Supporting Information for

Dominant Role of Subtropical Pacific Warming in Extreme Eastern Pacific Hurricane Seasons: 2015 and the Future

Hiroyuki Murakami[1,2], Gabriel A. Vecchi[1,2], Thomas L. Delworth[1,2],

Andrew T. Wittenberg[1], Seth Underwood[3], Richard Gudgel[1], Xiaosong Yang[4],

Liwei Jia[1,2], Fanrong Zeng[1], Karen Paffendorf[1,2], and Wei Zhang[1,2]

[1]National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

[2]Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ, USA

[3]Engility Corporation, Chantilly, VA, USA

[4]University Corporation for Atmospheric Research, Boulder, CO, USA

Introduction

To elucidate the potential influence of natural variability on the frequency of TCs in the Eastern Pacific Ocean (EPO), we focus on the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Interdecadal Pacific Oscillation (IPO), Pacific Meridional Mode (PMM), and Atlantic Multi-decadal Oscillation (AMO). We compare these indices with TC frequency during the boreal summer of May–November. Here we describe the calculation of these climate indices. Most of the descriptions below for the ENSO, PDO, and IPO are reprinted from Murakami et al. (2015a) with some modifications.

ENSO (Niño-3.4 index)

We used the Niño-3.4 index to represent ENSO. The Niño-3.4 index is obtained from the mean SST anomaly in the region bounded by 5°N and 5°S, and between 170°W to 120°W. The SST anomaly is calculated by subtracting the climatological mean value. For the 1860- (1990-) control simulation, we use the 3500-yr (500-yr) mean for the climatological mean. For the multi-decadal simulations, we define the climatological mean value for each year using a 21-yr moving average to smooth the nonlinear trend of global warming. The Niño-3.4 index is standardized after calculating the anomaly (i.e., its mean value is zero and its standard deviation is one). We define a positive phase of ENSO (i.e., El Niño) as years in which the Niño-3.4 index exceeds one standard deviation. Likewise, we defined a negative phase of ENSO (i.e., La Niña) years in which the Niño-3.4 index falls below minus one standard deviation.

Figure S1 shows the observed Niño-3.4 index as well as the regression of SST onto the Niño-3.4 index. When the Niño-3.4 index is positive (i.e., an El Niño year), the tropical eastern Pacific is warmer than normal. The predicted Niño-3.4 index during the 2015 TC season is +2.3.

Pacific Decadal Oscillation (PDO index)

We calculate the PDO index following Mantua et al. (1997). The PDO is the leading empirical orthogonal function (EOF) of SST anomalies over the North Pacific (20°N–70°N, 110°E–100°W) after the global mean SST has been removed. The PDO index is the standardized principal component time series. We define a positive (negative) phase of the PDO as years in which the filtered PDO index is greater than (less than) one (minus one) standard deviation.

Figure S2 shows the observed PDO index as well as the regression of SST onto the PDO index. When the PDO index is positive, the subtropical eastern Pacific (north Pacific) is warmer (cooler) than normal. The predicted PDO index during the 2015 TC season was +1.5.

Inter-decadal Pacific Oscillation (IPO index)

We calculate the IPO index following Power et al. (1999) and Folland (2002). The IPO index is the standardized principal component of the 3rd EOF for the 13-yr low-pass filtered global SST. The IPO manifests as a low-frequency El Niño-like pattern of climate variability, whose spatial pattern is similar to that of the global warming hiatus seen in recent decades (England et al. 2014). We defined a positive (negative) phase of the IPO as years in which the IPO index is greater than (less than) one (minus one) standard deviation.

Figure S3 shows the IPO index as well as the regression of SST onto the IPO index. When the IPO index is positive, the subtropical eastern Pacific (north Pacific) is warmer (cooler) than normal, which is similar to the PDO (Figure S2). The predicted IPO index during the 2015 TC season is 0.6.

