

## RESEARCH LETTER

10.1002/2015GL063184

## Key Points:

- Spring NTA SST anomaly significantly correlates with WNP TC genesis frequency
- The remote teleconnection initiated from the Atlantic affects WNP TC genesis
- Spring NTA SST anomaly could be a new predictor for seasonal WNP TC activity

## Supporting Information:

- Figures S1–S6 and Tables S1–S4

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## Citation:

Huo, L., P. Guo, S. N. Hameed, and D. Jin (2015), The role of tropical Atlantic SST anomalies in modulating western North Pacific tropical cyclone genesis, *Geophys. Res. Lett.*, 42, 2378–2384, doi:10.1002/2015GL063184.

Received 21 JAN 2015

Accepted 7 FEB 2015

Accepted article online 11 FEB 2015

Published online 1 APR 2015

## The role of tropical Atlantic SST anomalies in modulating western North Pacific tropical cyclone genesis

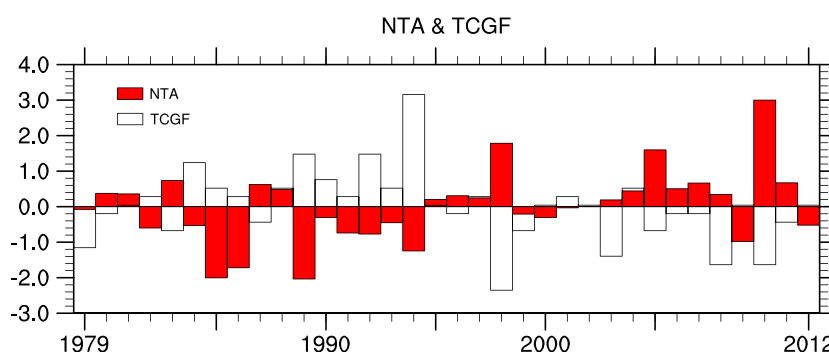
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**Abstract** The connection between north tropical Atlantic (NTA) sea surface temperature (SST) anomalies and tropical cyclone (TC) genesis over the western North Pacific (WNP) and associated physical mechanisms are investigated in this study. We demonstrate a remarkable negative correlation of WNP TC genesis frequency with the (preceding) boreal spring NTA SST anomalies. Our analysis suggests that major factors for TC genesis including distributions of large-scale vorticity and midtropospheric humidity are rendered unfavorable by remote teleconnections while barotropic energy conversion from the large-scale flow is suppressed. As shown in recent studies, the remote teleconnection from the Atlantic is sustained and enhanced throughout the typhoon season through local air-sea interactions. These results suggest that boreal spring NTA SST anomaly could be a new predictor for the seasonal WNP TC activity.

## 1. Introduction

The interannual variability of tropical cyclone (TC) activity over the western North Pacific (WNP) has been widely studied since mid-1980s [Landsea, 2000; Camargo et al., 2010]. The dominant interannual mode in the tropical Pacific, the El Niño–Southern Oscillation (ENSO), is considered as a major contributing factor to influence for WNP TC variability. ENSO has important impacts on the mean genesis location [Chan, 1985; Chen et al., 1998; Chia and Ropelewski, 2002], duration [Wang and Chan, 2002], and intensity [Camargo and Sobel, 2005; Chan, 2007] of TC over the WNP. In addition, Wang and Chan [2002] found that the number of WNP TCs increased during strong El Niño events while a decrease was noted during the summer following an El Niño event, in spite of not finding significant linear relationship between annual TC formation frequency and ENSO indices.

