Global warming hiatus contributed to the increased occurrence of intense tropical cyclones in the coastal regions along East Asia

Jiuwei Zhao1,2, Ruifen Zhan2,3 & Yuqing Wang2

The recent global warming hiatus (GWH) was characterized by a La Niña–like cooling in the tropical Eastern Pacific accompanied with the Indian Ocean and the tropical Atlantic Ocean warming. Here we show that the recent GWH contributed significantly to the increased occurrence of intense tropical cyclones in the coastal regions along East Asia since 1998. The GWH associated sea surface temperature anomalies triggered a pair of anomalous cyclonic and anticyclonic circulations and equatorial easterly anomalies over the Northwest Pacific, which favored TC genesis and intensification over the western Northwest Pacific but suppressed TC genesis and intensification over the southeastern Northwest Pacific due to increased vertical wind shear and anticyclonic circulation anomalies. Results from atmospheric general circulation model experiments demonstrate that the Pacific La Niña–like cooling dominated the Indian Ocean and the tropical Atlantic Ocean warming in contributing to the observed GWH-related anomalous atmospheric circulation over the Northwest Pacific.

Tropical cyclones (TCs) can cause enormously devastating losses of human life and property damages, especially for coastal areas, including China, Korea, and Japan over East Asia1–3. With the rapid increase in populations and economic growth, coastal countries in East Asia are likely to face greater risk during intense TC (ITC) events. Therefore, regional change in ITC activity in the coastal regions along East Asia over the western Northwest Pacific is a critical scientific and socioeconomic issue.

A large increasing trend in the number and proportion of category 4–5 TCs has been observed over the main TC basins in recent decades1,4–9. This increase has often been linked to global warming7,10–13. Global warming not only induces the increase in sea surface temperature (SST) but also enhances the upper-ocean stratification due to the reduction of surface salinity by the upper-ocean freshening11. The latter in turn reduces the TC-induced vertical mixing and sea surface cooling and favors the intensification of ITCs10,11,14,15.

Recent studies have also reported a significant westward shift of the prevailing TC tracks over the Northwest Pacific with an increase in landfalling ITCs in recent three decades3,16. This westward shift of prevailing TC tracks has been attributed to the expansion of subtropical high over the Northwest Pacific and local ocean surface warming3,17,18. Since both the increase in landfalling ITCs and the westward shift in TC tracks over the Northwest Pacific imply the increasing threat by more ITCs to the coastal regions of the East Asian countries, it is important to further explore the regional change in ITC occurrences and understand possible mechanisms that contributed to the related regional change based on a perspective of global SST anomalies.

The global surface warming over the 20th century was found to slow down during 1998–2013. This phenomenon was referred to as the global warming hiatus (GWH) and has been discussed in numerous studies19–26. The GWH was shown to be characterized by a La Niña–like cooling in the tropical eastern Pacific (EP) accompanied with the Indian Ocean (IO) and the tropical Atlantic Ocean (AO) warming. Previous studies have proposed that the GWH could be triggered by the internal variability of the coupled ocean-atmospheric system, such as the Pacific Decadal Oscillation, or the external natural forcing, such as volcanic eruption and aerosols.

1Pacific Typhoon Research Center, Key Laboratory of Meteorological Disaster of Ministry of Education (KLME), Nanjing University of Information Science and Technology, Nanjing, China. 2International Pacific Research Center and Department of Atmospheric Sciences, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii, USA. 3Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China. Correspondence and requests for materials should be addressed to R.Z. (email: zhanrf@typhoon.org.cn)
or both\textsuperscript{19,20,24,27,28}. Regardless of its triggering mechanisms, the GWH has been demonstrated to have imposed important impact on the North American climate and the Asian monsoon variability\textsuperscript{29,30}.

Here we will report a new finding that the recent GWH contributed significantly to the regional changes of ITC activity over the Northwest Pacific, in particular the increase in the coastal regions along East Asia. This has been demonstrated by the Singular Value Decomposition (SVD) analysis, which allows us to examine the relationships between the regional variability of TCs over the Northwest Pacific and climate variability on global scales.

