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Project Title: Improvement to the Tropical Cyclone Genesis Index (TCGI)

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Project/Grant Period: 09/01/2015 - 08/31/2018
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Reporting Period Start/End Date: 09/01/2015 - 08/31/2018

Report Term or Frequency: Quarterly

Reporting Timeline: Final Report (Revised)

1. ACCOMPLISHMENTS

The main goal of this project is to implement improvements to the Tropical Cyclone (TC) Genesis Index (TCGI) that was transitioned to operations at the NOAA National Hurricane Center (NHC) in October 2014. TCGI is a disturbance-following scheme designed to provide forecasters with an objective tool for identifying the 0-48hr and 0-120hr probability of TC genesis in the North Atlantic basin. Progress made under this current funded project includes expanding the TCGI North Atlantic database to include the years 2001-2014, developing a new 2001-2014 Pacific (i.e., eastern north Pacific (EPAC) and central North Pacific (CPAC)) TCGI database, identifying new predictors to test in both the Atlantic and Pacific versions of TCGI, deriving an eastern/central Pacific basin TCGI utilizing predictors that were employed in the previously developed Atlantic basin version and developing an ECMWF-based Atlantic TCGI using predictors and predictor weights that were developed for the GFS version of TCGI. The following tasks were conducted and/or completed during this project:

i. Collect, quality control, and format 2011-2014 AL Dvorak information (completed October 2015)

- This element of the proposal effort (led by Co-PI Cossuth) involved expanding the current TCGI NHC invest database by an additional 4 years (2011-2014). The new 2001-2014 database includes 6-hourly information including Dvorak T-Num, CI number, and invest position for all Atlantic disturbances that were tracked by NHC over the 14-year period. This 2001-2014 Atlantic invest database provided two vital components to TCGI project: 1) a climatology of developing and non-developing tropical disturbances that were tracked by NHC in the Atlantic (including 6-hourly positions). This information was used as a training set for the improved TCGI; and

2) Dvorak T-numbers (i.e., "T-Num" satellite-derived intensity estimates) for these developing and non-developing tropical disturbances. *"T-Num"* is one of the predictors currently used in the operational version of TCGI and one of the top predictors for determining TC genesis in the 2-day timeframe.

ii. Collect, quality control, and format 2001-2014 EP/CP Dvorak information (completed December 2015)

- This element of the proposal effort involved developing a 2001-2014 TCGI NHC invest database for the Pacific basin. The new 2001-2014 database includes 6-hourly information including Dvorak T-number, CI number, and invest position for all Pacific disturbances that were tracked by NHC over the aforementioned 14-year period. This 2001-2014 Pacific invest database provided two vital components to the TCGI project: 1) A climatology of developing and non-developing tropical disturbances that were tracked by NHC in the Pacific (including 6-hourly positions). This information was used as a training set for the new Pacific TCGI; 2) Dvorak T-Nums for these developing and non-developing tropical disturbances. Dvorak T-Num is one of the predictors currently used in the operational version of the Atlantic and Pacific versions of TCGI and one of the top predictors for determining TC genesis in the 2-day timeframe.

iii. Complete identification/development of new Atlantic and Pacific TCGI predictors (completed May 2016)

- With the completion of the 2001-2014 TCGI Atlantic and Pacific invest databases and preliminary testing of the current operational predictors in each version, efforts then focused on examining the predictors that would be tested and eventually implemented in the new Atlantic and eastern/central Pacific versions of TCGI. The original 60 predictors that were tested in the original TCGI and several new predictors (Table 1) were all examined for statistical significance as potential predictors. Variable predictor search areas that were smaller for the 0-48 hr forecast period (i.e., R=0-200, 0-300, and 0-400 km) and larger for the 0-120 hr forecast period (i.e. R=0-500 km) were also examined for possible inclusion in the new Atlantic and Pacific versions of TCGI. Several of the original 60 TCGI predictors and new TCGI predictors with varying search areas were identified that were highly statistically significant at the 95%-99.9% level. This effort set the stage for subsequent predictor sensitivity testing that was conducted (deliverable *vi*).

New TCGI Predictor	Data Source
600-800 hPa RH	GFS/ECMWF model
925-1000 hPa RH	GFS/ECMWF model
Theta-E excess	GFS/ECMWF model
850 hPa vorticity	GFS/ECMWF model
850 hPa vorticity x divergence	GFS/ECMWF model
850 hPa moisture convergence	GFS/ECMWF model
Tropical Overshooting Tops (TOTs)	GOES/Meteosat (UW-CIMSS)
Lighting Strike Density	World Wide Lightning Location Network (WWLLN)

Table 1. New predictors tested in the Atlantic and Pacific versions of TCGI.

iv. Present year-1 results at the 70th Tropical Cyclone Operations and Research Forum (March 2016)

- PI Dunion presented a project update at the TCORF/70th IHC in Miami, FL, 15-17 March 2016
- Dunion, J.P., J. Kaplan, A. Schumacher, J. Cossuth, P.A. Leighton, and K. Musgrave, 2016: Improvement to the Tropical Cyclone Genesis Index (TCGI). Preprints, *70th TCORF Conf.,* Miami, FL. NOAA OFCM (Available online at https://www.ofcm.gov/meetings/TCORF/ihc16/2016presentations.html).

v. Begin development of an ECMWF-based Atlantic TCGI using predictors and predictor weights that were developed for the GFS version of TCGI (completed September 2017)

- Code for testing the ECMWF-based Atlantic TCGI was installed on the NOAA/NCEP Weather and Climate Operational Supercomputing System (WCOSS) [September 2016].
- Development of the ECMWF TCGI was completed and real-time code was implemented and tested on WCOSS (September 2017).