The tropical Indian Ocean (IO) has been also found to exert influence on climate variability over the western Pacific and East Asia [Saji and Yamagata, 2003; Yoo et al., 2006; Yang et al., 2007; Xie et al., 2009]. Xie et al. [2009] suggested El Niño can induce tropical IO warming, which can force a warm tropospheric Kelvin wave that propagates into the western Pacific and exert influence on TC formation [Du et al., 2011; Zhan et al., 2011]. The Atlantic basin is the site of several modes of climate variability, such as the Atlantic multidecadal oscillation (AMO) [Goldenberg et al., 2001], a natural mode of variability in the North Atlantic Ocean on multidecadal time scales, and the Atlantic meridional mode (AMM) [Servain et al., 1999], a coupled ocean-atmospheric mode of variability in the tropical Atlantic associated with meridional displacements of the Intertropical Convergence Zone and attendant shifts in SST and winds. Both AMM and AMO have vital influence on climate variations and hurricane activity in the Atlantic [Landsea et al., 1999; Goldenberg et al., 2001; Vitart and Anderson, 2001; Vimont and Kossin, 2007; Wang et al., 2008; Patricola et al., 2014]. Moreover, many studies suggested that the Atlantic Ocean variability can affect the variability and predictability of ENSO [Dommenget et al., 2006; Jansen et al., 2009; Rodríguez-Fonseca et al., 2009; Frauen and Dommenget, 2012; Ding et al., 2012; Ham et al., 2013]. Recently, Ham et al. [2013] suggested that anomalies in the north tropical Atlantic (NTA) SST can serve as a trigger for warm-pool El Niño events [Ashok et al., 2007; Kug et al., 2009]. They suggested a subtropical teleconnection linking the NTA SST anomalies with the Pacific atmospheric anomalies, through which NTA SST anomalies affect the tropical Pacific atmospheric circulation and SST. Ham et al. [2013] also showed that the anomalies induced by teleconnection from the Atlantic can be persisted over the typhoon formation season through local air-sea interactions in the western and central Pacific. Since these circulation



**Figure 1.** Time series of north tropical Atlantic ( $90^{\circ}\text{W}$ – $15^{\circ}\text{E}$ ,  $0^{\circ}$ – $25^{\circ}\text{N}$ ) SST anomaly (NTA; red bars) in boreal spring (MAM) and the WNP TC genesis frequency (tropical cyclone genesis frequency (TCGF); white bars) during the typhoon season (JJASO). Both time series are unfiltered and are standardized by dividing with their respective standard deviation ( $\sigma_{\text{NTA}} = 0.31 \text{ K}$ ).

changes can potentially modify large-scale kinematic and thermodynamic conditions crucial to TC formation over the WNP [e.g., Gray, 1968], it is of interest to explore whether the NTA teleconnection demonstrated by Ham *et al.* [2013] would have an impact on WNP TC formation.

To this end, we have analyzed the relation between NTA SST anomalies and WNP TC genesis during the 1979–2012 period and explored possible physical mechanisms linking TC genesis to NTA SST variability. Our analysis reveals a robust statistical relation between NTA SST anomalies and WNP TC genesis. This along with the plausibility of the mediating mechanisms revealed in this analysis strongly suggests that NTA SST variability could be used as a new predictor that can significantly improve the seasonal forecast of the WNP TC activity.

## 2. Data and Methods

The genesis frequency of WNP TC during the typhoon season (June–October, JJASO) is calculated using the best track TC data (location and intensity at 6-hourly intervals) produced by the Shanghai Typhoon Institute of China Meteorological Administration (CMA). We note that in the above data set, a TC is defined as a storm with 2 min sustained winds of 17.2 m/s or above. Considering the quality and reliability of data prior to the satellite era, our analysis is limited to a 34 year period (1979–2012). The genesis frequency is the total genesis number of TC during the typhoon season over the WNP (north of the equator and west of the international date line). The best track data from Japan Meteorological Agency (JMA) and Joint Typhoon Warning Center (JTWC) are also used to analyze the relationship between NTA SST and TC frequency. Since the data from all the three agencies agree quite well in representing the interannual variability of TC frequency (Figure S1 in the supporting information), here we show only the results based on the CMA best track data. Environmental variables are obtained from the U.S. National Centers for Environmental Prediction (NCAR) reanalysis [Kalnay *et al.*, 1996] and Outgoing Longwave Radiation (OLR) data from the National Oceanic and Atmospheric Administration (NOAA). SST data was obtained from the Met Office Hadley Centre (HadISST1) [Rayner *et al.*, 2003].