**Results**

Figure 1a shows the spatial distributions of the linear trend in ITC tracks (ITCTs) over the Northwest Pacific during 1980–2015 (shades) and the composite difference in ITCTs between the hiatus (1998–2015) and pre-hiatus (1980–1997) periods (contours). Here the ITCTs were defined as the frequency of ITC occurrence in each 5° × 5° grid box. There is a significant increasing trend in ITCTs along the East Asian coasts over the western Northwest Pacific, west of 135°E, and a decreasing trend over the southeastern Northwest Pacific. This northwest-southeast dipole trend pattern also appears in composite difference in ITCTs between the hiatus and pre-hiatus periods. This consistency suggests that the GWH might contribute to the observed trends in ITCTs over the Northwest Pacific. The pattern in ITCTs only including the points where TCs reached ITC only (with the SMWS larger than 96 knots); (c) composite differences in ITCTs between the hiatus (1998–2009) and pre-hiatus (1982–1997) periods using the ADT-HURSAT data; and (d) same as (c) but using the JTWC TC best-track data. Areas where composite differences are statistically significant above the 90% confidence level are shown in grey dots based on the Mann-Whitney U test. The slashes in (a) and (b) represent areas where the trend is statistically significant above the 90% confidence level based on Student’s t test. This figure was generated by the NCAR Command Language (Version 6.4.0) [Software]. (2017). Boulder, Colorado: UCAR/NCAR/CISL/TDD.

Figure 1. Trends and composite differences in the observed ITCTs. (a) Trends in ITCTs (shades; counts per decade) during 1980–2015 and composite differences in the observed ITCTs between the hiatus (1998–2015) and pre-hiatus (1980–1997) periods (contour; counts per decade); (b) same as (a) but calculated for the points where TCs reached ITC only (with the SMWS larger than 96 knots); (c) composite differences in ITCTs between the hiatus (1998–2009) and pre-hiatus (1982–1997) periods using the ADT-HURSAT data; and (d) same as (c) but using the JTWC TC best-track data. Areas where composite differences are statistically significant above the 90% confidence level are shown in grey dots based on the Mann-Whitney U test. The slashes in (a) and (b) represent areas where the trend is statistically significant above the 90% confidence level based on Student’s t test. This figure was generated by the NCAR Command Language (Version 6.4.0) [Software]. (2017). Boulder, Colorado: UCAR/NCAR/CISL/TDD.
1998 (Fig. 2b). Their correlation coefficient is as high as 0.91, significant at the 99% confidence level by Student’s t-test after adjusting the effective degrees of freedom. The results thus indicate that the first SVD mode of ITCT trends (Fig. 2a) is well coupled with that of SSTAs characterized by a uniform SST warming trend over the tropics except for an SST cooling trend appeared over the eastern Pacific (Fig. 2c). The similarity between Fig. 1a and 2a and that between Fig. 2c and 2d demonstrate that the pattern in the linear trends in ITCTs shown in Fig. 1a is closely tied to the recent GWH characterized by SSTA pattern shown in Fig. 2b. That is why we can divide the whole studied period into two sub-periods: the pre-hiatus (1980–1997) and the hiatus periods (1998–2015) based on the time series of SSTA derived from the first SVD mode (Fig. 2b). This is also consistent with previous studies.

For a comparison, we also performed the Empirical Orthogonal Function (EOF) analyses of the global SST anomalies and the ITCTs over the Northwest Pacific, respectively. In general, the first EOF modes (Fig. 3) are very similar to the coupled mode based on the SVD analyses shown in Fig. 2. The spatial pattern for the first EOF mode of the global SST anomalies also shows the recent GWH mode, characterized by a La Niña-like SST cooling pattern in the Pacific region accompanied with the IO and AO warming (Fig. 3a). The first EOF mode of the ITCTs over the Northwest Pacific displays an increased ITC occurrence over the East Asian coastal region and a decreased ITC occurrence over the southeastern Northwest Pacific in the hiatus period (Fig. 3b). The time series of the two first EOF modes show negative anomalies before 1998 and positive anomalies since 1998 (Fig. 3c), with contributions of 45.6% and 38.6%, respectively, to the corresponding total variances. The similarity between the EOF and SVD analyses strongly suggests that the results based on the SVD analyses above are robust.