vi. Begin sensitivity testing for optimal combinations of Atlantic and Pacific TCGI predictors (GFS version) (completed March 2017)

- New TCGI predictors using the 2001-2014 Atlantic and Pacific datasets were tested alongside ~60 other previously tested predictors. Sensitivity tests included WWLLN lightning data, Tropical Overshooting Tops (only available in the Atlantic), and several GFS-based predictors: (1) relative humidity (850-600 hPa and 1000-925 hPa), (2) moisture convergence at 850 hPa, (3) vertical wind shear magnitude and direction for the 850-500 hPa layer, (4) generalized vertical wind shear from 1000-100 hPa, and (5) vorticity x divergence at 850 hPa.
- All area-averaged predictors were calculated using the original TCGI 0-500 km predictor search radius, as well as several smaller search radii: 0-200, 0-300, and 0-

400 km. Although dependent dataset tests indicated that smaller search radii were increasingly skillful, simulated real-time tests for 2011-2016 showed that smaller search radii, in fact, produce increasingly less skillful TCGI forecasts. This discrepancy likely relates to the fact that the dependent test benefitted from "perfect prog" forecasts (i.e. tropical disturbance positions were known throughout the storm lifecycle), which is not representative of real-time operations. The 2011-2016 simulated real-time tests suggest that track forecast uncertainty inherent in weak tropical disturbances is significant and requires the use of 0-500 km search radii for both 0-48 and 0-120 hr TCGI forecasts.

- Sensitivity tests were conducted to identify the optimal combination of predictors for the expanded version of the Atlantic TCGI and new Pacific TCGI. These 6 optimal predictors calculated using the 0-500 km search radius are highlighted in Fig. 1 and were used for both the Atlantic and Pacific versions of TCGI. Figure 2 shows the cross-validated Brier Skill Score for the new Atlantic and Pacific versions of TCGI derived from the 2001-2014 TCGI invest database.

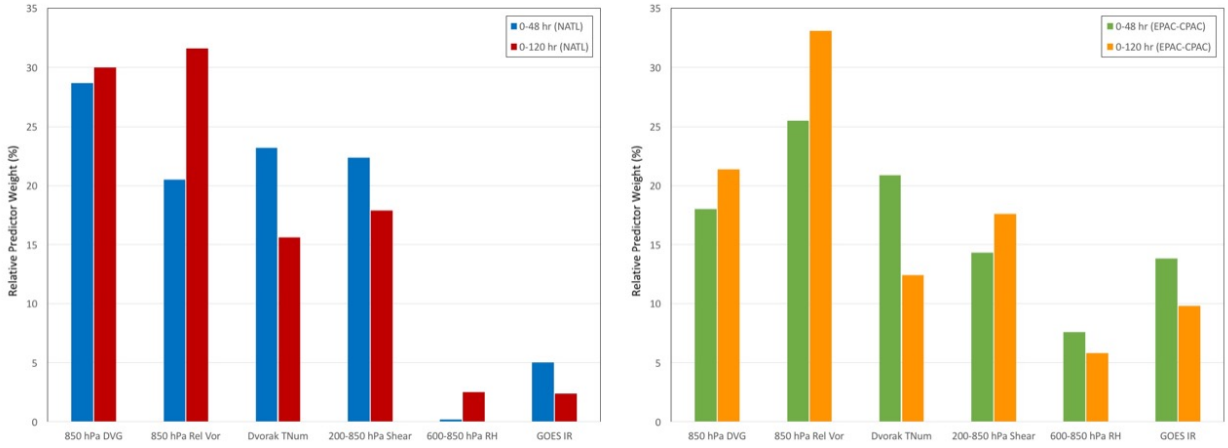

Fig. 1: Relative predictor weights for the new 2001-2014 Atlantic (left) and Pacific (right) versions of TCGI. The 0-48 hr predictor weights are shown in blue (Atlantic TCGI) and green (Pacific TCGI) and the 0-120 hr predictor weights are shown in red (Atlantic TCGI) and orange (Pacific TCGI). Predictors include: 850 hPa divergence (DVG), 850 hPa relative vorticity (Rel Vor), Dvorak T-number (T-Num), 200-850 hPa vertical wind shear (Shear), 600-850 hPa relative humidity (RH), and GOES water vapor pixels <-40°C (GOES IR). Predictor weights were derived using 0-500 km search radii.

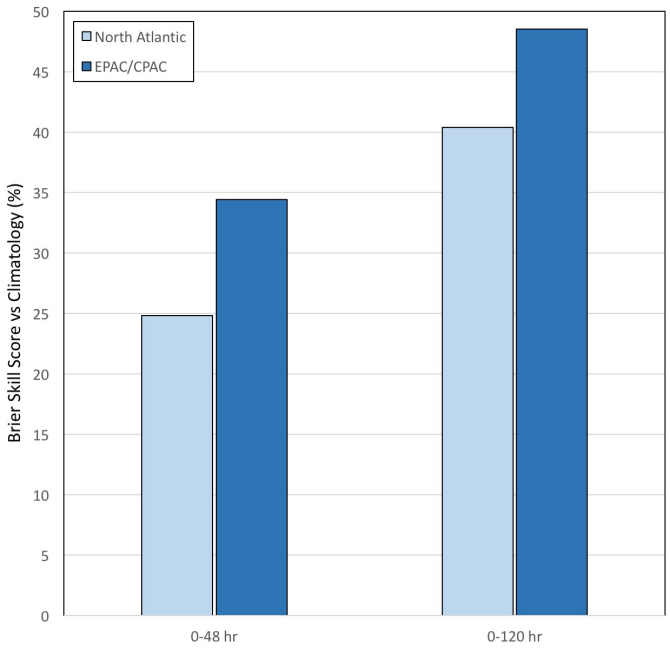

Fig. 2: Cross-validated Brier Skill Score (relatively to climatology) for the new Atlantic and Pacific versions of TCGI based on the 2001-2014 TCGI invest database.