## 3. Results

### 3.1. Time Series Analysis

Figure 1 displays the unfiltered time series of NTA ( $90^{\circ}\text{W}$ – $15^{\circ}\text{E}$ ,  $0^{\circ}$ – $25^{\circ}\text{N}$ ) SST anomalies during March–May (MAM) (red bars) together with WNP TC genesis frequency over the typhoon season (JJASO). We can see that there is a strong inverse relation between the two, with TC frequency lowered during warm NTA SST anomaly years and vice versa. The correlation coefficient is noted to be  $-0.67$  (significant at the 99% level). The time series also displays significant low frequency variability, such as a multidecadal signal. The impact of such variations on the inverse relation will be discussed in the analysis to follow.

It is well known that NTA SST is affected partly by the ENSO [Alexander and Scott, 2002]. In particular NTA SST has a robust lagged relationship with ENSO variability [Chiang and Sobel, 2002]. Therefore, it is possible that NTA SST is acting simply as a proxy for ENSO variability. To account for this, we model and remove the

**Table 1.** Linear Correlation Analysis Between the WNP TC Genesis Frequency During Typhoon Season (JJASO) and the NTA Index for MAM and JJASO<sup>a</sup>

	NTA MAM/JJASO			
	Raw	<i>dtrend</i>	noENSO	IAV
TCGF	−0.67/−0.66	−0.64/−0.64	−0.60/−0.61	−0.52/−0.58

<sup>a</sup>The subheading raw refers to the case where correlation is calculated using unfiltered anomalies. Correlations are repeated after removing linear trend (*dtrend*) and decadal anomalies (IAV) from both the time series. In noENSO, the lagged ENSO effect is removed only from the NTA time series.

lagged effect of ENSO by linear regression of spring (March–May, MAM) NTA SST with the preceding winter (December–February, DJF) Niño 3.4 SST (170°W–120°W, 5°S–5°N).

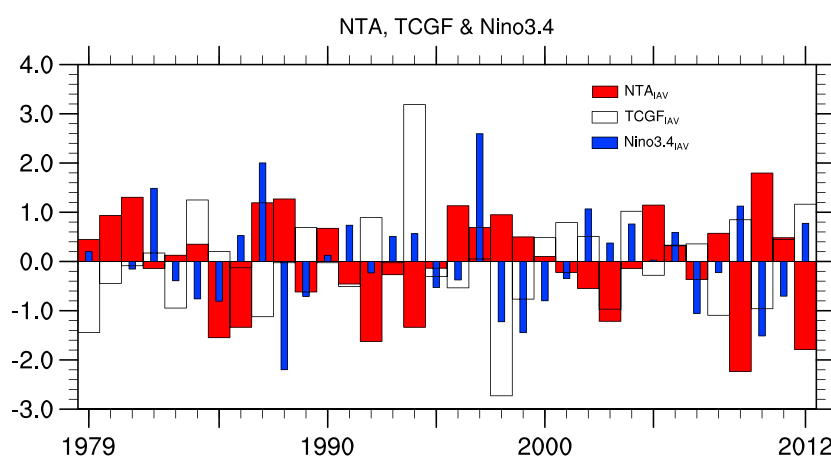
Table 1 shows that the correlation between NTA and TC genesis frequency is essentially unchanged even after removing the ENSO effect from the former. In addition, we also carried out a correlation analysis between DJF Niño 3.4 and WNP TC

frequency, which revealed negligible correlation between the two (see Table S4), as reported by previous researchers [e.g., *Ramage and Hori*, 1981; *Lander*, 1994; *Wang and Chan*, 2002]. Together, these suggest that the inverse relation between NTA SST anomalies and TC genesis frequency variations is quite robust.

