

Effect of Upper-Ocean Evolution on Projected Trends in Tropical Cyclone Activity

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ABSTRACT

Recent work has highlighted the possible importance of changing upper-ocean thermal and density stratification on observed and projected changes in tropical cyclone activity. Here seven CMIP phase 5 (CMIP5)-generation climate model simulations are downscaled under IPCC representative concentration pathway 8.5 using a coupled atmosphere–ocean tropical cyclone model, generating 100 events per year in the western North Pacific from 2006 to 2100. A control downscaling in which the upper-ocean thermal structure is fixed at its monthly values in the year 2006 is compared to one in which the upper ocean is allowed to evolve, as derived from the CMIP5 models. As found in earlier work, the thermal stratification generally increases as the climate warms, leading to increased ocean mixing–induced negative feedback on tropical cyclone intensity. While trends in the frequency of storms are unaffected, the increasing stratification of the upper ocean leads to a 13% reduction in the increase of tropical cyclone power dissipation over the twenty-first century, averaged across the seven climate models. Much of this reduction is associated with a moderation of the increase in the frequency of category-5 storms.

1. Introduction

As our climate continues to warm, the incidence of high-category tropical cyclones is expected to increase along with rainfall produced by these storms (Knutson et al. 2010). Coupled with rising sea levels, the risks associated with storm surges are expected to rise together with the incidence of freshwater flooding. Economic damage from tropical cyclones is projected to mount over this century, partly as a result of increasing coastal population and built environment and partly as a result of escalating tropical cyclone hazard (Mendelsohn et al. 2012; Houser et al. 2014). Thus, for practical reasons, as well as for the sake of advancing general knowledge, it is important to better understand and quantify the effects of changing climate on tropical cyclone activity.

To date, four principal methods have been applied to projecting changes in tropical cyclone activity. First, basic theory suggests that the thermodynamic bound on tropical cyclone intensity increases with increasing greenhouse gas concentration (Emanuel 1987), although a limiting

potential intensity is reached when the net infrared flux at the surface vanishes (Emanuel and Sobel 2013). Observations suggest that the probability distribution of tropical cyclone intensity scales with potential intensity (Emanuel 2000), indicating that actual intensity should increase with potential intensity, but on the other hand many more factors are known to affect the frequency of these storms (Gray 1979).

Second, tropical cyclones can be directly simulated in global models and their statistics assessed as a function of the climate state (e.g., Camargo 2013). While this technique has the advantage of producing storms whose physics are consistent with those of their large-scale environments, current resolutions are far too low to simulate the high-intensity events that are most important to society (Zhao et al. 2009). Today's global models tend to underpredict tropical cyclone activity in general and show little systematic sensitivity to global climate (Camargo 2013).

Statistical relationships between large-scale environmental properties and various measures of tropical cyclone activity can be developed using historical climate and cyclone data and can then be applied to changing climates. When applied to storm frequency, these relationships have come to be known as genesis indices, the first of which was developed by Gray (1979). Many others have followed since (e.g., DeMaria et al. 2001;

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Emanuel and Nolan 2004; Emanuel 2010; Tippett et al. 2011). These are increasingly based on large-scale environmental parameters known to be important in tropical cyclone physics and have been tuned to optimize their ability to reproduce observed seasonal, spatial, and interannual variability. On the other hand, they mostly address a single storm metric, overall frequency, and it is not entirely clear that they can represent a response to global warming for which they cannot be tuned.

Finally, global models can be “downscaled” by embedding within them regional and/or local computational domains with finer resolution. This technique was pioneered by Knutson et al. (2007) and has been applied by many others since. The key advantage of this technique is that it can better resolve tropical cyclones, thus capturing a greater fraction of the intensity distribution. Among the drawbacks of downscaling is that the regional model physics may not be entirely consistent with those of the global model or reanalysis used for initial and boundary conditions, while computational expense still limits the resolution and the total number storms that can be simulated.