To understand how the GWH affected the regional changes in the ITCTs, we examined the changes in the large-scale atmospheric circulation over the Northwest Pacific in response to the GWH. Figure 4 shows the composite differences in winds and relative vorticity at 850 hPa, sea level pressure (SLP), vertical wind shear (VWS) between 200 and 850 hPa, and the mass-weighted mean winds (or steering flow) from 850 to 300 hPa between the hiatus and pre-hiatus periods based on both the NCEP/NCAR reanalysis (Fig. 4a–c) and the ERA-interim reanalysis (Fig. 4d–f). We can see that the overall patterns of these changes from the two independent reanalysis datasets are highly consistent. During the hiatus period, the equatorial easterly anomalies dominate the tropical western Pacific, with an anomalous cyclonic circulation with positive vorticity anomalies and reduced SLP north of 20°N and extending westward from 145°E to East Asia, and an anomalous anticyclonic circulation with negative vorticity anomalies and increased VWS dominates the southeastern Northwest Pacific between 120°E and
160°E. The former is favorable for TC genesis and intensification over the western Northwest Pacific, while the latter greatly suppresses TC genesis and intensification locally. Furthermore, the southeasterly steering flow north of 20°N over the western Northwest Pacific (Fig. 4c and f) favored more TCs to head to the coastal regions of East Asian countries. These explain why the ITCTs significantly increased over the western and decreased over the southeastern Northwest Pacific during the hiatus period.

Changes in the atmospheric circulation over the Northwest Pacific are primarily driven by the tropical oceanic conditions. For example, the intensification of the Walker circulation was closely related to the La Niña-like SSTA pattern, which has been considered as one of the main features of the GWH. The intensified Walker circulation induced low-level easterly anomalies, suppressing TC genesis and frequency of occurrence over the southeastern Northwest Pacific. In sharp contrast, the western Northwest Pacific was controlled by local SST warming and an anomalous cyclonic circulation, which was favorable for TC intensification. In addition to the La Niña-like SSTA pattern, the composite difference of SSTA in the two periods also shows positive SSTAs over the IO and AO as also shown in the first SVD SST mode. Some previous studies have proposed that the IO and AO SSTAs can also play important roles in the Walker circulation strengthening and changes in the atmospheric circulation over the Northwest Pacific and thus the TC activity over the Northwest Pacific, in particular on interannual time scales. To see the relative contributions of the GWH-related SSTAs in different ocean basins (namely the Pacific Ocean, the IO, and the AO) to the long-term changes in atmospheric circulation over the Northwest Pacific identified based on reanalysis data discussed above, we conducted a series of sensitivity experiments as summarized in Table 1.

Figure 5 shows the difference fields in the simulated SLP, 850 hPa relative vorticity and winds between each of the four sensitivity experiments and the control run (CTRL run). The model quantitatively reproduced the observed decadal anomalies in low-level winds, relative vorticity and SLP over the Northwest Pacific as seen in the hiatus run (HTS run) minus the CTRL run (Fig. 5a). An anomalous cyclonic circulation with positive vorticity anomalies occupies the area from East Asia to the Northwest Pacific west of 140°E, accompanied with equatorial easterly anomalies over the southeastern Northwest Pacific, although the simulated anticyclonic circulation to the east of the Philippines is slightly weaker and more eastward than that observed. This demonstrates that the model reproduced the main features in the large-scale atmospheric circulation changes in response to the recent GWH. The low-level circulation difference between the PO run and the CTRL run (Fig. 5b) is characterized by a strong anomalous cyclonic circulation with positive vorticity anomalies over the Northwest Pacific and relatively weak equatorial easterly anomalies over the eastern part of tropical western Pacific, similar to those shown in Fig. 5a except that the simulated anomalous cyclonic circulation is somewhat weaker. This suggests that the Pacific SSTAs with the warming in the western Pacific and cooling in the eastern Pacific contributed largely to the observed circulation changes induced by the GWH. The low-level circulation differences between the IO run and the CTRL run shows a strong anomalous anticyclonic circulation accompanied by positive SLP anomalies over the Northwest Pacific (Fig. 5c), similar to the atmospheric response to the IO warming found in previous studies but is different from those shown in Fig. 5a. This suggests that the IO warming contributed negatively to