A spectral analysis of the NTA SST index reveals that there are significant decadal and interdecadal variations besides interannual scales in the tropical Atlantic (Figure S2), consistent with previous studies [*Xie and Carton*, 2004]. To examine if the connection between NTA SST and WNP TC genesis is affected by decadal and multidecadal variations, we have repeated the correlation analysis after filtering the decadal variability using an 11 year running mean filter. After removing the decadal variations, the NTA SST index is still significantly correlated with the WNP TC frequency, with a correlation coefficient of −0.52 (above 99% confidence level).

Therefore, we conclude that there is a robust inverse relationship between the WNP TC frequency during JJASO and the NTA SST in MAM and that the relationship operates mostly on interannual time scales. Please note that in the following analyses that we describe and discuss, we will use only the interannual NTA time series from which decadal and lower frequencies are filtered out.

Based on the detrended and low-pass filtered NTA time series during 1979–2012 shown in Figure 2, we select six warm NTA years (1981, 1987, 1988, 1996, 2005, and 2010) and seven cool NTA years (1985, 1986, 1992, 1994, 2003, 2009, and 2012) with NTA exceeding 1 standard deviation for further analysis of the relationship. In particular, we have explored if there are systematic changes in the genesis location during cool and warm NTA SST anomaly years. However, it is seen that the genesis location of the WNP TC displays no particular differences between warm and cool NTA years (Figures S3 and S4).



**Figure 2.** Time series of MAM NTA SST index (red bars), JJASO Niño 3.4 index (blue bars), and JJASO WNP TC genesis frequency anomaly (TCGF, black solid line). All time series are normalized by dividing with their respective standard deviation ( $\sigma_{\text{NTA}} = 0.21$  K;  $\sigma_{\text{Niño3.4}} = 0.70$  K). The subscript IAV indicates that decadal and longer time scales are removed from the time series.

**Table 2.** Linear Correlations Between the WNP TC Genesis Frequency During JJASO and the Equatorial Central Pacific (ECP; 5°S–10°N, 170°E–130°W) SST Index During MAM and JJASO

	ECP MAM/JJASO		
	Raw	<i>dtrend</i>	IAV
TCGF	−0.02/0.33	−0.08/0.33	−0.21/0.27

### 3.2. Large-Scale Circulation Patterns

Having demonstrated a robust relationship between anomalies of NTA SST in boreal spring with TC genesis frequency in the WNP, we turn our focus on understanding possible dynamical/thermodynamical factors that are responsible for this remote

effect. We first carried out a linear regression analysis of spring NTA SST anomalies with surface wind and SST anomalies over the Pacific at various lags. Our results agree well with that of *Ham et al.* [2013] in all essential details and hence are not shown (see Figure S6). In agreement with *Ham et al.* [2013], we also find that the Atlantic to Pacific teleconnection is initiated as a Matsuno-Gill type Rossby-wave atmospheric circulation anomaly [*Matsuno*, 1966; *Gill*, 1980] during boreal spring. Lag regression analysis then suggests that the anomalous atmospheric and oceanic variations over the central and eastern tropical Pacific are gradually intensified throughout the typhoon season, presumably due to local air-sea coupling and instability [*Ham et al.*, 2013; *Sasaki et al.*, 2014]. At the same time NTA SST anomalies and associated atmospheric response persists over the Atlantic throughout the typhoon season (Table S3), augmenting Pacific anomalies.

