2017 Atlantic storms that was requested by NHC.

Milestone: 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.

The final updated SHIPS/LGEM/RII code will be provided to NHC after additional verification is completed. The additional verification will include reruns for the 2017 season using the most updated 2017 version of SHIPS and LGEM.

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 PI, Galina Chirokova (in 2016 and 2017), and Collaborator, John Knaff (in 2016) participated in the 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 both 2016 and 2017. 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) The DSWR code has been provided to NHC and Naval Research Laboratory (NRL), Monterey for implementation at JTWC. The modified SHIPS/LGEM code, the global and regional daily SST data, and the new ocean data climatology together with the code for creating these datasets have been provided to NHC. The results of the verification of the retrospective and parallel runs were also provided to NHC.

4) The updated climatology of OHC, D20, D26, and mixed layer depth, 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?

During the next reporting period we plan to conduct additional retrospective runs of the experimental version of the 2017 SHIPS/LGEM with DSST and DAVT assuming either constant or variable mixing depth. In addition, final adjustments and modifications to the code will be implemented based on the results of the retrospective runs. We will further work with JHT and NHC TSB staff to implement experimental versions of SHIPS/LGEM and DSWR on quasi-production on WCOSS for the 2018 season and/or will implement parallel runs at CIRA. There are also plans to implement DSWR on the operational JTWC Automated Tropical Cyclone Forecast system at JTWC, where it will become a member of the RVCN forecast aid.

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
2016 SHIPS/LGEM code modified to work with DSST	Provided to NHC as planned
Verification of SHIPS/LGEM runs with DSST for 2010 - 2016	Provided to NHC as planned
DSST database in SHIPS format for global and regional files for 1982 - 2016	Provided to NHC as planned
Updated climatology for OHC, MLD, and depths of 26° (D26) and 20° (D20) isotherms	Provided to NHC in addition to what was planned
DSWR code	Provided to both NHC and JTWC as planned
Verification of DSWR runs	Provided to NHC as planned

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

Presentations:

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.

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:

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.

-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, yet routinely measured ocean parameters.

-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.

- Database of daily Reynolds SST data converted to SHIPS input format. The database includes both global and regional files.
- Updated climatology of OHC, MDL, D26, and D20, based on the 2005 - 2016 NCODA ocean data
- Database of NCODA OHC, D26, D20, 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. Examples include 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.
None
-Actual or anticipated problems or delays and actions or plans to resolve them.
Additional testing was requested by NHC. That testing includes the use of the most updated 2017 version of SHIPS/LGEM and evaluation of the performance for the recent 2017 Atlantic storms. A one-year NCE for the project was requested and approved by NOAA. The extension will be 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.
-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: RL6-7

-If not already reported on in Section 1, please discuss:
-- Transition to operations activities

The transition to operations for this project is scheduled after the end of Year 2, in the spring of 2018, if accepted by NHC. However, some minor computer bugs in the SHIPS/LGEM/RII processing were identified in the course of this work, and were implemented in the 2016 operational version of the NHC guidance suite on WCOSS. The timing of the final transition will depend on the availability of NHC Technology and Science Branch (TSB) resources.

-- 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) 2016 version of SHIPS modified to use DSST was provided to NHC.

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

6) Database of DSST global and regional data from 1982 – 2016 in SHIPS format was provided to NHC

7) Updated NCODA-based climatology of OHC, MLD, D26, and D20 was provided to NHC together with the code to create that climatology and add it to SHIPS diagnostic files

8) 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 2018 season will depend on the availability of NHC resources.

9) The possibility of implementing SHIPS with daily SST and DAVT in the quasi-production version of SHIPS on WCOSS for 2018 seasons has been discussed with NHC POCs and NHC TSB staff. The implementation of SHIPS with DSST and DAVT in the quasi-production for 2018 season will depend on the availability of NHC TSB resources.

