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Effect of Climate Variability and Change in Hurricane Activity in the North Atlantic

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Executive Summary

In support of the goals of the Ultra-Deepwater Environment, Safety and Regulatory and Metocean area of interest, this award produced: assessments of hurricane activity and potential impacts for current climate and changes over the coming decades; tools to aid immediate response and planning needs; and knowledge to mitigate future costs, and minimize environmental and safety risks.

A powerful combination of observational analysis and statistical and dynamical modeling produced new views of tropical cyclone activity in current and future climate. For tropical cyclone frequency, a new statistical downscaling tool applied to a climate model ensemble projects a future increase over the North Atlantic. However, when looking at the sub-region of the Gulf of Mexico, a dynamical model ensemble projects a future decrease in hurricane frequency. For tropical cyclone intensity, a new statistical-dynamical tool shows a future increase in the proportion of major hurricanes for the North Atlantic. Observational analysis indicates this change has already started on global scales, and when accounting for the physical upper limit of hurricane intensity, a limit is found in the increasing proportion of major hurricanes, one that is already being approached.

The inclusion of tropical cyclone parameters in addition to wind speed and frequency allows assessments that are more relevant to industry impacts. The plausible future scenario of increased wind speed and decreased size applied to historical Gulf of Mexico hurricanes leads to overall future increases in the extremes of metocean variables, with the biggest proportional increase in the significant wave height. In agreement, a Cyclone Damage Potential index (that accounts for the key damaging tropical cyclone parameters of intensity, size and forward speed) applied to a dynamical model ensemble projects future increases in the maximum damage potential for the North Atlantic and the Gulf of Mexico. Ensemble members disagree, however, on future change in the average Cyclone Damage Potential for the Gulf of Mexico.

Based on these new views of hurricane activity and potential impacts, our overall recommendation is for the industry to be aware of the potential for increased hurricane impacts in the future. As our understanding of hurricane activity in current climate and the future change advances the potential industry impacts will be reassessed. A new program, the Engineering for Climate Extremes Partnership, has grown out of interactions between NCAR, RPSEA and others. Some of the techniques pioneered here are being included in the applications under the associated Global Risk, Resilience and Impacts Toolbox, where they can be accessed in the future.

1. Introduction

RPSEA research award 10121-4802-01 funded this project on the effect of climate variability and change in hurricane activity in the North Atlantic. This three-year project proceeded as three phases, each phase lasting one year. This report summarizes the major accomplishments of Phase 3. The Phase 3 period of performance was July 11, 2014 – Sept 30, 2015 at a cost of $690,000 ($552,000 from RPSEA and $138,000 in cost share). A three-month no-cost extension was approved in late June 2015. The reasons for the extension were that key NCAR people were on extended leave and to allow more time for feedback from the Technical Advisory Committee. The no-cost extension enabled this final report to be prepared, discussed and formally submitted in the proper manner to maximize industry impact. The extended end date is Sept 30, 2015 and the Phase III deliverables were extended by 3 months.

The prime contractor, the University Corporation for Atmospheric Research (UCAR), manages the National Center for Atmospheric Research (NCAR) on behalf of National Science Foundation to address pressing scientific and societal needs involving Earth system science. NCAR is therefore well aligned with the RPSEA mission, and is proud to be partnering with RPSEA.

The next section provides a brief project overview. Section 3 details accomplishments for all the tasks required of Phase 3. Finally, a summary discussion is provided in Section 4.

2. Project Overview

According to recent assessments, hurricane strength will likely increase in the future (Walsh et al. 2015; Knutson et al. 2013; Done et al. 2013; Knutson et al. 2010). Specifically, global average hurricane wind speeds are expected to increase, and the proportion of major hurricanes is expected to increase. If true, this will have far reaching impacts on the offshore energy industry, and raises the possibility that new coastal and offshore facilities are being under-designed, and that older facilities may need hardening in order to maintain presently accepted risk levels. This project is providing new knowledge that has the potential to mitigate costs and minimize environmental and safety risks by providing credible projections of changes in hurricane activity and industry impacts in the Gulf of Mexico.

This technical area of interest follows on from the successful RPSEA Project 07121-1801 on the effects of climate variability and change in hurricane activity in the North Atlantic. The results of this prior work contributed to ongoing debate in the scientific community on the expected future change in North Atlantic tropical cyclone frequency. Some studies suggest a future increase while others suggest a future decrease. This demonstrated the value of seeing these technologies matured to the next level. This ambitious project aims to quantify future changes in the frequency, duration, and intensity of Gulf hurricanes and their impacts using a powerful combination of the latest theoretical, statistical and enhanced dynamical modeling capability. Next generation atmosphere-ocean coupled multi-scale modeling systems are configured together with the statistics of extremes specifically to provide projections of hurricane characteristics critical to engineering design, productions

efficiency, safety and environmental protection for the offshore energy industry. Confidence levels in the results are being established using multiple independent techniques, advanced statistics and targeted sensitivity analysis.

The major accomplishments of Phase 1 (detailed in Holland and Done 2014) included:

- A tool to explore empirical relationships between hurricanes and their environment.
- Extreme value assessments of future changes in the exceedance probability of major hurricanes.
- Evidence for a saturation in the proportion of major hurricanes, with further warming seeing no further increase in the proportion of major hurricanes
- Cyclone damage potential forecasts made in real-time for Isaac and Sandy (2012), and used by the reinsurance industry to assess potential damages in advance of landfall.

The major accomplishments of Phase 2 (detailed in Holland et al. 2015a) included:

- Combined decision tool development with statistical downscaling techniques.
- Credible bounds on annual North Atlantic Tropical Cyclone (TC) frequency and general locations of TC activity in current climate established.
- Initial case study testing of coupled wind-wave-current simulations.
- Expanding wind-wave-current simulations to more historical cases under current conditions and future scenarios.
- Proven regional modeling capacity with MPAS.

One remaining deliverable from Phase 1 was Task 6.0, Milestone 2 to use the extreme value approach that we used to assess extreme winds, to assess extreme damage potential. This outstanding deliverable was delayed while the extreme wind assessments were completed. This deliverable has been met and is reported in the summary of Task 13 below.

3. Accomplishments

Accomplishments and significant findings for the major tasks required of Phase 3 are outlined in this section.

Task 3: Technology Transfer

Technology transfer consisted of both project and program level activities amounting to not less than 2.5% of the total cost of the project. NCAR worked with RPSEA throughout the project to implement the Technology Transfer Plan and NCAR reported the cost associated with project level technology transfer activities on each monthly report and invoice. Work and activities completed towards the technology transfer commitment are outlined below.

1) Phase 3 results are being published in reputable peer-reviewed journals so that the outcomes of the program can be shared widely. Major papers related to Phase 3 are listed below.

Tye, M. R., Youngman, B. D., Holland, G. J. and D. B. Stephenson (2015): A smooth Bayesian Approach to Recalibrate Climate Extremes. *Journal of Climate* (in review).

Holland, G. J., Done, J. M., Douglas, R., and M. Ge (2015): Global Tropical Cyclone Damage Potential. *Natural Hazards Review* (in review)

Done, J. M., PaiMazumder, D., Towler, E. and C. Kishtawal (2015): Estimating Avoided Tropical Cyclone Impacts Using an Index of Damage Potential. *Climatic Change*. (In press).

Hashimoto, A and J.M. Done (2015): Tropical Cyclone Activity in Nested Regional and Global Mesh-Refined Simulations. *Climate Dynamics.* (In press).

Fowler, L., C. Bruyère, M., Ge, and W. C. Skamarock (2015): Regional Climate Modeling using a Variable-Resolution Mesh in MPAS. *Journal of Advances in Modeling Earth Systems* (In review).

In addition to published papers, two datasets have been published for community use. These climate datasets were generated by this project and are being used by the broader research community for a variety of regional climate research:

Bruyère, C.L., J.M. Done, S. Fredrick, and A. Suzuki-Parker. (2013) NCAR Nested Regional Climate Model (NRCM). http://dx.doi.org/10.5065/D6Z899DW.

Monaghan, A. J., D. F. Steinhoff, and C. L. Bruyère. (2014) NCAR CESM Global Bias-corrected CMIP5 Output to Support WRF/MPAS Research. http://rda.ucar.edu/datasets/ds316.1/

2) Interim reports were presented at two UDW Technology Conferences; Sep 4, 2014 and Sep 10, 2015, and at RPSEA Technical Advisory Committee (TAC) meetings on Sep 23, 2014, Jan 22, 2015 and May 6, 2015.

3) The performers participated in a number of academic and industry conferences and workshops (listed below) to gain critical project feedback from the broader academic and industry communities. Presentation materials are available on request.

Oct 2014: James Done presented research results at the Ocean Energy Safety Institute's Research Roadmap workshop, Texas A&M University.

Nov 2014: James Done met with Craig Fugate, administrator of FEMA, at NCAR. Administrator Fugate was very interested in the RPSEA project, in particular the development of hurricane impact indices for real-time decision-making.

Dec 2014: James Done and Greg Holland presented at the American Geophysical Union Fall Meeting, San Francisco. Greg gave a talk on the newly established 'Engineering for Climate Extremes Partnership' at a

dedicated oral session. TAC member Jim Stear (Chevron) also gave a talk in the dedicated session on developing resilient offshore energy production.

Feb 2015: James Done presented research results to NCAR visitor Joe Nolan, legislative assistant to Senator Thom Tillis.

Feb 2015: James Done, Greg Holland, Mari Tye and Cindy Bruyère traveled to Washington DC to discuss NCAR's new Engineering for Climate Extremes Partnership with USGS, FEMA, the Navy, and the World Bank. The purpose of the trip was to gain broad support for the Partnership, and research outputs from this project were presented as examples of successful public-private partnerships.

Apr 2015: James Done presented research results to visitors to NCAR from Metraweather and the Red Cross.

May 2015: James Done presented research results in a talk in the special session 'RPSEA UDW Technology Development Program: Selected Projects Progress' at the 2015 Offshore Technology Conference, Houston TX: Done J.M., C.L. Bruyère, and G.J. Holland, 2015: Future Changes in Gulf of Mexico Hurricane Impacts. Paper OTC-25671-MS.

Jul 2015: Project results were incorporated into a 3-day tutorial on regional climate science, held at NCAR.

Aug 2015: Mari Tye and Greg Holland led the third annual Engineering for Climate Extremes workshop at NCAR. The workshop brought together representatives from Indigenous Americans, Re/Insurance, Local Government, Industry and Business, and National and International Universities to identify the critical priorities to support robust and resilient decision-making for extreme weather and climate. The first day focused on incorporating "Graceful Failure" into resilient decision-making and the development of a Global Risk, Resilience and Impacts Toolbox to support decision needs. The work of this project featured heavily as an example of a successful industry-research collaboration to address industry needs. A workshop summary is available at:

https://www.ecep.ucar.edu/sites/default/files/ECEP%20Meeting%20write%20up_final.pdf

Extension to Task 5.0: Statistical Downscaling of Hurricane Response to Climate Variability and Change

Before documenting the tasks completed for Phase 3, we report here on extensions to Phase 1, Task 5: Statistical Downscaling of Hurricane Response to Climate Variability and Change. As described in the Phase 1 final report (Holland et al. 2014) this task supported two milestones: to develop improved downscaling approaches to assess hurricane response accounting for changes in climate, and to refine the technique specific to the Gulf of Mexico to assess the potential for regional changes in hurricane climatology within the Gulf of Mexico.

We know that hurricane activity is strongly influenced by the large-scale climate (e.g., Emanuel 2010), and these relationships form the basis of many indices of hurricane activity. Existing indices (e.g., the Genesis Potential (GP) index, Emanuel and Nolan (2004)) perform well at capturing the seasonal cycle of hurricane activity and the major global patterns of activity. However, on smaller scales such as sub-regions of the North Atlantic basin the indices perform less well (Bruyère et al. 2012). Using a data-mining approach, regions of highest correlation between the index and hurricane frequency have been identified. Figure 1 shows the correlation between large-scale climate variables and North Atlantic hurricane frequency as a function of climate variable, region, hurricane intensity and lag relative to the peak hurricane season. This figure shows that the strongest correlations exist for sea surface temperature (SST)-based variables (SST, relative SST, and Potential Intensity[1]) over the North Atlantic and wind shear (a strong negative correlation). Relative humidity (RH), specific humidity (SH) and vorticity have weak to no correlation. Bruyère et al. (2012) developed the Cyclone Genesis Index (CGI) as a simple function of Potential Intensity and wind shear, and this index performed best over the Main Development Region (MDR, 10-20°N, 20-60°W) in explaining total basin hurricane frequency. Note that no climate variable showed correlation when averaged over the Gulf of Mexico. This is because the majority of Gulf hurricanes have their origins outside the Gulf, with a strong connection to the MDR.

[1] Potential Intensity is the maximum wind speed a hurricane can achieve given the thermodynamic environment, without accounting for dynamical influences such as wind shear.