The author and colleagues (Emanuel et al. 2006, 2008) developed a downscaling technique that uses a simple, coupled atmosphere–ocean tropical cyclone model phrased in angular momentum coordinates, which gives very high resolution in the critical inner core of the storms in proportion to their intensity. When driven by current climate reanalysis boundary conditions, the downscaling reproduces the full observed intensity distribution; captures observed spatial, seasonal, and interannual variability; and detects well-known signals associated with short-period climate fluctuations such as ENSO. The model is computationally cheap enough to allow for the simulation of tens or hundreds of thousands of events. This model was applied to a suite of six CMIP phase 5 (CMIP5)-generation models forced by IPCC Fifth Assessment Report (AR5) representative concentration pathway 8.5 (RCP8.5) over the twenty-first century and predicted a general global increase in both the intensity and frequency of tropical cyclones (Emanuel 2013).

One limitation of this earlier study was the use of a monthly mean climatology of upper-ocean thermal structure (Levitus 1982) that does not evolve as the climate changes. It is that weakness we here seek to redress. Recently, Huang et al. (2015) presented evidence that the increasing thermal stratification of the upper ocean as climate warms could substantially reduce any increase in tropical cyclone intensity that might otherwise result from the warming. Since the ocean mixed layer in general warms more rapidly than sub-mixed

layer waters, the surface cooling induced by strong upper-ocean mixing associated with tropical storms should itself increase, all other things being equal. By applying an upper-ocean mixing model to 22 CMIP5-generation climate models, each driven by application of generic tropical cyclone wind fields, the authors showed that the negative feedback indeed increases substantially as the climate warms, though there is regional variation in the magnitude of this effect. Since the tropical cyclone wind fields were specified, however, the ocean surface cooling did not actually feed back onto the intensity of the winds.

Here we explore the effect of evolving upper-ocean thermal structure on tropical cyclones downscaled as in Emanuel (2013), but we use the CMIP5 models’ upper-ocean thermal profiles rather than the invariant climatology used in that paper. Details of the modeling and results are described presently.

2. Methods

We closely follow the methodology used in Emanuel (2013). We begin with a climate state as represented by monthly mean thermodynamic conditions, including sea surface temperature, and daily winds at the 250- and 850-hPa levels. These are derived from reanalyses or, in this case, from climate models. The daily winds are used to synthesize time series of winds at the two levels, using Fourier series of random phase such that the monthly mean winds and monthly mean variances and covariances of the two wind components at the two levels are correct and have a -3 power law in eddy kinetic energy. We then introduce weak protocyclone disturbances, distributed randomly in space and time, into the climate state represented by these monthly mean thermodynamic conditions and synthesized winds. The seeds move with a suitably weighted mean of the 850- and 250-hPa flow plus a correction for the beta drift of closed vortices (the beta-and-advection model; Marks 1992). Their intensity is evolved using the aforementioned coupled ocean–atmosphere tropical cyclone intensity model. In practice, most of the initial seed disturbances die away; the small fraction of remaining disturbances that amplify to at least tropical storm intensity are regarded as constituting the tropical cyclone climatology of the given climate state.

The ocean model consists of a string of independent, one-dimensional (1D) ocean columns arranged along the path of the storm. The only physics operating in this model are those of vertical mixing, formulated according to the hypothesis of fixed bulk Richardson number (Pollard et al. 1973). This parameterization of entrainment through the base of the mixed layer works well

TABLE 1. Models used in this study. (Expansions of acronyms are available at <http://www.ametsoc.org/PubsAcronymList>.)