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

Some of the testing for this project was planned for the experimental quasi-production version of the NHC Guidance Suite on WCOSS during 2017 season. However, because of NHC/TSB resource limitations, it was not possible to implement this before the 2017 season. The very active 2017 season prevented NHC/TSB from implementing this in quasi-production in late August, which was the secondary plan. Therefore all of the testing so far was done at CIRA.

-- 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 was planned (personal communication, Mark DeMaria) on quasi production for forecasting during the 2017 season, but was delayed because of the NHC/TSB resource limitations and the very busy 2017 hurricane season.

3) 2016 version of SHIPS model with the option to use DSST was provided to NHC.
4) Updated climatology of ocean data, including IHC, D26, D20, and MLD climatology and related software.

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 DSST
- 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 DSST, DAVT, and the new climatology 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 2017 version of SHIPS/LGEM
- derive updated coefficients for different version of SHIPS and for DSWR

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 - Apr 2018)
- Coordinate with TSB staff to implement parallel runs on quasi-production on WCOSS or implement them at CIRA (Oct 2017 - Aug 2018)
- Complete post-season verification (Dec 2017 - Jan 2018)

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

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.

Knaff, J. A., S. P. Longmore, and D. A. Molenar, 2014a: An Objective Satellite-Based Tropical Cyclone Size Climatology. *J. Climate*, **27**, 455–476. doi: http://dx.doi.org/10.1175/JCLI-D-13-00096.1

I.-I. Lin, P. Black, J. F. Price, C.-Y. Yang, S. S. Chen, C.-C. Lien, P. Harr, N.-H. Chi, C.-C. Wu and E. A. D'Asaro, 2013: An ocean coupling potential intensity index for tropical cyclones. *Geophysical Res. Letters*, **40**, 1878–1882. DOI: 10.1002/grl.50091

Price, J. F., 2009: Metrics of hurricane-ocean interaction: vertically-integrated or vertically-averaged ocean temperature. *Ocean Sci*., **5**, 351-368, doi:10.5194/os-5-351-2009.

Sampson, C. R., and J. A. Knaff, 2015: A consensus forecast for tropical cyclone gale wind radii. *Wea. Forecasting*, **30**, 1397–1403, doi:10.1175/WAF-D-15-0009.1.

Yablonsky, R.M. and I. Ginis, 2009: Limitation of One-Dimensional Ocean Models for Coupled Hurricane–Ocean Model Forecasts. *Mon. Wea. Rev.*, **137**, 4410–4419, doi: 10.1175/2009MWR2863.1.

Appendix B

NOAA READINESS LEVELS (RLs)

There are nine readiness levels defined in NOAA Administrative Order 216-105A as follows:

A. Research

RL 1: Basic research: experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view. Basic research can be oriented or directed towards some broad fields of general interest, with the explicit goal of a range of future applications;

RL 2: Applied research: original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific, practical aim or objective. Applied research is undertaken either to determine possible uses for the findings of basic research or to determine new methods or ways of achieving specific and predetermined objectives.

B. Development

RL 3: Proof-of-concept for system, process, product, service or tool; this can be considered an early phase of experimental development; feasibility studies may be included;

RL 4: Successful evaluation of system, subsystem, process, product, service or tool in laboratory or other experimental environment; this can be considered an intermediate phase of development;

RL 5: Successful evaluation of system, subsystem process, product, service or tool in relevant environment through testing and prototyping; this can be considered the final stage of development before demonstration begins;

C. Demonstration

RL 6: Demonstration of prototype system, subsystem, process, product, service or tool in relevant or test environment (potential demonstrated);

RL 7: Prototype system, process, product, service or tool demonstrated in an operational or other relevant environment (functionality demonstrated in near-real world environment; subsystem components fully integrated into system);

RL 8: Finalized system, process, product, service or tool tested, and shown to operate or function as expected within user's environment; user training and documentation completed; operator or user approval given;

D. Deployment

RL 9: System, process, product, service or tool deployed and used routinely.