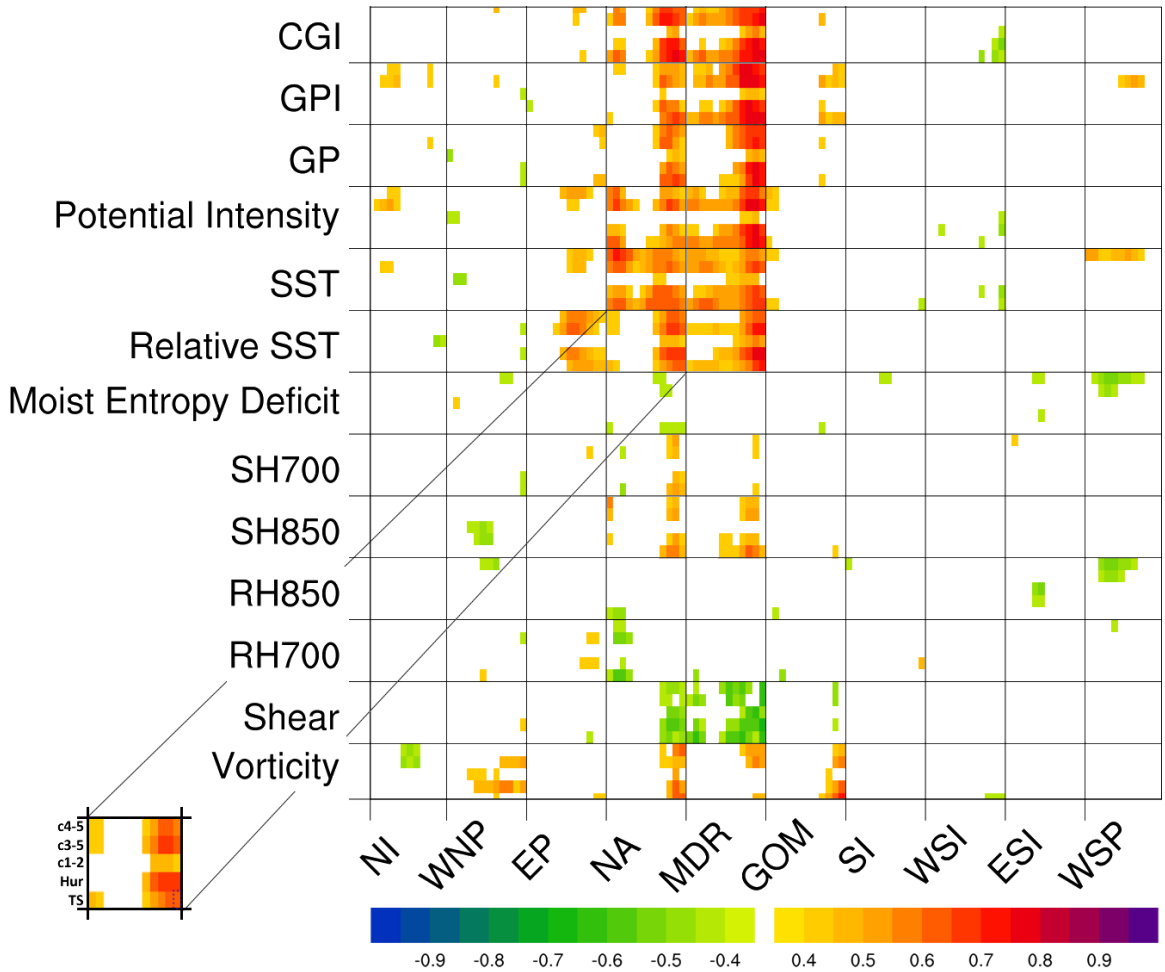
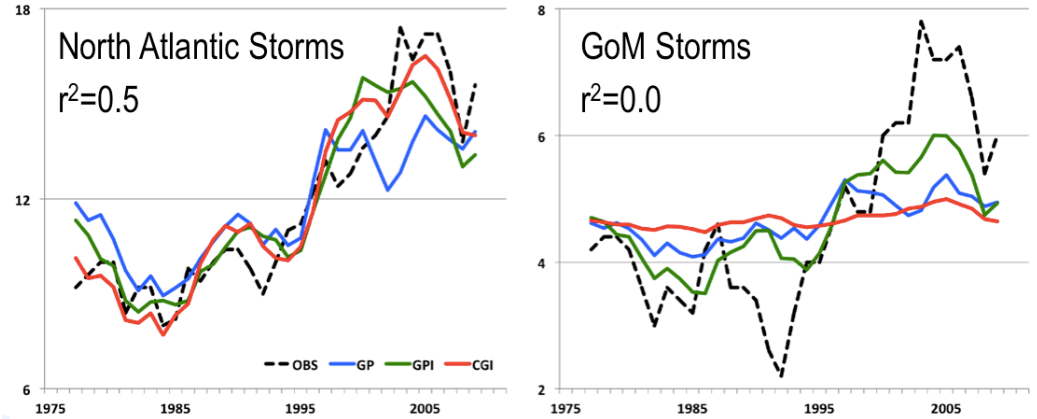


Figure 1: *Treemap for interannual correlations between large-scale climate variables and North Atlantic TC frequency. The major x- and y-axes represent the different basins and variables. The minor x- and y-axes represent month and hurricane intensity. Color represents correlation (R^2).*

A new tool has thus been developed using the CGI averaged over the MDR to assess North Atlantic basin hurricane frequency. Figure 2 shows the dramatic improvement in capturing Gulf of Mexico TC frequency when changing from a basin average index to an index averaged over the MDR. The variance explained increases from 0 to 40 percent. There is also a slight improvement in explaining total basin TC frequency.



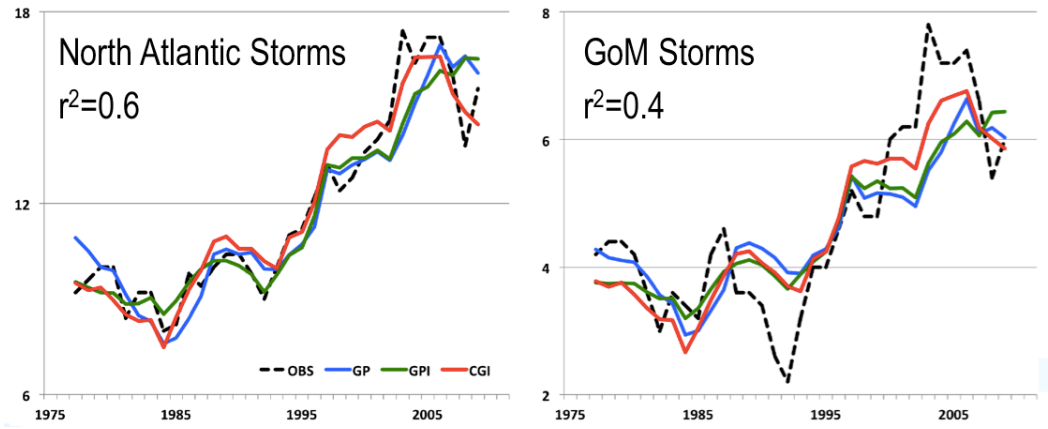


Figure 2: *North Atlantic (left column) and Gulf of Mexico (right column) TC frequency. Observed (black dashed line) and predicted (colored lines) using CGI, GP and GPI. The top row uses averages of the indices over the entire basin and the bottom row used averages over the Main Development Region. A 5-year running mean has been applied to all data.*

The power of the CGI is that it can be applied to large climate datasets to make rapid assessments together with uncertainty. Figure 3 shows projections of TC frequency using CGI applied to an ensemble of climate model projections using the Community Climate System Model version 3. The ensemble predicts a future increase in TC frequency of about 20 percent by 2050 due to more favorable future environments for hurricane genesis and intensification.

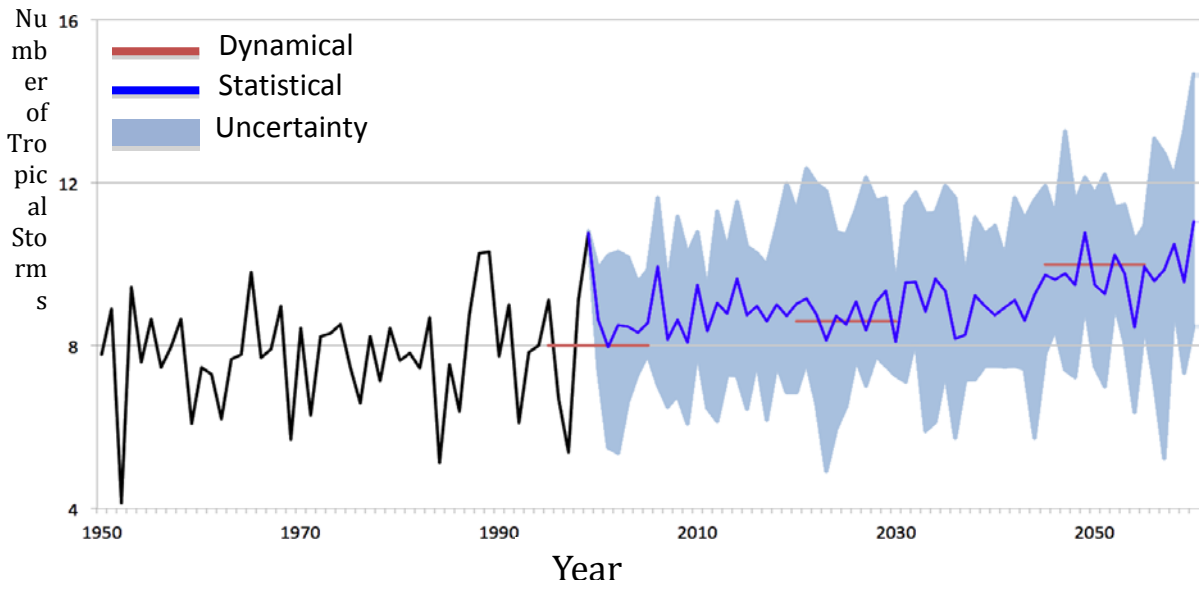


Figure 3: *Simulated North Atlantic basin TC frequency generated using CGI applied to simulated current climate from 1950 to 2000 under a 20th Century emissions scenario (black line) and an ensemble of future climate projections under a prescribed greenhouse gas emissions scenario from 2000 to 2060. The blue line indicates the*

ensemble mean and the 10th to 90th percentile is shaded. The results of dynamical model simulations conducted under RPSEA project 07121-1801 are also shown in the red line as 10-year average frequencies for the decades 1995-2005, 2020-2030 and 2045-2055.

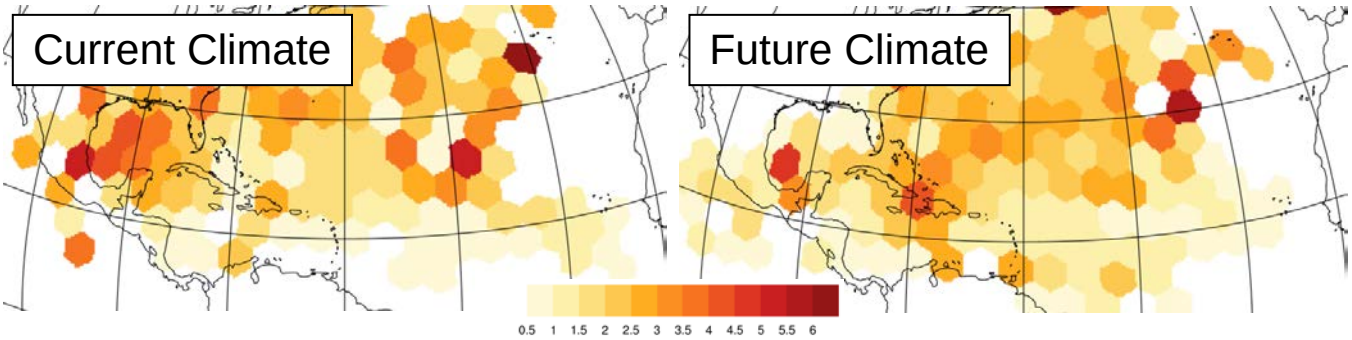
Task 12.0: Comprehensive Sensitivity Analyses

This task is a continuation of Phase 2 Task 9.0 to conduct specific sensitivity studies as the project progresses with the end goal of establishing confidence in the results.

Establishing Confidence in Hurricane Projections

Sensitivity studies have been conducted to explore levels of confidence in today's hurricanes and uncertainty in the future change in hurricanes, and relationships between the two. A 24-member dynamical model ensemble simulation of current climate hurricane activity, described in the Phase 2 report (Holland et al. 2015a), was generated to assess the range of hurricane activity possible under current climate conditions, by expanding the historical record. Each ensemble member differs by a slightly different representation of physical processes, such as radiation, microphysics, surface boundary layer, and deep convection. The following goal is then to assess a credible range in the future change of hurricane activity.

The problem is illustrated in Fig. 4 that shows the Cyclone Damage Potential (CDP, Holland et al. 2015b) applied to a single simulation of current climate and a single simulation of future climate. The CDP assesses the damage potential of TCs using the key damaging TC parameters of intensity, size, and translational speed. The CDP represents offshore wind, wave and current damage and onshore wind and coastal surge damage. Figure 4 shows a future reduction in damage potential in the Gulf of Mexico. The goal of this task, then, is to assign a level of confidence in this predicted reduction of damage potential.



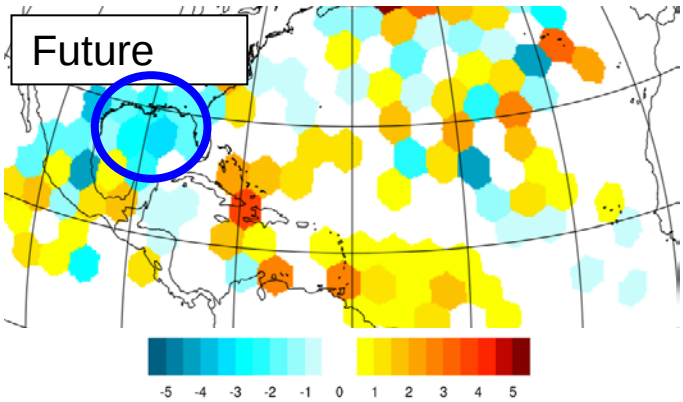


Figure 4: *Average cyclone damage potential for (top left) simulated current climate, (top right) simulated future climate representative of the 2050s, and (bottom) the future change (future – current). The simulations used are dynamical model simulations at 36km for the periods 1995-2005 and 2045-2055 generated under RPSEA project 07121-1801.*

The current climate ensemble was analyzed for TC activity (Fig. 5) with emphasis on the Gulf of Mexico. Results show large spread in hurricane activity in the Gulf of Mexico with some members producing higher levels of activity than in the historical record and some members producing no hurricane activity at all (Fig. 5, and discussed in the Phase 2 report). Owing to computational limitations we are not able to run all 24 members for future climate, nor would we want to since some members do not produce credible climates. We selected three members (indicated in Fig. 5) based on the simulated hurricane activity and other regional climate attributes, to span the physically plausible range rather than selecting three members that were similar to each other.

