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Westward shift of western North Pacific tropical cyclogenesis

Liguang Wu[1], **Chao Wang**[1], **and Bin Wang**[2]

[1]Pacific Typhoon Research Center and Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing, China, [2]Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Honolulu, Hawaii, USA

Key Points:
- The TUTT controls the annual mean typhoon genesis longitude
- The mean typhoon genesis longitude has significantly shifted since 1979
- The genesis longitude shift may be associated with global warming

Correspondence to:
L. Wu,
liguang@nuist.edu.cn

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Abstract Tropical cyclones (TCs) in the western North Pacific or typhoons account for one third of all TCs in the world and the change of the mean TC genesis location can affect billions of people in Pacific islands and Asian countries. The annual mean TC genesis longitude is generally controlled by the east-west shift of the tropical upper tropospheric trough (TUTT). A pronounced westward shift in the TUTT is found in all of the available reanalysis data sets during 1979–2012, suppressing TC genesis in the eastern portion (east of 145°E) of the western North Pacific basin due to the enhanced vertical wind shear associated with the TUTT shift. As a result, the annual mean TC genesis longitude has significantly shifted westward since 1979. The westward shifting trends in the TUTT and TC genesis are associated with the enhanced tropical tropospheric warming, which is consistent with the response of the tropospheric temperature to global warming.

1. Introduction

Tropical cyclones (TCs) in the western North Pacific (WNP) or typhoons account for one third of all TCs in the world and the change of the mean TC genesis location can affect billions of people in Pacific islands and Asian countries. One of the deepest societal concerns about the consequence of global warming is how TC activity has changed or will change in this region. Considerable effort has been made to understand the response of TC activity to global warming, but so far relatively few studies have been conducted on possible changes in the mean TC genesis location and impact area [*Knutson et al.*, 2010; *Seneviratne et al.*, 2012; *Christensen et al.*, 2013; *Kossin et al.*, 2014].

Recently, *Kossin et al*. [2014] identified a pronounced poleward migration in the average latitude of the global mean TC lifetime maximum intensity from the global historical records over the past 30 years. They argued that the migration away from the tropics is linked to changes in the mean meridional structure of environmental vertical wind shear and potential intensity. Using a regional climate model, *Stowasser et al*. [2007] suggested an increasing trend in TC genesis in the South China due to increasing midtroposphere relative humidity and decreasing wind shear, while *Li et al*. [2010] argued that global warming could lead to a shift of the TC genesis location from the western to central Pacific because of relatively increasing tropical synoptic-scale disturbances, which are necessary for TC genesis [*Riehl*, 1948; *Ramage*, 1959; *Gray*, 1968, 1998; *Zehr*, 1992]. These studies suggest that the TC genesis location may change in responses to the ongoing global warming.

The tropical upper tropospheric trough (TUTT) in the North Pacific, also known as a mid-oceanic trough, is a semipermanent feature that extends east-northeast to west-southwest roughly from 35°N in the eastern Pacific to 15°N in the western Pacific, which can be identified in the summertime 200 hPa wind field [*Sadler*, 1976]. Although sometimes the TUTT may promote TC genesis [*Sadler*, 1976, 1978], the associated strong westerly vertical wind shear in its eastern flank generally limits the eastward extension of TC activity in the WNP [*Kelley and Mock*, 1982; *Fitzpatrick et al.*, 1995]. The objective of this study is to demonstrate that the mean TC genesis longitude over the WNP has significantly shifted westward since 1979 due to a westward shift of the TUTT.

