

## FINAL REPORT

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**Title:** Quantifying the Practical Predictability of Tropical Cyclone Intensity Forecasts

**Grant Number #:** N00014-18-1-2588

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**Total Amount:** \$319,786

### 1. Major goals and objectives of the project?

The main aims of this proposal are to 1) examine a potential saturation of tropical cyclone (TC) intensity errors for the US Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) model, and 2) understand how the maximum potential intensity (MPI) imposes a limit on the intensity error saturation under different large-scale conditions beyond the traditional metrics. With these aims, the *specific objectives* of this proposal are:

Objective 1: Determine the dependence of the intensity error growth rate on storm intensity at different stages of TC development.

This objective focuses on measuring the TC intensity error growth rate at different stages of TC intensification, as well as the structure of errors that can indicate the fastest growing of intensity errors. Outcomes from this objective will bring new insight into the spread of TC intensity during rapid intensification, thus providing a practical guidance to the future development of the US Navy's TC models.

Objective 2: Quantify the practical predictability limit of the COAMPS-TC model in forecasting TC intensity in different basins.

This objective will directly assess the potential existence of chaotic variability at the quasi-stationary MPI limit, how sensitive the MPI is to different initial conditions and variations in large-scale environments, and the spectrum of error energy power at the MPI limit in different ocean basins. Addressing this question provides an upper bound on the accuracy of TC intensity forecasts from a practical standpoint, thus serving as a guidance for the US Navy's future development and expectation of operational TC models in predicting TC intensity.

### 2. Accomplishment

During the 3-year period of this project, a number of scientific and educational outcomes towards the main goals of this project have been achieved. A summary of major outcomes are listed below:

#### A. Scientific accomplishments

1. **Intrinsic intensity error growth and predictability:** In this study (Kieu et al. 2018, Keshavamurthy and Kieu 2020), we have conducted thorough analyses of TC intensity error saturation at the maximum intensity limit as well as the error growth during TC rapid intensification, using a full-physic model. By varying large-scale environments under idealized environment, the dependence of TC intrinsic intensity variability on the large-scale conditions was obtained. Among several environmental factors, we found that sea surface temperature and tropospheric static stability are the main two affecting the saturation of TC intensity errors, with a larger error saturation at the maximum intensity equilibrium for warmer SST or less stable troposphere (Figure 1a-b). Using idealized simulations, we also showed how the growth of TC intensity errors depends on a range of environmental conditions. Similar to the error saturation, it was found that sea surface temperature and tropospheric static stability are the most dominant factors, with a faster error growth rate during rapid intensification for warmer SST or less stable troposphere (Figure 1c-d).

Results from this study highlight the fundamental characteristics of TC intensity predictability that appears to vary with environmental conditions, instead of being a universal measure for TCs in all ocean basins. These results also indicates a limit on TC intensity forecast accuracy that is governed by the large-scale environment, which needs to be taken into consideration for future TC model development. The outcomes from this study directly address the Objective # 1 of this project, and have been published in the *Quarterly Journal of the Royal Meteorological Society*.