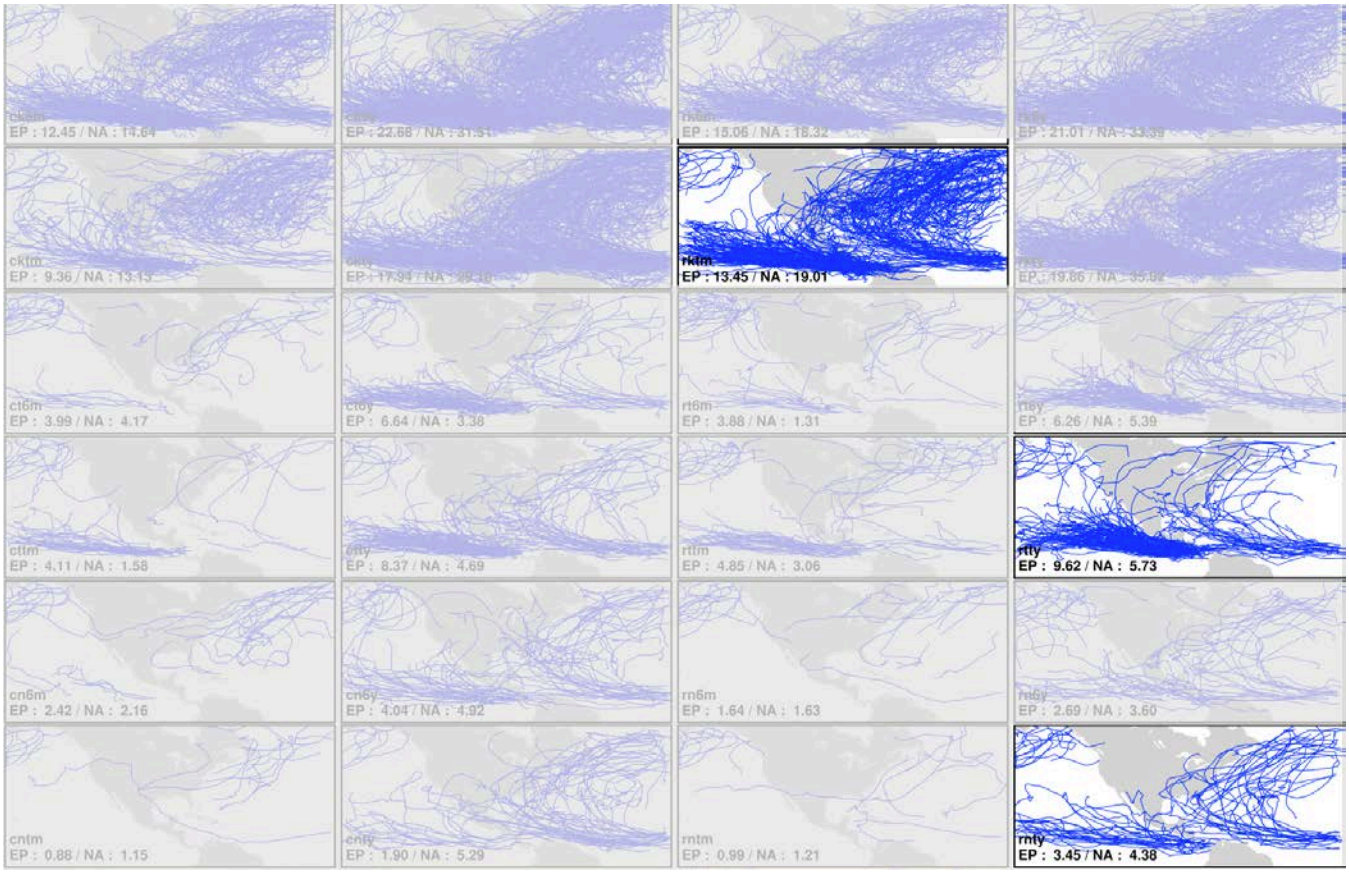
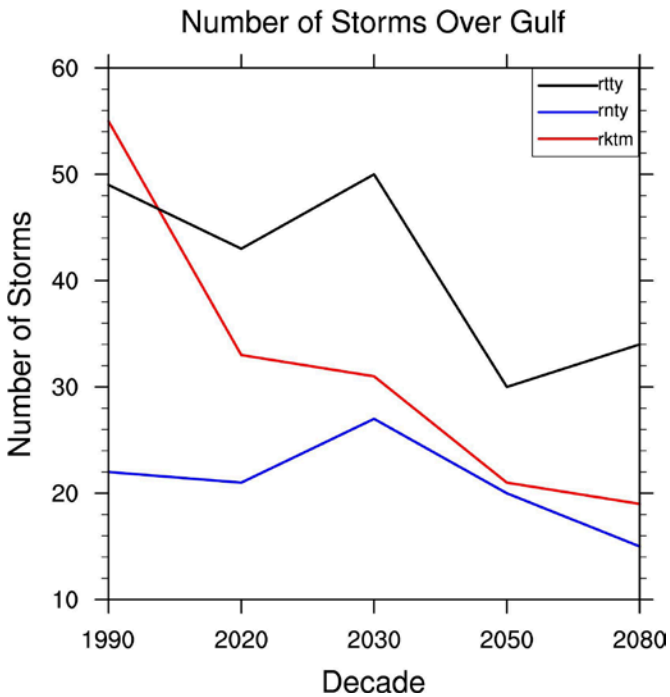


Figure 5: *Simulated TC tracks (blue lines) for 24 simulations of the current climate period 1990-2000. Note that the tracks extend upstream to capture the pre-storm disturbance. The four alphanumeric characters indicate the specific simulation and the numbers indicate the annual average numbers of TCs in the East Pacific (EP) and the North Atlantic (NA). The equivalent observed values are 16.0 for the East Pacific and 11.1 for the North Atlantic. The three highlighted members were selected to run for future climate.*



The 3-member future climate ensemble was created using a single bias-corrected global climate model projection (Monaghan et al. 2014; Bruyère et al. 2015) to drive the high-resolution regional model. The ensemble was run for five time periods: one current climate decade (1990 - 2000) and four future climate decades (2020 - 2030, 2030 - 2040, 2050 – 2060, and 2080 - 2090). Figure 6 shows the future predicted number of TCs per decade in the Gulf of Mexico. Each ensemble member predicts a future decrease in numbers of Gulf of Mexico TCs. The results in terms of the future change of hurricane damage potential are presented in Phase 3 Task 13 below.

Figure 6: *Simulated numbers of Gulf of Mexico TCs per decade by the 3 ensemble members.*

Establishing the Capacity of the Model for Prediction Across Scales for Seasonal Hurricane Simulation

The Model for Prediction Across Scales (MPAS) is new technology we are developing and applying to hurricane simulation. This task is to explore sensitivity of the simulated hurricane season to way physical processes are represented by the model.

We conducted four yearlong simulations, each with a different representation of physical processes, to explore sensitivity of seasonal climate and TC simulation to model assumptions. Specifically, we explored the performance of two representations of deep convection (thunderstorms), and two representations of solar and terrestrial radiation. The large-scale global circulation, rainfall amounts, and TC frequencies were different among the simulations. Basin TC numbers, for example, were up to 50 percent different among the simulations (see for example Fig. 7). This sensitivity study allowed us to select the best performing combination of physical processes for longer period simulations in Task 15.

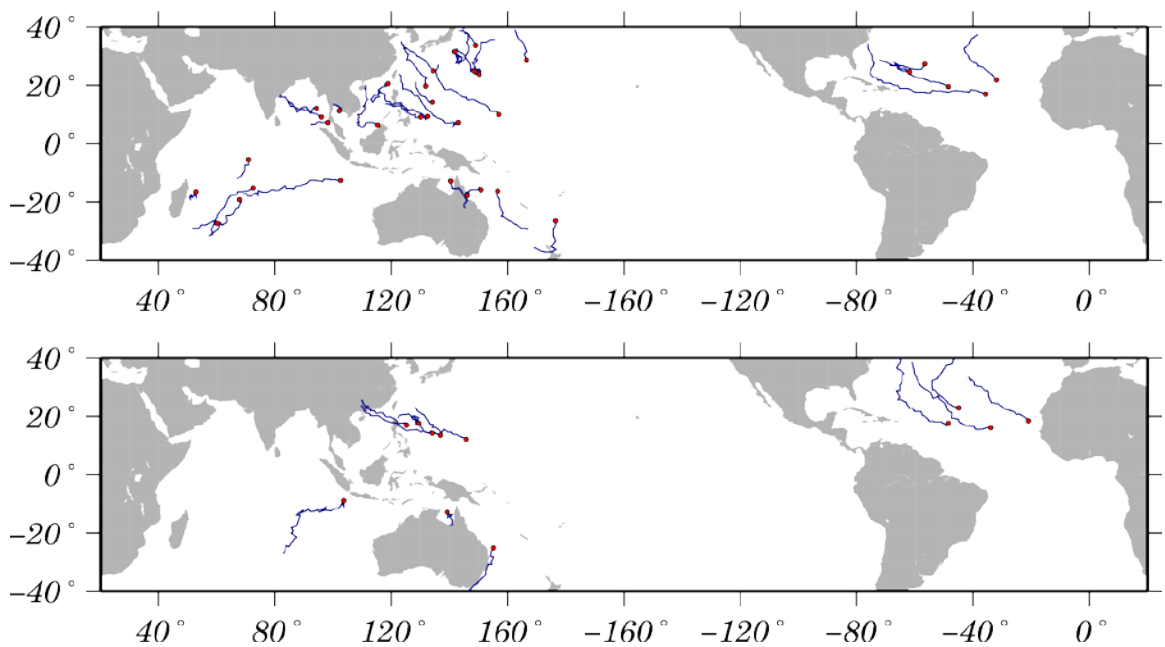


Figure 7*: TC genesis points (red) and TC tracks (blue) in two yearlong simulations, each with different model physics. TC frequency is very different among the simulations. Note that overall numbers of storms are low because these simulations were conducted at a fairly coarse level of detail (Source: Atsushi Hashimoto, CRIEPI).*

Figure 8 shows that the structure of TCs is also very different between the simulations. The simulation on the left using the Kain-Frtisch representation of convective thunderstorms was able to produce cyclones with lower central pressure and higher maximum wind speeds than the simulation on the right using the Tiedtke

representation of convective thunderstorms. It is likely that the differences in TC intensity distribution among the simulations is due to differences in the way convective thunderstorms are represented in the model. The Kain-Fritsch representation responds more vigorously to an unstable atmosphere than does the Tiedtke representation.

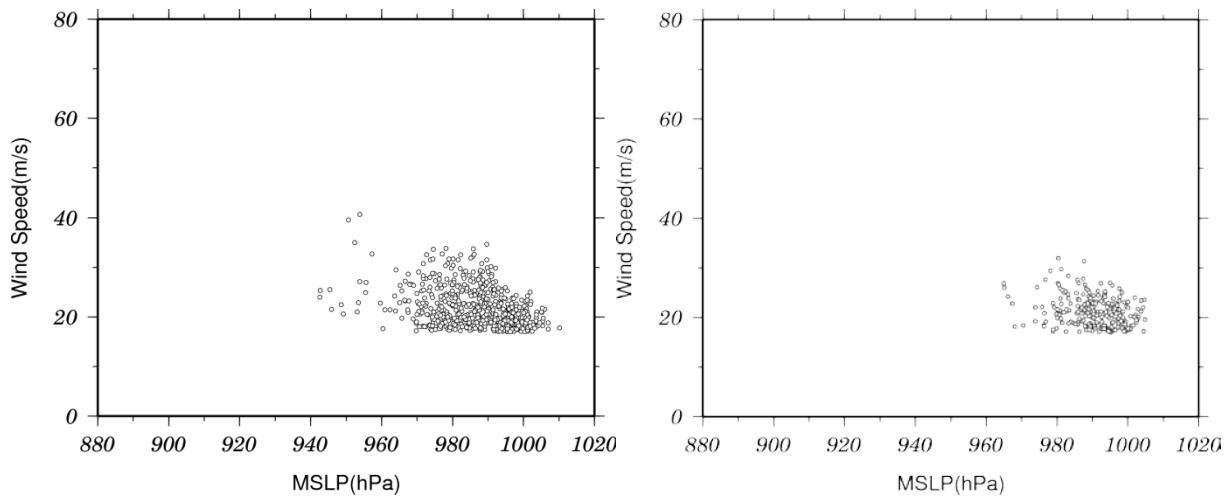
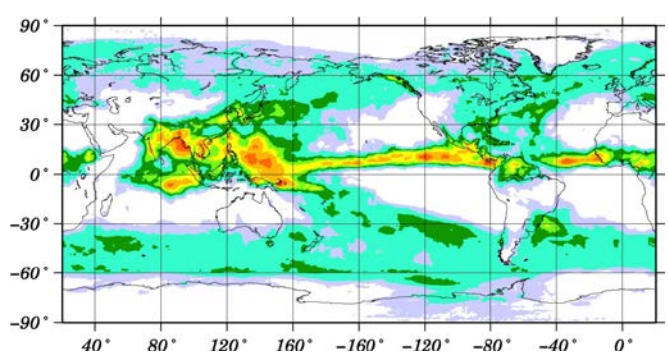


Figure 8: *Wind-pressure relationship for all 6-hourly TC points in two yearlong simulations, each with different model physics. TC structure is very different among the simulations. Note that overall storm intensity is low because these simulations were conducted at a fairly coarse level of detail. Longer-term simulations for Task 15 are being conducted at a much higher level of detail to capture all storms. (Source: Atsushi Hashimoto, CRIEPI).*

Rainfall responds to the full 4-dimensional structure of the global circulation and is therefore a critical indicator of simulation skill. Two simulations are compared with observations. Geographic maps of northern summer rainfall (Figure 9) show the simulations capture the broad global rainfall patterns including the tropical maxima and belts of mid-latitude storm tracks. This sensitivity study has allowed us to select the best performing combination of physical processes (in terms of both global seasonal rainfall patterns and TC locations and frequency with more weight given to the performance of the TC simulation) that are being used for longer period simulations in Task 15.