Modeling center	Institute identifier	Model name	Avg horizontal resolution (lon × lat)
NOAA/Geophysical Fluid Dynamics Laboratory	GFDL	GFDL CM3	2.5° × 2.0°
Met Office Hadley Centre	HadGEM	HadGEM2-ES	1.875° × 1.25°
L'Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR	3.75° × 1.89°
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5	1.4° × 1.4°
Max Planck Institute for Meteorology	MPI	MPI-ESM-MR	1.88° × 1.86°
Meteorological Research Institute	MRI	MRI-CGCM3	1.12° × 1.12°
National Center for Atmospheric Research–Center for Ocean–Land–Atmosphere Studies	NCAR–COLA	SP-CCSM4	1.25° × 0.94°

when the turbulence is dominated by shear production, as it is in a hurricane, and the overall surface cooling produced by it performs at least as well as more general turbulence schemes in hurricanes (Jacob et al. 2002). While the one-dimensional mixing cannot capture the important lateral advection that occurs in the storm wake, the cooling that affects storm intensity is most important under the eyewall, and unless the storm is moving very slowly, the use of the 1D model, in its capacity to produce the correct feedback on storm intensity, compares favorably to the results of coupling to a full three-dimensional ocean model (Schade 1997). This is also evident in the more recent work of Yablonsky and Ginis (2009), who imposed a uniformly translating hurricane wind field on both 3D and 1D oceans. For the average western North Pacific translation velocity of 5.5 m s^{-1} , there is hardly any difference in the ocean cooling in the storm core region; however, for slowly moving storms, the 1D model fails to capture upwelling effects and undercools the surface, though this effect is exaggerated by a lack of feedback of the cooling on storm intensity.

The initial state of the upper ocean is represented by only two variables: the mixed layer depth and the thermal stratification in the first $\sim 100\text{m}$ below the mixed layer. In previous applications, these variables were calculated from monthly mean climatology (Levitus 1982). Here we calculate them directly from the CMIP5 model output, defining the mixed layer base to be the first level (linearly interpolated between model levels) at which the temperature is at least 1°C less than the surface temperature and calculating the temperature gradient over about 100m (depending on the model's vertical structure) below the base of the mixed layer.

The method was applied to the seven CMIP5 models listed in Table 1. These are the models used in Emanuel (2013) except that we have substituted a superparameterized version NCAR–COLA CCSM4 (SP-CCSM4; Stan and Xu 2014) for the standard version of the NCAR CCSM4 and

have added the IPSL-CM5A-LR of L'Institut Pierre-Simon Laplace. We created 100 events each year from 2006 to 2100 from the RCP8.5 simulations, downscaled for the western North Pacific region (K. Emanuel 2015, unpublished data). This was one of the two regions that Huang et al. (2015) focused on, and it is also the part of the globe that experiences the largest increase in tropical cyclone activity in our previous work (Emanuel 2013). We use the Pacific as a representative case; future work will examine other ocean basins.

To detect the effect of increasing ocean thermal stratification on tropical cyclones, we compare two sets of simulations. In the first set (labeled Fixed), the upper-ocean mixed layer depth and thermal stratification are held fixed at their monthly values in 2006 (the first year of the simulation). In the second set (labeled Variable), the upper-ocean mixed layer depth and sub-mixed layer thermal stratification evolve over the 95-yr period, as derived from the CMIP5 models. In both cases, the sea surface temperature and tropical cyclone potential intensity evolve identically; only the subsurface thermal structures differ. The time evolutions of the mixed layer depths and sub-mixed layer thermal stratifications averaged over the western North Pacific main development region ($5^\circ\text{--}15^\circ\text{N}$, $130^\circ\text{E--}180^\circ$) and averaged over July–November are shown in Fig. 1 for each of the seven CMIP5 models. The two Japanese models, MIROC5 and MRI-CGCM3, have much larger mixed layer depths than do the other five models, and, consistent with the warming of the upper ocean, these depths decrease toward the end of the century. Among the remaining models, three show essentially no change in mixed layer depths, whereas the IPSL-CM5A-LR and HadGEM2-ES actually show increasing mixed layer depths over time, presumably because of increased convective and/or wind forcing of mixed layer turbulence. All models show increasing sub-mixed layer thermal stratification. These changes are qualitatively similar to those reported

