Evaluation of the NMME-2 skill for advancing seasonal hurricane forecasts in the Atlantic and Eastern Pacific basins

A Proposal from
NOAA/Atlantic Oceanographic and Meteorological Laboratory
To
NOAA/CPO/MAPP FY2015 (NOAA-OAR-CPO-2015-2004099); Competition-6 North American Multi-Model Ensemble system evaluation and application (ID: 2488571);
Area-A and -B

By

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Institutional Endorsements

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Institutions:	NOAA/AOML
Principal Investigator:	Frank Marks (Lead PI), and Chunzai Wang (co-PI)
Budget Period:	September 1, 2015 to August 31, 2016 (1 year)
Total Proposed Cost:	$68.8K

Abstract: Seasonal prediction (or outlook) of hurricanes in the Atlantic and eastern North Pacific has been a challenge. The actual number of Atlantic hurricanes fell inside the predicted ranges in only 4 of the last 13 years (i.e., a success rate of only 31%). Another important shortcoming of the current NOAA seasonal outlook for hurricanes is that it only provides a range of expected number of tropical storms, hurricanes and major hurricanes. In order to minimize the vulnerability of the society from anomalous weather extremes and to adequately organize the social resources for hurricane preparedness, a much more detailed seasonal outlook of Atlantic hurricane activity, such as storm track, storm formation region, duration, and regional landfalling probability, is required. The main goals of proposed work are (1) assess the skill of NMME-2 in forecasting TC activity over three decades (1982-2010); (2) help us understand if and how the NMME-2 system adds value to the current NOAA seasonal outlook for the Atlantic and eastern north Pacific hurricanes; (3) assess the value of new indices such as the ratios of landfalling hurricanes; and (4) develop an improved weighting and/or selection of NMME models for constructing operational predictors of the TC environment. Our strategy to evaluate the NMME-2 system for advancing seasonal hurricane forecasts includes two straightforward steps. In the first step, we will use the NMME-2 system analysis, which will be treated as the observation, along with the recently revised HURDAT2 database to examine and quantify the link between various hurricane indices (i.e., the number of major and U.S. landfalling hurricanes, ACE, and tropical cyclone tracks), and critical hurricane environmental factors. In the second step, we will evaluate the skill of NMME-2 system forecasting various new and old indices of the Atlantic and Eastern Pacific hurricanes with the target lead-time from one to nine months. The proxy hurricane indices forecasted by the NMME-2 system will be evaluated against the observed hurricane indices for the period of 1981-2010. The outcome of the proposed work will help us understand if and how the NMME-2 system adds value to the current NOAA seasonal outlook for the Atlantic and eastern north Pacific hurricanes.

Relevance to the Competition: The proposed work contributes directly to NOAA CPO FY2015 MAPP funding Competition-6 Area-A Evaluation of NMME system predictions: "Proposed NMME evaluations will examine the skill of NMME system predictions focusing on less well documented, yet potentially important aspects of the predictions." and Area-B Exploration of new applications of NMME system predictions: "Application of the NMME for the development of new prediction products may be proposed as part of exploratory pilot studies. Projects should build on existing NMME forecast variables and may include the offline prediction of secondary physical quantities of interest to various sectors. Proposed applications should build on those aspects of the NMME predictions for which a theoretical basis for expecting predictability exists and significant prediction skill can be expected based on previous evaluations."

Results from Prior NOAA Support (Last three years)

(1) NOAA/CPO MAPP Program: "Diagnostic and modeling studies on impacts, mechanisms and predictability of the Atlantic warm pool", PIs: C. Wang, D. B. Enfield and S.-K. Lee, $318K, 7/1/2009 to 6/30/2012.
(2) NOAA/CPO/ESS AMOC Program: "Relationship of the Atlantic warm pool with the Atlantic meridional overturning circulation", PIs: C. Wang and D. B. Enfield, $361.9K, July 1, 2011 to June 30, 2014.
(3) NOAA/CPO DYNAMO Program: "Upper ocean processes associated with the Madden-Julian oscillation in the Indian Ocean", PI: C. Wang, $138.0K, July 1, 2011 to June 30, 2014.
(4) NOAA/CPO MAPP Program: "Variability and predictability of the Atlantic warm pool and its impacts on extreme events in North America" PIs: C. Wang, S.-K. Lee and D. B. Enfield, $442.2K, August 1, 2012 to July 31, 2015.
(5) NOAA/CPO MAPP Program: "Toward developing a seasonal outlook for the occurrence of major U. S. tornado outbreaks" PIs: S.-K. Lee, R. Atlas, C. Wang, D. B. Enfield, and S. Weaver, $430.0K, August 1, 2012 to July 31, 2015.

These NOAA projects cover climate studies in the Atlantic, Pacific and Indian Oceans. Most of our research activities during the past three years are focused on the Atlantic, especially on the Atlantic warm pool (AWP). Through the panoply of papers listed below, these NOAA/CPO-supported projects have established AOML as the primary center for research on the AWP and its climate impacts. These research results have contributed directly to key elements of the NOAA/CPPA Science Plan and the Science and Implementation Plan for IASCLIP (Intra-Americas Study of Climate Processes, an endorsed component of CLIVAR/VAMOS.

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Statement of Work

1. Introduction:

The ability to provide pre-season outlooks for tropical cyclone (TC) activity is of fundamental importance for the economic activity and emergency preparedness of the nation. However, the seasonal prediction of hurricane activity in the Atlantic and eastern North Pacific has been a challenge and has seen no improvement in recent decades. The actual number of Atlantic hurricanes fell inside the predicted ranges in only 4 of the last 13 years (i.e., a success rate of only 31%) as summarized in Table 1.

Year	**Atlantic Hurricanes**		
	Forecast		**Observed**
	Min	**Max**	
2013	**7**	**11**	**2**
2012	**4**	**8**	**10**
2011	**7**	**10**	**7**
2010	**8**	**14**	**12**
2009	**4**	**7**	**3**
2008	**6**	**9**	**8**
2007	**7**	**10**	**6**
2006	**8**	**10**	**5**
2005	**7**	**9**	**15**
2004	**6**	**8**	**9**
2003	**6**	**9**	**7**
2002	**6**	**8**	**4**
2001	**5**	**7**	**9**

Table 1. NOAA seasonal Atlantic hurricane forecasts during 2001-2012, issued in May of each year, and actual number of hurricanes. Orange (blue) rows are for years when the number of hurricanes was larger (lower) than forecasted. During the last 13 years, 9 seasonal forecasts have been erroneous.