Figure 3. Spatial and temporal structures of the first EOF modes of global SST anomalies and ITCTs over the Northwest Pacific. (a,b) The spatial patterns for the first EOF modes of (a) the global SST anomalies and (b) ITCTs over the Northwest Pacific with the corresponding interannual variabilities removed, and (c) the time series of their principal components with red for ITCTs and blue for SST. This figure was generated by the NCAR Command Language (Version 6.4.0) [Software]. (2017). Boulder, Colorado: UCAR/NCAR/CISL/TDD.
the ITCT trend induced by the SSTAs over the Pacific Ocean as shown in Fig. 5b. Finally, the low-level circulation differences between the AO run and the CTRL run are considerably weak except for the equatorial easterly anomalies (Fig. 5d). This confirms the hypothesis of previous study 30, namely contribution by the Atlantic warming to the regional trends in ITCTs over the Northwest Pacific is likely to be secondary. These results demonstrate that the GWH, especially its SST pattern in the Pacific, played predominant roles in the strengthened ITCT activity in the coastal regions along East Asia over the western Northwest Pacific.

Conclusions and Discussion
We have investigated the long-term trend in ITC tracks over the Northwest Pacific and its relationship with global SST changes based on observations and a set of general circulation model experiments. We found that there is an increasing trend in ITCTs in the coastal regions along East Asia over the western Northwest Pacific since 1998, posing increasing coastal risk to East Asian countries, while a downward trend over the most of the southeastern Northwest Pacific. Our results demonstrate that the recent La Niña-like SST anomalies, which is often dubbed the GWH in the period 1998–2013, is responsible for the significant trends in ITCTs. The recent GWH strengthened an anomalous cyclonic circulation over the western Northwest Pacific, which provided favorable conditions for TC genesis and intensification, intensifying ITCT activity along East Asia. The GWH also induced equatorial
easterly anomalies, an anomalous anticyclonic circulation with negative vorticity anomalies, and increased VWS in the southeastern quadrant of the Northwest Pacific, greatly suppressing TC genesis and intensification and thus leading to the decreasing trend in ITCTs over the southeastern Northwest Pacific. Results from numerical experiments further demonstrate that the Pacific La Niña-like SST cooling contributed predominantly to the observed ITCT trend, and contribution by the AO warming were secondary, while the IO warming played an opposite role. The strengthened equatorial easterly over the western Pacific in the recent hiatus period is associated with the La Niña-like SST pattern addressed in previous studies. The IO and AO SSTAs are also shown to contribute to the strengthened Walker circulation. As mentioned in section 1, some external forcings, such as natural volcanic eruption and aerosol forcings, might also have played some roles in intensifying the Walker circulation, but these have not been considered in this study.

Furthermore, the coupled SSTAs pattern shows a similarity to the mega-ENSO pattern over the Pacific as shown in aforementioned studies. The GWH exhibits the negative phase of mega-ENSO. This suggests that there exists a coupled mode in the Pacific with a time scale longer than the decadal/interdecadal time scales. This possibility is hard to be detected at present because the relatively reliable TC intensity data are not long enough for such an analysis. Nevertheless, it should be noted that although some previous studies attributed the increasing trends in ITCs to global warming, care needs to be taken when a projection is made for the future since the global warming often displayed a permanent negative phase of mega-ENSO or a negative phase of the coupled trends.

Table 1. Experimental Design of Atmospheric General Circulation Model (AGCM) Simulations.

| Name                        | Region                      | SST                                                                 |
|-----------------------------|-----------------------------|---------------------------------------------------------------------|
| Control run (CTRL)          | Global                      | Observed climatological monthly mean SST during 1980–2015.          |
| Hiatus run (HTS)            | 60°S–60°N; 0°–360°          | Identical to CTRL except that the individual monthly mean SST anomalies between the hiatus and pre-hiatus periods were added to the belt region. |
| Pacific Ocean (PO)          | 60°S–60°N; 110°E–60°W       | Identical to CTRL except that the individual monthly mean SST anomalies between the hiatus and pre-hiatus periods were added to the Pacific Ocean. |
| Indian Ocean (IO)           | 60°S–60°N; 0°–110°E        | Identical to CTRL except that the individual monthly mean SST anomalies between the hiatus and pre-hiatus periods were added to the Indian Ocean. |
| Atlantic Ocean (AO)         | 60°S–60°N; 60°W–0°          | Identical to CTRL except that the individual monthly mean SST anomalies between the hiatus and pre-hiatus periods were added to the Atlantic Ocean. |