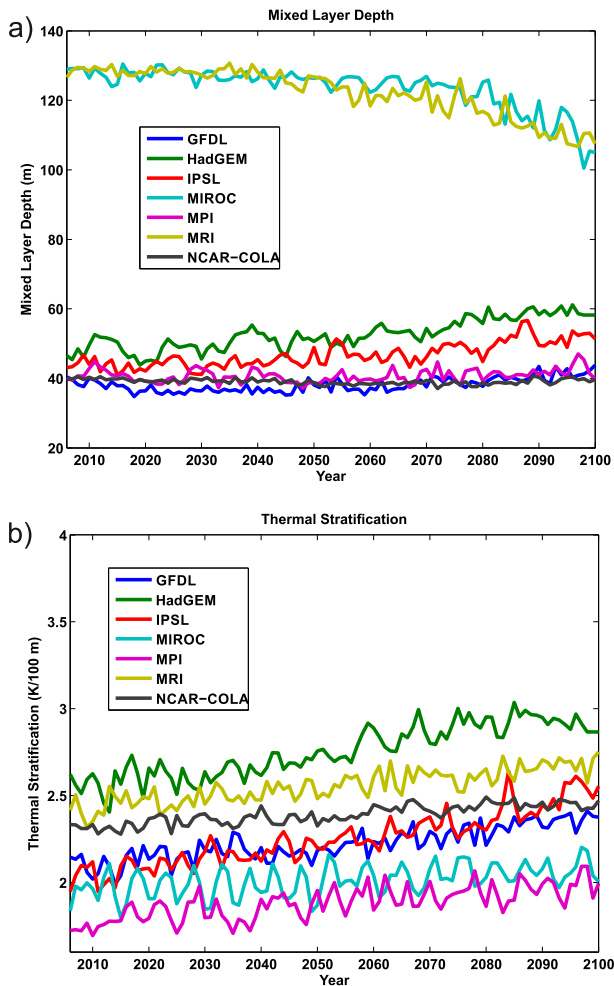


FIG. 1. Evolutions of the (a) mixed layer depths and (b) sub-mixed layer thermal stratifications averaged over the western North Pacific main development region (5° – 15° N, 130° E– 180°) and over July–November for each of the seven CMIP5 global coupled climate models used in this work. Each model was run under IPCC AR5 RCP8.5.

by Huang et al. (2015) for a larger 22-member ensemble of global climate models.

The same sequence of random seeds was used in both sets of simulations to minimize the purely random

component of the differences between the two sets of simulations. By comparing these two sets, we can quantify the effect of upper-ocean thermal evolution on trends in tropical cyclone activity downscaled from the CMIP5 models in the western North Pacific.

3. Results

Trends in various tropical cyclone metrics, expressed as percentage increases from 2006 to 2100, are shown for each model in Table 2 for the Variable set of experiments in which the upper ocean evolves over the period. Large and highly statistically significant upward trends in the frequency of Saffir–Simpson category 5 cyclones and in overall power dissipation occur for all models, and most models have significant upward trends in other quantities as well. This reflects the upward trends in potential intensity and genesis potential index in this region and is consistent with the results of Emanuel (2013), which used monthly climatological upper-ocean properties. These increases occur in spite of the generally increasing thermal stratification of the upper ocean in these experiments.

More to the point, Fig. 2 compares time series of overall storm frequency and power dissipation between the two sets of experiments (Fixed and Variable). The solid curves represent the multimodel means for each year, the shading represents one standard deviation up and down among the downscalings of the seven models, and the dashed lines show the linear trends of the multimodel means. There is no significant difference in annual frequency between the two experiments. This is because, to qualify as a tropical cyclone in these downscalings, a storm must achieve a lifetime maximum intensity of 40 kt (20.6 m s^{-1}), which is not enough to cause appreciable ocean mixing and attendant surface cooling. Thus, upper-ocean feedback hardly affects tropical cyclogenesis. On the other hand, the increasing stratification of the upper ocean causes a 13% reduction in the increase in annual power dissipation compared to what occurs if the upper-ocean stratification does not evolve.

TABLE 2. Percentage change in western North Pacific tropical cyclone metrics from 2006 to 2100, from linear regression of Variable simulations for the models denoted by institution identifier in Table 1. The P values are shown in parentheses if they are greater than 0.01.