Pacific Meridional Mode (PMM index)

We calculated the PMM index following Chiang and Vimont (2004). The PMM index is the standardized 1st expansion coefficient of the singular decomposition (SVD) mode for the SST and zonal and meridional components of the 10-m wind field. The input data are defined over the tropical to subtropical region (21ºS–32ºN, 175ºE–95ºW), and seasonal cycle, Niño-3.4 index, and linear trend are removed for each grid cell. We define a positive (negative) phase of the PMM as years in which the PMM index is greater than (less than) one (minus one) standard deviation.

Figure S4 shows the PMM index as well as the regression of SST (shading) and 10-m wind field (vectors) onto the PMM index. The PMM manifests as meridional gradient of SST anomaly along with meridional wind anomaly. When the PMM index is positive, the subtropical eastern Pacific (north Pacific) is warmer (cooler) than normal along with northward (southward) meridional wind. The predicted PMM index during the 2015 TC season is +0.9.

Atlantic Multi-decadal Oscillation (AMO index)

We calculated the AMO index following Deser et al. (2010). The AMO index is defined as the area-average SST anomaly over the North Atlantic (0–70°N, 90°W–0) minus the global mean SST anomaly. The AMO index was standardized after calculating the anomalies. We defined a positive (negative) phase of the AMO as years in which the AMO index exceeds one (minus one) standard deviation.

Figure S5 shows the observed AMO index as well as the regression of SST and TC density onto the AMO index. When the AMO index is positive, the North Atlantic is warmer than normal. Unlike other indices, TC density decreases in the eastern Pacific when the AMO index is positive, indicating that TC frequency in EPO increase when the AMO index is negative. The AMO index during the 2015 TC season was –1.7.

Reference:

Chiang, J. C. H., and D. J. Vimont, 2004: Analogous Pacific and Atlantic meridional modes of tropical atmosphere–Ocean variability *J. Climate*, **17,** 4143–4158.

Deser, C., M. A. Alexander, S.-P. Xie, and A. S. Phillips, 2010: Sea surface temperature variability: Patterns and mechanisms. *Annu. Rev. Mar. Sci.,* **2,** 115–143.

England, M. H., and coauthors, 2014: Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nat. Climate Change*, **9,** 222–227.

Folland, C. K., J. A. Renwick, M. J. Salinger, and A. B. Mullan, 2002: Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. *Geophys. Res. Lett.* **29,** 211–214.

Mantua, N. J., S.R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.,* **78,** 1069–1079.

Murakami, H., G. A. Vecchi, T. L. Delworth, K. Paffendorf, R. Gudgel, L. Jia, and F. Zeng, 2015a: Investigating the influence of anthropogenic forcing and natural variability on the 2014 Hawaiian hurricane season. [in "Explaining Extremes of 2014 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, S115–S119.

Power, S., T., Casey, C. Folland, A. Colman, and V. Mehta, 1999: Interdecadal modulation of the impact of ENSO on Australia. *Climate Dyn.* **15,** 319–324.