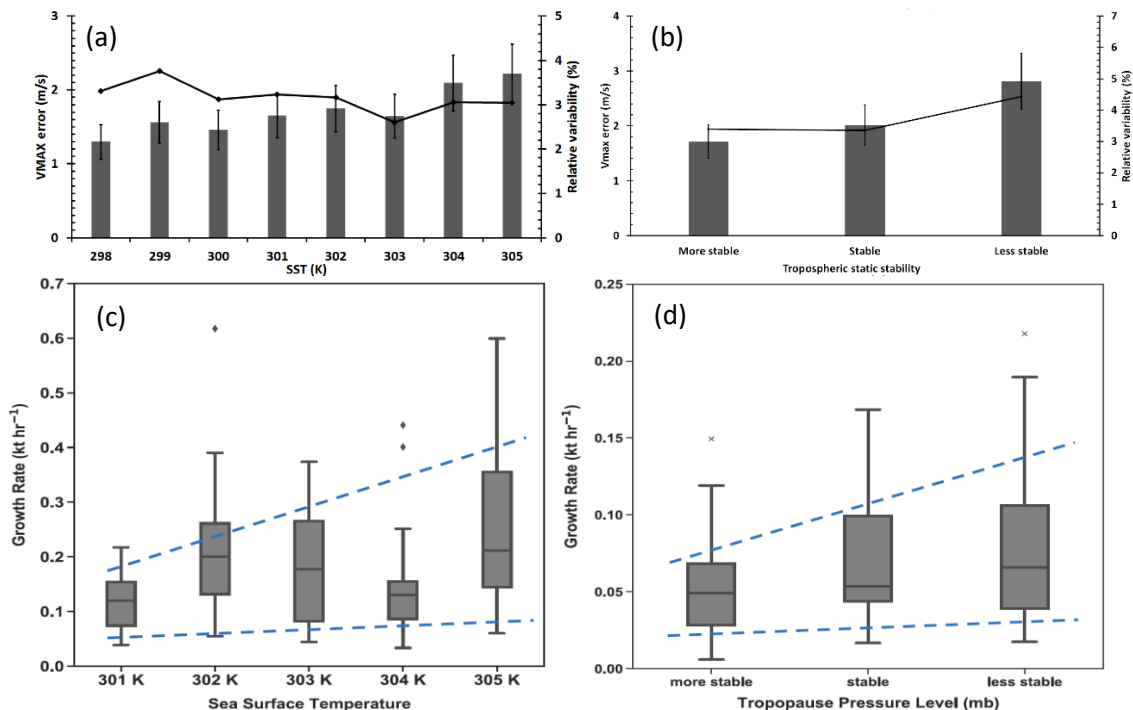


Figure 1. The saturation of VMAX errors (column) averaged during the quasi-stationary state and the relative variability of VMAX errors relative to the model maximum intensity (solid) as a function of (a) SST, and (b) tropospheric static stability. (c)-(d) A box-plot distribution of the 18-h VMAX error growth rate as a function of SST and static stability, respectively. Dashed lines in (c)-(d) denote the lower and upper bounds of the error growth rate estimations.

2. **COAMPS-TC intensity forecast error limit:** In this study (Kieu et al. 2021), we have completed analyses of the dependence of TC intensity forecast errors on the track forecast errors for the COAMPS-TC model, using the real-time forecast along with retrospective experiments during 2015-2017 seasons for three major basins. The main results from this study showed that reducing track errors by 50-70% can help improve intensity forecast by 18-20% in the COAMPS-TC model, which is most realized at 4-5 day lead times in all basins including North Atlantic, Northwestern Pacific, and Northeastern Pacific. However, additionally reducing track errors does not improve TC intensity forecast further. Instead, the 4-5 day intensity errors for TC cases with small track errors appear to be saturated at around 10-12 kt (Figure 2a-c). These results capture the dependence of the intensity forecast accuracy in the COAMPS-TC model on track forecasts, thus providing evidence of inherent intensity variability in the COAMPS-TC model beyond global model guidance.

Additional simulations under a perfect model scenario pointed out that the COAMPS-TC model possesses an intrinsic intensity variation at the TC mature stage in the range of 4-5 kt, regardless of the large-scale environment (Figure 2d). Such intrinsic intensity variability in the COAMPS-TC model highlights the importance of potential chaotic TC dynamics, rather than model deficiencies, in determining TC intensity errors at 4-5 day lead times. These results suggest a fundamental limit in the improvement of TC intensity forecasts by numerical models that one should consider in future model development and evaluation. These results help address the Objective # 2 of this proposal, and have been published in the *Weather and Forecasting*.

