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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Award Period: 9/1/15-8/31/17

Reporting Period End Date: 8/31/16

Report Term or Frequency: semi-annual

Final Annual Report? No

1. ACCOMPLISHMENTS

Summary of the 1st Year accomplishments for the 3 main project tasks:

1) **Replace in SHIPS and LGEM weekly 1° degree 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 were completed. A new module was added to SHIPS/LGEM to handle the selection of SST and OHC data and that module has been implemented in the 2016 version of SHIPS on WCOSS. All changes for this tasks were incorporated into the 2016 version of SHIPS, retrospective runs with daily SST and verification have been completed, and SHIPS/LGEM code with daily SST has been prepared for parallel runs.

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 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 ocean heat content (OHC). The algorithm for the estimating depth-averaged temperature (DAVT) assuming constant 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 and OHC or DAVT has been added to both SHIPS and LGEM, and the modified code has been prepared for parallel runs.

3) **Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM.** A statistical-dynamical method to predict tropical cyclone wind structure 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. (2016).

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: Apr – Aug 2016	Actual: Apr – Aug 2016
Modify SHIPS and LGEM to use 0.25° daily Reynolds SST	Conduct algorithm changes based on the feedback and prepare the code for parallel runs either on WCOSS or at CIRA	Minor algorithm adjustments were completed and the code has been prepared for parallel runs. Some minor code modifications made as part of that task were implemented in the 2016 operational SHIPS version at WCOSS
Modify SHIPS and LGEM models to use DAVT	Modify SHIPS/LGEM code to work with DAVT assuming constant mixing depth and prepare code for parallel runs	The SHIPS/LGEM code was modified to work with DAVT estimated assuming constant mixing depth and prepared for parallel runs
Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM	Modify algorithm based on feedback and prepare code for the parallel runs either on WCOSS or at CIRA	Bias corrections were added to the code based on the feedback received. The modified code was prepared for the real-time runs and is running at CIRA

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	85%	Aug 2017	Yes
Modify SHIPS and LGEM models to use DAVT	20%	Aug 2017	Yes
Add forecasts of TC structure (wind radii and MSLP) to SHIPS/LGEM	85%	Aug 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
Present year 1 results at IHC and gather feedback	Completed as proposed
Conduct algorithm changes based on feedback and validation results	Completed as proposed. In addition, changes to use daily SST were implemented in the 2016 version of SHIPS and the model regression coefficients were re-derived to make it easier to compare with the 2016 operational SHIPS and LGEM.
Develop code to read daily N Shay and NCODA upper ocean datasets and estimate DAVT, convert data to input data format used by SHIPS	Completed as proposed
Modify SHIPS to use DAVT to account for SST cooling, assuming constant mixing depth	Completed as proposed
Prepare final updated version of the modified SHIPS code for parallel runs during the 2016 season (to include use of daily SST, use of DAVT to account for SST cooling, and TC-size estimates) for Atlantic and East and Central Pacific basins.	Completed as proposed. In addition, the parallel runs of TC-size estimates were setup ahead of time and some minor changes to the SHIPS code were implemented in the operational 2016 version on WCOSS.
Coordinate with JHT and TSB staff to implement updated SHIPS code on NCEP supercomputer (WCOSS) or implement code at CIRA	Completed as proposed

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

Milestone: Present Year 1 results at IHC and gather feedback. Galina Chirokova presented project results at IHC in March, 2017. The project results were discussed with NHC points of contact, Dan Brown, Lixion Avila, and Chris Landsea.

Milestone: Conduct algorithm changes based on feedback and validation results
No major algorithm changes were suggested. Based on the validation results for use of daily SST (DSST) it was found that for the real-time runs the available DSST is always 1 or 2 days old. The algorithm was adjusted to use 1- or 2- day old DSST for reruns and statistics.

Adjustments were also made to the statistical-dynamical method to predict tropical cyclone wind structure in terms of wind radii. A bias correction that is proportional to the distance between the mean wind radii (R_{th}) and the radius of maximum wind (R_m) was applied to the mean wind radii used in the parametric model.

$$B = 0.0607\ln(R_{th} - R_m) + 0.6395,\ (R_{th} - R_m) > 0,$$

where R_{th} are the wind radii thresholds 34-, 50- and 64-kt. The larger the distance the less pronounced the correction. This bias correction is meant to correct for the use of non-zero averaged wind radii being used to estimate the azimuthal mean extents of 34-, 50- and 64-kt winds. The results of adding a bias correction to the underlying vortex model presented in Knaff et al. (2016) are shown in Figure 1. To provide additional guidance for applications and users that require forecasts of central pressure, a wind-pressure relationship (i.e., Courtney and Knaff 2009) that is a function of TC motion, intensity, wind radii (i.e., size), and latitude is then applied to these forecasts.