Figure 5. The relative contributions of the GWH-related SSTAs in different ocean basins. Differences in the simulated SLP (green and red contours, unit: hPa), 850 hPa relative vorticity (blue and red shades, unit: $2 \times 10^{-7} \text{s}^{-1}$) and winds (grey and black vectors, unit: 0.8 m s$^{-1}$) between (a) the HTS run, (b) the Pacific Ocean (PO) run, (c) the Indian Ocean (IO) run, (d) the Atlantic Ocean (AO) run, and the control (CTRL) run. All difference fields were averaged in JASON. This figure was generated by the NCAR Command Language (Version 6.4.0) [Software]. (2017). Boulder, Colorado: UCAR/NCAR/CISL/TDD.
identified in this study. Finally, the relative importance of the local SST warming over the western Northwest Pacific and the basin scale or global scale SSTA modes needs to be addressed in future studies.

Methods

The TC best-track data during 1980–2015 over the Northwest Pacific obtained from the Joint Typhoon Warning Center (JTWC) were used in this study, including the location of each TC center and 1-minute averaged surface maximum sustained wind (SMSW) at 6-h intervals. An ITC was defined as a TC with the SMSW larger than 96 knots (namely, categories 3, 4 and 5 TCs) according to the Saffir-Simpson scale. The ITC tracks (ITCTs) were defined as the frequency of ITC occurrence in each 5° × 5° grid box. The frequency of occurrence meant how often TCs affected a specific grid box. Here, to minimize the subjectivity in the identification of weak systems, the ITCTs only considered the locations with SMSW ≥ 34 knots (tropical storms) in the whole lifetimes of ITCs.

To address the uncertainties in the trend analysis using the TC best track data54,55, we also used the advanced Dvorak technique (ADT) HURRSAT dataset during 1982–2009 to confirm our analyses because this is a homogeneous satellite dataset and suitable for trend analysis56–59.

The National Centers for Environmental Prediction/National Centers for Atmospheric Research reanalysis I (NCEP/NCAR)60 and the ERA-Interim reanalysis data3 were used to analyze the large-scale atmospheric circulation features, including 850-hPa winds and relative vorticity, sea level pressure (SLP), vertical wind shear (VWS), which was defined as the difference of vector winds between 200 and 850 hPa, and steering flow, which was defined as the mass-weighted mean winds between 300 and 850 hPa. The monthly mean SST data were derived from the Hadley Center Sea Ice and Sea Surface Temperature dataset50 (HadISST). We focused on the atmospheric and oceanic conditions during the typhoon season of the Northwest Pacific, namely July–November (JASON).

The atmospheric general circulation model (AGCM) ECHAM4.8 developed by the Max Planck Institute (MPI) was adopted to conduct five experiments as listed in Table 1. The ECHAM model was configured with 19 vertical levels and run at spectral T42 horizontal resolution with the mass-flux type convective parameterization scheme51,52. A detailed model description can be found in Roeckner et al.53. The control run (CTRL) was forced by the observed climatological monthly mean SST during 1980–2015. The hiatus run (HTS) was identical to the CTRL except that the monthly SST difference between the hiatus (1998–2015) and pre-hiatus (1980–1997) were added to each climatological monthly mean SST in the belt region (60°S–60°N; 0°–360°). To estimate the relative contributions of SST anomalies over the Pacific Ocean (PO), the IO, and the AO to the trends in atmospheric conditions controlling the ITCT change, we further conducted the PO run, the IO run, and the AO run. These three runs were also identical to the CTRL run except that the hiatus SST differences were prescribed only over the PO (60°S–60°N; 110°E–160°W), the IO (60°S–60°N; 0°–110°E), and the AO (60°S–60°N; 60°W–0°), respectively. The model was integrated for 30 years for all experiments and the last 20-year model outputs were used in our analyses.