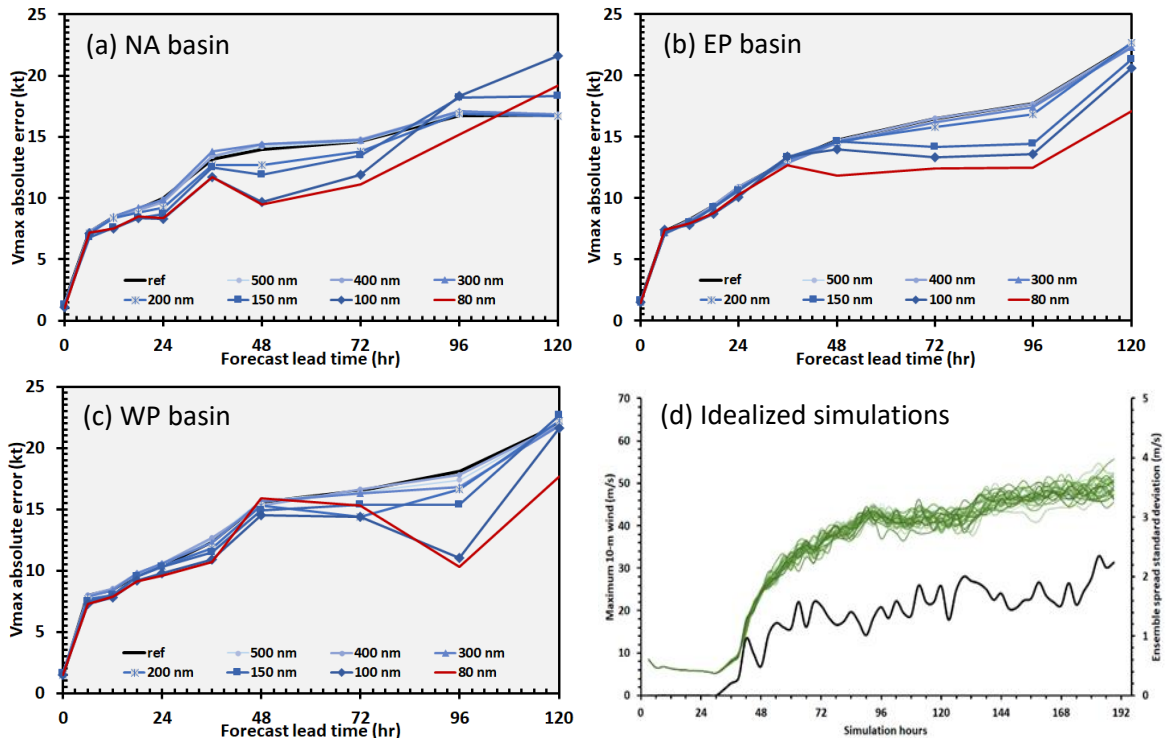


Figure 2. Verification of the absolute intensity errors obtained from the COAMPS-TC retrospective experiments with different 5-day track error thresholds for (a) the NA, (c) EP, and (c) WP basins; and (d) different intensity realizations (green) in ensemble idealized simulations of the COAMPS-TC model. Red solid lines in (a)-(c) denote the retrospective intensity verification for which the 5-day track errors < 80 nm, and black solid line in (d) denotes the standard deviation of the ensemble spread in the COAMPS-TC idealized experiments.

3. **Large-scale influence on TC intensity variability:** In this study (Kieu and Zhang 2018, Downs and Kieu 2020), we examined the dependence of the TC maximum potential intensity (MPI) on environmental stratification beyond the traditional MPI framework. Unlike the previous MPI framework that is based on the moist neutrality assumption, we presented in these analyses a different MPI formulation that explicitly incorporates the effects of environmental stratification. The new formulation is examined within an axisymmetric modelling framework by using various initial vertical thermodynamic structures and verified with observational data in two major ocean basins. Our results revealed the strong dependence of the TC maximum intensity on environmental stratification, with a lower maximum intensity for a more stable troposphere (Figure 3a). This modelling result is further confirmed by best track analyses (Figure 3b), and shows that the tropospheric static stability plays significantly role in both the North Atlantic and Western Pacific basins. Given the growing evidence from recent studies showing that a warmer sea surface temperature would induce a more stable troposphere, our finding suggests a smaller change in the TC maximum intensity in the future warming climate than that estimated from the current MPI framework. The new formulation presents the importance of environmental stratification in TC development and the long-term variability of hurricane intensity, which may explain different forecast skills of operational TC models in different basins and help address Objective # 2. The results from this study have been published on the *Journal of Climate* and *Geophysical Research Letter*.