For instance, the number of Atlantic hurricanes expected by NOAA in May 2005 was between 7 and 9. However, a record number of 15 hurricanes formed in that year. Similarly, the numbers of Atlantic hurricanes forecast in May 2001, 2002 and 2006 were very different from the actual numbers of hurricanes formed in those years. One recent example was the preseason outlook issued in May 2012 for a near-normal Atlantic hurricane season, but which proved to be an extremely active season that had the third largest number of named storms on record.

The NOAA pre-season outlook for Atlantic hurricane activity is based on the prediction of a range of expected values for the Accumulated Cyclone Energy (ACE) index, a measure of overall tropical cyclone activity in the course of a single six-month season (June – November) as summarized in http://www.cpc.ncep.noaa.gov/products/outlooks/hurricane.shtml. The basis for predicting ACE is the historical relationship of overall TC activity with climate patterns such as El Niño – Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Atlantic multidecadal Oscillation (AMO). These are aperiodically recurring cycles of ocean-atmosphere interaction in the Pacific and North Atlantic basins that are, in turn, associated with changes in the atmospheric environment of developing TCs, primarily sea surface temperature (SST), vertical wind shear (V_z) and mid-tropospheric relative humidity (RH). Then, the ranges predicted for the numbers of tropical storms, hurricanes, and major hurricanes are obtained by looking at the years in the historical record that had observed values for ACE in the predicted range for the current year.

Aside from the inaccuracy in predicting overall TC activity, an important shortcoming of the current NOAA seasonal outlook for hurricanes is that it only provides a basin-wide range of expected number of tropical storms, hurricanes and major hurricanes. In order to minimize the vulnerability of the society from anomalous weather extremes and to adequately organize the social resources for hurricane preparedness, a more informative and detailed seasonal outlook of Atlantic hurricane activity is required, one that also includes measures such as storm formation region and regional landfalling probability.

One would think that using one or more numerical-dynamical ocean-atmosphere models to predict the hurricane environment directly could show greater skill than two cascading sets of statistical relationships between climate patterns and ACE and between ACE and TC activity, thus finessing the known physical effects of the atmospheric environment on the TCs that develop within it. Unfortunately, the development of reliable numerical-dynamical models has been plagued by problems such as the inability of models to predict Pacific ENSO extremes beyond the April-May "forecast barrier" or to faithfully reproduce fundamental features of the Atlantic basin such as equatorial ocean-atmosphere dynamics and the related wind-evaporation-SST (WES) feedback that governs tropical Atlantic SST patterns during the spring months leading up to the start of the Atlantic TC season in June.

Climate modeling by NOAA and others has been improving and NOAA now uses as its mainstay the Climate Forecast System (CFS) model, as yet unexplored as a tool for TC prediction. More importantly there is now an organized national effort by NOAA and other research insitutes to harness the power of model ensembles for producing US national climate forecasts, known as the North American Multi-Model Ensemble system (NMME). Hence, the two main goals of proposed work are (1) to evaluate seasonal prediction skill for the seasonal environmental factors for the Atlantic and Eastern Pacific hurricanes in the North American Multi Model Ensemble Phase 2 (NMME-2) system; and (2) to explore new enhancements of the NOAA seasonal hurricane outlook using the NMME-2 system predictions.

2. Background

There is ample justification in the literature for the idea that strong SST anomalies in the Pacific (ENSO) will alter the tropical circulation and SST in the Atlantic and therefore, the TC environment (e.g., Goldenberg and Shapiro, 1996; Gray, 1984). Thus, during the onset year of El Niño (year 0) a warm tropical Pacific energizes an atmospheric Kelvin wave response that carries downstream over the tropical Atlantic and beyond, heating the troposphere and producing stronger westerly winds in the upper troposphere (e.g., Chiang and Sobel, 2002; Lintner and Chiang 2007). The net effect of these changes is to increase the atmospheric stability, decrease the maximum potential intensity (MPI) for TCs, and increase the vertical wind shear, making the troposphere over the main development region (MDR) for TCs unfavorable for TC development. However, recent studies suggested that while the canonical El Niño pattern has a strong suppressing influence on Atlantic TC activity, non-canonical El Niño patterns, namely central Pacific warming (or El Niño Modoki) have insubstantial impact on Atlantic TC activity (Larson et al., 2012; Lee et al., 2010). Following the maximum SST anomalies at the end of the onset year, reduced boreal winter convection over the Amazon heating region leads to a weakened Hadley Circulation into the subtropical North Atlantic during the boreal spring of the El Niño mature phase (year +1) (Misra and DiNapoli, 2013). The net effect is a weakened North Atlantic Subtropical High (NASH), decreased NE trades and greater SSTs in the Tropical Northern Atlantic (TNA) region, favoring TC development in the year following maximum SST anomalies in the Pacific (e.g., Enfield and Mayer, 1997; Lee et al., 2008; Enfield et al., 2006). If the El Niño is followed directly by cool conditions in the Pacific (La Niña), the Atlantic environment becomes more favorable for TCs.

Similarly, research in the last few decades indicates a strong relationship between the late spring development of the Atlantic warm pool (AWP) and the subsequent tropospheric environment over the MDR in the TNA region (Wang and Enfield 2001, 2003). A large AWP is associated with weakened NE trades over the TNA region, weakened vertical wind shear over the MDR and a weakened Caribbean low-level jet (CLLJ), all of which favor Atlantic TC development during the summer period, as confirmed by the strong relationship between AWP size and hurricane activity (Wang et al. 2007, 2008). However, only about one-third of the large interannual variability in the AWP is explained by ENSO (Wang et al. 2006), and it is well known that the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) also influence the AWP and its TC environment at the interannual and decadal timescales, respectively (e.g., Muñoz et al. 2010, Goldenberg et al. 2001). The multidecadal modulation of TC activity (Goldenberg et al. 2001) primarily comes about because the warm phase of the AMO is associated with the more frequent occurrence of large annual AWPs (Wang et al. 2008). Recent studies showed that a large AWP also induces barotropic stationary wave patterns that weaken the North Atlantic subtropical high and produce the eastward steering flow anomalies along the eastern seaboard of the United States (Lee et al., 2009; Wang et al., 2011). Due to this mechanism, during a large AWP year, hurricanes are steered toward the northeast without making landfall in the United States (Wang et al., 2011).