vii. Develop and test graphical TCGI products with real-time cases

- Based on feedback from the NOAA NHC points of contact on this project, development of a graphical version of TCGI has been eliminated as a funded deliverable for this current project.

viii. Develop code for running a real-time version of the Atlantic and Pacific TCGI (GFS version) (completed December 2016)

- All of the FORTRAN code used to process the developmental genesis datasets and subsequently derive the TCGI was modified to make it possible to assess the significance of the various TCGI predictors that were tested as well as to evaluate the impact of varying the averaging radius of each of the GFS-based environmental variables from 200-500 km.
- The original version of TCGI determined 5-day invest forecast tracks from the GFS model when available and filled in any missing track positions using the BAMG model. NHC's latest statistical track forecast model, the Medium-Layer Trajectory and Beta Model (TABM), was tested in TCGI in research mode and its performance was determined to be superior to the BAMG model. Therefore, code to generate real-time invest forecast tracks from the new TABM was developed and implemented in TCGI.

ix. Present year-2 results at the 71st Tropical Cyclone Operations and Research Forum (March 2017)

- PI Dunion presented a project update at the TCORF/71st IHC in Miami, FL, 13-15 March 2017

- Dunion, J.P., J. Kaplan, A. Schumacher, J. Cossuth, P.A. Leighton, and K. Musgrave, 2017: Improvement to the Tropical Cyclone Genesis Index (TCGI). Preprints, *71st TCORF Conf.,* Miami, FL. NOAA OFCM (Available online at https://www.ofcm.gov/meetings/TCORF/ihc17/2017presentations.htm).

x. Based on POC and IHC feedback, refine TCGI graphical products

- Based on year-1 feedback from the NOAA NHC points of contact on this project, development of a graphical version of TCGI has been eliminated as a funded deliverable for this current project.

xi. Perform real-time tests of TCGI graphical products in-house at NHC or online at: http://rammb.cira.colostate.edu/realtime_data/nhc/tcgi/

- Based on year-1 feedback from the NOAA NHC points of contact on this project, development of a graphical version of TCGI has been eliminated as a funded deliverable for this current project.
- As an unfunded effort, members of the proposal team did develop graphical versions of 2- and 5-day TCGI forecasts which are available in real-time at CIRA: http://rammb.cira.colostate.edu/projects/tc_genesis/

xii. Perform real-time tests of 0-48 and 0-120 h Atlantic and Pacific TCGI (GFS version) on NESDIS computers at CIRA with output being made available online (completed May 2017): http://rammb.cira.colostate.edu/realtime_data/nhc/tcgi/

- The new Atlantic and Pacific versions of TCGI were run and tested in real-time at CIRA through the 2017 season. Real-time and archived TCGI output is available online at: http://rammb.cira.colostate.edu/projects/tc_genesis/

xiii. Perform real-time tests of 0-48 and 0-120 h Atlantic and Pacific TCGI (ECMWF version) at NHC (requires computing and IT support from NHC) (completed November 2018)

- Development of the ECMWF TCGI was completed and real-time code was implemented and tested on WCOSS (September 2017). At this time, the proposal team was still working with the Technology & Science Branch (TSB) at NHC to obtain real-time ECMWF tracks and forecast fields at CIRA so that parallel runs could be performed.
- The proposal team successfully worked with the Technology & Science Branch (TSB) at NHC to obtain real-time ECMWF tracks and forecast fields at CIRA so that real-time parallel runs could be performed and the real-time version of the ECMWF-based TCGI could be run (September 2018).
- The proposal team ran real-time tests of the ECMWF version of TCGI on WCOSS at NHC for the Pacific throughout the 2018 hurricane season. However, due to IT restrictions accessing WCOSS remotely, these output data files have only been available internally at NHC and the proposal team has not been able to access them. During a recent visit to NHC (September 2018), Co-I Musgrave was able to access ECMWF PACK files from 2018. Co-PI Schumacher was then able to re-run ECMWF-based TCGI forecasts for all Atlantic and EPAC/CPAC cases from 2018 (Figs. 3 and 4). These tests demonstrated that the ECMWF and GFS-based TCGI produce consistent forecasts and helped the proposal team check and debug the

ECMWF-based TCGI code. This test of the ECMWF-based TCGI generated forecast tracks using NHC's TABM model running off of ECMWF model synoptic forecast fields. The proposal team plans to re-run these ECMWF-based TCGI 2018 cases using ECMWF forecast fields and storm tracks and plans to present these results in peer reviewed journal.