2. Data

Two TC data sets are used in this study due to uncertainty in the historical records of TC intensity. One is the Joint Typhoon Warming Center (JTWC) best track data set, and the other is the advanced Devorak technique-Hurricane

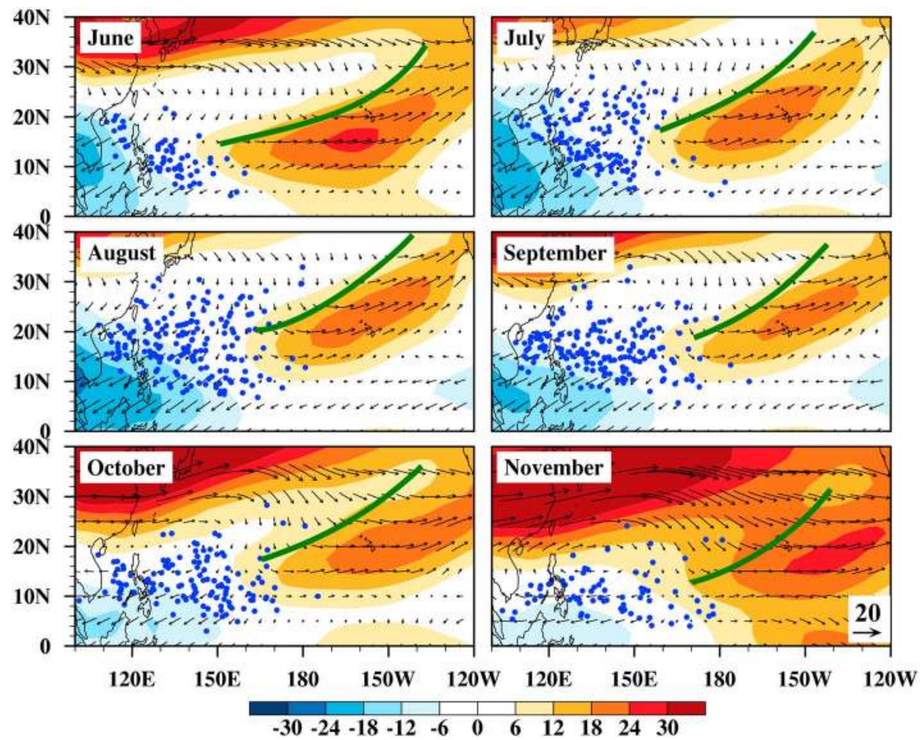

Figure 1. Monthly mean 200 hPa wind field (vectors, m s^{-1}) and vertical shear of zonal wind between 850 hPa and 200 hPa (shaded, m s^{-1}) during June–November. Blue dots indicate TC genesis locations and thick lines are the TUTT trough line.

Satellite (ADT-HURSAT) data set [*Kossin et al.*, 2013]. The ADT-HURSAT data set (1979–2009) contains more temporally consistent records of TC intensity than the JTWC data set since a state-of-the-art automated algorithm was applied to globally homogenized satellite data [*Knapp and Kossin*, 2007; *Kossin et al.*, 2007, 2014].

The temperature and wind field data are derived from an ensemble of seven reanalysis data sets: (1) the National Oceanic and Atmospheric Administration Earth System Research Laboratory Twentieth Century Reanalysis (20CRv2, 2° latitude × 2° longitude with 24 vertical levels, 1870–2010 [*Compo et al.*, 2006]); (2) the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR, 2.5° latitude × 2.5° longitude with 17 vertical levels, 1948–2012 [*Kalnay et al.*, 1996]); (3) ERA-Interim (1.5° latitude × 1.5° longitude with 37 vertical levels, 1979–2012 [*Dee et al.*, 2011]); (4) the Japanese Re-Analysis (JRA-25, 1.25° latitude × 1.25° longitude with 23 vertical levels, 1979–2012 [*Onogi et al.*, 2005]); (5) the National Aeronautics and Space Administration Modern Era Reanalysis for Research and Applications (MERRA, 1/2° latitude × 2/3° longitude with 42 vertical levels, 1979–2012 [*Rienecker et al.*, 2011]); (6) the National Centers for Atmospheric Research-Department of Energy second reanalysis (NCEP-DOE, 2.5° latitude × 2.5° longitude with 17 vertical levels, 1979–2012 [*Kanamitsu et al.*, 2002]); and (7) the NCEP Climate Forecast System Reanalysis (CFSR, 0.5° latitude × 0.5° longitude with 64 levels, 1979–2012 [*Saha et al.*, 2010]).