The Singular Value Decomposition (SVD) was used to identify the coupled modes between the global SST anomalies and the ITCTs over the Northwest Pacific. The SVD was first introduced to document the simultaneous relationship between two meteorological fields54 and further developed to find the coupled patterns in climate variables55. The Empirical Orthogonal Function (EOF) analyses of the global SST anomalies and the ITCTs over the Northwest Pacific were also conducted to compare with results based on the SVD analyses. Since we focused on long-term changes, the interannual signals (less than 10 years) in the ITCT and SST data were removed using fast Fourier transform (FFT) before the SVD was performed. The Mann-Whitney U test58 was used to check the significance of the composite differences between hiatus and pre-hiatus periods.

Data availability. The JTWC best track TC data are downloaded from https://metoc.ndbc.noaa.gov/web/guest/jtwc/best_tracks/western-pacific. The SST analysis data are downloaded from the Hadley Centre website http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html. The ERA-Interim data are downloaded from http://apps.ecmwf.int/datasets/. The NCEP/NCAR reanalysis I is downloaded from https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html.

References

1. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436, 686–688 (2005).
2. Li, R. C. Y., Zhou, W., Shun, C. M. & Lee, T. C. Change in destructiveness of landfalling tropical cyclones over China in recent decades. J. Clim. 30, 3367–3379 (2017).
3. Mei, W. & Xie, S. P. Intensification of landfalling typhoons over the northwest Pacific since the late 1970s. Nat. Geosci. 9, 753–757 (2016).
4. Elsner, J. B. & Kossin, J. P. & Jagger, T. H. The increasing intensity of the strongest tropical cyclones. Nature 455, 92–95 (2008).
5. Holland, G. & Bruyère, C. L. Recent intense hurricane response to global climate change. Clim. Dyn. 42, 617–627 (2014).
6. Kang, N. Y. & Elsner, J. B. Consensus on climate trends in western North Pacific tropical cyclones. J. Clim. 29, 1051–1057 (2016).
7. Webster, P. J. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309, 1844–1846 (2005).
8. Balaguru, K. et al. Ocean barrier layers' effect on tropical cyclone intensification. Proc. Natl. Acad. Sci. 109, 14343–14347 (2012).
9. Balaguru, K., Foltz, G. R., Leung, L. R. & Emanuel, K. A. Global warming-induced upper-ocean freshening and the intensification of super typhoons. Nat. Commun. 7, 13870 (2016).
10. Mei, W., Xie, S.-P., Primeau, F., McWilliams, J. C. & Pasquero, C. Northwestern Pacific typhoon intensity controlled by changes in ocean temperatures. Sci. Adv. 1, 1500014 (2015).
11. Sobel, A. H. et al. Human influence on tropical cyclone intensity. Science 353, 242–246 (2016).
12. Lloyd, I. D. & Vecchi, G. A. Observational evidence for oceanic controls on hurricane intensity. J. Clim. 24, 1138–1153 (2011).
13. Sprintall, J. & Tomczak, M. Evidence of the barrier layer in the surface layer of the tropics. J. Geophys. Res. 97, 7305 (1992).
14. Wu, L., Wang, B. & Geng, S. Growing typhoon influence on East Asia. Geophys. Res. Lett. 32, L18703 (2005).
15. Sprintall, J. & Tomczak, M. Evidence of the barrier layer in the surface layer of the tropics. J. Geophys. Res. 97, 7305 (1992).
16. Wu, L., Wang, B. & Geng, S. Growing typhoon influence on East Asia. Geophys. Res. Lett. 32, L18703 (2005).
17. Ho, C. H., Baik, J. J., Kim, J. H., Gong, D. Y. & Sui, C. H. Interdecadal changes in summertime typhoon tracks. *J. Clim.* 17, 1767–1776 (2004).

18. Tu, J. Y., Chou, C. & Chu, P. S. The abrupt shift of typhoon activity in the vicinity of Taiwan and its association with western North Pacific–East Asian climate change. *J. Clim.* 22, 3617–3628 (2009).

19. Kosaka, Y. & Xie, S. P. Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature* 501, 403–407 (2013).

20. Meeth, G. A., Hu, A., Arblaster, J. M., Fasullo, J. & Trenberth, K. E. Extremes forced and internally generated decadal climate variability associated with the Interdecadal Pacific Oscillation. *J. Clim.* 26, 7298–7310 (2013).