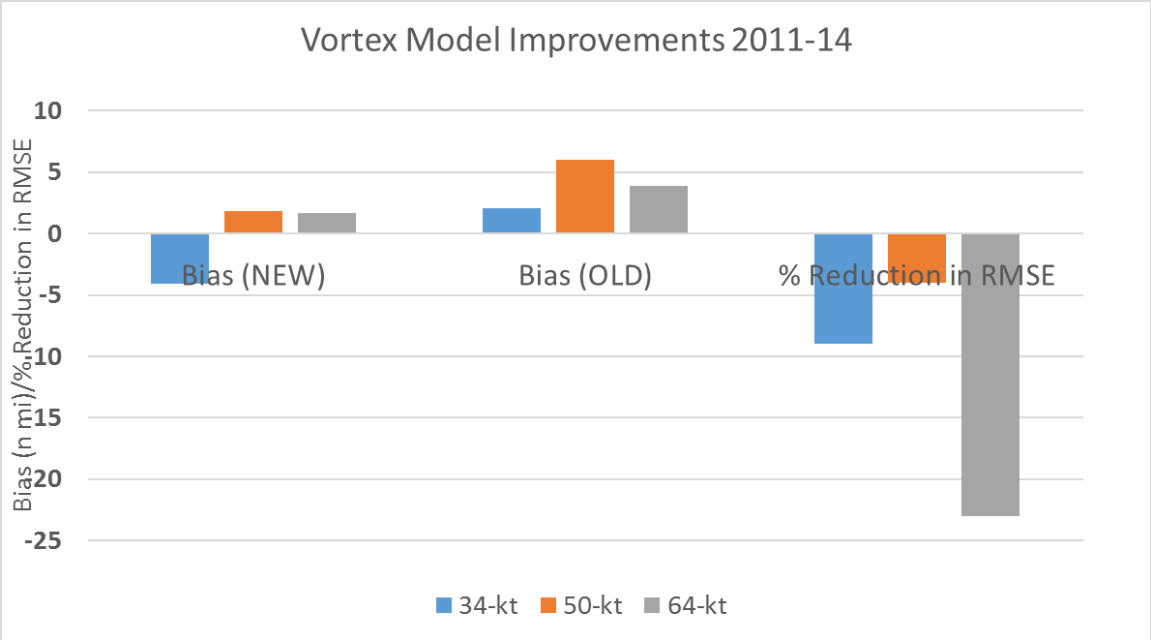

Figure 1: Results of adding a bias correction to the vortex model presented in Knaff et al. (2016) based on best track intensities and storm motions applied to 2011-2014 Atlantic and East Pacific tropical cyclones.

Milestone: Develop code to read daily N Shay and NCODA upper ocean datasets and estimate DAVT, convert data to input data format used by SHIPS. Fortran code has been developed to read N Shay and NCODA upper-ocean datasets. The updated climatology for the depth of the 20°C (D26) and 26°C (D20) isotherms and for mixed layer depth (MLD) using NCODA data for the years 2005 - 2015 has been created. Further, the algorithm for filling missing values developed for the daily SST at the earlier stage of the project has been applied to datasets for MLD, D26, and D20 to remove bad and overland values to simplify further processing such as data interpolation. The code has been developed to estimate DAVT for a constant mixing depth, and to write the output data in the format required by SHIPS (the lsdiag data files).

Milestone: Modify SHIPS to use DAVT to account for SST cooling, assuming constant mixing depth. The SHIPS and LGEM code has been modified to use DAVT to account for SST cooling assuming constant mixing depth. Both SHIPS and LGEM use SST to estimate the Maximum Potential Intensity (MPI), which is one of the key parameters for forecasting intensity. A new option has been added to the code to allow the use of either weekly SST, daily SST, or

DAVT to estimate MPI. For the Atlantic basin operational SHIPS and LGEM models use Joe Cione's cooling parameterization. That cooling has been empirically derived for the Atlantic basin only, and should not be needed with the use of the DAVT. The model has been set up so that the cooling is not used when the model is run with DAVT. In addition, the OHC predictor has been turned off for the model runs with DAVT. The SHIPS model code includes multiple other modules that require the use of SST rather than DAVT, such as several rapid intensification (RI) modules and the annular hurricane index. The code has been setup in such a way that both SST and DAVT variables are available, so that different parts of the code can use a different variable for SST.