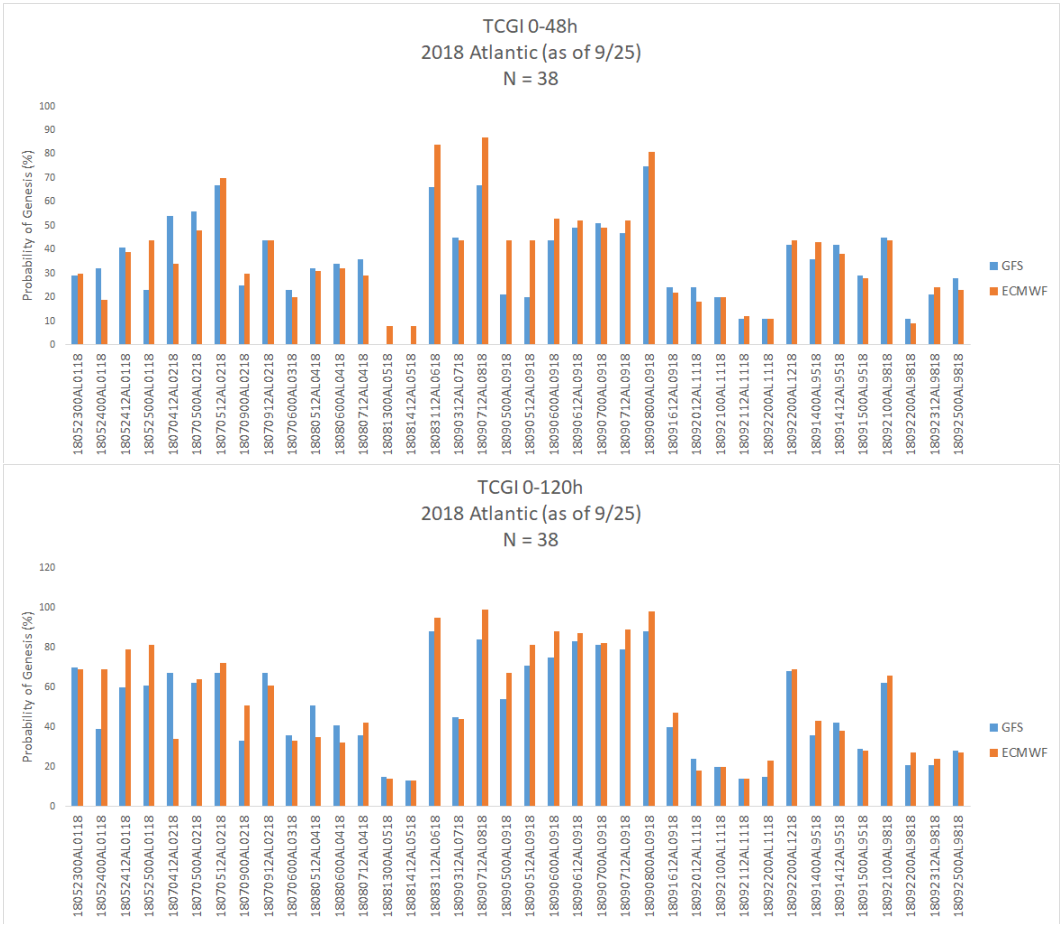

Fig. 3: (top) 0-48 hr and (bottom (0-120 hr) genesis forecasts for a homogenous sample of 2018 Atlantic tropical disturbances generated by the GFS-based TCGI and new ECMWF-based TCGI. TCGI forecast tracks were generated using NHC's TABM model running off of ECMWF model synoptic forecast fields. TCGI forecasts include all cases through 25 Sep 2018.

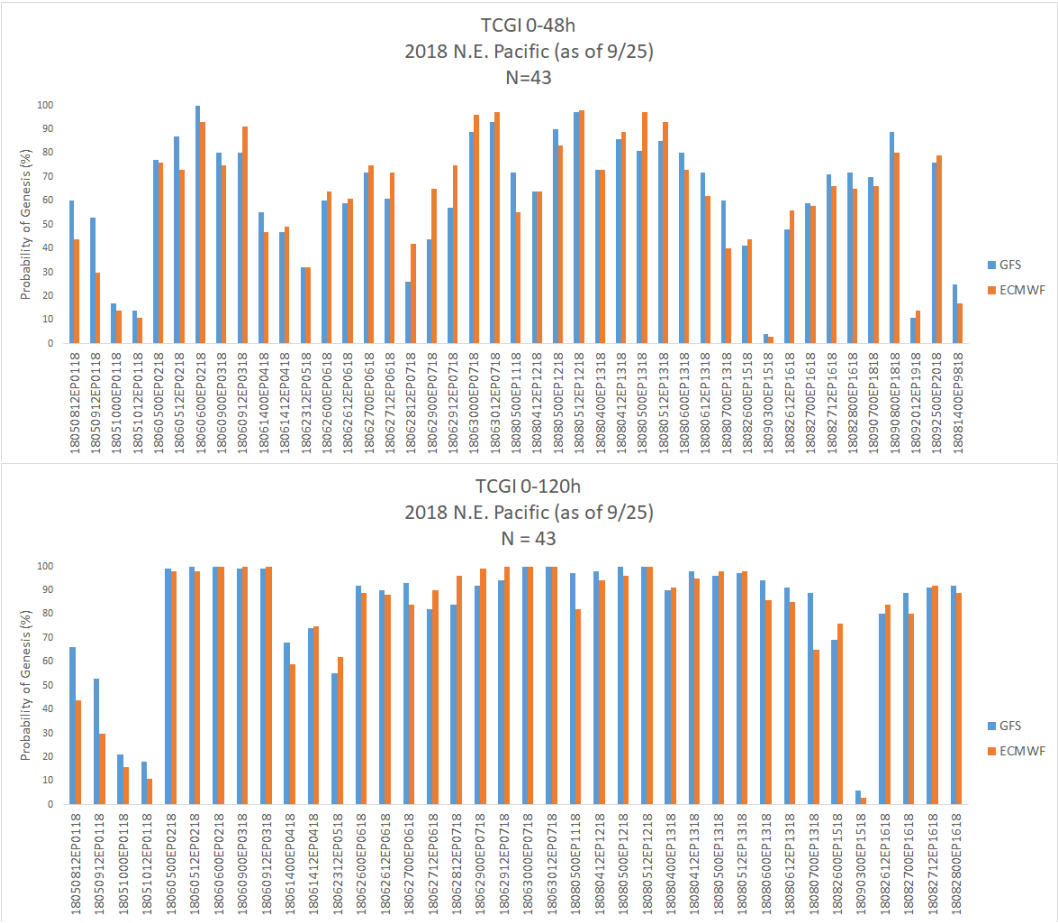

Fig. 4: Same as Fig. 3, except for the eastern and central North Pacific.