	GFDL	HadGEM	IPSL	MIROC	MPI	MRI	NCAR-COLA	Multimodel mean
Overall frequency	49	100	32	73	24 (0.02)	38	73	54
Frequency of hurricanes	45	96	40	70	21 (0.05)	33	74	52
Frequency of category 1	30	—	17 (0.04)	45	−23 (0.02)	24 (0.03)	50	35
Frequency of category 2	24 (0.07)	38	12 (0.34)	51	−16 (0.24)	−10 (0.44)	34 (0.04)	27
Frequency of category 3	20 (0.09)	60	30	54	5 (0.64)	26 (0.06)	26 (0.1)	36
Frequency of category 4	53	104	53	87	26 (0.08)	37	89	64
Frequency of category 5	74	188	130	231	82	63	338	104
Power dissipation	56	142	60	107	62	47	126	70

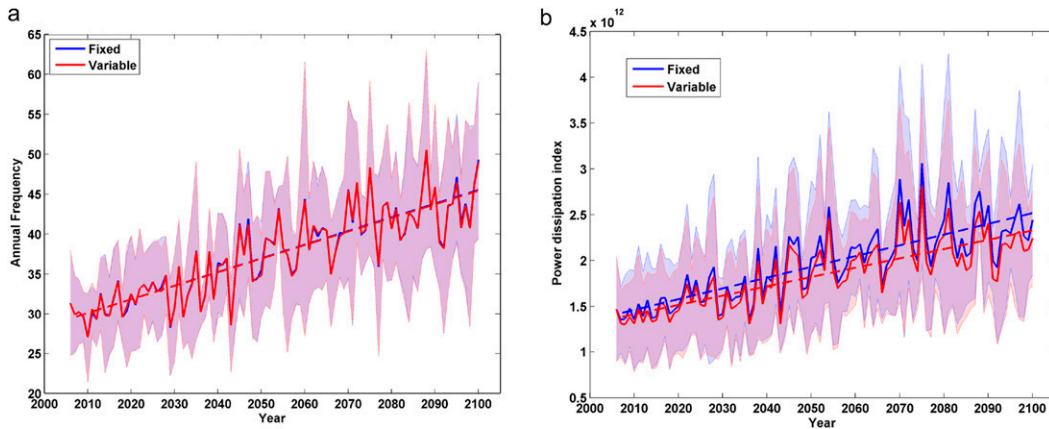


FIG. 2. Time series of (a) annual frequency and (b) power dissipation ($\text{m}^3 \text{s}^{-2}$) for fixed (blue) and variable (red) upper-ocean thermal structure, from downscaling seven global climate models in the western North Pacific under emissions according to RCP8.5. The solid curves and dashed lines represent the multimodel means and linear trends, respectively, while the shading shows standard deviations among the seven models.

A more detailed comparison of the two sets of simulations is tallied in Table 3. Most of the differences between the simulations of subcategory-5 events, both in individual models and in the multimodel mean, are insignificant, with the exception of a significant increase in the frequency of category-2 storms going from the Fixed to the Variable simulations. This is because the increase in stratification in the Variable simulations causes storms to become weaker, shunting higher-category storms to lower categories while preserving the total. There is a robust, statistically significant decrease in the upward trend of both the frequency of category-5 storms and power dissipation, showing the expected effect of increasing ocean thermal stratification on intense storms.

4. Summary

Downscalings of seven CMIP5-generation climate models run under representative concentration pathway 8.5 (RCP8.5) show a robust increase in the frequency

and intensity of tropical cyclones in the western North Pacific, as found in previous work (Emanuel 2013). This increase remains robust when the evolution of the upper-ocean thermal structure is accounted for. This evolution has little effect on the overall frequency of tropical cyclones but decreases the upward trend in category-5 storms and in overall power dissipation by 15% and 13%, respectively. This is qualitatively consistent with the results of Huang et al. (2015), although quantitatively smaller in magnitude than they estimated using noninteractive tropical cyclone wind fields to estimate ocean cooling. Results of this study naturally depend on the climate model used, the downscaling technique, and the concentration pathway. For example, Mei et al. (2015) examined output from 20 CMIP5-generation climate models run under RCP4.5 and found that under that more gentle warming scenario, the temperature increase at 75-m depth was nearly identical to that at the surface in the western North Pacific region.