In the Western Hemisphere, TCs form and develop in both the tropical North Atlantic and eastern Pacific Oceans, which are separated by the narrow landmass of Central America. Wang et al. (2009) showed that Atlantic TC activity varies out-of-phase with that in the eastern Pacific on both interannual and multidecadal timescales. That is, when Atlantic TC activity increases (decreases), TC activity in the eastern Pacifc decreases (increases). Their analyses show that both vertical wind shear and convective instability contribute to the out-of-phase relationship. An implication is that seasonal hurricane outlook can be improved by considering the Atlantic and eastern Pacific TCs together.

To summarize, the direct and indirect influences of several climate patterns associated with ENSO, NAO, AMO and the Amazon convection are thought to be primary factors in the interannual and multidecadal modulation of Atlantic and eastern Pacific TC activity. We think that the poor performance of statistical outlook methods presents a low bar for improvement by using the latest developments in climate models in forecasting the combined influence of these climate patterns on the TC environment. To this end, the added reliability that is likely to result from the ensemble approach places a premium on trying to adapt the NMME-2 for this purpose. This is partly confirmed by the success of the NMME in reproducing the observed climate over the continental U.S. (Kirtman et al. 2014, see Figure 1). Although that study does not directly apply to the MDR region for TC development, we know that the tropical Atlantic low level winds and moisture transports are predictors of summer rainfall east of the Rocky Mountains. Hence, it does not seem likely that the NMME can show high skill over the U.S. unless they are also skillful for the Atlantic environment that funnels moisture into the continental interior.

The NMME Phase 2 ensemble consists of nine North American models from NOAA (CFSv2), NASA (GEOSS), NCAR/University of Miami (CCSM4.0), NCAR (CESM), GFDL (CM2.1, FLORa06, FLORb01) and Environment Canada (CanCM3, CanCM4). These models are global, high-resolution, coupled atmosphere-ocean-land surface-sea ice forecast systems. For example, the CFSv2's atmosphere resolution is about 38 km (T382) with 64 levels extending from the surface to 0.26 hPa. The CFSv2 ocean model is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels to a depth of 4737 m. The CFSv2 land surface model has 4 soil levels and the global sea ice model has 3 levels. The CFSv2 atmospheric model contains observed variations in carbon dioxide (CO_2), together with changes in aerosols and other trace gases and solar variations. With these variable parameters, the analyzed states include estimates of changes in the Earth system climate due to these factors. All available conventional and satellite observations were assimilated in the CFSv2. The CFSv2 covers the period of 1982–2010 with a 24-member ensemble forecast per calendar month out to nine months into the future (Saha et al. 2010).