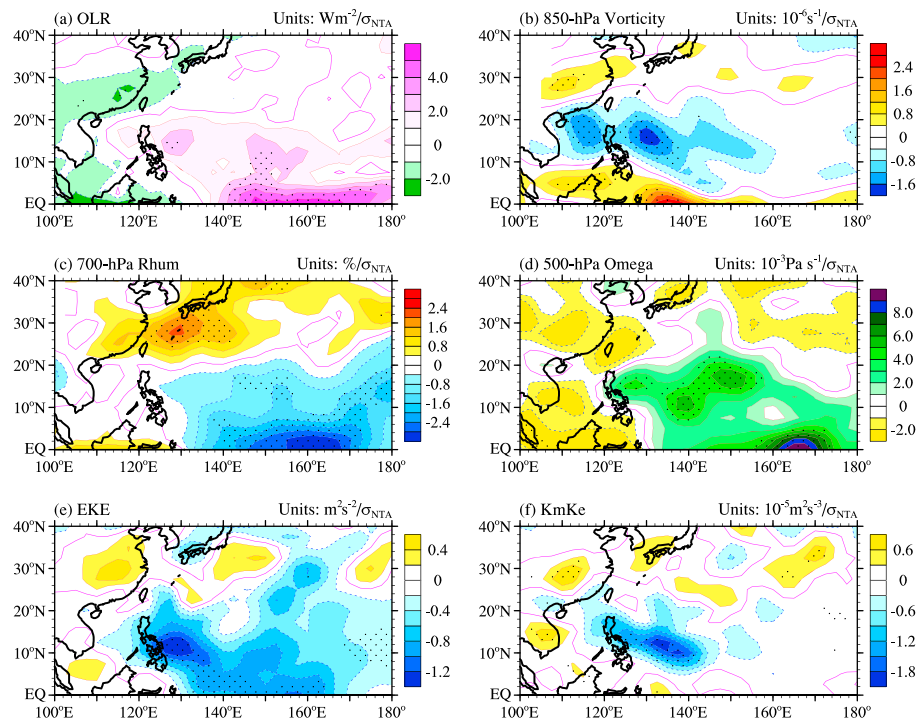
Interestingly, the SST anomaly pattern over the tropical Pacific as revealed by the lag regression analysis with NTA SST anomalies [Figure S6] has some resemblance to the so-called ENSO Modoki/Central Pacific El Niño [*Ashok et al.*, 2007] and raises the possibility that the correlations described in Figure 1 and Table 1 are possibly related to these ENSO flavors. In order to study this issue, we select a rectangular region (5°S–10°N, 170°E–130°W) that is highly correlated with the NTA index to calculate the equatorial central Pacific (ECP) SST index, with which lagged and simultaneous correlations with the TC frequency are calculated (Table 2). However, it is seen that lagged correlations are negligible, while simultaneous correlation is weak. This suggests that the WNP TC genesis frequency is only modulated by Pacific variability that is associated with NTA SST anomalies.

Thus, it is clear that significant SST and circulation anomalies develop and persist throughout the typhoon season over the tropical Atlantic and Pacific following the NTA SST signal. However, do these circulation anomalies have a consistent relationship with the observed tendency in TC genesis frequency as dynamic and/or thermodynamic factors?

To explore this, we have linearly regressed various dynamic/thermodynamic factors that are known to control TC genesis and activity with the NTA index. Figure 3 in particular presents the regressed fields of the OLR, vorticity, relative humidity, vertical velocity, eddy kinetic energy (EKE), and barotropic energy conversion from low frequency to EKE (KmKe) with respect to the NTA over the WNP. The EKE tendency equations used in this study are the same as those in *Seiki and Takayabu* [2007]. KmKe is also included in the analysis since it is an extra energy source for eddies contributing to TC formation and development [*Zhan et al.*, 2011].

Figure 3 provides insights into the dynamical/thermodynamical factors mediating the influence of NTA SST anomalies on TC genesis. All the factors shown in Figure 3 have a sign that is consistent with the time series analysis elucidated in the previous section. For instance, dynamic factors such as vorticity and vertical velocity are seen to favor increased (decreased) TC genesis during cool (warm) NTA SST years. A variety of observational and numerical studies have suggested that midtropospheric humidity is an important control on the genesis and intensification of TCs [*Gray*, 1975; *Yokoi and Takayabu*, 2010]. In fact, it is clearly seen that midtropospheric humidity is indeed significantly reduced (enhanced) during warm (cool) NTA SST anomaly years.