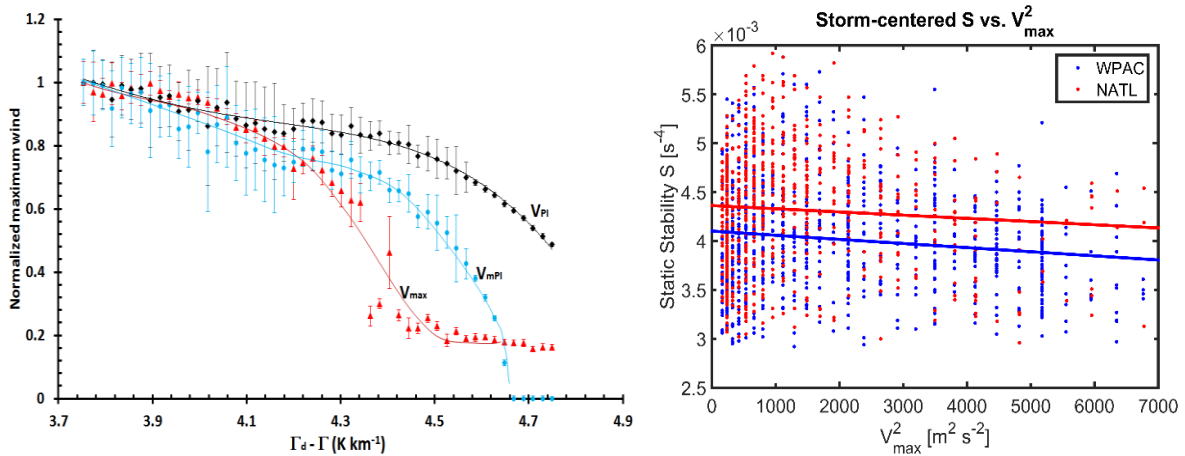


Figure 3. (a) The dependence of the model-simulated  $V_{max}$  (red triangle marks, unit  $\text{m s}^{-1}$ ) on the static stability ( $\Gamma_d - \Gamma$ ) (unit,  $\text{K km}^{-1}$ ) as obtained from CM1 model simulations. Superimposed are the  $V_{PI}$  (black) obtained from Emanuel's MPI equation, and  $V_{mPI}$  obtained from a new formula (cyan) using the hourly sounding output from the CM1 model simulations. Error bars denote the corresponding standard deviations during the averaged period, and the solid line denotes the best polynomial fit; and (b) Scatter plots of the storm-following averaged static stability for the entire tropospheric layer versus the annually-averaged observed TC intensity for the NATL basin during 1974-2017 (red) and WPAC basin during 1988-2017.

4. **TC turbulence spectra and intensity predictability:** In this study (Kieu and Rotunno 2021), we investigated the characteristics of TC turbulence and its related predictability implications in an operational TC model. Using the Fourier-Bessel spectral decomposition

for convective-permitting simulations, we found that TC turbulence possesses different spectral properties in the azimuthal and radial directions, with a steeper power law in the radial-wavenumber than those in the azimuthal-wavenumber direction (Figure 4). This spectral difference between the azimuthal and radial directions prevents one from using a single wavenumber to interpret TC intensity predictability as for classical homogeneous isotropic turbulences. Analyses of spectral error growth for a high-wavenumber perturbation further confirms that the spectral growth is more rapid for high azimuthal wavenumbers than for the radial wavenumbers, reaching saturation after  $\sim 9$  hrs and  $\sim 18$  hrs for the azimuthal and radial directions, respectively. This result highlights the key difficulty in quantifying TC intensity predictability based on spectral upscale error growth for future applications. These results address both Objectives # 1 and # 2 of this project, and are currently under review for publication in *Geophysical Research Letter*.