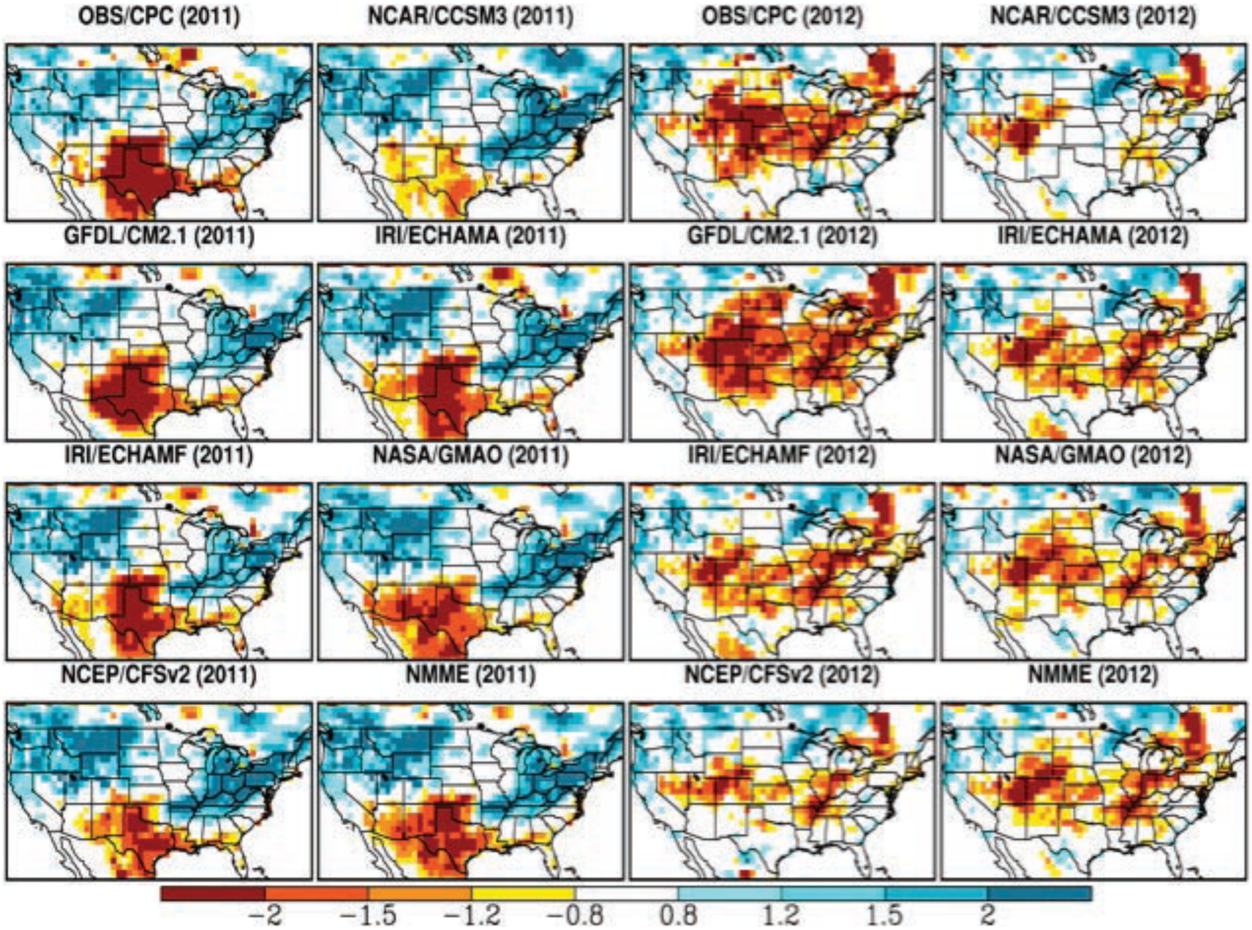

Figure 1. NMME SPI6 forecasts initialized in June 1, 2011 and June 1, 2012. Observed precipitation is combined with JJA model ensemble-mean forecast. The NMME forecast is the equally weighted ensemble model average.

The daily atmosphere and land fields and monthly ocean fields noted in Table 2, 3 and 4 cover the retrospective forecast period of 1982-2010. Retrospective forecasts were initialized each month of each year. The lead-time and number of ensemble members varies with forecast provider but lead times out to 9 months are typical. Kirtman et al. (2014) describe the NMME-1 and NMME-2 ensembles and their development and rationale, and they provide a preliminary description of model performance at the global and North American scales.

The NMME Phase 2 retrospective hindcast data will be provided at the server https://www.earthsystemgrid.org/search.html?Project=NMME.

Table 2. Daily atmospheric and land surface fields (22) available from the NMME-2 system

Variable	**Var. Name**	**CF Standard Name**
Surface temperature (SST+land)	Ts	surface_temperature
2m T daily max	Tasmax	air_temperature
2m T daily min	Tasmin	air_temperature
Mean sea level pressure	Psl	air_pressure_at_sea_level
Water equivalent snow depth	snowhlnd	Water equivalent snow depth
Total soil moisture	Mrsov	volume_fraction_of_water_in_soil
Total precipitation	prlr	precipitation_rate
Downward surface solar	Rsds	surface_downwelling_shortwave_flux_in_air
Downward surface longwave	Rlds	surface_downwelling_longwave_flux_in_air
Net surface solar	Rss	surface_net_downward_shortwave_flux
Net surface longwave	Rls	surface_net_downward_longwave_flux
Top net solar	Rst	toa_net_downward_shortwave_flux
Top net longwave	Rlt	toa_net_downward_longwave_flux
Surface latent flux	Hflsd	surface_downward_latent_heat_flux
Surface sensible flux	Hfssd	surface_downward_sensible_heat_flux
Surface stress (x)	Stx	surface_zonal_stress
Surface stress (y)	Sty	Surface_meridional_stress
2m temperature	Tas	air_temperature
Total cloud cover	Clt	cloud_area_fraction
10m wind (u)	Uas	eastward_wind
10m wind (v)	Vas	northward_wind
10m specific humidity	Qas	Specific humidity

Table 3. Daily atmospheric pressure level fields (5) provided at 850, 500, 200, 100, 50 hPa available from the NMME-2 system

Variable	**Var. Name**	**CF Standard Name**
Geopotential	G	Geopotential
Temperature	Ta	air-temperature
Zonal velocity	Ua	eastward_wind
Meridional velocity	Va	northward_wind
Specific humidity	hus	specific_humidity

Table 4. Monthly ocean fields (7) provided at depths of 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400m available from the NMME-2 system

Variable	**Var. Name**	**CF Standard Name**
Potential temperature	thetao	sea_water_potential_temperature
Salinity	ao	sea_water_salinity
Zonal velocity	uo	sea_water_x_velocity
Meridional velocity	vo	sea_water_y_velocity
Vertical velocity	wo	upward_sea_water_velocity
Sea level	zoh	sea_surface_height_above_geoid
Mixed layer depth	zmlo	ocean_mixed_layer_thickness

3. Summary of Work:

Our strategy to evaluate the NMME-2 system for advancing seasonal hurricane forecasts includes two straightforward analysis phases:

The first phase is essentially a "model training step" in which we will use the NMME-2 system analysis (not the retrospective forecasts), treated as observations, along with the recently revised HURDAT2 database to examine and quantify the link between various hurricane indices (i.e., the number of major and U.S. landfalling hurricanes, ACE, and tropical cyclone tracks), and critical hurricane environmental factors, such as the tropospheric vertical wind shear and moist static instability over the main TC development regions, as well as a characterization of the tropical cyclone steering flow and the seasonal fraction of landfalling storms. We will perform various statistical analyses (e.g., partial linear regression analysis) to derive a list of proxy hurricane indices based on the hurricane environmental factors.

We will also explore other predictors. In particular, given that the upper ocean thermal structure has been shown to play a critical role in determining the maximum intensity of TCs (e.g., Lin et al. 2013; Goni et al. 2009; Mainelli et al. 2008), we will explore if the upper (above 100 m) ocean heat content in the tropical Atlantic Ocean adds value to the partial regression model. Various ENSO indices will be used to distinguish the impacts of canonical versus non-canonical El Niño patterns on Atlantic TC activity (Larson et al., 2012; Lee et al., 2010). Based on new findings from recent studies (e.g, Wang et al, 2011; Lee et al., 2009), we will also attempt to develop statistically significant new proxy hurricane indices such as the ratio of U.S. landfalling versus non-U.S. landfalling hurricanes.

In the second step, we will evaluate the skill of NMME-2 system in forecasting various new and old indices of the Atlantic and Eastern Pacific hurricanes with target lead-times from one to nine months for the target outlook indices. That means both the environmental indices (e.g., MDR SST, MDR-averaged wind shear and humidity, and TNA-averaged upper ocean heat content, etc.) and the TC statistics (ACE, named storms, hurricanes major hurricanes and landfalling ratio). The retrospective forecasts will be performed for the same pre-season (May) and mid-season (August) times as has been the practice at NOAA-CPC. These 29 yearly retrospective forecasts will then be evaluated against the actual historical outcomes for the period 1982-2010 using various evaluation merics, namely anomaly correlation, RMSE, mean absolute error, amplitude and biases. Finally, these NMME-2 performance statistics will be compared with the historical performance of the NOAA-CPC outlooks.