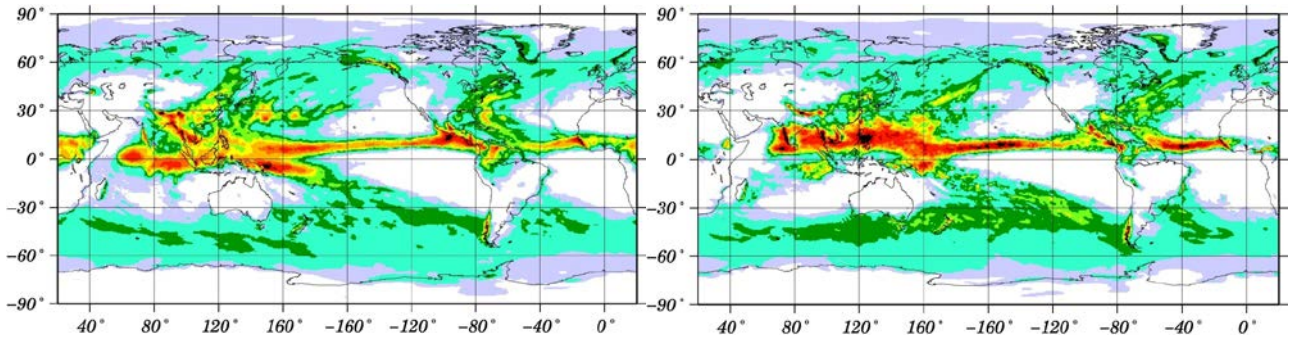


Figure 9: *Mean daily precipitation (mm/day) for July-August-September for (top) observations using Global Precipitation Climatology Project data, (right) MPAS simulation using Kain-Fritsch convection parameterization, and (left) MPAS simulations using Tiedtke convection parameterization. (Source: Atsushi Hashimoto, CRIEPI).*

Task 13.0: Direct Impact Assessments

There is a growing need for timely information on the expected damage caused by hurricanes for immediate response and industry planning purposes. These needs may be met through the development of decision support tools that enable a quantitative specification of industry impacts based on model predictions. Existing tools and new tools developed under Task 7.0 have been applied to new hurricane and climate datasets generated under the previous two phases to make comprehensive damage assessments.

Historical Cyclone Damage Potential

Application of the CDP index (Holland et al. 2015b) to historical data (Fig. 10) shows the geographic spread of historical CDP. TC data are taken from the IBTrACS archive (Knapp et al. 2010), a compilation and standardization of archives from worldwide TC warning centers. For the North Atlantic, size is included using the mean radius of hurricane force winds obtained from U.S. National Hurricane Center advisory archives collated by Demuth et al (2006) and known as the Extended Best Track Dataset. The archive at the Joint Typhoon Warning Center (JTWC, http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/) is used for the other TC basins.

Data are visualized by spatially tessellating the hurricane basins using equal-area hexagons and binning the 6-hourly hurricane track data by hexagon (Fig. 10). These summaries show a rich spatial texture that is masked by a consideration of TC intensity alone. For the North Atlantic, damage pathways follow the major belts of recurving storms off the U.S. east coast. Other damage pathways track from the Caribbean into the Gulf of Mexico. The Yucatan and North Carolina are highlighted as damage hotspots that are not immediately apparent using intensity alone. For other basins, global damage potential pathways are co-located with recurving storm tracks, and damage potential hotspots lie east of the Philippines and across the north Australian coast (Fig. 10)

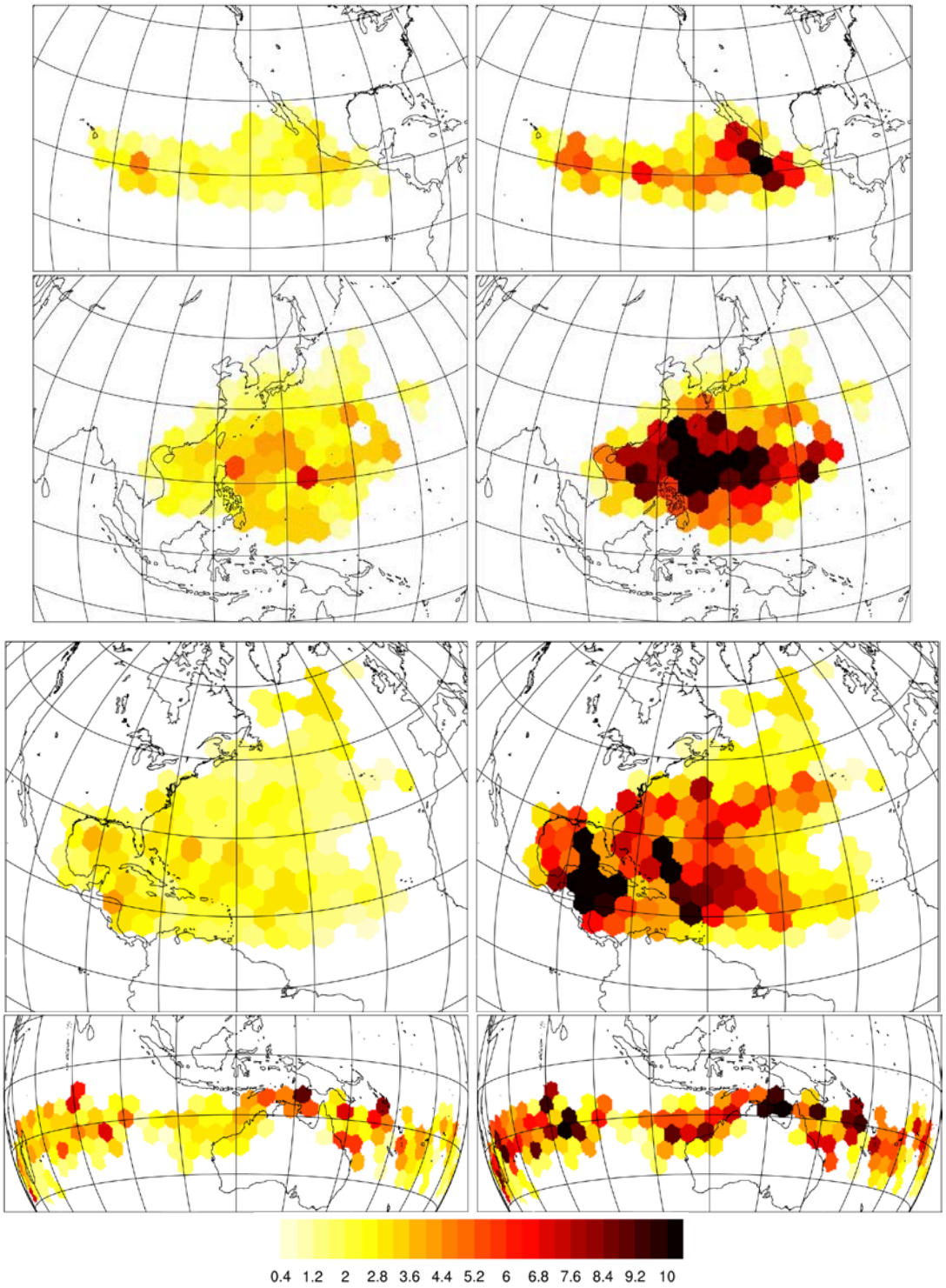


Figure 10*: (left) Median and (right) maximum seasonal CDP for the Eastern North Pacific (2001-2013), the Western North Pacific (2004-2013), the North Atlantic (1988-2013), and Southern Hemisphere (2004-2013).*

A twenty-six-year time series of seasonal (August to October) accumulated CDP for the North Atlantic (Fig. 11) indicates no trend for the entire basin. There also is large interannual variability for which TC duration and frequency are additional contributors to the three component terms of the CDP. The high frequency years of 1995 and 2005 also show the highest seasonal CDP reflecting a contribution from TC frequency, yet the high frequency

period of 2010 - 2012 is not a period of high CDP, reflecting contributions from the other terms. A statistically significant ($p < 0.04$) correlation between seasonal CDP and the Niño3.4 index averaged over August to October indicates a modulation of seasonal basin CDP by El Niño Southern Oscillation (ENSO).

Isolating the CDP of landfalling storms presents a different view of historical CDP. A 26-year time series of landfalling CDP (accumulated CDP at the 6-hourly data points prior to landfall) for the North Atlantic Basin shows large interannual variability and increasing (but not statistically significant) linear trend (Fig. 11) over the period 1988 - 2013. Seasonal landfall CDP, however, shows no significant modulation by ENSO.

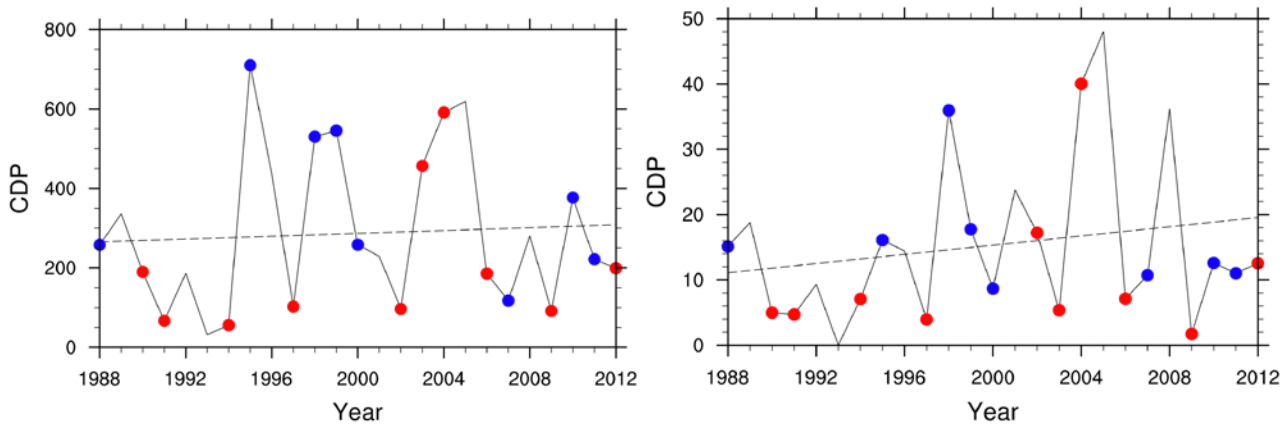


Figure 11: *Timeseries of seasonal accumulated CDP (1988-2012) for (left) the entire North Atlantic basin, and (right) landfalling storms anywhere in the basin at the 6-hourly track points prior to landfall. Years with Oceanic Niño Index (3 month running mean SST anomalies in the Niño 3.4 region 5°N-5°S, 120°-170°W) for August-October >0.5K (El Niño) are indicated in red, and ONI <0.5K (La Niña) are indicated in blue (ONI data source: NOAA/CPC).*

Future Cyclone Damage Potential

The 24-member dynamical model current climate ensemble and 3-member future climate ensemble described in Task 12 above has been analyzed for the spread in the Cyclone Damage potential for current and future climate. Each ensemble member differs in the representation of model physics and therefore produces a slightly different view of current climate. There are commonalities among the views, with generally higher damage potential at lower latitudes and lower damage potential at higher latitudes associated with the stronger large-scale flow and faster moving storms. Differences are apparent at smaller (sub-basin) scales (not shown).

Figure 12 shows the geographic distribution of the future change (compared to current climate) in the maximum Cyclone Damage Potential for one example ensemble member. The change is positive everywhere where there are sufficient data, and the magnitude of the change increases the further we look into the future. The other two ensemble members also predict future increases in the maximum Cyclone Damage Potential everywhere there are sufficient data (not shown). The magnitude of the change, however, varies spatially among the ensemble members. Future changes in the average Cyclone Damage Potential, however, can be positive or negative (not shown for this ensemble, but Fig. 4 shows an example future change in the average Cyclone Damage Potential for

a single dynamical model projection generated under RPSEA project 07121-1801) and the spatial pattern of the change varies between ensemble members.

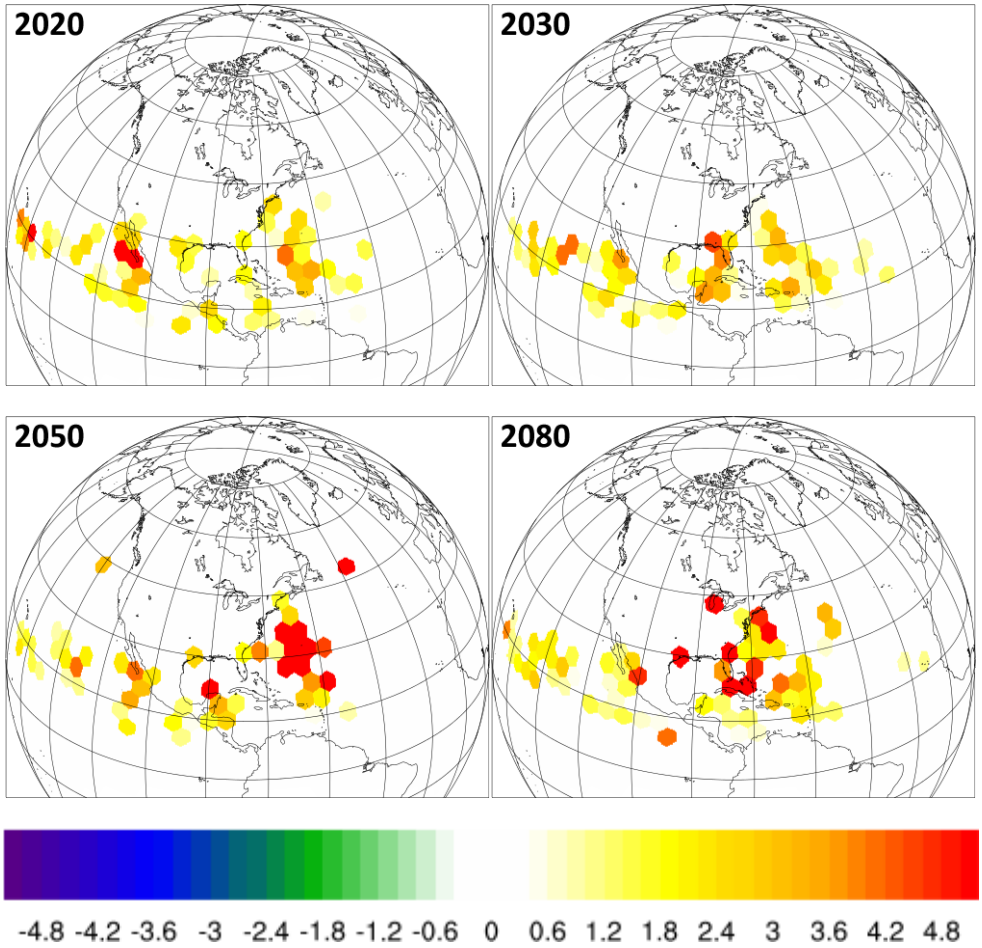


Figure 12. *Future change in the maximum CDP (future - current) for four future decades for one ensemble member. Only the locations of sufficient hurricane activity in current and future climate are shown.*

Extremes in Cyclone Damage Potential

The delayed Phase 1 Task 6 Milestone 2 to extend the extreme value approach of Phase 1 Task 6 to incorporate direct impact assessments from the extremes has now been completed and is reported here. The Phase 1 final report documented a new approach to assess changes in the most extreme wind speeds. Briefly, theoretical distributions are fitted to hurricane intensity distributions from observations and dynamical simulations. The low intensity bias in the simulations is then corrected by transforming the fitted distributions (Holland et al. 2015; Tye et al. 2015). A similar approach was trialed for Task 6 Milestone 2 to assess future changes in the extreme CDP.