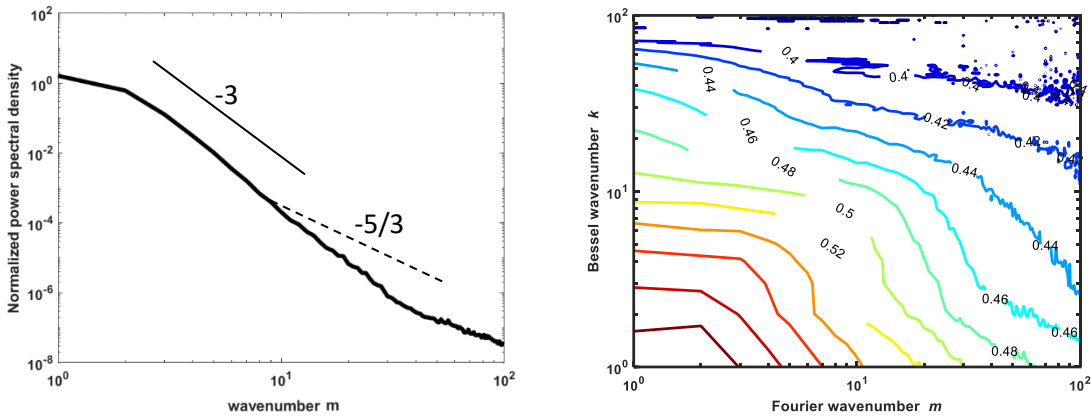


Figure 4. (a) Stationary error kinetic energy spectra as a function of the Fourier azimuthal wavenumber  $m$  that is area-averaged from 0-250 km; b) the 2D spectral decomposition coefficient  $\hat{E}(k, m)$  of error energy using Fourier-Bessel transform. This stationary background spectrum is constructed from the mature stage of the HWRP simulation during  $t = 84 - 120$  hours.

- 5. Feedback mechanism in TC development:** In these theoretical studies (Kieu and Quan 2017a,b; Kieu et al. 2020), we examined the role of different feedback processes and their relative importance in the rapid intensification of TCs. Using a reduced model for TC dynamics, we showed that a feedback between frictional convergence and convective heating in the absence of slantwise moist neutrality is capable of producing a stable maximum intensity limit, even without surface fluxes. However, the efficiency of this frictional-convergence feedback depends crucially on how effectively boundary-layer moisture convergence is converted into convective heating, which decreases rapidly as the TC inner core approaches a state of moist neutrality. This decreasing efficiency during TC intensification explains why the effect of the frictional-convergence feedback is generally small compared to that of the WISHE feedback under the strict conditions of slantwise moist neutrality. Examination of the reduced TC model with a constant heating source confirms that TC intensification is not peculiar to any specific feedback mechanism, but rather, is a direct consequence of the inward advection of absolute angular momentum, regardless of feedback mechanism. These theoretical analyses help address the fundamental mechanisms underlying the rapid development of TCs and the potential factors that are responsible for

intensity variability, thus addressing Objective # 1 of this project. These results have been published in the *Journal of the Atmospheric Sciences* and *Discrete & Continuous Dynamical System*;

### B. Educational accomplishments

Under the support of this project during the 2017-2021 period, two graduate students, Cole Evan (2019) and Kushal Keshavamurty (2020), graduated with a Master degree from the Department of Earth and Atmospheric Sciences, Indiana University Bloomington. One Postdoctoral Associate (Dr. Patra Mashaweta) was fully supported during the 2020-2021 academic year, and one doctoral student (The-Anh Vu) has been partially supported in Fall 2019. The graduate and postdoctoral research funded by this project focused on i) carrying out model simulations using the COAMPS-TC model, ii) analyzing TC intensity error growth rate and intrinsic variability for different ocean basins, and iii) writing research publications/reports.