We have not here considered the possible effects of changing upper-ocean salinity on tropical cyclone–ocean

TABLE 3. Percentage change in the difference of linear trends of western North Pacific tropical cyclone metrics from 2006 to 2100 between Fixed and Variable simulations for the models denoted by institution identifier in Table 1. The P values are shown in parentheses if they are greater than 0.01.

	GFDL	HadGEM	IPSL	MIROC	MPI	MRI	NCAR-COLA	Multimodel mean
Overall frequency	-2 (0.19)	0 (0.60)	0 (0.96)	-2 (0.03)	1 (0.82)	-2 (0.79)	0	-1 (0.14)
Frequency of hurricanes	-2 (0.31)	0 (0.91)	-4 (0.21)	-5	1 (0.80)	-1 (0.56)	0 (0.67)	-2 (0.02)
Frequency of category 1	5 (0.65)	2 (0.55)	7 (0.73)	6 (0.42)	9 (0.35)	9 (0.41)	1 (0.87)	3 (0.02)
Frequency of category 2	46 (0.07)	27 (0.06)	94 (0.25)	3 (0.83)	-33 (0.30)	-114	-1 (0.94)	34
Frequency of category 3	20 (0.42)	-1 (0.92)	14 (0.67)	13 (0.43)	106 (0.36)	14 (0.47)	9 (0.59)	11 (0.19)
Frequency of category 4	7 (0.56)	17 (0.04)	-3 (0.84)	-17 (0.13)	21 (0.39)	-5 (0.74)	10 (0.12)	4 (0.40)
Frequency of category 5	-19	-16	-24	-22	-8 (0.13)	-15	-6 (0.05)	-15
Power dissipation	-22	-10	-13	-14	-14 (0.07)	-24	-2 (0.05)	-13

feedback. This can and should be considered in future work, but the present results suggest that evolving upper-ocean stratification is a second-order effect on changes in tropical cyclone activity caused by global warming.