It is stressed here that we will not simply assess the large all-model assemblage (combined model ensembles) of the NMME-2 retrospective forecasts. Our assessment will start by looking at the performance of individual model ensembles to see how their computed diagnostics of the TC environment (e.g., area-averaged SST, wind shear, etc.) compare with historical reanalysis data. Based on that analysis we may elect to adopt a subset of better performing models and/or to use a model-weighted average of ensembles for the final evaluation.

We expect the proposed work will accomplish four things: (1) assess the skill of NMME-2 in forecasting TC activity over three decades; (2) help us understand if and how the NMME-2 system adds value to the current NOAA seasonal outlook for the Atlantic and eastern north Pacific hurricanes; (3) assess the value of new indices such as the ratios of landfalling hurricanes; and (4) develop an improved weighting and/or selection of NMME-2 models for constructing operational predictors of the TC environment.

4. Work plan

F. Marks and C. Wang will lead the the proposed tasks. Under their leadership, D. Enfield will perform the statistical analyses and coordinate progress with S.-K. Lee while bringing in the expertise of F. Marks and C. Wang at critical junctures. S.-K. Lee (aided by J. Harris) will reformat and prepare all NMME-2 model fields and HURDAT2 data into the form required for statistical analysis in Matlab for D. Enfield. D. Enfield and S.-K. Lee will prepare a manuscript for submission to a major journal with the added help from F. Marks and C. Wang.

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Lee, S.-K., C. Wang and B. E. Mapes, 2009: A simple atmospheric model of the local and teleconnection responses to tropical heating anomalies. *J. Climate*, **22**, 272-284.

Lee, S.-K., C. Wang and D. B. Enfield, 2010: On the impact of central Pacific warming events on Atlantic tropical storm activity. *Geophys. Res. Lett*., **37**, L17702, doi:10.1029/2010GL044459.

Lin, I.-I., 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 cooling potential intensity index for tropical cyclones, *Geophys. Res. Lett.*, 40, 1878-1882, doi:10.1002/grl.5009.

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Muñoz, E., C. Wang, D. B. Enfield, 2010: The Intra-Americas Sea springtime surface temperature anomaly dipole as fingerprint of remote influences. *J. Climate*, **23**, 43-56.

Wang, C., and D.B. Enfield, 2001: The tropical western hemisphere warm pool. *Geophys. Res. Lett.*, **28**, 1635-1638.

Wang, C., and D. B. Enfield, 2003: A Further Study of the Tropical Western Hemisphere Warm Pool. *J. Climate.* **16**(10), 1476-1493.

Wang, C., D. B. Enfield, S.-K. Lee, and C. Landsea, 2006: Influences of the Atlantic warm pool on Western Hemisphere summer rainfall and Atlantic hurricanes. *J. Climate,* **19**, 3011-3028.

Wang, C., S.-K. Lee, and D. B. Enfield, 2008: Climate response to anomalously large and small Atlantic warm pools during the summer. *J. Climate*, **21**, 2437–2450.

Wang, C. and S.-K. Lee, 2009: Co-variability of tropical cyclones in the North Atlantic and the eastern North Pacific. Geophys. Res. Lett., 36, L24702, doi:10.1029/2009GL041469.

Wang, C., H. Liu, S.-K. Lee and R. Atlas, 2011: Impact of the Atlantic warm pool on United States landfalling hurricanes. Geophys. Res. Lett., doi:10.1029/2011GL049265

Budget Justification

Salary requests from NOAA/CPO include funds for D. Enfield (2 months) and S.-K. Lee (2 months). F. marks, and C. Wang will work on this project for one month per year at no salary cost to the project. One trip for attending a scientific meeting for dissemination of scientific results budgeted each year. Publication page charges are also budgeted.

				Person Months			
Name	Role/Title	Monthly Salary and Benefits	Employee Type	Funded in kind by institution	Requested	Total In Kind	Total Requested
F. Marks	Co-PI	**$16,813**	Federal	1.00	0.00	$16,813	$0
C. Wang	PI	**$14,857**	Federal	1.00	0.00	$14,857	$0
J. Harris	IT support	**$13,768**	Federal	0.00	0.20	$0	$2,754
D. Enfield	Scientific support	**$13,507**	Joint Institute	0.00	2.00	$0	$27,014
S.-K. Lee	Scientific support	**$10,926**	Joint Institute	0.00	2.00	$0	$21,851
			Total Salaries	2.00	4.20	$31,671	$51,619
Total Labor contribution (includes indirect costs)						**$48,456**	**$65,783**
Supplies and other expenses							
Description			Comments				
Publications						**$0**	$1,500
			Total Supplies				$1,500
Travel							
Destination/Purpose			Comments				
Meeting							$1,500
			Total Travel				$1,500
Indirect costs							
Description			Comments				
FTE		53%	Salary & Benefits			$16,786	$1,459
Joint Instuitute		26%	Salary & Benefits			$0	$12,705
			Total Indirect costs			$16,786	$14,164
			Total Budget Request			$48,456	**$68,783**

Curriculum Vitae: Frank D. Marks, Jr.

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Education:

Belknap College	Meteorology	B.S.	1973
Massachusetts Institute of Technology	Meteorology	M.S.	1975
Massachusetts Institute of Technology	Meteorology	Sc.D.	1981

Professional Experience:

Meteorologist, NOAA/Environmental Data Service	July 1975 to July 1976
Research Meteorologist, NOAA/AOML/HRD	July 1980 to present
Director, NOAA/AOML/HRD	February 2003 to present
Adjunct Professor, Univ. of Miami/RSMAS/MPO	September 1993 to present
Fellow, Univ. of Miami/RSMAS/CIMAS	January 1997 to present
Senior Fellow, University of Hawaii at Manoa/JIMAR	July 1997 to 2013

Honors and Awards:

2014	AMS Banner I. Miller Award (with Fuqing Zhang, Yonghui Weng, and John Gamache)
2012	NOAA Administrators Award for outstanding management of the G-IV Tail Doppler Radar project (group award)
2011	2010 NOAA/OAR Outstanding Scientific Paper Award for Weather and Water
2011	AMS Verner E. Suomi Award
2010	NOAA Distinguished Career Award
2008	NOAA Research Employee of the Year
2007	NOAA Bronze Medal for Hurricane Research Division Performance during Hurricanes Rita and Katrina (group award)
2005	NOAA Administrator's Award for establishing and administering the Joint Hurricane Testbed (group award)
2005	OFCM Richard H. Hagemeyer Award at the 59th Interdepartmental Hurricane Conference
2005	USWRP Joint Hurricane Testbed Outstanding Contributor Award
2003	NOAA Diversity Council Spectrum Achievement Award for Managers
2001	NOAA TECH 2002 award for best wireless application for development of satellite-cell based WLAN for NOAA WP-3D aircraft
1997	US Department of Commerce Silver Medal for performance as the Research Mission Manager for the NOAA High Altitude Jet procurement
1992	US Department of Commerce Gold Medal for Hurricane Research Division's Performance in Hurricane Andrew (group award)
1989	Distinguished Authorship Award, National Oceanic and Atmospheric Administration, Environmental Research Laboratories

AMS Activities:

2013-present	Councilor, American Meteorological Society
2000-present	Fellow, American Meteorological Society

1973-present member, American Meteorological Society

Career refereed publications: 104
H-index: 30
ResearcherID: http://www.researcherid.com/rid/A-5733-2011

Recent Publications (last three years):

Ming, J., J. A. Zhang, R. F. Rogers, F. D. Marks, Y. Wang, and N. Cai, 2013: An observational study of the atmospheric boundary layer structure during landfall of Typhoon Morokot (2009). *J. Atmos. Sci*. (accepted)

Marks, F. D., 2014: Advancing Tropical Cyclone Forecasts Using Aircraft Observations, *Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change*. Ed. U. C. Mohanty, M. Mohapatra, O. P. Singh, B. K. Bandyopadhyay, and L. S. Rathore, Springer, 169-191. doi: http://dx.doi.org/10.1007/978-94-007-7720-0_15

Zhang, J. A., M. T. Montgomery, F. D. Marks, and R. K. Smith, 2014: Comments on "Symmetric and Asymmetric Structures of Hurricane Boundary Layer in Coupled Atmosphere–Wave–Ocean Models and Observations". *J. Atmos. Sci*., 71, 2782-2785. doi: http://dx.doi.org/10.1175/JAS-D-13-0207.1

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Vukicevic, T., A. Aksoy, P. Reasor, S. D. Aberson, K. J. Sellwood, and F. Marks, 2013: Joint impact of forecast tendency and state error biases in Ensemble Kalman Filter data assimilation of inner-core tropical cyclone observations**.** *Mon. Wea. Rev*., **141**, 2992–3006. doi: http://dx.doi.org/10.1175/MWR-D-12-00211.1

Rogers, R., S. Aberson, A. Aksoy, B. Annane, . Black, J. Cione, N. Dorst, J. Dunion, J. Gamache, S. Goldenberg, S. Gopalakrishnan, J. Kaplan, B. Klotz, S. Lorsolo, F. Marks, S. Murillo, M. Powell, P. Reasor, K. Sellwood, E. Uhlhorn, T. Vukicevic, J. Zhang, and X. Zhang, 2013: NOAA's Hurricane Intensity Forecasting Experiment (IFEX): A Progress Report, *Bull. Amer. Meteor. Soc*., **94**, 859–882. doi: http://dx.doi.org/10.1175/BAMS-D-12-00089.1.

Gall, R., J. Franklin, F. D. Marks, E. N. Rappaport, F. Toepfer, 2013: The Hurricane Forecast Improvement Project. *Bull. Amer. Meteor. Soc.* , **94**, 329–343 doi: http://dx.doi.org/10.1175/BAMS-D-12-00071.1.

Zhang, J., S. Gopalakrishnan. F. Marks, R. Rogers, V. Tallapragada, 2013: A developmental framework for improving hurricane model physical parameterizations using aircraft observations. *Trop. Cyclone Res. and Rev.,* **1**, 419-429, doi: http://dx.doi.org/10.6057/2012TCRR04.01.

Gopalakrishnan, S., F. D. Marks, J. Zhang, X. Zhang, J.-W. Bao, and V. Tallapragada, 2013: A study of the impact of vertical diffusion on the structure and intensity of tropical cyclones using the high-resolution HWRF system. *J. Atmos. Sci*., **70**, 524–541, doi: http://dx.doi.org/10.1175/JAS-D-11-0340.1

Bao, J.-W., S. G. Gopalakrishnan, S. A. Michelson, F. D. Marks, M. T. Montgomery, 2012: Impact of physics representations in the HWRF model on simulated hurricane structure and

wind-pressure relationships. *Mon. Wea. Rev*., **140**, 3278–3299, doi: http://dx.doi.org/10.1175/MWR-D-11-00332.1.

Gopalakrishnan, S. G., S. Goldenberg, T. Quirino, F. D. Marks, X. Zhang, K.-S. Yeh, R. Atlas, and V. Tallapragada, 2012: Towards improving high-resolution numerical hurricane forecasting: Influence of model horizontal grid resolution, initialization, and physics, *Wea. Forecast*., **27**, 647–666, doi: http://dx.doi.org/10.1175/WAF-D-11-00055.1.

Rogers, R., S. Lorsolo, P. Reasor, J. Gamache, and F. D. Marks, 2012: Multiscale analysis of mature tropical cyclone structure from airborne Doppler composites, *Mon. Wea. Rev*., **140**, 77-99. doi: http://dx.doi.org/10.1175/MWR-D-10-05075.1.

Curriculum Vitae: Chunzai Wang

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Education:

Ph.D., Physical Oceanography, University of South Florida, 1995.
M.S., Atmospheric Sciences, Oregon State University, 1991.
B.S., Marine Meteorology, Ocean University of China, China, 1982.

Professional Experience:

Oceanographer, NOAA Atlantic Oceanographic and Meteorological Laboratory, 2000 – Present.
Associate Scientist, CIMAS/RSMAS, University of Miami, 1999 – 2000.
Research Associate, College of Marine Science, University of South Florida, 1997 – 1999.
Postdoctoral Associate, College of Marine Science, University of South Florida, 1995 – 1997.