## 3. Opportunities for training and professional development

Two major opportunities for training and professional development was achieved under the support of this project:

1. Built on the previous collaboration, the PI has continued interacting with NRL scientists (Drs. James Doyle, Yi Jin, John Moskatis, Hao Jin, Pete Finocchio) on the COAMPS-TC model, and NCAR scientists (Rich Rotunno) on TC intensity predictability for this project. Specifically, the PI had a 2-week visit of NRL in August 2018 to learn the COAMPS-TC model as well as get familiar with various retrospective experiments carried out at NRL. The direct outcome from this collaboration with the NRL team on the use of the COAMPS-TC model was a peer-reviewed publication on the *Weather and Forecasting* journal co-authored by NRL scientists on the intrinsic variability of TC intensity errors for the COAMPS-TC model. In addition, an idealized configuration of the COAMPS-TC model used in this project was also optimized and shared among different research groups to study TC rapid intensification.
2. During the course of this project, two graduate student assistants have been trained on how to configure, compile, and run the COAMPS-TC model for research, with different settings and options. The students also learned how to explain and interpret model output, as well as design sensitivity experiments to verify research hypotheses. These modelling and data analysis skillsets will be important so they can apply for their future research/career.

## 4. How were the results disseminated to communities of interest?

These results from this project have been disseminated to communities in several different ways

### **I. Peer reviewed publications (16 manuscripts)**

1. Kieu, C. Q., and R. Rotunno, 2021: Tropical cyclone intensity predictability. (Under review)

2. Kieu, C., C. Evans, Y. Lin, J. Doyle, H. Jin, and J. Moskaiti, 2021: On the Track-Dependence of the Tropical Cyclone Intensity Forecast Errors in the COAMPS-TC Model. *Weather and Forecasting*. DOI: <https://doi.org/10.1175/WAF-D-20-0085.1>.
3. Fan, W-T., C Kieu, D. Sakellariou, and M. Patra, 2021: Hitting Time of Rapid Intensification Onset in Hurricane-like Vortices. *Physics of Fluid*. <https://doi.org/10.1063/5.0062119>.
4. Keshavamurthy, K, and C. Kieu, 2021: Environmental impact on the hurricane intensity variability. *Q. J. Roy. Meteo. Soc.* 1– 20. <https://doi.org/10.1002/qj.3984>.
5. Vu, T.A., Kieu, C., Q. Wang, D. Chavas 2020: Global simulation of tropical cyclone formation. *Journal of Advanced Earth System Modelling*. 13, e2020MS002207. <https://doi.org/10.1029/2020MS002207>.
6. Kieu, C. Q., Q. Wang, and R. Rotunno, 2020: On the feedback mechanism in tropical cyclone development *Journal of Atmospheric Sciences*. **77**, 3821-3831.
7. Tran, Q-D, H. Pham, T.A Vu, T. Phan, C. Kieu 2019: Climatic shift of the tropical cyclone in the Vietnam Coastal region. *Journal of Applied Meteorology and Climatology*. **59**, 1755-1768.
8. Nguyen, P., C. Kieu, and L. Fan, 2020: Stochastic Variability of Tropical Cyclone Intensity at the Maximum Potential Intensity Equilibrium. *Journal of Atmospheric Sciences*. **77**, 3105-3118.
9. Downs, A., and C. Kieu, 2019: A Look at the Relationship between the Large-Scale Tropospheric Static Stability and the Tropical Cyclone Maximum Intensity. *Journal of Climate*. <https://doi.org/10.1175/JCLI-D-19-0307.1>.
10. Kieu, C. Q., and Q. Wang, 2019: The structure and stability of the global atmospheric circulation. *AIP Advances*, **9**, 015001.
11. Kieu, C. Q., and D.-L. Zhang, 2018: On the environmental control of the large-scale stratification on hurricane maximum potential intensity. *Geophysical Research Letter*. **45**, 6272-6280.
12. Kieu, C., K. Keshavamurthya, V. Tallapragada, S. Gopalakrishnan, and S. Trahan, 2018: On the growth of intensity forecast errors in operational tropical cyclone models. *Quarterly Journal of the Royal Meteorological Society*, **144**, 1803-1819.
13. Kieu, C. Q., Q. Wang, and S. Wang 2018: Existence of the steady state of hurricane eyewall. *Tellus A*. (accepted). doi:10.1080/16000870.2018.1487218
14. Qin, N., D.-L. Zhang, W. Miller, and C. Q. Kieu, 2018: On the rapid intensification of hurricane Wilma (2005). Part IV: inner-core dynamics during the steady RMW stage. *Quarterly Journal of the Royal Meteorological Society* (accepted). <https://doi.org/10.1002/qj.3339>.
15. Kieu, C. Q. and Q. Wang, 2017: Stability of tropical cyclone equilibrium. *J. Atmos. Sci.* **74**, 3591-3608.
16. Kieu, C. Q. and Q. Wang, 2017: On the scale dynamics of tropical cyclone intensity. *Dis. Cont. Dynamical System. Series B*, **22**, 44-54.