xiv. Final code for running both the Atlantic and Pacific versions of TCGI on operational NCEP computers will be provided to NHC/NCEP IT personnel if the project is accepted for operational transition (completed October 2018)

- Final code for both the Atlantic and Pacific versions of the TCGI was delivered to TSB and installed on NOAA's Weather and Climate Operational Supercomputing System (WCOSS) in September 2017. Since the final code delivery, NHC switched their operational GOES-East satellite feed from GOES-13 to the new GOES-16 satellite, which has different water vapor channels and different file formats than its predecessor. Project scientists delivered a software patch to TSB in October 2018 that TSB plans to implement on WCOSS prior to the start of the 2019 season (this patch will also be applicable to the new GOES-17 satellite when it becomes the operational GOES-W satellite). Project scientists will provide support to TSB during patch implementation as needed. New readers have been in place at CIRA since the beginning of the 2018 season and the GFS-based TCGI has been available to NHC forecasters via the web throughout the season: http://rammb.cira.colostate.edu/projects/tc_genesis/

- Completion of the final implementation phase of this project has been slowed due to the project team's inability to access both the NHC version of TCGI and real-time ECMWF data from outside of NHC. The near-final code for the ECMWF version of the TCGI was delivered to TSB and installed on WCOSS in September 2017, but CIRA's lack of access to the ECMWF files used at NHC (which are a specialized data format used exclusively at NHC) made it difficult to fix a few bugs and finalize that code. During a recent visit to NHC, Co-I Musgraves secured access to a large sample of 2018 ECMWF PACK files which has helped the ECMWF-based TCGI effort to once again progress. The final ECMWF TCGI code has now been thoroughly vetted at CIRA and was delivered to TSB personnel in October 2018. This final code will be implemented by TSB prior to the 2019 season. Once again, project scientists will provide support to TSB during patch implementation as needed.
- Per a request from our NHC POCs, the proposal team conducted verification statistics for the new GFS version of TCGI for both the Atlantic and Pacific basins. This included performing retrospective re-runs of TCGI for the Atlantic (728 TCGI runs) and eastern/central North Pacific (882 TCGI runs) hurricane seasons for a five-year period (2013-2017) and for 2017. Verification analyses include reliability diagrams and Brier Skill Scores [relative to climatology (derived from the 2001-2014 TCGI invest database)] for TCGI and NHC TWO 0-48 and 0-120-hr forecasts for 2013-2017 (Figs. 5 and 6) and 2017 (Figs. 7 and 8). The NHC Best track for the 2018 hurricane season was not finalized at the time of this report and was therefore not included here.