Linear trends are calculated and significance testing is conducted using the nonparametric Mann-Kendall method with autocorrelation in the data being checked for the effective sample size [*Kundzewicz and Robson*, 2000]. Student's *t* test is used for checking the correlation significance. A confidence level of 95% is used in this study.

3. Control of the Mean TC Genesis Longitude by the TUTT

Figure 1 shows the climatologic relationship between the TUTT and the TC genesis location in the WNP, indicating that the TUTT generally limits the eastward extension of TC genesis. We can see that nearly all TCs formed to the west of the TUTT line in June–November, mostly over the Philippine Sea and South China Sea in the region (5°–20°N, 115°–160°E). As shown in this figure, the TUTT generates strong vertical wind shear

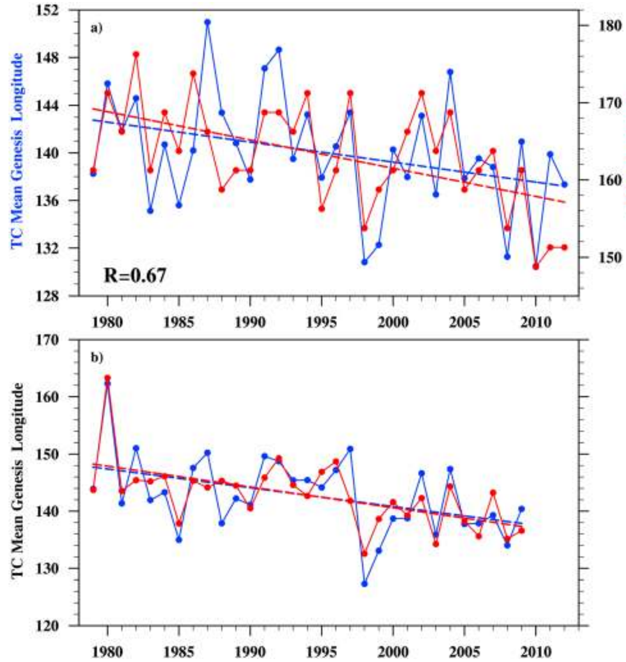

Figure 2. Time series of (a) the annual mean TC genesis longitude (blue) from the JTWC dataset and the annual mean TUTT longitude (red) and (b) the annual mean TC longitude from the ADT-HURSAT data set with (blue) and without (red) the ENSO effect. Note the ADT-HURSAT data are available only for the period 1979–2009.

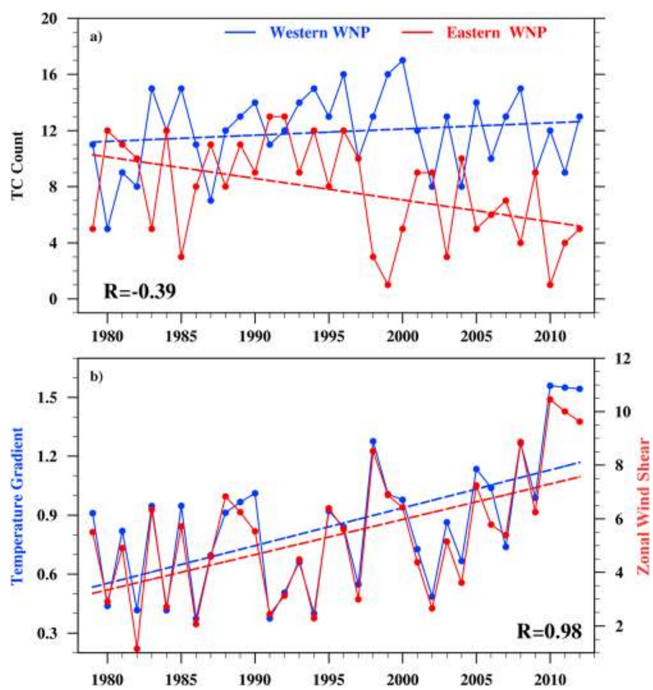

Figure 3. (a) TC formation frequency in the western and eastern portions of the WNP basin, and (b) the difference of the tropospheric temperature (red, K) between the tropics (10°S–5°N, 145°E–180°E) and the subtropics (15°N–30°N, 145°E–180°E) and the vertical shear or difference of the zonal wind (m s^{-1}) between 200 hPa and 850 hPa averaged over 5°N–25°N, 145°E–180°E.