Service:

Co-chair, Intra-Americas Study of Climate Processes (IASCLIP) Program, 20014 – Present.
Editor, Journal of Geophysical Research (Oceans), 2009 – Present.
Associate Editor, Journal of Climate, 2006 – Present.
American Geophysical Union Books Board, 2005 – 2010.

Recent Publications (last three years):

Zhang, L., C. Wang, Z. Song, and S.-K. Lee, 2014: Remote effect of the model cold bias in the tropical North Atlantic on the warm bias in the tropical Southeastern Pacific. *J. Adv. Model. Earth Syst.*, in press.

Ling, Z., G. Wang, and C. Wang, 2014: Out-of-phase relationship between tropical cyclones generated locally in the South China Sea and non-locally from the northwest Pacific Ocean. *Clim. Dyn.*, in press.

Yeh, S.-W., X. Wang, C. Wang, and B. Dewitte, 2014: On the relationship between the North Pacific climate variability and the Central Pacific El Niño. *J. Climate*, in press.

Yang, L., Y. Du, D. Wang, C. Wang, and X. Wang, 2014: Impact of intraseasonal oscillation on the tropical cyclone track in the South China Sea. *Clim. Dyn.*, in press.

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Wang, C., C. Deser, J.-Y. Yu, P. DiNezio, and A. Clement, 2014: El Niño-Southern Oscillation (ENSO): A review. In *Coral Reefs of the Eastern Pacific*, P. Glymn, D. Manzello, and I. Enochs, Eds., Springer Science Publisher, in press.

Liu, H., C. Wang, S.-K. Lee, and D. B. Enfield, 2014: Inhomogeneous influence of the Atlantic warm pool on United States precipitation. *Atmos. Sci. Lett.*, in press.

Song, Z., H. Liu, L. Zhang, F. Qiao, and C. Wang, 2014: Evaluation of the eastern equatorial Pacific SST seasonal cycle in CMIP5 models. *Ocean Sci. Discuss.*, **11**, 1129-1147.

Li, Y., W. Han, T. Shinoda, C. Wang, M. Ravichandran, and J.-W. Wang, 2014: Revisiting the wintertime intraseasonal SST variability in the tropical South Indian Ocean: Impact of the ocean interannual variation. *J. Phys. Oceanogr.*, **44**, 1886-1907.

Wang, C., 2014: [The Tropics] Atlantic warm pool [in "State of the Climate in 2013"]. *Bull. Amer. Meteor. Soc.*, **95** (7), S105-S109.

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Wang, C., and L. Zhang, 2013: Multidecadal ocean temperature and salinity variability in the tropical North Atlantic: Linking with the AMO, AMOC and subtropical cell. *J. Climate*, **26**, 6137-6162.

Liu, H., C. Wang, S.-K. Lee, and D. B. Enfield, 2013: Atlantic warm pool variability in the CMIP5 simulations. *J. Climate*, **26**, 5315-5336.

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Shinoda, T., T. Jensen, M. Flatau, S. Chen, W. Han, and C. Wang, 2013: Large-scale oceanic variability associated with the Madden-Julian oscillation during the CINDY/DYNAMO field campaign from satellite observations. *Remote Sens.,* **5**, 2072-2092.

Wang, X., C. Wang, W. Zhou, L. Liu, and D. Wang, 2013: Remote influence of North Atlantic SST on the equatorial westerly wind anomalies in the western Pacific for initiating an El Niño event: An atmospheric general circulation model study. *Atmos. Sci. Lett.*, **14**, 107-111.

Zheng, J., Q. Liu, C. Wang, and X.-T. Zheng, 2013: Impact of heating anomalies associated with rainfall variations over the Indo-Western Pacific on Asian atmospheric circulation in winter. *Climate Dynamics*, **40**, 2023-2033.

Lee, S.-K., R. Atlas, D. B. Enfield, C. Wang, and H. Liu, 2013: Is there an optimal ENSO pattern that enhances large-scale atmospheric processes conducive to major tornado outbreaks in the U. S.? *J. Climate*, **26**, 1626-1642.

Wang, C., L. Zhang, and S.-K. Lee, 2013: Response of freshwater flux and sea surface salinity to variability of the Atlantic warm pool. *J. Climate*, **26**, 1249-1267.

Wang, C., and X. Wang, 2013: Classifying El Nino Modoki I and II by different impacts on rainfall in southern China and typhoon tracks. *J Climate*, **26**, 1322-1338.

Wang, X., W. Zhou, D. Wang, and C. Wang, 2013: The impacts of the summer Asian jet stream biases on surface air temperature in mid-eastern China in IPCC AR4 models. *Int'l J. Clim.,* **33**, 265-276.

Wang, G., J. Li, C. Wang, and Y. Yan, 2012: Interactions among the winter monsoon, ocean eddy and ocean thermal front in the South China Sea. *J. Geophys. Res.*, **117**, C08002, doi: 10.1029/2012JC008007.

Zhang, L., C. Wang, and L. Wu, 2012: Low-frequency modulation of the Atlantic warm pool by the Atlantic multidecadal oscillation. *Climate Dynamics*, **39**, 1661–1671.

Zhang, L., and C. Wang, 2012: Remote influences on freshwater flux variability in the Atlantic warm pool region. *Geophys. Res. Lett.*, **39**, L19714, doi:10.1029/2012GL053530.

Liu, H., C. Wang, S.-K. Lee, and D. B. Enfield, 2012: Atlantic warm pool variability in the IPCC AR4 CGCM simulations. *J. Climate*, **25**, 5612-5628.

Wang, C., 2012: Atlantic multidecadal oscillation (AMO) [in "State of the Climate in 2011"]. *Bull. Amer. Meteor. Soc.*, **93** (7), S119-S122.

Wang, C., S. Dong, A. T. Evan, G. R. Foltz, and S.-K. Lee, 2012: Multidecadal covariability of North Atlantic sea surface temperature, African dust, Sahel rainfall and Atlantic hurricanes. *J. Climate*, **25**, 5404-5415.