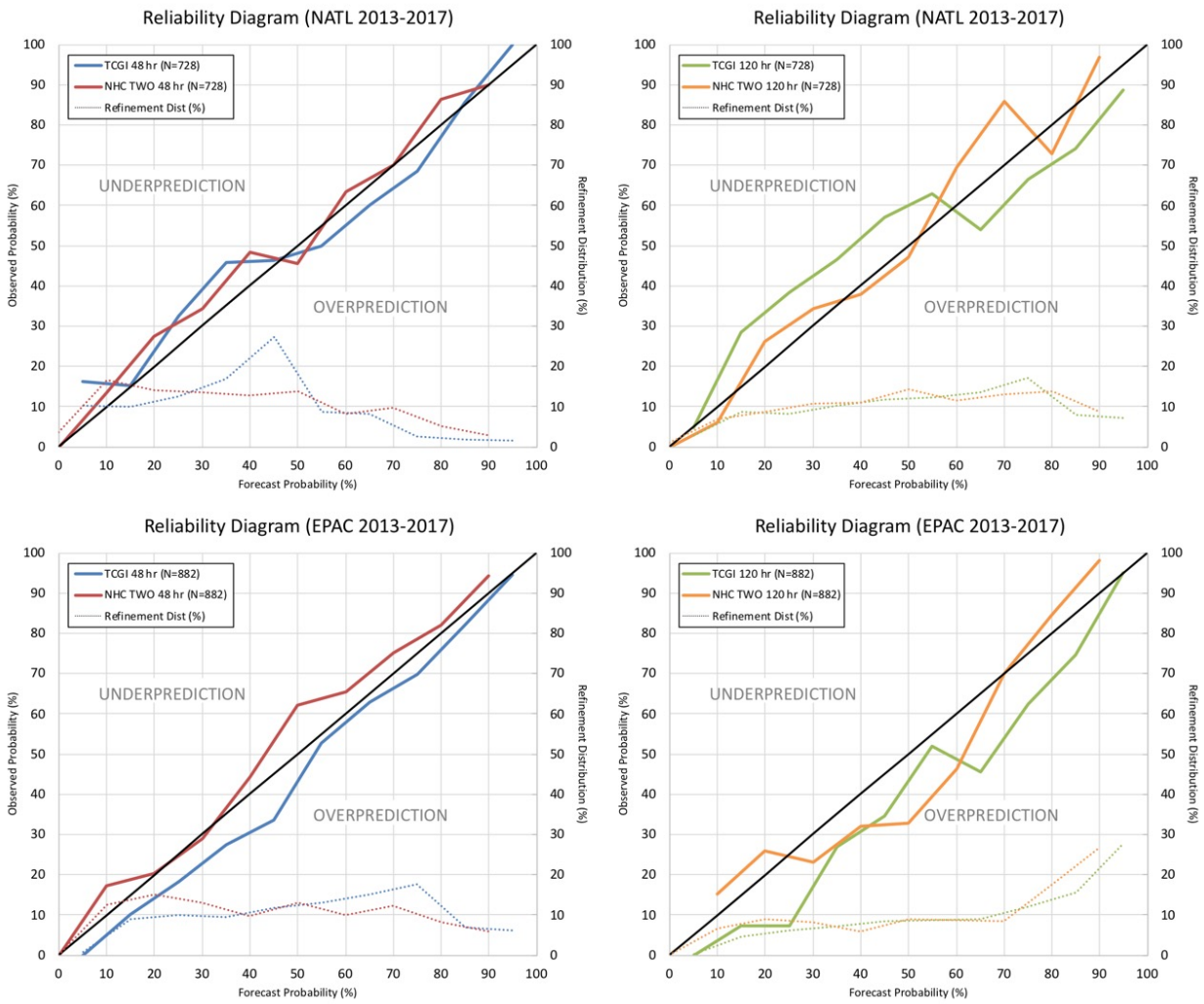

Fig. 5: Reliability diagrams for TCGI and a homogeneous sample of NHC TWO Atlantic probabilistic TC genesis forecasts for the 2013-2017 Atlantic and EPAC/CPAC hurricane seasons. The solid blue, red, green, and orange lines indicate the relationship between the 48-hr (120-hr) forecast and verifying genesis percentages, with perfect reliability indicated by the thin diagonal black line. The dashed lines indicate how the corresponding forecasts were distributed among the possible forecast values.

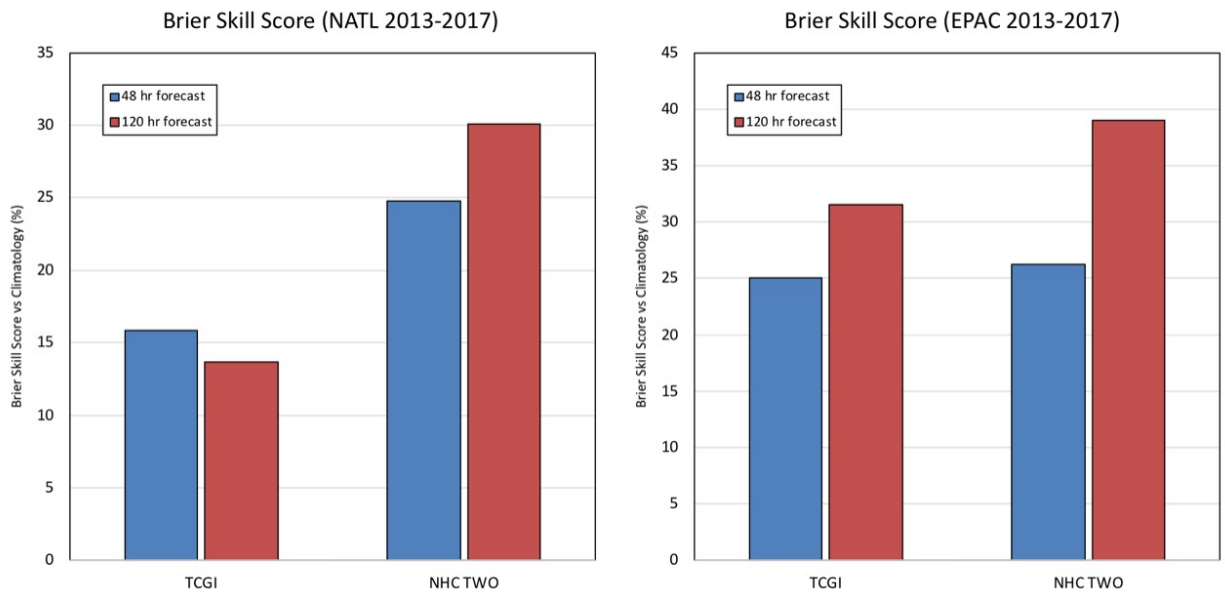

Fig. 6: Brier Skill Scores for TCGI and a homogenous sample of NHC TWO Atlantic probabilistic TC genesis forecasts for the 2013-2017 Atlantic and EPAC/CPAC hurricane seasons. Skill was measured against the climatological probability of tropical cyclogenesis determined from a 2001-2014 dataset of Atlantic and EPAC/CPAC invests.