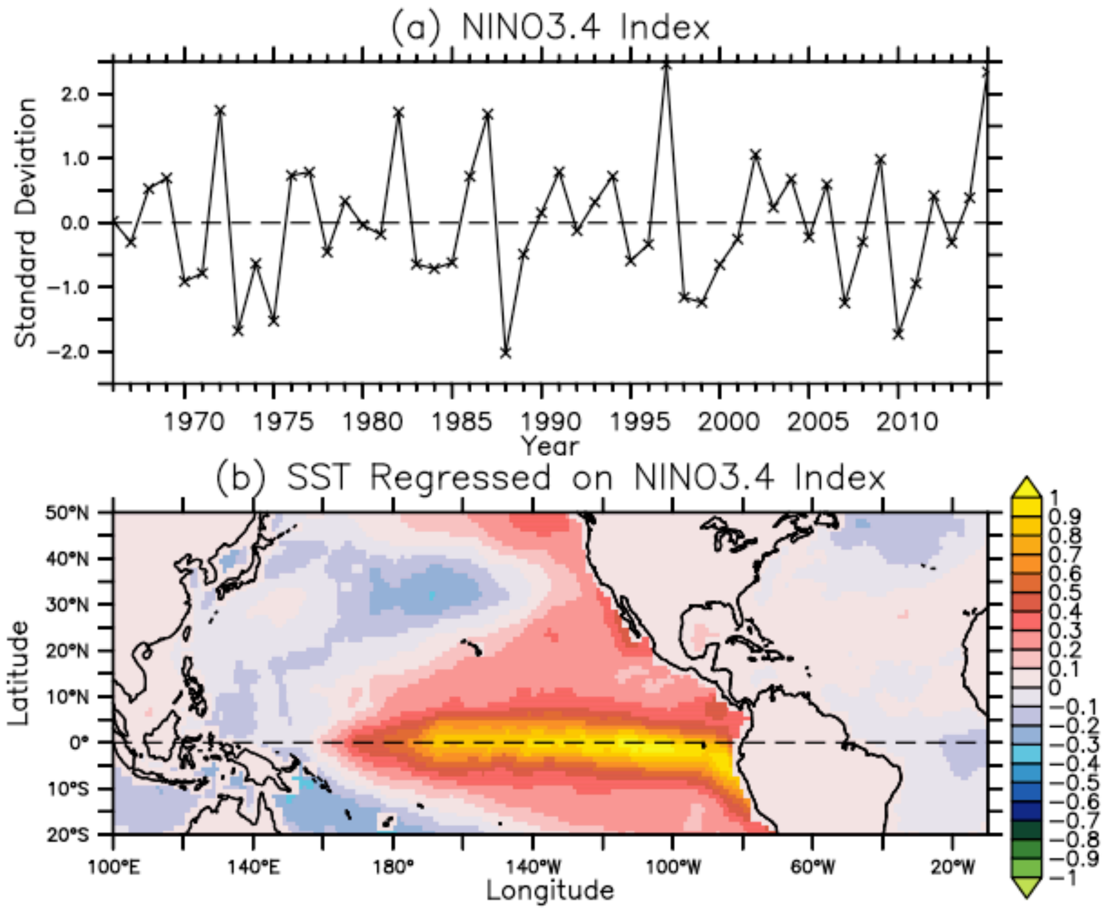

FIGURE S1 Mean Niño-3.4 index for May–November (1966–2015). (a) Time series of Niño-3.4 index for the period 1966–2015 [units: 1σ (one standard deviation)]. (b) Seasonal mean SST regressed onto the Niño-3.4 index [units: K σ^{-1}].