Milestone: Prepare final updated version of the modified SHIPS code for parallel runs during the 2016 season (to include use of daily SST, use of DAVT to account for SST cooling, and TC-size estimates) for Atlantic and East and Central Pacific basins. The updated versions of SHIPS and TC-size estimate codes have been prepared for the parallel runs during the 2016 season. Specifically:

1) The version of the SHIPS code with DSST has been updated to take into account changes made to the 2016 operational SHIPS and LGEM code to simplify the comparison of the results. The dependent sample statistics have been re-derived for the updated version of the model. The past season's reruns for 2004-2015 and for 2016 have been completed and verified. Figure 2 shows the verification results of the updated SHIPS with DSST for the years 2004-2015 and Figure 3 shows the independent verification for 2016. The results show the most improvement for the LGEM forecast for the East Pacific, and overall are consistent with the previous results.

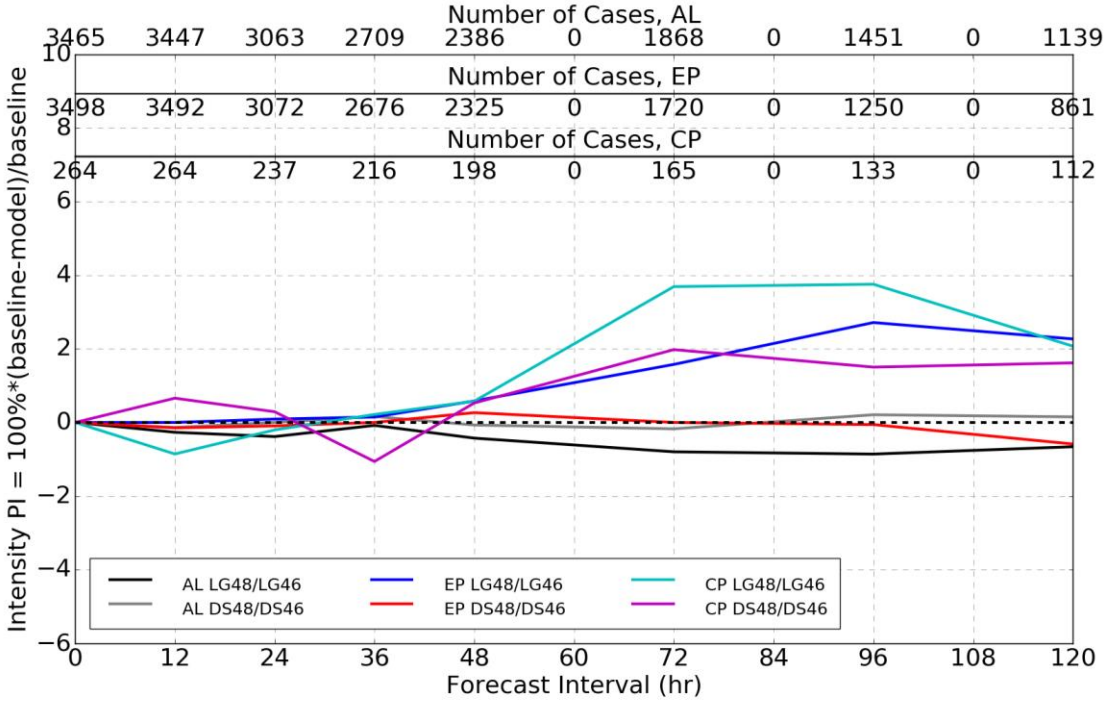

Figure 2: SHIPS verification for 2004 - 2016 with daily SST for the 2016 version of the model. Percent improvement relative to baseline version using weekly SST for Atlantic (black – LGEM, grey - SHIPS) and East (blue - LGEM; red - SHIPS) and Central Pacific (magenta - LGEM, cyan - SHIPS). The most significant improvement is seen in the EP for LGEM (blue line).