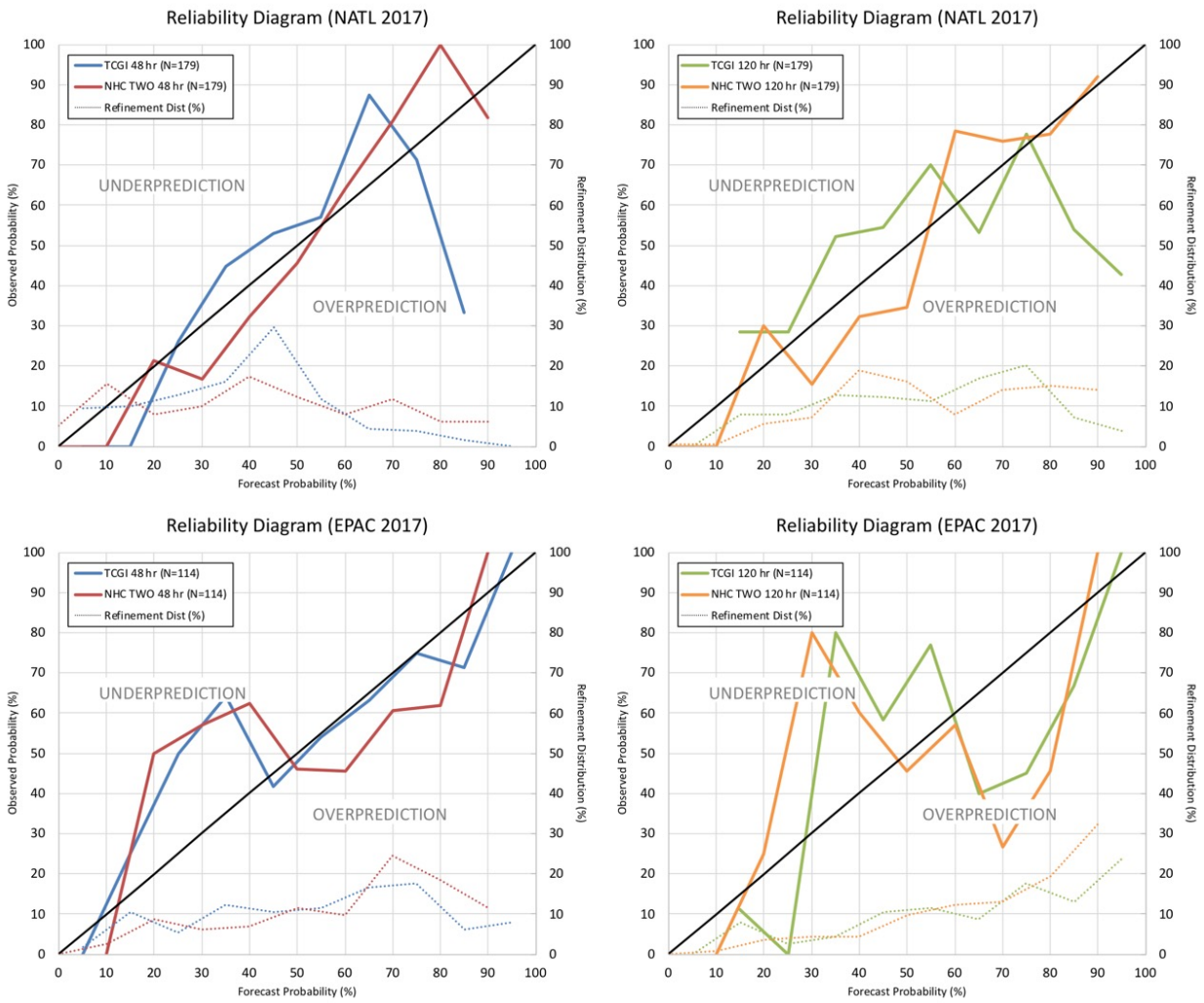

Fig. 7: Reliability diagrams for TCGI and a homogeneous sample of NHC TWO Atlantic probabilistic TC genesis forecasts for the 2017 Atlantic and EPAC/CPAC hurricane seasons. The solid blue, red, green, and orange lines indicate the relationship between the 48-hr (120-hr) forecast and verifying genesis percentages, with perfect reliability indicated by the thin diagonal black line. The dashed lines indicate how the corresponding forecasts were distributed among the possible forecast values.

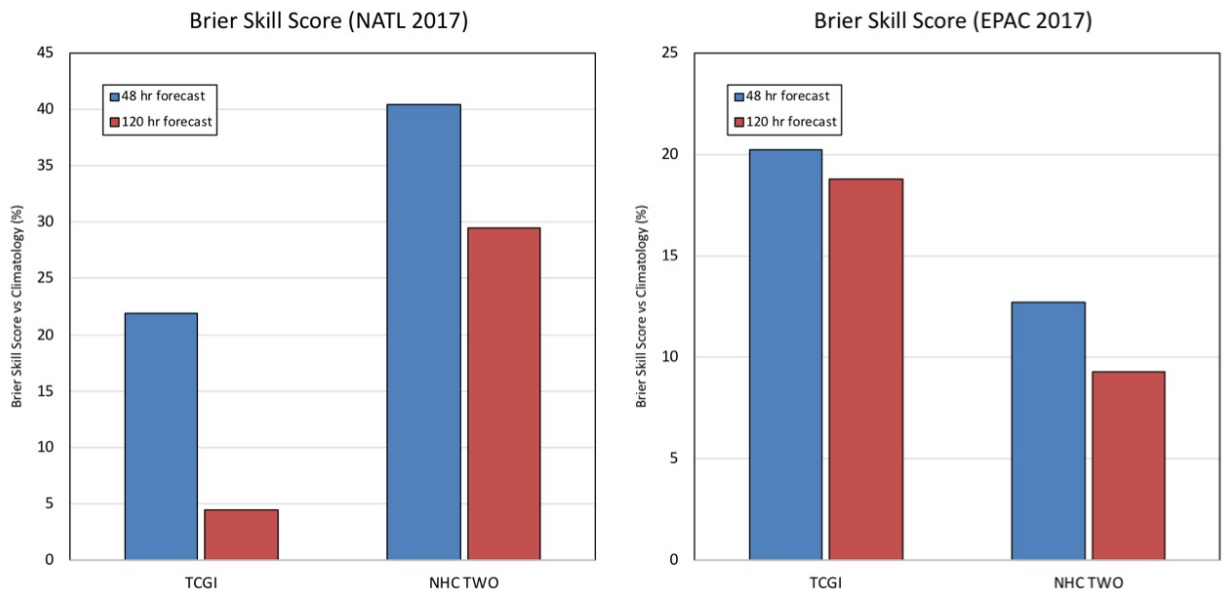

Fig. 8: Brier Skill Scores for TCGI and a homogenous sample of NHC TWO Atlantic probabilistic TC genesis forecasts for the 2017 Atlantic and EPAC/CPAC hurricane seasons. Skill was measured against the climatological probability of tropical cyclogenesis determined from a 2001-2014 dataset of Atlantic and EPAC/CPAC invests.