between 850 hPa and 200 hPa in its eastern flank. It is conceivable that the east-west migration of the TUTT can shift the TC genesis location since the associated vertical wind shear tends to suppress TC genesis in the eastern portion of the WNP basin [*Gray*, 1968].

The control of the TC genesis location by the TUTT can be identified on the interannual and longer time scales. For this purpose, the annual mean east-west shift of the TUTT in July–November is measured with the dividing boundary between the easterly and westerly winds in the trough (the zero contour of zonal wind speed over 5°N–20°N) and the basin-wide mean TC genesis location is defined as the mean longitude of all TCs that first reached an intensity of 25 knots (about 13 m s^{-1}) each year. Accompanied by considerable interannual fluctuations, the TUTT has persistently shifted westward by 12.6° longitudes (0.37° longitude/yr) during the period 1979–2012, as suggested by the significant linear trend (Figure 2a). When the TUTT moved westward, the annual mean TC genesis location has also shifted westward by 5.8° longitudes (0.17° longitude/yr) since 1979.

The two time series are significantly correlated with a coefficient of 0.67 over the period from 1979 to 2012 (Figure 2a). The correlation mainly indicates the relationship of the east-west migration between the TUTT and the mean TC genesis location on the interannual time scale. That is, the westward (eastward) shift of the TUTT corresponds to the westward (eastward) shift of the mean TC genesis location. Previous studies found that the interannual variations of the mean TC genesis location are closely associated with El Niño-Southern Oscillation (ENSO) events [*Chan*, 2000; *Wang and Chan*, 2002; *Wang et al.*, 2013]. Following *Kossin et al.* [2014], we regressed the two time series in Figure 2a onto the Niño-3.4 index to examine the ENSO effect on the trends.