Figure 13 shows a Weibull and an exponential distribution fitted to the historical distribution of North Atlantic CDP using the period 1960-2011. The goodness of fit may be assessed using quantile-quantile plots shown in Fig. 14. The Weibull fits well (points lie close to the diagonal line) for CDP less than 7 whereas the exponential fit departs from observations for CDP greater than 4. Therefore we choose to use the Weibull fit to assess extreme CDP.

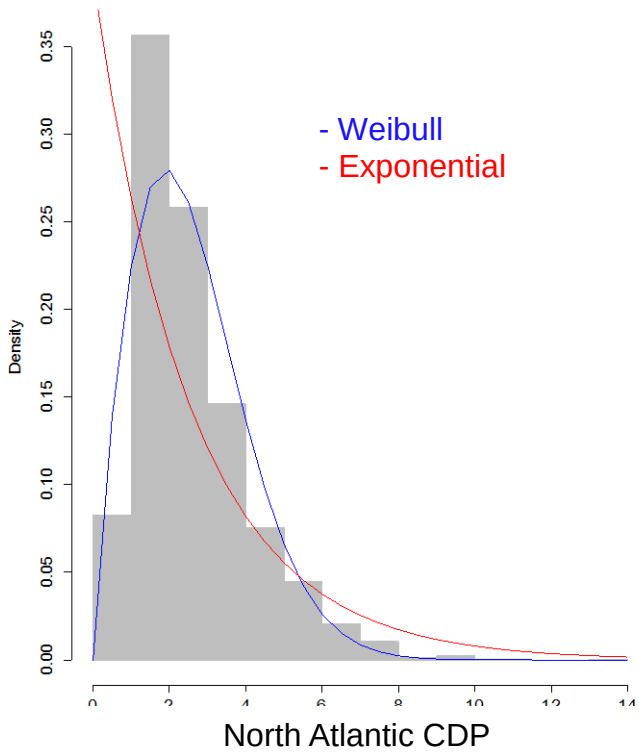


Figure 13: *Probability distribution of historical North Atlantic Cyclone Damage Potential for the period 1960-2011 (gray bars). CDP values are calculated using 6-hourly track data from IBTrACS (Knapp et al. 2010). Fitted Weibull and Exponential distributions are shown in the colored lines.*

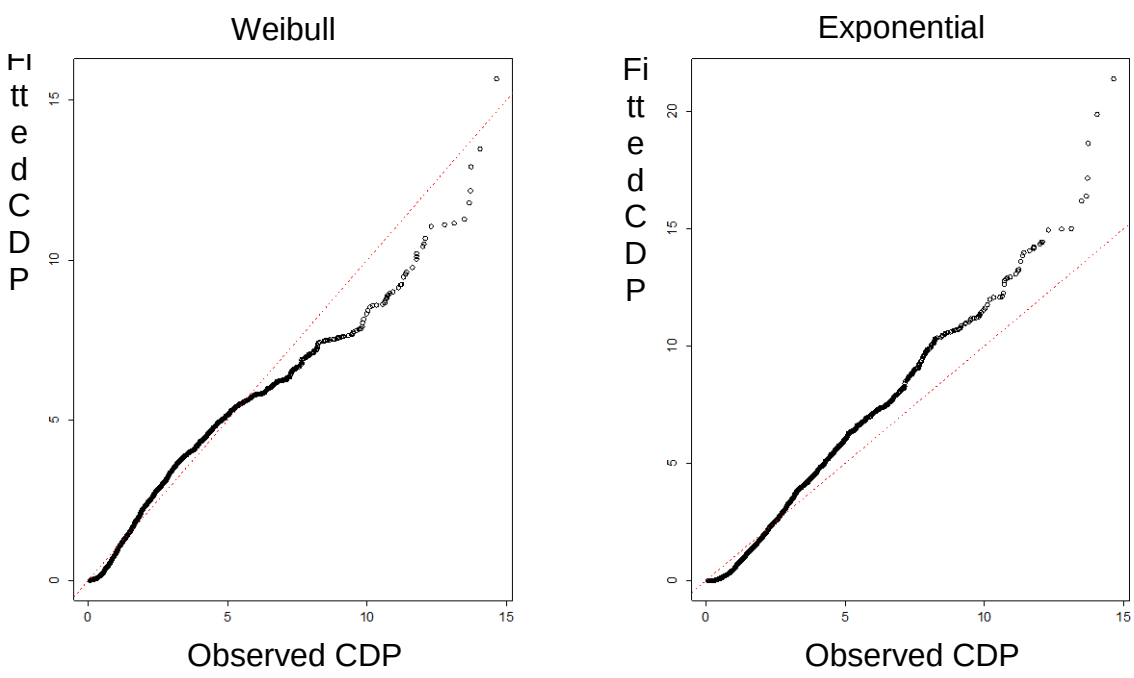


Figure 14: *Quantile-quantile plots of observed and fitted North Atlantic Cyclone Damage Potential using (left) the Weibull and (right) the exponential distribution.*

Figure 15 shows the fitted Weibull distributions to the historical CDP, simulated current climate CDP and simulated future climate CDP. The simulations used are dynamical model simulations at 36km for the periods 1995-2005 and 2045-2055, generated under RPSEA project 07121-1801, and used for the extreme wind speed assessments for the first milestone of Phase 1 Task 6 of this project (Holland et al. 2014). These data are also presented in Figure 4 of this report.

The formula of the CDP index contains two standardization factors, one for the maximum wind speed and one for the radius to hurricane force winds, to ensure each term is of the same order. These factors are chosen to be average values. Although we know the simulated wind speeds contain a low bias (Holland et al. 2014) and the simulated radius to hurricane force winds contain a high bias (not shown), these biases can be limited through a rescaling simply by using the average values from each dataset in the standardization. The result is that the observed and simulated current climate CDP distributions are similar (Fig. 15). Using the same rescaling factor for the future climate gives a future CDP distribution that has a higher proportion of low values and a shorter tail (Fig. 15). The impact of this future shift may be quantified using exceedance probabilities of the fitted distributions. Table 1 shows a 19 percent decrease in the 90th percentile (P90) and a 31 percent decrease in the 99.9th percentile (P99.9). A similar analysis is being performed on the 3-member future climate ensemble simulations described under Task 12. This will allow us to assess a credible range of the future change in extreme values of CDP.

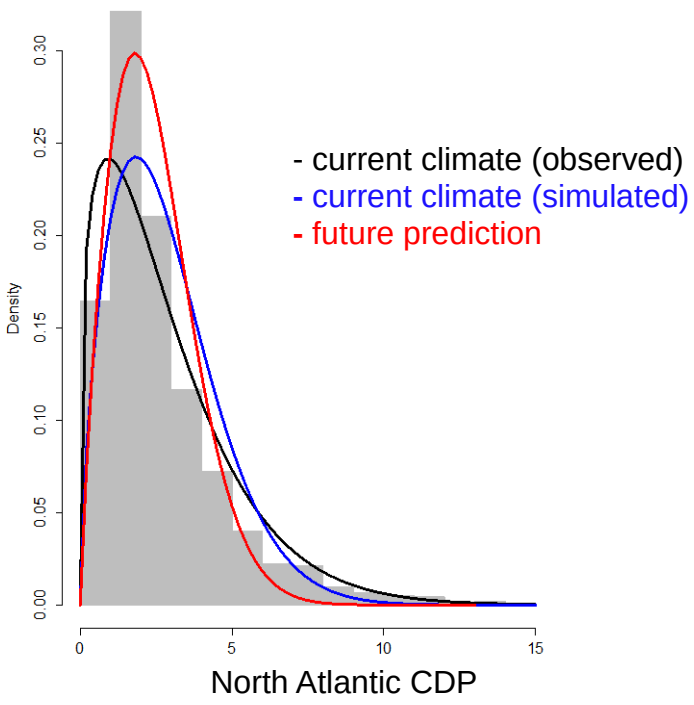


Figure 15: *Probability distribution of historical North Atlantic Cyclone Damage Potential for the period 1960-2011 (gray bars). Also shown are the fitted Weibull distributions to historical observations (black line), simulated current climate CDP (blue line), and simulated future climate CDP (red line).*

Percentile	Historical Observations	Simulated current climate	Simulated future climate	% Change (future – current)
P90	5.9	5.3	4.3	-19
P99	10.1	8.0	6.3	-21
P99.9	13.9	10.2	7.8	-31

Table 1: *Percentiles of North Atlantic CDP for observed and simulated current climate and future climate. The final column gives the percent change (simulated future climate – simulated current climate).*

Future Cyclone Damage Potential Assessments using Large-Scale Climate Variables.

The CDP has been adapted to use large-scale climate data rather than hurricane data. This work was described in the Phase 2 report (Holland et al. 2015a) and published in the peer-reviewed literature (Done et al. 2015). This new index uses the ratio of the relative SST[2] to the weighted steering flow as the predictor variable, and is formulated as:

$$\mathrm{CDP_{climate}} = 67\frac{\mathrm{SST_{relative}}}{\mathrm{STR_w}} + 6, \qquad (1)$$

where $\mathrm{SST_{relative}}$ is the relative SST (Vecchi and Soden 2007) and $\mathrm{STR_w}$ is the weighted steering flow. This index has been applied to climate model simulations of current climate and a climate model ensemble of future climate scenarios. Figure 16 shows a future decrease in damage potential is predicted. This decrease is driven by the more rapid warming of the Pacific Ocean than the North Atlantic Ocean in the ensemble. The major caveat here is that the projected future reduction in TC damage potential is dependent on the climate model ensemble used. Application of $\mathrm{CDP_{climate}}$ to multiple climate models would likely show both future increases and decreases in damage potential (evidenced by the lack of agreement in relative SST change, Villarini and Vecchi 2012). Improving understanding of spatial SST change may therefore be key to understanding future change in TC damage potential.

[2] Relative SST is the difference between the local SST and the average SST around the tropics.

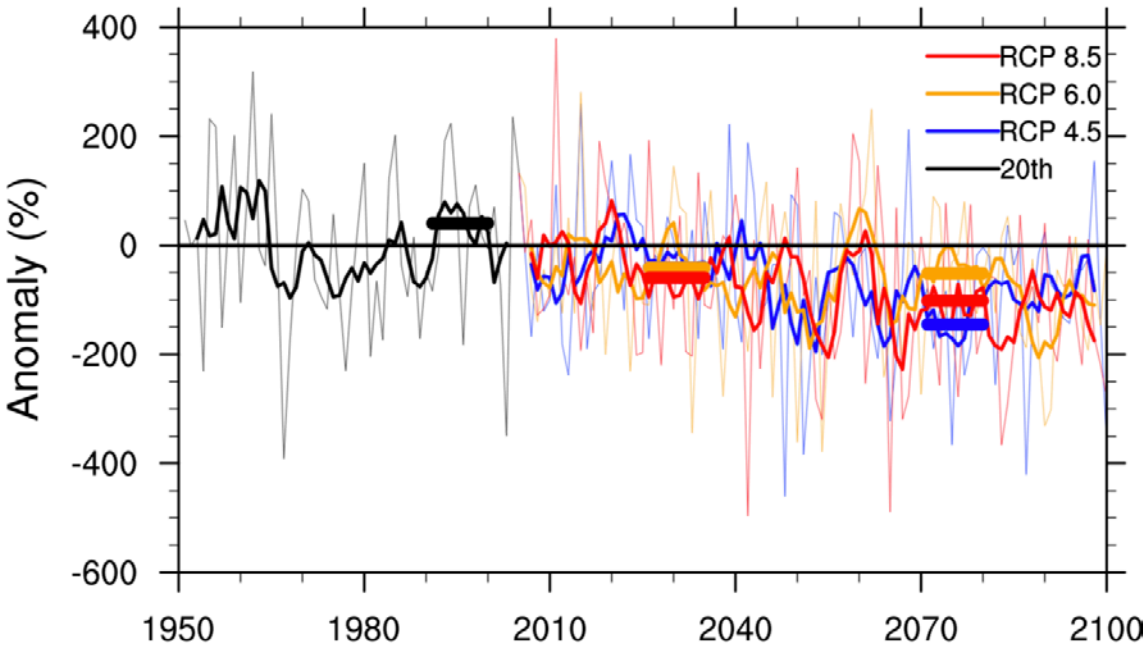


Figure 16: *Time series of cyclone damage potential for the North Atlantic basin under 20th Century emissions for the period 1950-2005, branching by future emissions scenarios: low emissions (blue lines), medium emissions (orange lines), and high emissions (red lines) from 2005 to 2100. Thicker lines are the 5-year running average, and horizontal lines indicate 10-year means for the periods 1990-1999, 2026-2035, and 2071-2080. Percent anomaly is from the period 1950-2005.*

Task 14.0: Assessing the Impact of Atmosphere-Ocean Interaction

This task is a follow-on from Phase 2, Task 10.0 to analyze the new hurricane datasets generated by coupled wind wave and current simulations. As described in the Phase 2 report (Holland et al. 2015a), and following discussion and agreement among the TAC members, our approach changed to focus more on case scenarios rather than free-running climate simulations. This has the advantage of assessing historical hurricanes under different scenarios, rather than looking at simulated events that, although physically possible, do not have one-to-one correspondence with historical hurricanes.