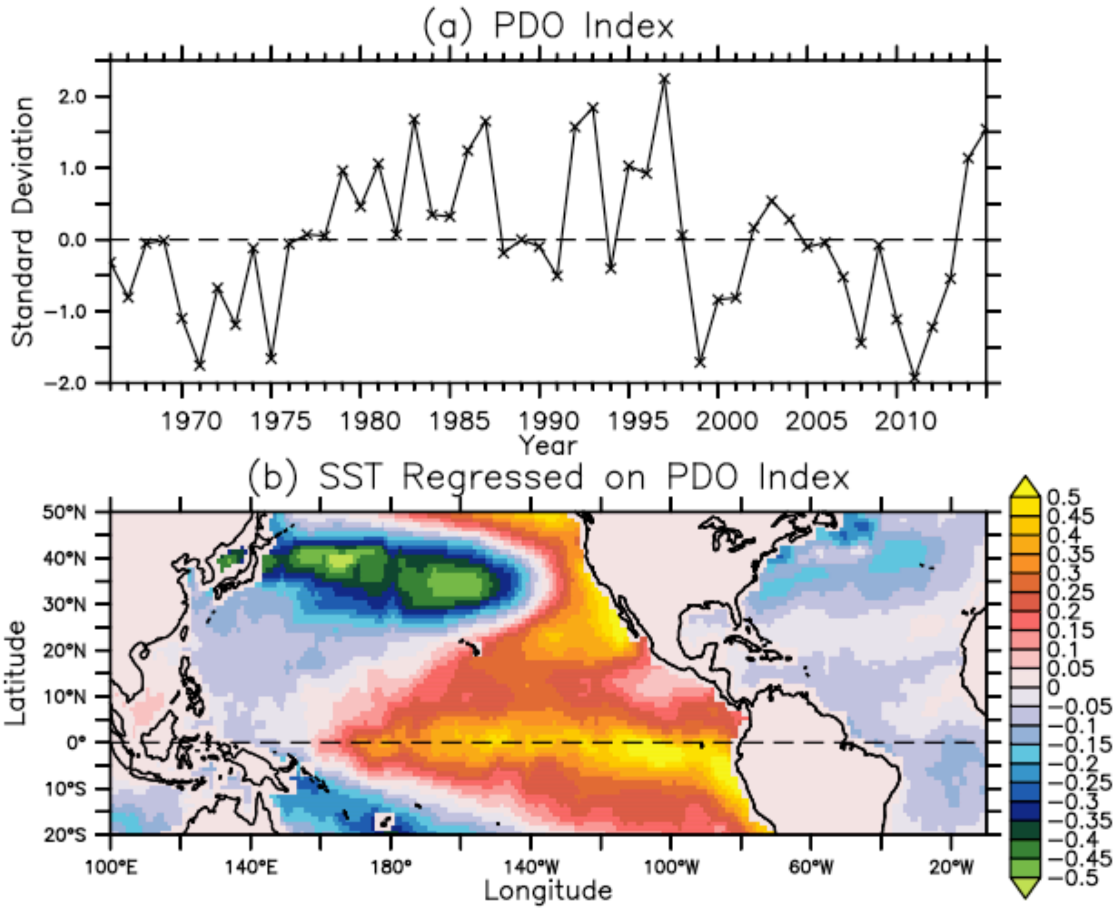

FIGURE S2 As Figure S1, but for the PDO index.