2. PRODUCTS

Efforts related to this project's current reporting period have produced the following:

a. Updated Real-Time TCGI Website (hosted by the Colorado State University-CIRA):
   - http://rammb.cira.colostate.edu/projects/tc_genesis/

b. TCGI Computer Code
   - New readers have been developed for the CIRA version of the Atlantic TCGI code that can process the new GOES-East and anticipated GOES-West (GOES-17) water vapor imagery and resume calculating one of TCGI's critical satellite-based predictors.
   - The proposal team is currently working with TSB staff on developing new subroutines for TCGI that will read GOES-16 (and GOES-17) rectilinear files. The goal of this effort is to restore the capability for operational testing of the Atlantic version of TCGI (both GFS and ECMWF versions).
   - New software has also been developed by the proposal team to graphically display the trends in both the 0-48 h and 0-120 h TCGI probabilities. This new TCGI output graphic is currently being tested and made available in real-time via the CIRA web site.

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

The following team members have contributed to this project (no changes to senior/key project personnel has occurred since the last reporting period and only the personnel and institutions listed below have contributed to this project's deliverables):

PI:
Jason Dunion, University of Miami/CIMAS – NOAA/AOML/HRD, jason.dunion@noaa.gov
Co-PIs:
John Kaplan, NOAA/AOML/Hurricane Research Division, john.kaplan@noaa.gov
Andrea Schumacher, Colorado State University/CIRA, schumacher@cira.colostate.edu
Joshua Cossuth, Naval Research Laboratory-Monterey, Joshua.Cossuth.ctr@nrlmry.navy.mil
Co-Is:
Paul Leighton, NOAA/AOML/Hurricane Research Division, paul.leighton@noaa.gov
Kate Musgrave, Colorado State University/CIRA, Kate.Musgrave@colostate.edu

4. IMPACT

This project is now complete. The NOAA-identified impacts for this reporting period do not apply. None of this project's awarded budget has been spent in a foreign country.

5. CHANGES/PROBLEMS

This project is now complete.

6. SPECIAL REPORTING REQUIREMENTS

The readiness level for this project is estimated to be RL 8 for the GFS version of the Atlantic and Pacific TCGI and RL 7 for the ECMWF version of the Atlantic and Pacific TCGI. The following outlines test plans for this USWRP-supported testbed project:

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

- New subroutines that read GOES-16 and GOES-17 rectilinear files were successfully tested for the version of TCGI running at NHC. This testing was coordinated with TSB staff and resulted in the development of a new patch for the TCGI code that will help restore the capability to run both the ECMWF and GFS-based versions of the Atlantic TCGI in real-time at NHC. TSB plans to implement this code in early 2019 and the proposal team will assist with the implementation, if needed.
- TC genesis forecasts from the new ECMWF model-based Atlantic and Pacific versions of TCGI were successfully run in real-time on the NOAA/NCEP WCOSS computer. Statistics summarizing these 2018 TCGI forecasts will be included in a planned manuscript submission to a peer reviewed journal.

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?

- The new Atlantic and Pacific versions of TCGI are being run in a parallel real-time mode to the current operational version of TCGI. The computer code for the new TCGI has also been installed on WCOSS and is running in real-time.

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?

- Testing and evaluation of the new GFS-based TCGI code has been conducted since the beginning of the 2017 Atlantic hurricane season. Testing of the ECMWF-based TCGI was successfully conducted during the 2018 season.

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

- The new TCGI is set up to run in parallel on both the NOAA/NCEP WCOSS computer and on servers at the Cooperative Institute for Research in the Atmosphere. Project personnel tested and evaluated TCGI on both computing systems.

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

- The entire project team is involved in testing and evaluating the new TCGI. Feedback from this project's NHC points of contact have also been vital and they have been included during the ongoing testing and evaluation process. Some support/input from IT personnel at NOAA NHC has been required to ensure that critical readers for GOES-16 (and GOES-17) water vapor imagery were developed for the NHC version of the Atlantic TCGI and that ECMWF model data was available in real-time for use in the ECMWF-based Atlantic TCGI.

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?

- This project is now complete.

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?

- Real-time availability of TCGI on the WCOSS computer is needed and comparisons between TCGI output from WCOSS and CIRA are necessary to demonstrate success and advance the readiness level.
- The final ECMWF TCGI code has now been thoroughly vetted at CIRA and was delivered to TSB personnel in October 2018. This final code will be implemented by TSB prior to the 2019 season with support from the proposal team, if needed. This final implementation will advance TCGI to the RLs discussed at the beginning of Sec. 6.

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

- Verification that the NHC version of TCGI running on WCOSS runs identically to the CIRA version of TCGI that was run and tested in real-time during the 2018 hurricane season will be made and provided to the proposal team's NHC points of contact at the conclusion of the 2018 season.

7. BUDGETARY INFORMATION

This project is now complete.

8. PROJECT OUTCOMES

The main deliverable of this project was to implement improvements to the Tropical Cyclone Genesis Index (TCGI) that was transitioned to operations at NOAA NHC in October 2014. The outcome of this effort was to turn over the operational code for running the upgraded GFS-based TCGI to NOAA by August 2017 and to deliver the operational code for running the ECMWF-based TCGI to NOAA by November 2018. Performance measures that are defined in this project have been achieved and the TCGI code has been delivered to NHC. The final effort for this project will be for TSB to implement the GOES-16 patch implementation prior to the 2019 season. Once again, the project team will provide support to TSB as needed.