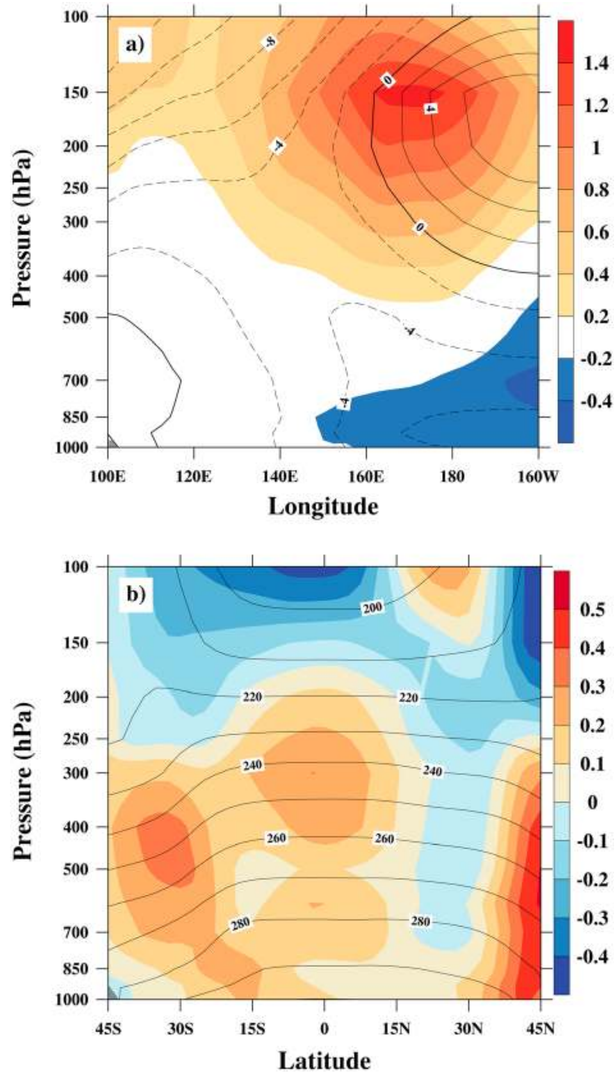

Figure 4. (a) July–November mean zonal wind speed (contour, m s^{-1}) and the associated trends (shaded, m s^{-1} decade^{-1}) averaged over 5°N–25°N during 1979–2012 and (b) July–November mean temperature (contour, K) and the associated trend (shaded, K decade^{-1}) averaged over 145°E–170°W.

In fact, ENSO events have little influence on the westward trends in the TUTT and the mean TC genesis location. After removing the ENSO effect, the westward trends in the TUTT and the TC genesis location are 0.36° longitude/yr and 0.16° longitude/yr, respectively.

We can see that the shifting rate of the TC genesis location is much smaller than that of the TUTT. The difference is mainly due to uncertainty in the intensity records of the JTWC data set. To demonstrate this, we also calculated the annual mean genesis location in the ADT-HURSAT data set (Figure 2b). The time series without the ENSO effect is also plotted in this figure. In this case, the ENSO effect slightly reduced the trend in the mean genesis location. The westward trend without (with) the ENSO effect in the mean genesis location is 0.36° (0.33°) longitude/yr. Note that the shifting rate of the mean genesis location in the ADT-HURSAT data set is the same as that of the TUTT after removing the ENSO effect. We further estimated the westward shift in longitudes where TCs first reached the storm intensity (35 knots) in the ADT-HURSAT data set. The shifting rate is 0.34° (0.36°) longitude/yr without (with) the ENSO effect, well comparable to the shifting rate in the mean genesis location. It is suggested that TC intensity records in the ADT-HURSAT data set are more reasonable than those in the JTWC data set.

We should mention that the westward shift trend of the TUTT can be found in all of the seven individual reanalysis data sets. The trends in the five modern reanalysis data sets range from −2.7 longitudes/decade to −4.0 longitudes/decade and all of the trends are statistically significant (figure not shown). The westward shifting trend of the TUTT is consistent with the significant linear downward trend in the TC genesis frequency (−1.5 TCs per decade) in the eastern portion of the basin (east of 145°E), while the TC genesis frequency in the western portion (west of 145°E) has slightly increased (Figure 3a).

The westward migration of the annual mean TC genesis location is rooted in the enhanced vertical shear of zonal wind associated with the westward shift of the TUTT since it is well known that sufficiently large vertical wind shear inhibits TC genesis [*Gray*, 1968]. The vertical shear of zonal wind, which is averaged over the eastern portion of the WNP major TC genesis zone (5°N–25°N, 145°E–180°E), shows a significant upward trend as the TUTT shifted westward (Figure 3b). As suggested by the linear trend, the vertical shear has been doubled over the period 1979–2012.

4. Discussion

Why did the TUTT shift westward since 1979? Figure 4a shows the vertical distributions of the July–November zonal wind trend over the period 1979–2012 and the associated climatologic mean zonal wind speed, which are averaged over a latitude belt of 5°N–25°N. Trade easterlies are overlapped by relatively strong westerly winds centered at about 200 hPa east of 165°E, while the weak monsoon westerlies in the lower troposphere can be merely seen west of 120°E. While the low-level negative trends enhance the easterly winds, the positive trends to the west of the maximum center of the zonal westerly wind suggest that the upper level westerly winds associated with the TUTT extend westward, and thus, the TUTT shifts westward.

The enhanced vertical wind shear is physically linked to the increased temperature gradient because of thermal balance, as shown in Figure 3b. Here the temperature gradient is represented by the difference in the 850–200 hPa mean temperature between the following two rectangular regions: one over the tropics (10°S–5°N, 145°E–180°E) and the other over the subtropics (15°N–30°N, 145°E–180°E). Figure 4b shows the vertical distribution of the tropospheric temperature trends averaged over the longitude belt of 145°E–170°W. The increased tropospheric temperature gradient is related to the warming trends in the tropical troposphere and the relatively weak cooling trends in the subtropics.