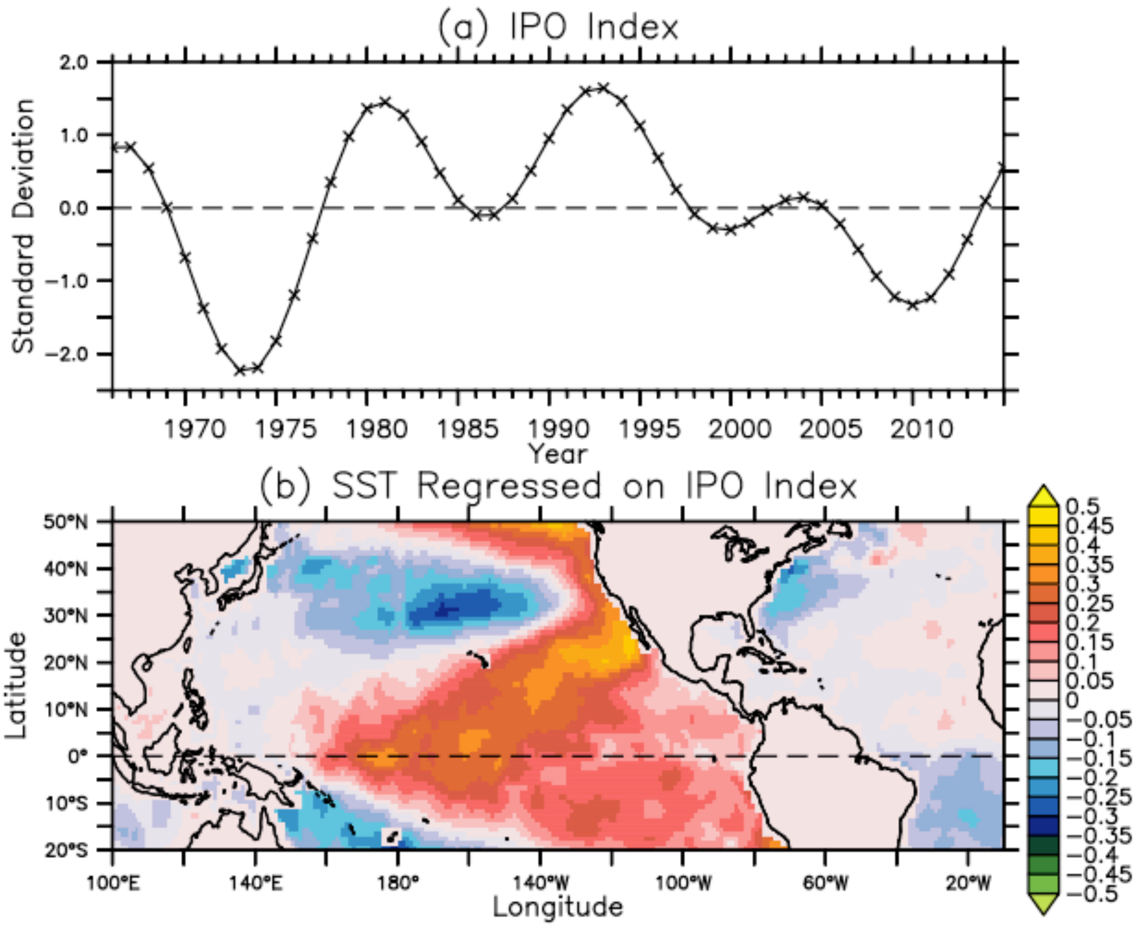

FIGURE S3 As Figure S1, but for the IPO index.