The Phase 2 report described the simulation of hurricane Katrina using the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST). This simulation system uses the same atmospheric model as used in the long-term simulations described in Task 12, the Regional Ocean Modeling System (ROMS), and the Shallow Waves Nearshore (SWAN) model. ROMS is a free surface hydrostatic primitive equation model. We use a 12km grid spacing on a 159x159 grid with 16 vertical sigma layers. Open boundaries along the eastern and southern portions of the domain are specified with values from the 1/25°, HYCOM + NCODA Southeast United States analysis (2003 - 2010) or the HYCOM + NCODA Global 1/12 degree Reanalysis (1995-2012). Boundary data for SWAN are provided by 3-hourly output from the 10 arc minute North Atlantic regional wave spectral

model WAVEWATCH III. We use 36 directional bins and 24 frequency bins of 1 s width between 1 and 25s. In addition, nonlinear quadruplet wave interactions are activated, wave bottom friction is parameterized using the Jonswap formulation, and the depth-induced breaking constant is set to 0.73. Whitecapping is activated and wind-wave growth is generated using the Komen formulation. The drag coefficient is capped at 0.0022, and data exchange between ROMS and SWAN occurs every 10 minutes.

Analysis showed a reasonable simulation of the hurricane Katrina's track, yet the hurricane maximum wind speed was too weak. This was due to the hurricane in the initial conditions being too weak by about 20m/s. This resulted in a damped ocean and wave response, and we were unable to recover the simulation from these weak initial conditions.

We then trialed a more constrained modeling approach whereby hurricane wind speeds are taken from observations and used to drive the ocean and wave models. We use NOAA's H*WIND wind field analysis product to create a more realistic wind field for historical hurricanes. H*WIND is our best guess at the actual wind field and is based on all available wind observations, yet covers only a small geographic region and so the less detailed North American Regional Reanalysis (NARR, Mesinger et al. 2006) was used to fill in the wind field in the surrounding environment. Figure 17 shows the impact of merging H*WIND with NARR for the case of hurricane Katrina. H*WIND captures smaller scale hurricane structure and higher maximum wind speeds than NARR alone.

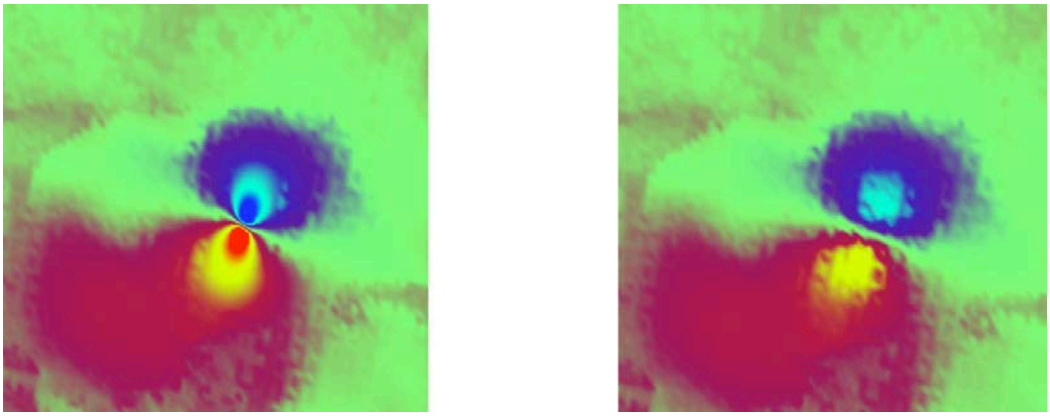


Figure 17: *Snapshots of the zonal (East-West) component of the wind field of Hurricane Katrina using (left) H*WIND combined with NARR and (right) NARR. Cool colors indicate winds from the East and warm colors indicate winds from the West.*

Ten historical Gulf of Mexico hurricanes (shown in Fig. 18) were simulated using this modeling system. The ten cases were chosen to include some that had a strong interaction with the loop current (Task 14, Milestone 2). These 10 cases allow us to build up statistics of the relationships between metocean variables in hurricane environments in current climate.

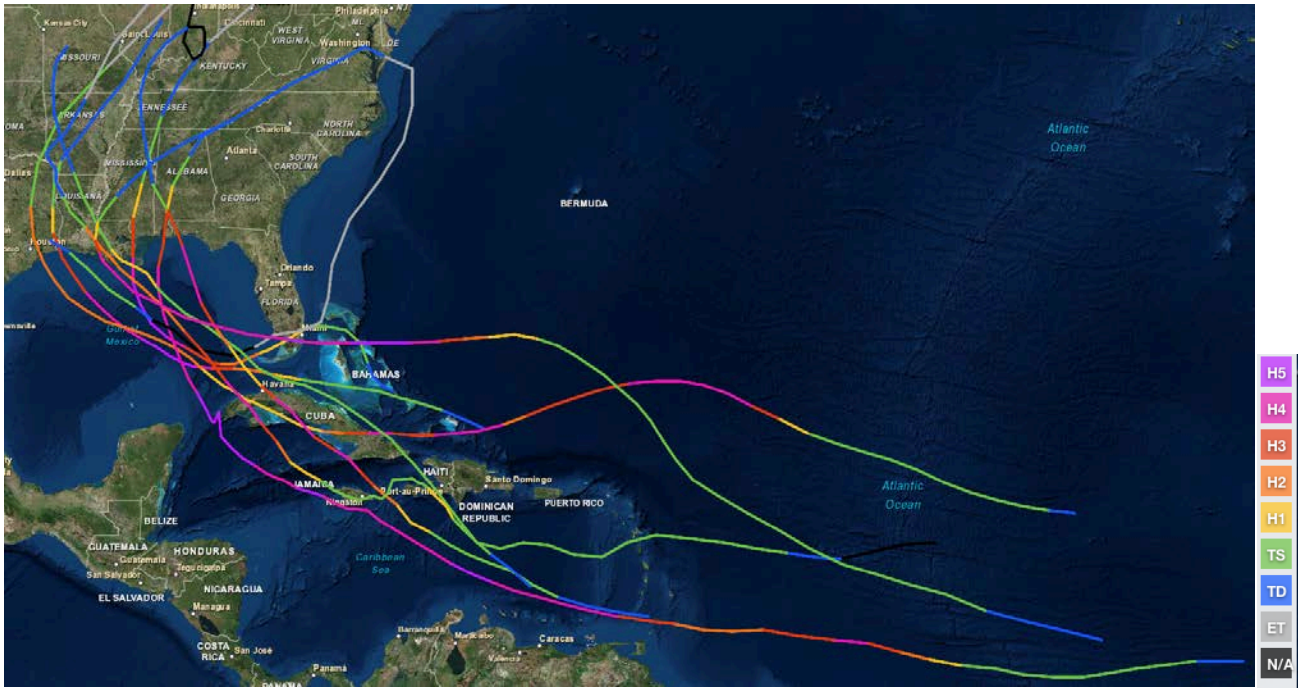


Figure 18: *Tracks of the 10 case study hurricanes (figure generated at: coast.noaa.gov/hurricanes/): Andrew (1992), Lili (2002), Ivan (2004), Dennis (2005), Katrina (2005), Rita (2005), Gustav (2008), Ike (2008), Ida (2009) and Isaac (2012).*

For the case of Hurricane Lili (2002) simulated and observed wind speed and significant wave heights are compared in Fig. 19 at the locations of seven buoys. The impact of additionally including the H*WIND data into the NARR wind field is to capture the inner hurricane winds (see wind speeds at buoys 42001 and 42041). This corresponds to much-improved maximum significant wave heights (Fig. 20).

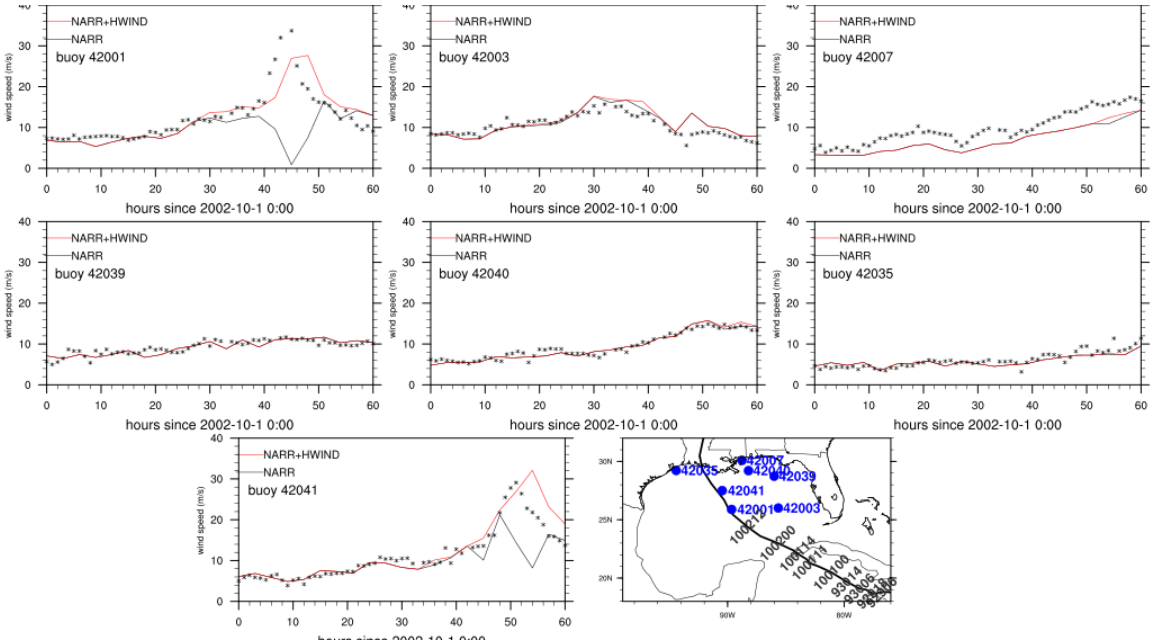


***Figure 19**: Time series of wind speed (m/s) during Hurricane Lili (2002) at selected buoy locations for (black stars) buoy observations, (black line) NARR winds, and (red line) NARR+HWIND combined winds. The track of Lili and buoy locations are shown in the bottom right plot.*

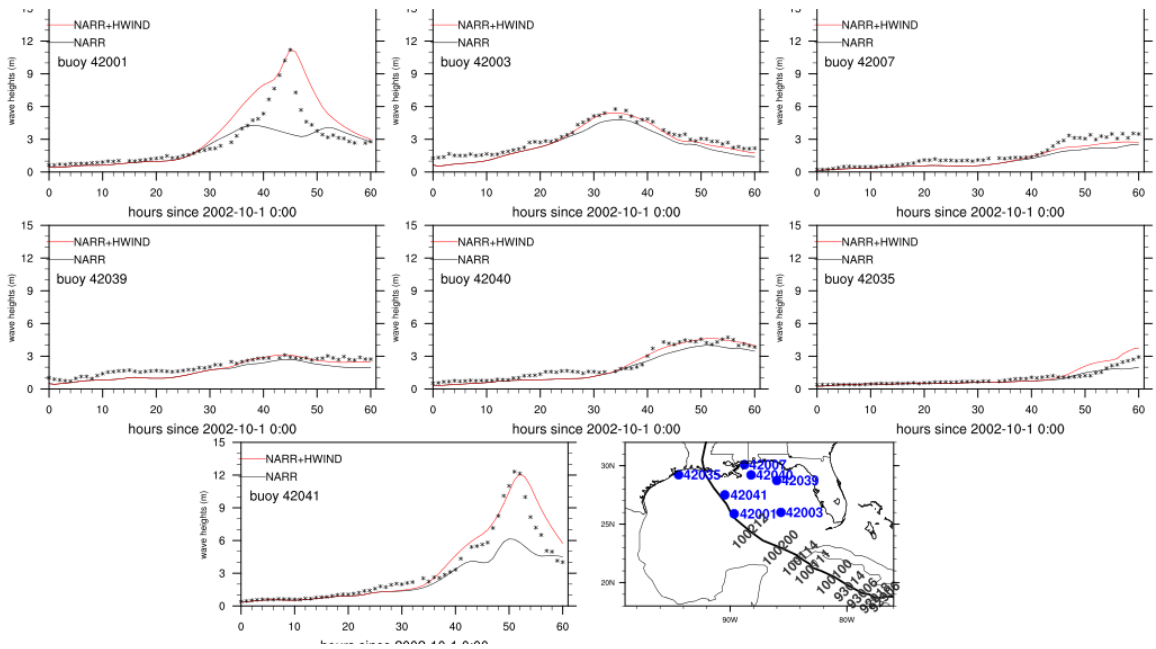


***Figure 20**: As in Fig. 19 but for significant wave height.*

We then simulated this suite of 10 historical hurricanes three more times, each under a future climate scenario. The future scenarios are a 10 percent increase in hurricane wind speeds, a 10 percent reduction in hurricane size (as defined by the radius of hurricane-force winds), and both a 10 percent increase in hurricane wind speeds and a 10 percent reduction in hurricane size. The 10 percent increase in hurricane wind speeds is at the upper end of community consensus in the literature of the change in hurricane intensity over the 21st century (Knutson et al 2010). The reduction of hurricane size is guided by the results of numerical modeling experiments conducted under RPSEA project 07121-1801. Figure 21 shows the impacts of the future climate scenarios on significant wave heights for the case of Hurricane Lili (2002). Changes are in the expected direction with the more intense hurricane increasing the significant wave heights and the smaller hurricane decreasing wave heights. The next step is to assess future changes in the relationships between metocean variables using the suites of 10 cases.