Calculation of the monthly trend of atmospheric temperature over the layer between 850 hPa and 200 hPa during the period 1979–2012 indicates that the cooling trends over the subtropical North Pacific occurred near the TUTT line in July-November, suggesting the relationship of the cooling trends with the TUTT shift (figure not shown), because the TUTT is a cold core system between 100 and 700 hPa [*Kelley and Mock*, 1982].

Theory and numerical modeling consistently predict, as a robust feature of global warming, an enhanced tropical tropospheric warming that increases with height and reaches its maximum around 200 hPa [*Manabe and Wetherald*, 1975; *Christensen et al.*, 2013]. Observational evidence has been increasingly accumulated to support the projected warming trend although research is still undergoing to reconcile the difference between tropospheric temperature trends from climate models and observations [*Fu et al.*, 2004; *Santer et al.*, 2005; *Allen and Sherwood*, 2008; *Thorne et al.*, 2011]. In Figure 4b, the enhanced warming trends in the upper troposphere over the equator and cooling trends in the lower stratosphere are consistent with the response of the tropospheric temperature to global warming.

5. Summary

In this study, we show that annual mean typhoon genesis location is generally controlled by the TUTT. By examining all of the seven reanalysis data sets during the period 1979–2012, we find a pronounced westward shift in the TUTT in all of the available reanalysis data sets since 1979 with a mean shift of about 12° longitudes (0.36° longitude/yr). The significant westward shift of the TUTT suppressed TC genesis in the eastern portion (east of 145°E) of the western North Pacific basin due to the strong vertical wind shear associated with the TUTT. As a result, the annual mean TC genesis location has significantly shifted westward since 1979. The westward shifting trends in the TUTT and TC genesis are associated with the enhanced tropical tropospheric warming, which is consistent with the response of the tropospheric temperature to global warming.

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References

Allen, R. J., and S. C. Sherwood (2008), Warming maximum in the tropical upper troposphere deduced from thermal wind, *Nat. Geosci.*, *1*, 399–403.

Chan, J. C. L. (2000), Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events, *J. Clim.*, *13*, 2960–2972.

Christensen, J. H., et al. (2013), Climate phenomena and their relevance for future regional climate change, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., pp. 1217–1308, Cambridge Univ. Press, Cambridge, U. K., and New York.

Compo, G. P., J. S. Whitaker, and P. D. Sardeshmukh (2006), Feasibility of a 100-year reanalysis using only surface pressure data, *Bull. Am. Meteorol. Soc.*, *87*, 175–190.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*, 553–597.

Fitzpatrick, P. J., J. A. Knaff, C. W. Landsea, and S. V. Finley (1995), A systematic bias in the Aviation model's forecast of the Atlantic tropical upper tropospheric trough: Implications for tropical cyclone forecasting, *Weather Forecasting*, *10*, 433–446.

Fu, Q., C. M. Johanson, S. G. Warren, and D. J. Seidel (2004), Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends, *Nature*, *429*, 55–58.

Gray, W. M. (1968), Global view of the origin of tropical disturbances and storms, *Mon. Weather. Rev.*, *96*, 669–700.

Gray, W. M. (1998), The formation of tropical cyclones, *Meteorol. Atmos. Phys.*, *67*(1–4), 37–69.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter (2002), NCEP-DOE AMIP-II Reanalysis (R-2), *Bull. Am. Meteorol. Soc.*, *83*, 1631–1643.

Kelley, W. E., Jr., and D. R. Mock (1982), A diagnostic study of upper tropospheric cold lows over the western North Pacific, *Mon. Weather Rev.*, *110*, 471–480.