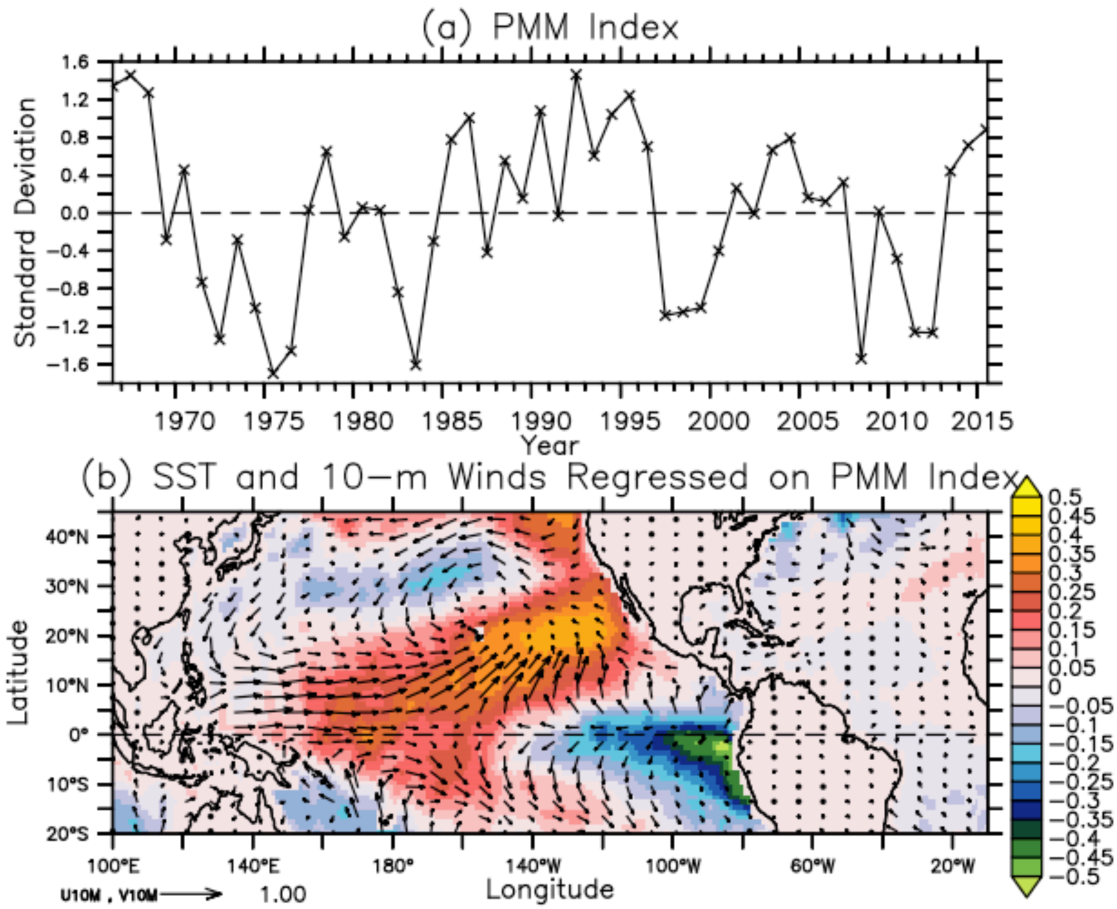

FIGURE S4 As Figure S1, but for the PMM index along with seasonal mean 10-m wind regressed onto the PMM index (vectors).

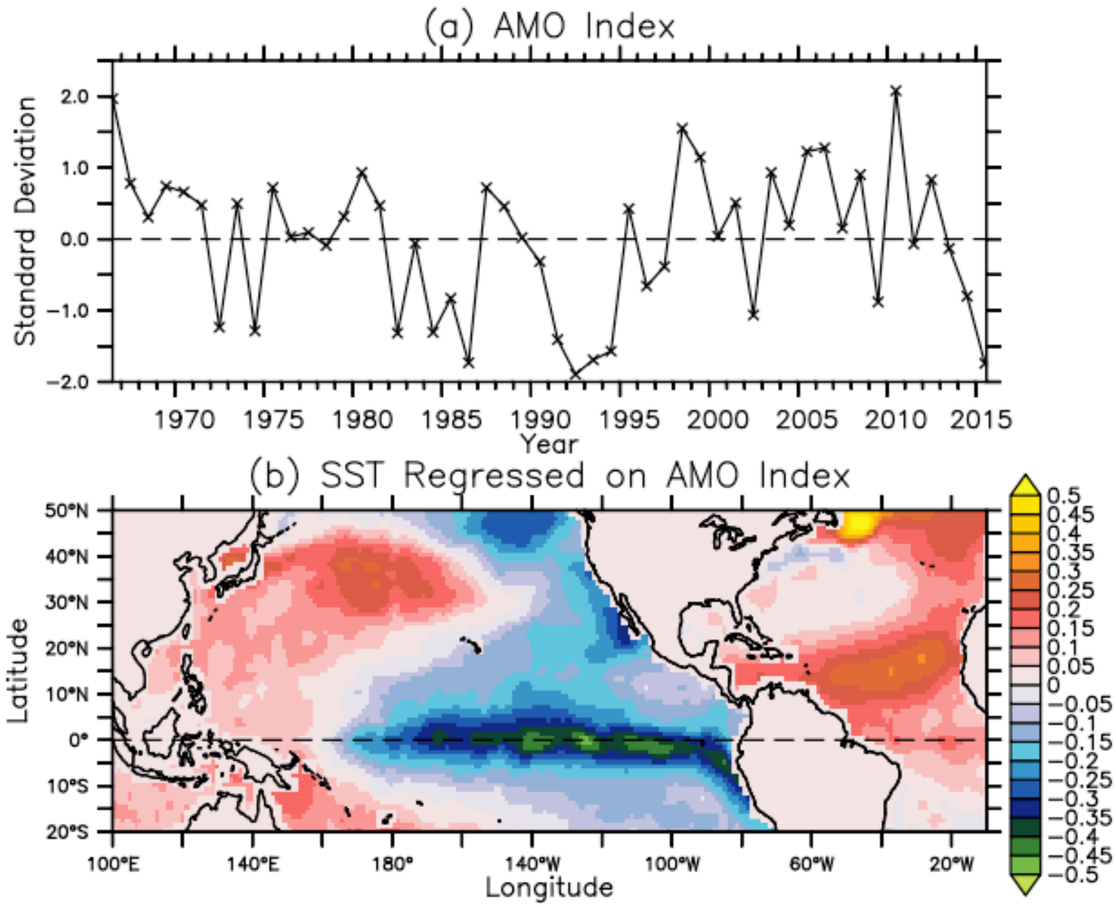

FIGURE S5 As Figure S1, but for the AMO index.