The analysis also reveals that negative EKE anomalies cover most of the tropical WNP collocated with regions of anomalous vorticity. It is noted that the center of EKE anomalies are situated east of the Philippines (Figure 3e) coincident with the climatological maximum in TC genesis intensity. In addition, KmKe, a measure of the barotropic energy conversion from the large scale to eddies, is seen to decrease (increase) during warm (cool) NTA SST anomaly years. In summary, the analysis suggests that there is a strong physical basis for the inverse relation between NTA SST anomalies and TC genesis frequency over the WNP.



**Figure 3.** Lagged regressed fields of (a) OLR, (b) 850 hPa relative vorticity, (c) 700 hPa relative humidity, (d) 500 hPa vertical velocity, (e) eddy kinetic energy (EKE), and (f) barotropic energy conversion (KmKe) at 850 hPa during JJASO with respect to the interannual MAM NTA SST index after removing DJF Niño 3.4 impact for 1979–2012 ( $\sigma_{NTA} = 0.21$  K). Regression coefficients exceeding 95% confidence level are stippled.

#### 4. Concluding Remarks

The relation between TC activity in the WNP and large-scale climate variability has been the subject of numerous studies over the past few decades. Most studies have naturally focused on the tropical Pacific and to some extent in recent years on the Indian Ocean, both of which by virtue of their relative proximity may be expected to influence the large-scale conditions relevant to TC genesis and development over the WNP. In this context, the strong relation between WNP TC genesis and NTA SST anomalies as revealed by our analysis is hugely surprising. Due to this, we have taken due care in our analysis to consider various alternative scenarios, for example, the indirect effects of ENSO and the influence of decadal modes. Further the statistical analysis is well supported by circulation diagnostics that show that the signatures of environmental changes associated with the NTA SST signal are quite consistent with our understanding of how such factors affect TC genesis.

While these findings support evidence for a link between the variability of North Atlantic SST and TC genesis over the WNP on interannual time scales, it also raises new questions. One of these questions relate to the nature of SST anomalies in the tropical Atlantic. Although ENSO is considered as a factor for variability of NTA SST anomalies, it is quite surprising that the relationship with WNP TC frequency remains strong even after accounting for the ENSO factor from the NTA SST. Additionally, it is seen that ENSO by itself does not appear either as a consistent precursor or a simultaneous factor in variations of WNP TC genesis frequency. However, it can be seen (Figure 2) that many of the notable SST anomalies in the NTA follows an ENSO signal. It may be tempting to hypothesize that these may be reflective of local air-sea coupling that are initially set up by external factors such as ENSO, and persisted and amplified in the North Atlantic through local air-sea interactions. However, one can note that the time series of NTA SST variability is characterized by an apparent multiyear persistence, which remains even after decadal variations are filtered. This suggests that there may be other important factors for such NTA SST variations that need to be explored in the future.



## Acknowledgments

The data for this paper are NCEP/NCAR Reanalysis 1 data sets available at <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>, NOAA Interpolated Outgoing Longwave Radiation (OLR) data sets obtained from [http://www.esrl.noaa.gov/psd/data/gridded/data.interp\\_OLR.html](http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html), Met Office Hadley Centre observations data sets: HadISST1 data available at <http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>. The best track data are produced by the Shanghai Typhoon Institute of China Meteorological Administration (CMA) obtained from [http://tcdata.typhoon.gov.cn/zljjsj\\_zhq.html](http://tcdata.typhoon.gov.cn/zljjsj_zhq.html), Japan Meteorological Agency (JMA) available at <http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html>, and Joint Typhoon Warning Center (JTWC) obtained from [http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best\\_tracks/wpindex.php](http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.php). This research was jointly supported by NSFC (41230422), the Special Funds for Public Welfare of China (GYHY 201206017), NCET Program, the Natural Science Foundation of Jiangsu Province of China under grant BK2004001, and project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD). L. Huo was also supported by the Research Innovation Program for college graduates of Jiangsu Province (CX10B\_289Z). D. Jin was supported by the Startup Foundation for Introducing Talent of NUIST (grant 2014r006).

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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