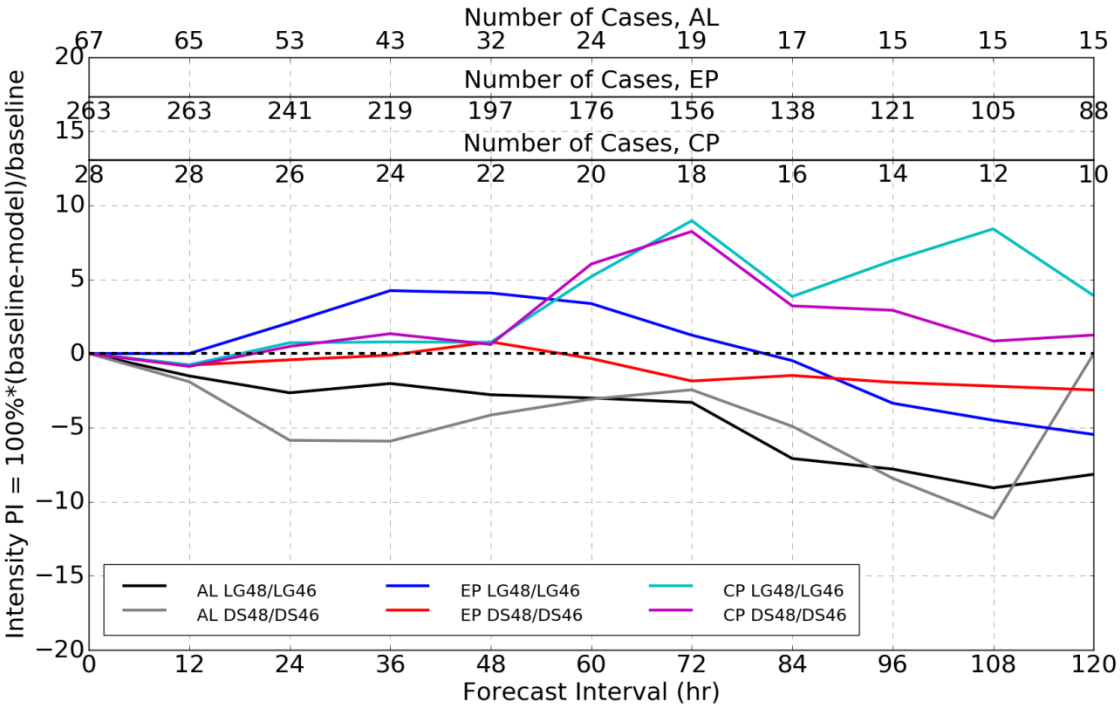

Figure 3: Same as figure 2, but for SHIPS independent forecast verification for the 2016 season.

2) The code modifications required for SHIPS/LGEM to work with DAVT have been merged with the 2016 operational version of the model. The driver scripts for creating estimates of the DAVT and running the SHIPS version with DAVT in real-time have been developed.
3) The statistical-dynamical method to predict tropical cyclone wind structure in terms of wind radii has been developed and has been setup for testing at CIRA during the 2016 hurricane season. Originally forecasts were planned to be created on Quasi-PROD and have the output put in the operational decks, but NHC has decided to not implement these in Quasi-PROD for this year, and a back-up plan to create these forecasts at CIRA was adopted. The forecasts were made available via the CIRA ftp server at ftp://rammftp.cira.colostate.edu/knaff/DSWR/ starting on the 18th of August. All of the 2016 forecasts are available at that location. The format of these files, which are updated every 6 hours by 30 min prior to the synoptic time, have been tested in the ATCF and should be easily added to real-time or post season A-decks for validation.

Milestone: Coordinate with JHT and TSB staff to implement updated SHIPS code on NCEP supercomputer (WCOSS) or implement code at CIRA.

The possibility of including Decay SHIPS Wind Radii (DSWR) and MSLP estimates in operational Automated Tropical Cyclone Forecast System (ATCF) A-decks were discussed with the NHC points of contact (POCs) prior to the season. Much work was done to get ready for this capability, however, the implementation was delayed by more pressing operational concerns at NHC. Pursuit of this goal will be reestablished following the 2016 season to make it ready for 2017.