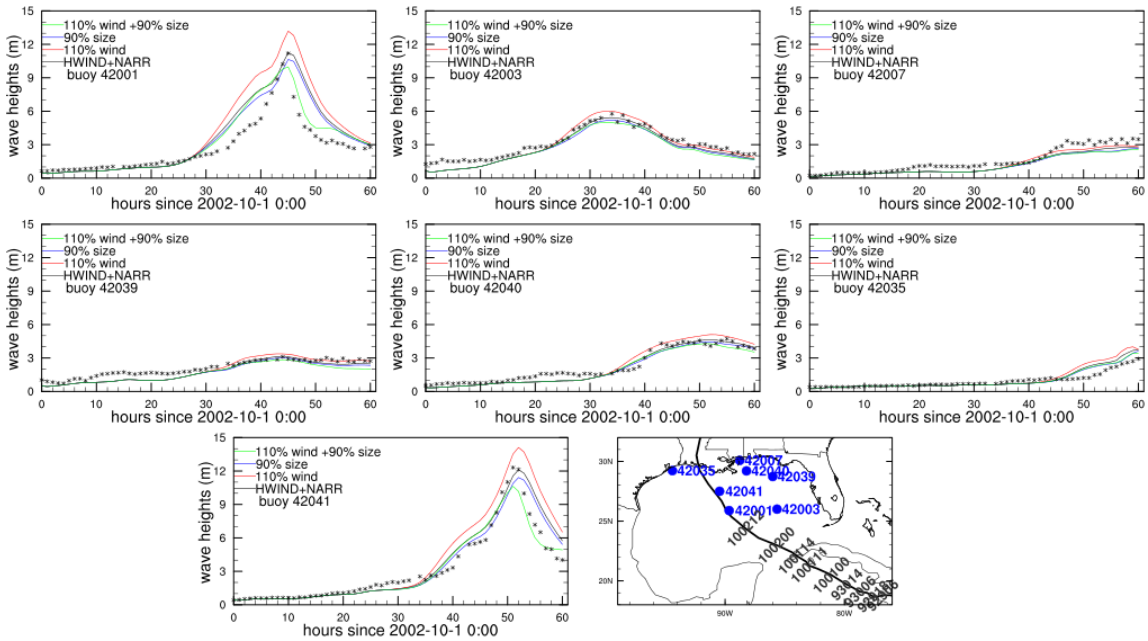


Figure 21: *Time series of significant wave height (m) during Hurricane Lili (2002) at selected buoy locations for (black stars) buoy observations, (black line) using observed winds, and three future climate scenarios: (red line) 10% increase in wind speed, (blue line) 10% decrease in size, and (green) 10% increase in wind speed and 10% decrease in size. The track of Lili and buoy locations are shown in the bottom right plot.*

In the absence of response functions to calculate time series of structural responses, we simply explore relationships among metocean variables by analyzing pairs of variables and exploring their correlations. The simulations produce spatial snapshots of wind, wave and current fields every hour. To minimize dependency between data points we only take a single data value for each variable each time. Given that the significant wave height is often the dominant variable, all variables are taken at the location of the maximum significant wave height anywhere in the Gulf of Mexico every hour.

Figure 22 shows probability distributions of wave period, significant wave height, maximum wind speed, and surface ocean current for all 10 historical hurricanes under current climate conditions. We are interested in the extremes of each variable, and in particular, combinations of the extremes. Fitting theoretical distributions to these simulated distributions allows us to assess the extremes. The Weibull was tested and fits the distributions very well (Fig. 22).

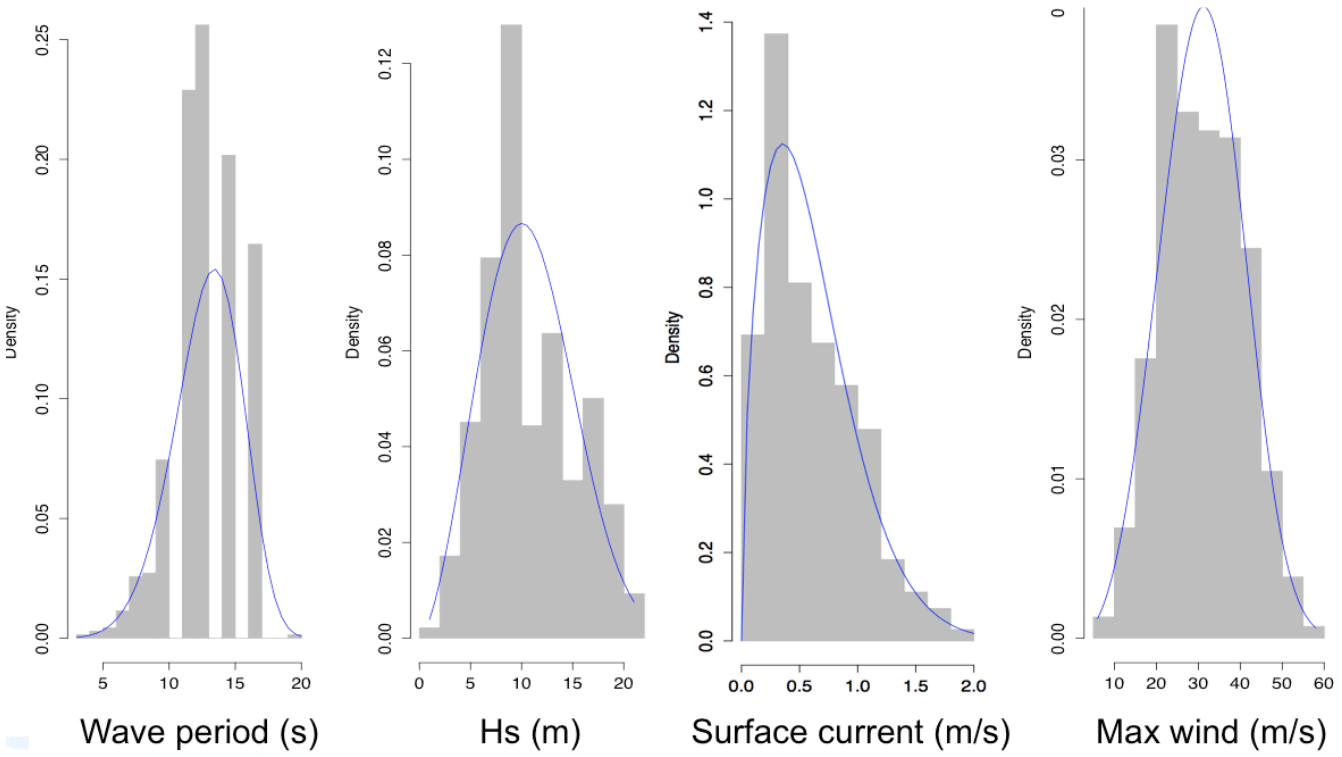


Figure 22: *Probability distributions of metocean variables for all 10 historical hurricanes under current climate conditions (grey bars). Data are at the location of the maximum significant wave height every hour through the simulations. Blue lines indicate the Weibull distribution fitted to the data.*

An example analysis of two variables is shown in Fig. 23 for significant wave height and wave period. Data are divided by the maximum value in the dataset, and referred to as significant wave height ratio and wave period ratio, to aid later assessments of proportional future climate changes. The fairly strong positive correlation indicates a high degree of correlation in hurricane environments. High percentile values are calculated from the fitted Weibull distributions and shown as red dots on Fig. 23. Figure 23 also shows the future change in the high percentiles under the future scenario of +10 percent winds and -10 percent size. The distribution shifts to higher wave heights and longer wave periods with the largest proportional increases at the highest percentiles.

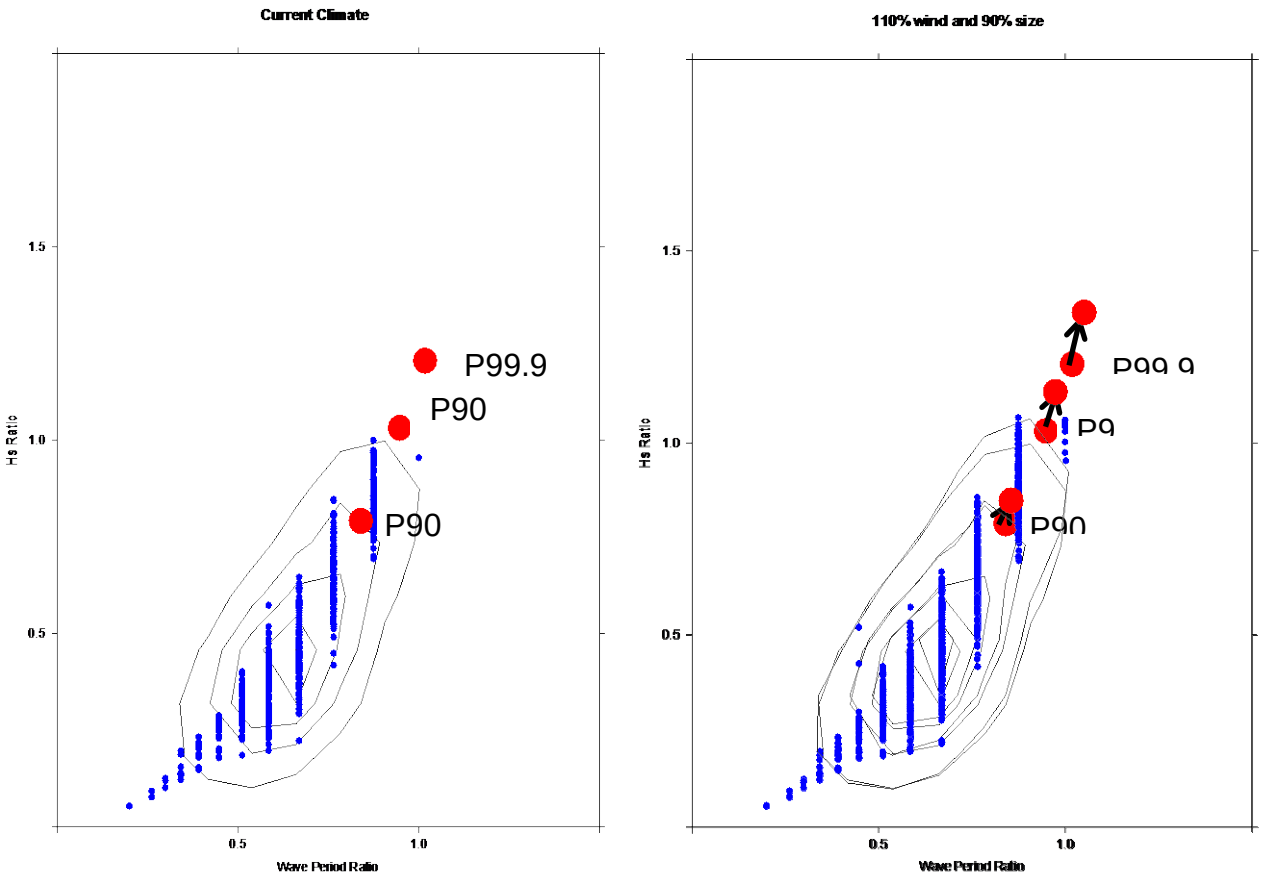


Figure 23: *Relationship between significant wave height ratio and wave period ratio over all 10 historical hurricanes under (left) current climate, and (right) current and future climate scenario of +10 percent winds and -10 percent size. Blue dots show data taken from the location of the maximum significant wave height every hour through the simulations, black contours indicate the density of the blue dots, and the red dots show the 90th, 99th and 99.9th percentile values (P90, P99 and P99.9, respectively).*

A second example analysis is shown in Fig. 24 for significant wave height and maximum wind speed. These data are taken at the locations of the maximum significant wave height and at the locations of the maximum wind speed, every hour over all 10 cases. Two sets of data are plotted: current climate and the future climate scenario of +10 percent winds and -10 percent size. As we would expect, there is a strong correlation between the two variables. The high percentiles show future increases of up to 10 percent (Table 2). This is a similar order magnitude change to the change in the 100 year return value when adding a single intense storm to the historical record (Cooper et al. 2005), and highlights the level of uncertainty in assessing extreme values.

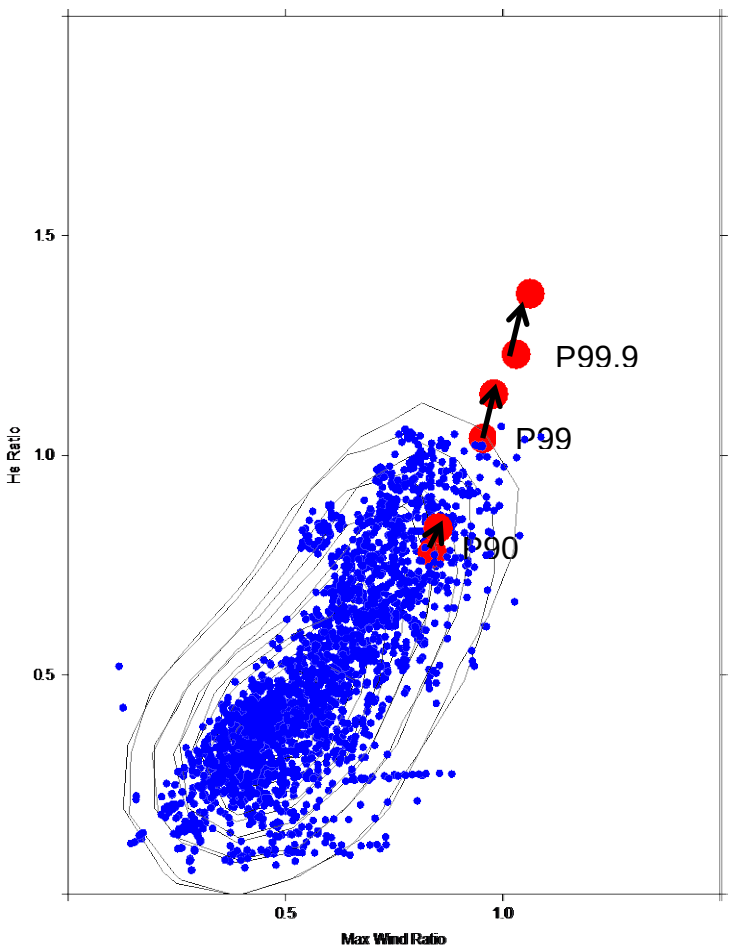


Figure 24: *Relationship between significant wave height ratio and maximum wind ratio over all 10 historical hurricanes under current climate and future climate scenario of +10 percent winds and -10 percent size. Blue dots show data taken from the locations of the maximum significant wave height and the locations of the maximum wind speed every hour through the simulations, black contours indicate the density of the blue dots, and the red dots show the 90th, 99th and 99.9th percentile values (P90, P99, P99.9, respectively).*

	P90	P99	P99.9
Maximum Winds	+7	+9	+10
Significant wave height	+7	+10	+10
Wave period	+2	+3	+3

Table 2: *Percent future changes in P90, P99 and P99.9 for metocean variables.*

These datasets may be analyzed in a number of other ways, tailored to the needs of specific structures. For example, a simple analysis that reflects the high correlation of metocean variables in hurricane environments would be to combine the n-yr wave with 0.95*n-yr wind speed and 0.75*n-yr current speed. Alternatively, a more comprehensive view mapping the full space could be obtained through environmental contours, in recognition that the maximum structural response may not be at the maxima of the variables. Ultimately, the future changes should be presented in terms of design criteria for specific structures.