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REFERENCES

- Camargo, S., 2013: Global and regional aspects of tropical cyclone activity in the CMIP5 models. *J. Climate*, **26**, 9880–9902, doi:10.1175/JCLI-D-12-00549.1.
- DeMaria, M., J. A. Knaff, and B. H. Connell, 2001: A tropical cyclone genesis parameter for the tropical Atlantic. *Wea. Forecasting*, **16**, 219–233, doi:10.1175/1520-0434(2001)016<0219:ATCGPF>2.0.CO;2.
- Emanuel, K., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483–485, doi:10.1038/326483a0.
- , 2000: A statistical analysis of tropical cyclone intensity. *Mon. Wea. Rev.*, **128**, 1139–1152, doi:10.1175/1520-0493(2000)128<1139:ASAOTC>2.0.CO;2.
- , 2010: Tropical cyclone activity downscaled from NOAA-CIRES reanalysis, 1908–1958. *J. Adv. Model. Earth Syst.*, **2**, 1–12, doi:10.3894/JAMES.2010.2.1.
- , 2013: Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proc. Natl. Acad. Sci. USA*, **110**, 12 219–12 224, doi:10.1073/pnas.1301293110.
- , and D. Nolan, 2004: Tropical cyclone activity and global climate. *26th Conf. on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 240–241.
- , and A. H. Sobel, 2013: Response of tropical sea surface temperature, precipitation, and tropical cyclone-related variables to changes in global and local forcing. *J. Adv. Model. Earth Syst.*, **5**, 447–458, doi:10.1002/jame.20032.
- , S. Ravela, E. Vivant, and C. Risi, 2006: A statistical deterministic approach to hurricane risk assessment. *Bull. Amer. Meteor. Soc.*, **87**, 299–314, doi:10.1175/BAMS-87-3-299.
- , R. Sundararajan, and J. Williams, 2008: Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bull. Amer. Meteor. Soc.*, **89**, 347–367, doi:10.1175/BAMS-89-3-347.
- Gray, W. M., 1979: Hurricanes: Their formation, structure, and likely role in the tropical circulation. *Meteorology Over the Tropical Oceans*, D. B. Shaw, Ed., Royal Meteorological Society, 155–218.
- Houser, T., and Coauthors, 2014: American climate prospectus: Economic risks in the United States. Rhodium Group Rep., 197 pp. [Available online at <http://rhg.com/reports/climate-prospectus>.]
- Huang, P., I.-I. Lin, C. Chou, and R.-H. Huang, 2015: Change in ocean subsurface environment to suppress tropical cyclone intensification under global warming. *Nat. Commun.*, **6**, 7188, doi:10.1038/ncomms8188.
- Jacob, D. S., L. K. Shay, and G. R. Halliwell, 2002: Effects of entrainment closure on the oceanic mixed layer response during a tropical cyclone passage: A numerical investigation. *Extended Abstracts, 25th Conf. on Hurricanes and Tropical Meteorology*, San Diego, CA, Amer. Meteor. Soc., 17C.2. [Available online at <https://ams.confex.com/ams/pdfpapers/38205.pdf>.]
- Knutson, T. R., J. J. Sirutis, S. T. Garner, I. M. Held, and R. E. Tuleya, 2007: Simulation of the recent multidecadal increase of Atlantic hurricane activity using an 18-km-grid regional model. *Bull. Amer. Meteor. Soc.*, **88**, 1549–1565, doi:10.1175/BAMS-88-10-1549.
- , and Coauthors, 2010: Tropical cyclones and climate change. *Nat. Geosci.*, **3**, 157–163, doi:10.1038/ngeo779.
- Levitus, S., 1982: *Climatological Atlas of the World Ocean*. NOAA Prof. Paper 13, 173 pp. and 17 microfiche.
- Marks, D. G., 1992: The beta and advection model for hurricane track forecasting. NOAA Tech. Memo. NWS NMC-70, 89 pp.
- Mei, W., S.-P. Xie, F. Primeau, J. C. McWilliams, and C. Pasquero, 2015: Northwestern Pacific typhoon intensity controlled by changes in ocean temperatures. *Sci. Adv.*, **1**, e1500014, doi:10.1126/sciadv.1500014.
- Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen, 2012: The impact of climate change on global tropical cyclone damage. *Nat. Climate Change*, **2**, 205–209, doi:10.1038/nclimate1357.
- Pollard, R. T., P. B. Rhines, and R. O. R. Y. Thompson, 1973: The deepening of the wind-mixed layer. *Geophys. Fluid Dyn.*, **3**, 381–404, doi:10.1080/03091927208236105.
- Schade, L. R., 1997: A physical interpretation of SST feedback. Preprints, *22nd Conf. on Hurricanes and Tropical Meteorology*, Boston, MA, Amer. Meteor. Soc., 439–440.
- Stan, C., and L. Xu, 2014: Climate simulations and projections with a super-parameterized climate model. *Environ. Modell. Software*, **60**, 134–152, doi:10.1016/j.envsoft.2014.06.013.
- Tippett, M. K., S. Camargo, and A. H. Sobel, 2011: A Poisson regression index for tropical cyclone genesis and the role of large-scale vorticity in genesis. *J. Climate*, **24**, 2335–2357, doi:10.1175/2010JCLI3811.1.
- Yablonsky, R. M., and I. Ginis, 2009: Limitation of one-dimensional ocean models for coupled hurricane–ocean model forecasts. *Mon. Wea. Rev.*, **137**, 4410–4419, doi:10.1175/2009MWR2863.1.
- Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi, 2009: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. *J. Climate*, **22**, 6653–6678, doi:10.1175/2009JCLI3049.1.