## II. Professional workshop/conferences (7 abstracts)

1. Kieu, C., and Q. Wang, 2020: Large-scale dynamics of tropical cyclone formation associated with ITCZ breakdown. AMS 34th Conference on Hurricanes and Tropical Meteorology. 16D.1. (Talk).
2. Kieu, C., Q Wang, DR Chavas, 2020: A Numerical Study of the Global Formation of Tropical Cyclones. AMS 34th Conference on Hurricanes and Tropical Meteorology. 17C.3. (Talk). New Orleans, Louisiana
3. Evans, C., Y Jin, JD Doyle, H Jin, JR Moskaitis, C Kieu, 2020: On the Track Dependence of the Tropical Cyclone Intensity Forecast Errors in the COAMPS-TC Model. AMS 34th

Conference on Hurricanes and Tropical Meteorology. 11D.3. (Talk). New Orleans, Louisiana. New Orleans, Louisiana

4. Downs, A., C. Kieu, 2018: Large-scale control of the tropospheric stratification on tropical cyclone maximum intensity. 2018 AGU Fall meeting, 11-14 December, Washington DC.
5. Kieu, C., and Q. Wang 2018: Hurricane Maximum Intensity Stability. 33rd Conference on Hurricanes and Tropical Meteorology. Miami, FL. April 18-22. (12C.6)
6. Kieu, C., 2017: Large-scale Control of Tropospheric Stratification on the Hurricane Maximum Potential Intensity. Tropical Cyclones: Observations, Modeling, and Predictability, AGU Fall Meeting, New Orleans, Dec 10-15. A13N-08.
7. Keshavamurty, K., and C. Kieu 2018: Limit on the Tropical Cyclone Intensity Forecast Accuracy. 33rd Conference on Hurricanes and Tropical Meteorology. Miami, FL. April 18-22. (3C.7)

### **III. COAMPS-TC model community:**

1. Assisted a graduate student at Penn State to run the COAMPS-TC model (Christopher Hartman, Penn State Univ.)
2. Knowledge sharing of the idealized COAMPS-TC configurations with community

## **5. Participants**

1. Chanh Kieu, PI (4 months)
2. Cole Evans, graduate student assistant (25 months)
3. The-Anh Vu, graduate student assistant (4 months)
4. Kushal Keshavamurthy, graduate student assistant (2 months)
5. Patra Mahashweta, postdoctoral associate (10 months)

## **6. Technology transfer**

There is no technology transfer from this project.

## **7. Student training**

There are three graduate STEM participants working on this project, with two students completed their Master degree during the 3-year period of this project and one doctoral student was supported by this project.

# REPORT DOCUMENTATION PAGE

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<b>14. ABSTRACT</b>			
This proposal addressed two major questions in tropical cyclone (TC) intensity forecast, including 1) examine a potential saturation of TC intensity errors for the US Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) model, and 2) understand how the maximum potential intensity imposes a limit on the intensity error saturation under different large-scale conditions beyond the traditional metrics. Outcomes from this research brought new insights into the spread of TC intensity during rapid intensification, thus providing a practical guidance to the future development of the US Navy's TC models.			
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