Task 15.0: Next Generation Multi-Scale Modeling System

This task follows on from the initial testing of MPAS under Phase 2, Task 11.0 to further develop the technology

to improve assessments of future hurricane activity.

Seasonal TC simulation capacity using the Model for Prediction Across Scales (MPAS) has been established. The Phase 2 report (Holland et al. 2015a) documented an initial test of MPAS using two simulations of the active 2005 North Atlantic hurricane season; one simulation used a quasi-uniform global mesh of spacing 120km and a second simulation used a variable resolution mesh that refines down from 120km to 23km in the region of interest (global meshes are shown in Fig. 25). In addition to the high computational efficiency of MPAS on the latest supercomputers, simulation benefits include a computationally efficient approach to obtaining a wider distribution of the observed TC intensity distribution.

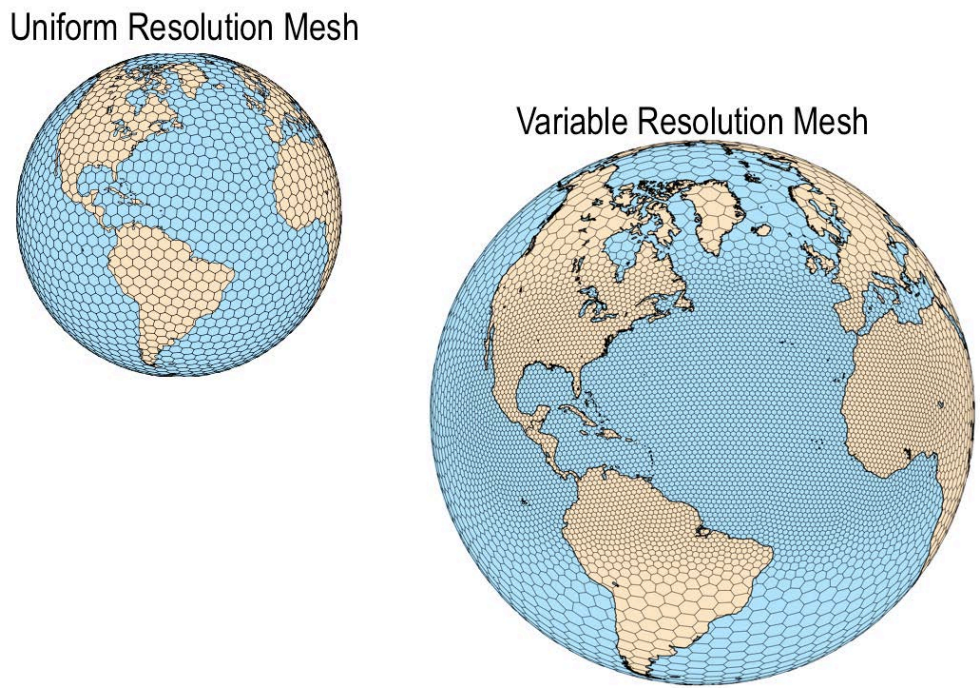


Figure 25: *Uniform and variable resolution global MPAS meshes used for seasonal hurricane simulations (source: Bill Skamarock, NCAR). The grids are larger than actual size to aid visualization.*

To test the robustness of the modeling system, we conducted a similar pair of simulations as in Holland et al. (2015a) but with the high-resolution region of the global mesh centered over the Northwest Pacific to capture typhoon activity. We also conduct a parallel pair of simulations using the WRF model to further assess simulation benefits of MPAS. WRF and MPAS simulations are conducted with and without regional grid refinement from approximately 100km to 20km grid spacing over the Northwest Pacific (Fig. 26).

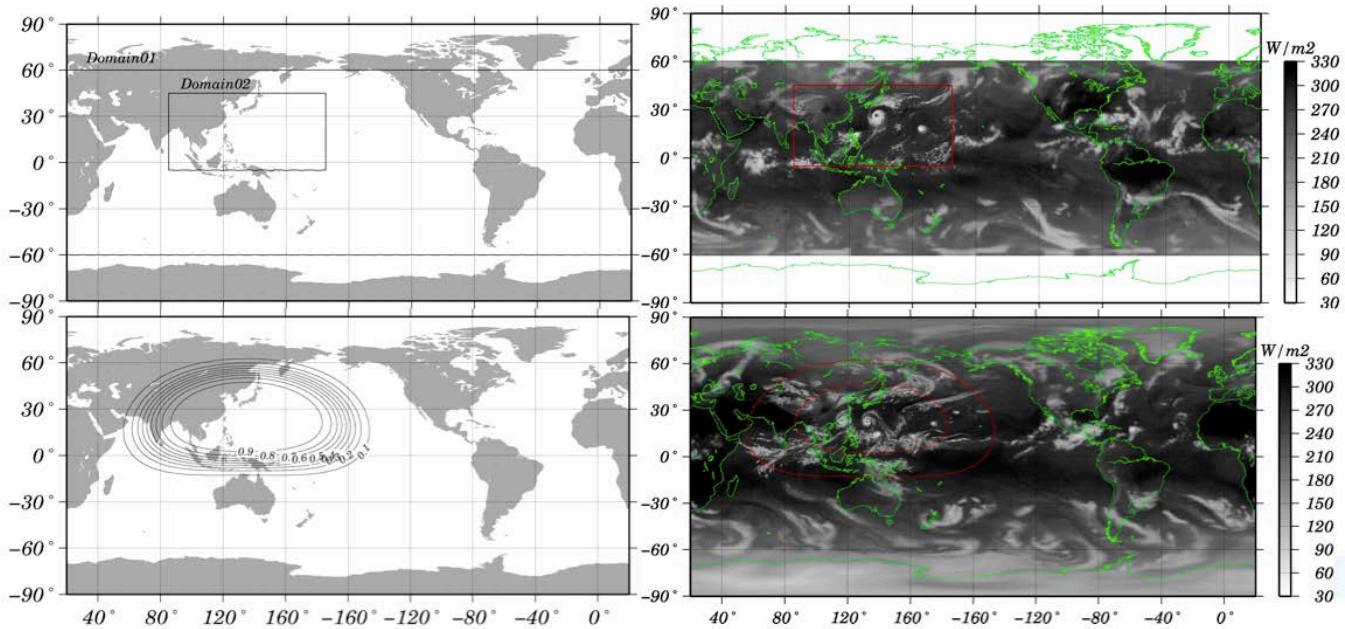


Figure 26: *(left column) Model domains for WRF (top left) showing the coarse large domain and the smaller high-resolution domain and the MPAS (bottom left) indicating the region of high resolution. (right column) Outgoing Longwave Radiation (Wm-2) at 1800UTC 15 September 2005 (137 days after initial time), for (top right) WRF (red solid line indicates the high resolution domain), and (bottom right) MPAS (red solid lines indicate the region of high resolution) (Hashimoto et al. 2015).*

All simulations reproduced seasonal climate reasonably well, but the ability to capture smooth transitions between the two resolutions varied between WRF and MPAS grid. The WRF simulation shows adverse influence of the nest boundary, with the boundary evident in seasonal average cloud patterns and precipitation (not shown), and contortions of the seasonal mean mid-latitude jet affecting the seasonal TC track (Fig. 27). The variable-mesh of MPAS, on the other hand, reduces many of these effects and produced smoother cloud patterns and mid-latitude jet structure. This task provided evidence that variable mesh brings benefits to seasonal TC simulation over traditional nesting.

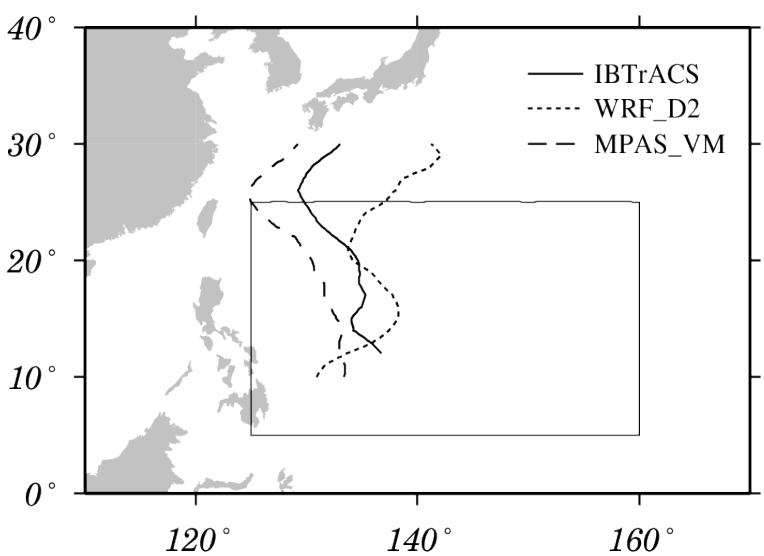


Figure 27*: Seasonal mean TC track for IBTrACS, WRF and MPAS. Average tracks are smoothed using a five-point moving average. The inner box indicates the region of the WRF high resolution domain (Hashimoto et al. 2015).*

Now that credible simulation capacity has been established with MPAS, we have started to explore this potentially transformational approach to TC simulation by conducting

decadal simulations using the uniform and variable meshes. This is a major simulation involving intensive high performance computing. The simulations and analysis will be performed over the next 12 months outside of this project. Results will be made available to RPSEA in advance of public dissemination through the peer-reviewed literature.

4. Summary

Phase 3 of RPSEA research award 10121-4802-01 has produced new understanding on future changes in North Atlantic and Gulf of Mexico hurricanes and impacts. The major accomplishments include:

Task 12: historical record expanded through simulations of 240 hurricane seasons to establish new views on hurricane activity in current climate.

Task 12: dynamical simulations of 120 future hurricane seasons have established a range of credible future change in hurricane activity. Specifically a future decrease in Gulf of Mexico TC frequency is projected.

Task 13: application of the cyclone damage potential index to available hurricane datasets has produced new views of historical and future damage potential of hurricanes. Application to the dynamical simulations produced for task 12 projects future increases in the maximum damage potential for the North Atlantic and the Gulf of Mexico.

Task 14: wind-wave-current simulations of 10 historical Gulf of Mexico hurricanes under current conditions and future scenarios show future increases in extreme Metocean conditions.

Task 15: proven hurricane season simulation capability with the Model for Prediction Across Scales.

Phase 3 tasks and milestones have been met together with some additional work completed on the statistical downscaling tool from Phase 2 using the MPAS modeling system.

In support of the goals of the Ultra-Deepwater Environment, Safety and Regulatory and Metocean area of interest, this award produced: assessments of hurricane activity and potential impacts for current climate and changes over the coming decades; tools to aid immediate response and planning needs; and knowledge to mitigate future costs, and minimize environmental and safety risks.

A powerful combination of observational analysis and statistical and dynamical modeling produced new views of TC activity in current and future climate. For TC frequency, a new statistical downscaling tool applied to a climate model ensemble projects a future increase over the North Atlantic. However, when looking at the sub-region of the Gulf of Mexico, a dynamical model ensemble projects a future decrease in hurricane frequency. For TC intensity, a new statistical-dynamical tool shows a future increase in the proportion of major hurricanes for the North Atlantic. Observational analysis indicates this change has already started on global scales, and when accounting for the physical upper limit of hurricane intensity, a limit is found in the increasing proportion of major hurricanes, one that is already being approached.

The inclusion of TC parameters in addition to wind speed and frequency allows assessments that are more relevant to industry impacts. The plausible future scenario of increased wind speed and decreased size applied to historical Gulf of Mexico hurricanes leads to overall future increases in the extremes of metocean variables, with the biggest proportional increase in the significant wave height. In agreement, a Cyclone Damage Potential index (that accounts for the key damaging TC parameters of intensity, size and forward speed) applied to a dynamical model ensemble projects future increases in the maximum damage potential for the North Atlantic and the Gulf of Mexico. Ensemble members disagree, however, on future change in the average Cyclone Damage Potential for the Gulf of Mexico.

Based on these new views of hurricane activity and potential impacts, our overall recommendation is for the industry to be aware of the potential for increased hurricane impacts in the future. As our understanding of hurricane activity in current climate and the future change advances the potential industry impacts will be reassessed. Moreover, we suggest sustained industry-research collaboration will further our understanding of how the project results can be integrated with industry planning and engineering design. A new program, the Engineering for Climate Extremes Partnership (ECEP, www.ecep.ucar.edu), has grown out of interactions between NCAR, RPSEA and others, and provides a vehicle for sustained collaboration. Some of the techniques pioneered in Project 10121-4802-01 are being included under ECEP's Global Risk, Resilience and Impacts Toolbox, where they can be accessed in the future.

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