Knapp, K. R., and J. P. Kossin (2007), A new global tropical cyclone data set from ISCCP B1 geostationary satellite observations, *J. Appl. Remote Sens.*, *1*, 013505.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi (2010), Tropical cyclones and climate change, *Nat. Geosci.*, *3*, 157–163.

Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper (2007), A globally consistent reanalysis of hurricane variability and trends, *Geophys. Res. Lett.*, *34*, L04815, doi:10.1029/2006GL028836.

Kossin, J. P., T. L. Olander, and K. R. Knapp (2013), Trend analysis with a new global record of tropical cyclone intensity, *J Clim.*, *26*, 9960–9976.

Kossin, J. P., K. A. Emanuel, and G. A. Vecchi (2014), The poleward migration of the location of tropical cyclone maximum intensity, *Nature*, *509*, 349–352.

Kundzewicz, Z. W., and A. Robson (Eds.) (2000), Detecting trend and other changes in hydrological data, Rep. WCDMP-45, Rep. WMO-TD 1013, 157 pp., World Meteorol. Org., Geneva, Switzerland.

Li, T., M. Kwon, M. Zhao, J.-S. Kug, J.-J. Luo, and W. Yu (2010), Global warming shifts Pacific tropical cyclone location, *Geophys. Res. Lett.*, *37*, L21804, doi:10.1029/2010GL045124.

Manabe, S., and R. Wetherald (1975), Effects of doubling CO2 concentration on climate of a general circulation model, *J. Atmos. Sci.*, *32*, 3–15.

Onogi, K., et al. (2005), JRA-25: Japanese 25-Year Re-Analysis Project—Progress and status, *Q. J. R. Meteorol. Soc.*, *131*, 3259–3268.

Ramage, C. S. (1959), Hurricane development, *J. Meteorol.*, *16*, 227–237.

Riehl, H. (1948), On the formation of typhoons, *J. Meteorol.*, *5*, 247–265.

Rienecker, M., et al. (2011), MERRA: NASA's Modern-Era Retrospective Analysis for research and applications, *J. Clim.*, *24*, 3624–3648.

Sadler, J. C. (1976), A role of the tropical upper tropospheric trough in early season typhoon development, *Mon. Weather Rev.*, *104*, 1266–1278.

Sadler, J. C. (1978), Mid-season typhoon development and intensity changes and the tropical upper tropospheric trough, *Mon. Weather Rev.*, *106*, 1137–1152.

Saha, S., et al. (2010), The NCEP Climate Forecast System Reanalysis, *Bull. Am. Meteorol. Soc.*, *91*, 1015–1057.

Santer, B. D., et al. (2005), Amplification of surface temperature trends and variability in the tropical atmosphere, *Science*, *309*, 1551–1556, doi:10.1126/science.1114867.

Seneviratne, S. I., et al. (2012), Changes in climate extremes and their impacts on the natural physical environment, in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*, edited by C. B. Field et al., pp. 109–230, Cambridge Univ. Press, Cambridge, U. K., and New York.

Stowasser, M., Y. Wang, and K. Hamilton (2007), Tropical cyclone changes in the western North Pacific in a global warming scenario, *J. Clim.*, *20*, 2378–2396.

Thorne, P. W., J. R. Lanzante, T. C. Peterson, D. J. Seidel, and K. P. Shine (2011), Tropospheric temperature trends: History of an ongoing controversy, *WIREs Clim. Change*, *2*, 66–88.

Wang, B., and J. C. L. Chan (2002), How strong ENSO events affect tropical storm activity over the western North Pacific, *J. Clim.*, *15*, 1643–1658.

Wang, C., C. Li, M. Mu, and W. Duan (2013), Seasonal modulations of different impacts of two types of ENSO events on tropical cyclone activity in the western North Pacific, *Clim. Dyn.*, *40*, 2887–2902.

Zehr, R. M. (1992), Tropical cyclogenesis in the western North Pacific NOAA Tech. Rep. NESDIS 61, 181 pp. [Available from NOAA/NESDIS, E/RA22, 5200 Auth Road, Washington, DC 20233.]