Larson, S., S.-K. Lee, C. Wang, E.-S. Chung, and D. Enfield, 2012: Impacts of non-canonical El Niño patterns on Atlantic hurricane activity. *Geophys. Res. Lett.*, **39**, L14706, doi:10.1029/2012GL052595.

Shu, Q., F. Qiao, Z. Song, and C. Wang, 2012: Sea ice trends in the Antarctic and their relationship to surface air temperature during 1979 to 2009. *Climate Dynamics*, **38**, 2355–2363.

Song, Z., F. Qiao, X. Lei, and C. Wang, 2012: Influence of parallel computational uncertainty on simulations of the coupled general climate model. *Geoscientific Model Development*, **5**, 313-319.

Li, W.-W., C. Wang, D. Wang, L. Yang and Y. Deng, 2012: Modulation of low-latitude west wind on abnormal track and intensity of tropical cyclone Nargis (2008) in the Bay of Bengal. *Adv. Atmos. Sci*., 29, 407-421.

Curriculum Vitae: David B. Enfield

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Education:

A.B., University of California, Berkeley (Geophysics/Physics)	1965
M.S., Oregon State University (Physical Oceanography)	1970
Ph.D., Oregon State University (Physical Oceanography)	1973

Professional Service:

UNESCO Phys. Oceanog. expert at the Naval Oceanogr. Inst. of Ecuador.	1973-1975
Science Liaison Officer for the IDOE JOINT-II Upwelling experiment in Peru.	1975-1977
Research Associate, School of Oceanography, Oregon State University	1977-1981
Assistant Professor (Sr. Research), School of Oceanography, Ore. St. Univ.	1981-1983
Assistant Professor (tenure track), School of Oceanography, Ore. St. Univ.	1983-1987
Associate Professor (tenure track), College of Oceanography, Ore. St. Univ.	1987
Research Oceanographer, NOAA Atlantic Oceanog. and Met. Lab. (AOML)	1987-2008
Scientist, Cooperative Institute for Marine & Atmospheric Science (U of M)	2009-

Career refereed publications: 67
H-index: 28
ResearcherID: www.researcherid.com/rid/I-2112-2013

Refereed publications (last 3 years):

Lee, S.-K., B. E. Mapes, C. Wang, D. B. Enfield and S. J. Weaver, 2014: Springtime ENSO phase evolution and its relation to rainfall in the continental U.S. *Geophys. Res. Lett*., 41, 1673-1680. doi:10.1002/2013GL059137.

Lee, S.-k., R. Atlas, D. B. Enfield, C. Wang, and H. Liu, 2013: Is there an optimal ENSO pattern that enhances large-scale processes conducive to tornado outbreaks in the U.S.? *J. Climate*, 26, 1626-1642.

Liu, H., S.-k. Lee, C. Wang, and D. B. Enfield, 2012: Atlantic warm pool variability in the IPCC AR4 CGCM simulations. *J. Climate*, 25, 5612-5628.

Larson, S., S.-K. Lee, C. Wang, E.-S. Chung, and D. B. Enfield, 2012: Impacts of non-canonical El Niño patterns on Atlantic hurricane activity. *Geophys. Res. Lett*., doi:10.1029/2012GL052595.

Liu, Y., S.-k. Lee, B. A. Muhling, J. T. Lamkin, and D. B. Enfield, 2012: Significant Reduction of the Loop Current in the 21st Century and Its Impact on the Gulf of Mexico, *J. Geophys. Res*., 117, C05039.

Five other publications:

Enfield, D.B., and L. Cid-Serrano, 2010: Secular and multidecadal warmings in the North Atlantic and their relationship with major hurricanes. *Int'l J. Clim.,* 28, DOI: 10.1002/joc.1881

Enfield, D.B., and L. Cid-Serrano, 2006: Projecting the risk of future climate shifts. *Int'l J. of Climatology,* 26(7):885-895.

Enfield D.B., S.-K. Lee, and C. Wang, 2006: How are large Western Hemisphere Warm Pools formed? *Progress in Oceanography*, 70(2-4), 346-365.

Enfield D. B., and S.-K. Lee, 2005: The Heat Balance of the Western Hemisphere Warm Pool. *J. Climate,* 18, No. 14, 2662–2681.

Enfield, D. B., A. M. Mestas-Nunez, and P. J. Trimble (2001), The Atlantic multidecadal oscillation and its relationship to rainfall and river flows in the continental US, *Geophys. Res. Lett*., 28, 2077–2080, doi:10.1029/2000GL012745.

Curriculum Vitae: Sang-Ki Lee

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Education:

PhD, Old Dominion University, Norfolk, Va (Oceanography)	1995
MSc, Old Dominion University, Norfolk, Va (Oceanography)	1993
BSc, Inha University, Incheon, South Korea (Oceanography)	1991

Professional Service:

Scientist, CIMAS, University of Miami	2011 - Present
Associate Scientist, CIMAS, University of Miami	2007 - 2010
Assistant Scientist, CIMAS, University of Miami	2005 - 2007
Postdoctoral Associate, CIMAS, University of Miami	2002 - 2004
Associate Scientist: Maritime Research Institute, Samsung Heavy Industries	1996 - 2001
Graduate Research Assistant, Old Dominion University	1991 - 1995

Refereed publications (last three years)

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Current and Pending Support

Current:

(1) NOAA/CPO MAPP Program: Variability and predictability of the Atlantic warm pool and its impacts on extreme events in North America, PIs: C. Wang, S.-K. Lee and D. B. Enfield, $442.2K, August 1, 2012 to July 31, 2015.

(2) NOAA/CPO MAPP Program: Toward developing a seasonal outlook for the occurrence of major U. S. tornado outbreaks, PIs: S.-K. Lee, R. Atlas, C. Wang, D. B. Enfield, and S. Weaver, $430.0K, August 1, 2012 to July 31, 2015.

(3) NOAA/CPO Climate Observations and Monitoring: Atlantic basin tropical cyclone database reanalysis and estimation of "missed" major hurricane and overall activity. PIs: F. Marks, C. Landsea, and G. Vecchi, $425.6K, August 1, 2014 to July 31, 2017.

Pending:

This proposal.