The possibility of implementing SHIPS with daily SST and DSRW in the quasi-production version on WCOSS for the 2016 season was also discussed with the NHC POCs and the NHC TSB staff. It was decided to implement that for the 2017 season since the NHC TSB staff did not have time to implement this on WCOSS in 2016.

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, and Collaborator, John Knaff participated in the IHC conference. There were no training activities during the reporting period.

How were the results disseminated to communities of interest?

The project results were presented at the IHC. The presentation is available at http://docs.google.com/viewer?url=http://www.nhc.noaa.gov/jht/ihc_16/ihc16chirokova-s04-04.pdf?time=0 . The 1st semi-annual project report is also available online at http://docs.google.com/viewer?url=http://www.nhc.noaa.gov/jht/15-17reports/JHT_Chirokova_midyear1.pdf?time=0 Additional details about the project were communicated to NHC points of contact, Dan Brown, Lixion Avila, and Chris Landsea. Real-time DSWR forecasts were also provided to NHC POCs via a ftp server.

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 begin SHIPS parallel runs, monitor the results of the parallel runs and modify SHIPS and LGEM to include DAVT based on the variable mixing depth. In addition, we will work to update the model coefficients through 2016, and get the software working on Quasi-PROD for the 2017 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)

No major deliverables were planned for the reporting period. The real-time parallel runs of DSWR were setup ahead of time.

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

Presentations:

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 submitted to Weather and Forecasting for publication.

Knaff, J. A., C. R. Sampson, and G. Chirokova, 2016: A Global Statistical-Dynamical Tropical Cyclone Wind Radii Forecast Scheme. *Submitted to Wea. Forecasting.*

Highlights of that paper suggest:

1. This method (DSWR in the decks) 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 consensus, never degrades the consensus, and in most cases improves the consensus forecasts, and
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.

Once the paper is accepted, it will be shared with NHC/JHT.

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

- The real-time DSRW forecasts are available at ftp://rammftp.cira.colostate.edu/knaff/DSWR/
- The real-time SHIPS parallel runs are available at ftp://rammftp.cira.colostate.edu/chirokova/JHT_2015_2017/rt_demo/

-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.

None

*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 for setting up parallel runs.

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 develops 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 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.
None
-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: RL5

-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 project is on schedule and both the upgraded SHIPS/LGEM/RII code and new TC-structure forecast code will be ready for operational transition by summer 2017, but will need to wait until the 2018 season since NHC does not do operational model upgrades during the hurricane season. 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) Bias corrections for DSRW were developed and implemented following discussions at the *AMS Conference on Hurricanes and Tropical Meteorology*.

3) Software was provided and tested on WCOSS for potential 2016 quasi-prod production. Implementation will occur for 2017.

4) 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). It was decided to implement these for the 2017 season because NHC TSB staff did not have the time to implement this for 2016.

5) SHIPS/LGEM parallel runs with daily SST and DAVT assuming constant mixing depth will be set up at CIRA during the 2016 hurricane season.

6) The possibility of implementing SHIPS with daily SST in the quasi-production version of SHIPS on WCOSS for 2016 season has been discussed with NHC POCs and NHC TSB stuff. It was decided to implement that for the 2017 season due to the lack of NHC TSB staff time.

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

The transition to operations for this project is scheduled after the end of Year 2, in the spring of 2018, if accepted by NHC. The project is on schedule and both the upgraded SHIPS/LGEM/RII code and new TC-structure forecast code will be ready for operational transition by summer 2017, but will need to wait until the 2018 season since NHC does not do operational model upgrades during the hurricane season. The timing of the final transition will depend on the availability of NHC Technology and Science Branch (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 were provided and tested on WCOSS.
3) 2015 version of SHIPS model with option to use DSST was provided to TSB

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 will be developed. The new statistical dynamical model for forecasting TC wind radii will be 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

Courtney, J., and J. A. Knaff, 2009: Adapting the Knaff and Zehr Wind-Pressure Relationship for operational use in Tropical Cyclone Warning Centres. *Australian Meteorological and Oceanographic Journal,* **58**, 3, 167-179.

Knaff, J.A., C. J. Slocum, K. D. Musgrave, C. R. Sampson, and B. R. Strahl, 2016: Using routinely available information to estimate tropical cyclone wind structure. *Mon. Wea. Rev*. **144**:4, 1233-1247. DOI: http://dx.doi.org/10.1175/MWR-D-15-0267.1

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

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.