21. Trenberth, K. E. & Fasullo, J. T. An apparent hiatus in global warming? *Earths Future* 1, 19–32 (2013).

22. England, M. H. et al. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nat. Clim. Change* 4, 222–227 (2014).

23. Huber, M. & Knutti, R. Natural variability, radiative forcing and climate response in the recent hiatus reconciled. *Nat. Geosci.* 7, 651–656 (2014).

24. Watanabe, M. et al. Contribution of natural decadal variability to global warming acceleration and hiatus. *Nat. Clim. Change* 4, 893–897 (2014).

25. Nieves, V., Willis, J. K. & Patzert, W. C. Recent hiatus caused by decadal shift in Indo-Pacific heating. *Science* 349, 532–535 (2015).

26. Liu, W., Xie, S. P. & Lu, J. Tracking ocean heat uptake during the surface warming hiatus. *Nat. Commun.* 7, 10926 (2016).

27. Dong, J. et al. The footprint of the Interdecadal Pacific Oscillation in Indian ocean sea surface temperatures. *Sci. Rep.* 6 (2016).

28. Takahashi, C. & Watanabe, M. Pacific trade winds accelerated by aerosol forcing over the past two decades. *Nat. Clim. Change* 6, 768–772 (2016).

29. Delworth, T. L., Zeng, F., Rosati, A., Vecchi, G. A. & Wittenberg, A. T. A link between the hiatus in global warming and North American drought. *J. Clim.* 28, 3834–3845 (2015).

30. Ueda, H. et al. Combined effects of recent Pacific cooling and Indian ocean warming on the Asian monsoon. *Nat. Commun.* 6, 8854 (2015).

31. Drineas, P., Drineva, E. & Huggins, P. S. An experimental evaluation of a Monte–Carlo algorithm for singular value decomposition. *Advances in Informatics* 2563, 279–296 (Springer Berlin Heidelberg, 2003).

32. Bretherton, C. S., Widmann, M., Dymnikov, V. P., Wallace, J. M. & Bladé, I. The effective number of spatial degrees of freedom of a time-varying field. *J. Clim.* 12, 1990–2009 (1999).

33. Xie, S. P. & Kosaka, Y. What caused the global surface warming hiatus of 1998–2013? *Carr. Clim. Change Rep.* 3, 128–140, https://doi.org/10.1007/s40641-017-0063-0 (2017).

34. Zhao, H. & Wu, L. Inter-decadal shift of the prevailing tropical cyclone tracks over the western North Pacific and its mechanism. *Adv. Atmos. Sci.* 30, 919–930 (2013).

35. Prohaska, J. T. A technique for analyzing the linear relationships between two meteorological fields. *Mon. Weather Rev.* 104, 1345–1353 (1976).

36. Bretherton, C. S., Smith, C. & Wallace, J. M. An intercomparison of methods for finding coupled patterns in climate data. *J. Clim.* 5, 541–560 (1992).

37. Chu, P. S. Large-scale circulation features associated with decadal variations of tropical cyclone activity over the central North Pacific. *J. Clim.* 15, 2678–2689 (2002).

Acknowledgements

We are grateful to two anonymous reviewers for their constructive review comments and to Dr. James P. Kossin for providing the ADT-HURSAT dataset. This study is supported by the National Key R&D Program of China under grant 2017YFC1501604 and the National Science Foundation of China (grants 41375093, 41575052, and 41575053).
41675044). Jiuwei Zhao acknowledges China Scholarship Council (File No. 201608320175) for the financial support. Ruifen Zhan was supported in part by the JAMSTEC through its sponsorship of the International Pacific Research Center (IPRC) in the School of Ocean and Earth Science and Technology (SOEST), University of Hawaii at Manoa and by the Typhoon Scientific and Technological Innovation Group of Shanghai Meteorological Service.

**Author Contributions**

J.Z. carried out data analyses and prepared all of the figures. R.Z. and Y.W. designed and organized the research. All authors contributed to the writing of the manuscript.

**Additional Information**

**Competing Interests:** The authors declare no competing interests.

**Publisher’s note:** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

---

© The Author(s) 2018