Science in China Series D: Earth Sciences

North Pacific sea ice cover, a predictor for the Western North Pacific typhoon frequency?

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The relationship between the sea ice cover in the North Pacific and the typhoon frequency has been studied in this paper. It follows that the index for the sea ice cover in the North Pacific (ISA) both in December-January-February (DJF) and in March-April-May (MAM) is negatively correlated with annual typhoon number over the western North Pacific (TNWNP) during 1965—2004, with correlation coefficients of –0.42 and –0.49 respectively (above 99% significant level). Large sea ice cover in the North Pacific tends to decrease TNWNP. Positive ISA (MAM) is associated with the tropical circulation and SST anomalies in the North Pacific, which may lead to unfavorable dynamic and thermal conditions for typhoon genesis over WNP from June to October (JJASO). The variability of the atmospheric circulation over the North Pacific, associated with the ISA anomaly in MAM is connected to the tropical atmospheric circulation variability in MAM via the teleconnection wave train. Besides, as the tropical circulation has strong seasonal persistency from the MAM to JJASO, thus, the ISA in MAM-related variability of the tropical atmospheric circulation as well as the SST can affect the typhoon activity over the western North Pacific.

typhoon, sea ice cover, North Pacific, teleconnection

1 Introduction

The interannual variability of Tropical Cyclone (TC) activities is scientifically and economically an important problem. Early studies indicate that the El Niño-Southern Oscillation (ENSO) and the stratospheric Quasi-Biennial Oscillation (QBO) appear to be the dominant factors in governing the interannual variability of the TC activities over the Western North Pacific (WNP)[1−10]. These results show that ENSO events can modify, to a large extent, the locations and intensities of TC formation as well as TC tracks. During El Niño years, fewer TCs were formed over the main TC genesis regions, while more were generated over the east of the main TC genesis regions in the WNP. There is usually a southeastward displacement in the genesis regions of the mean tropical storm and typhoon and there are more longer lifetime and stronger intensity TC during the El Niño years. The adverse situation usually occurred during the La Niña years. Chan[11] suggested that difference variability of TC in WNP associated with the year before (El Niño-1 and La Niña-1), El Niño and La Niña as well as after years (El Niño+1 and as well as La Niña +1)[12,13]. The change in the atmospheric circulation associated with ENSO causes anomalous Walker circulations with a shift in location, tropical convergence belt, SST, tropical convection, the magnitude of zonal wind vertical shear, etc., which then modify the locations of TC formation, and the intensities and the tracks of TC. Furthermore, it is also indicated that changes of TC formation and development are related to the phase of the stratospheric QBO[9,10].

Early literature in China noticed that the relationship

Received December 29, 2006; accepted March 2, 2007
doi: 10.1007/s11430-007-0076-y
Supported by the National Natural Science Foundation of China (Grant Nos. 40631005, 40620130113 and 40221503)

between TC activities in WNP and atmospheric circulation in both hemispheres, especially the Southern Hemisphere[14−20]. They suggested that the meridional circulation at low latitudes in the Southern Hemisphere, along with cold activity outbreak in Australian, may enhance the cross equatorial flow and the tropical convergence belt, which may induce the typhoon formation in WNP. Recently, it is found that the Antarctic Oscillation, a high latitude major atmospheric mode in the Southern Hemisphere, representing the mass exchange between the high latitude and middle latitude in the Southern Hemisphere, may have impact on both dust climate and summer rainfall in China[21−23]. Wang and Fan[24] discussed the relationship between the Antarctic Oscillation in June-September and the annual typhoon numbers in WNP. They found that the tropical atmospheric circulation as well as the sea surface temperature variability over the western Pacific associated with the positive phase of Antarctic Oscillation could provide unfavorable environment for the typhoon genesis, and *vice versa*.

More recently, Wang et al.1) explored the relationship between the North Pacific Oscillation (NPO) and typhoon as well as hurricane frequency. NPO is a major interannual atmospheric mode in the North Pacific, showing the seesaw pattern of the sea-level pressure between high and low latitudes in the Pacific. NPO index can be defined as the normalized sea-level pressure (SLP) difference between the point (65°N, 175°E) and point (25°N, 165°E) in the North Pacific1). Positive NPO represents weaker Aleutian Low and subtropical North Pacific High. They found that NPO index in June-July-August-September (JJAS) is positively correlated with annual Typhoon number in WNP and is negatively correlated with annual hurricane number in the tropical Atlantic for the period of 1949—1998. Wang[25−27] revealed that the Circum-Pacific teleconncetion pattern in meridional wind in the high troposphere may play roles in linking the two hemispheres. Their researches suggest that circulations at high latitudes in both hemispheres are important for both the Typhoon activities in the WNP and hurricanes in the tropical Atlantic. However, the variation of the typhoon activities are complex and the underlying physical mechanisms remain mostly unclear. Therefore, we aim to study the relationship between the extratropical variability (especially the sea ice cover in the North Pacific) and typhoon activities in the WNP in this work. We will also performe a preliminary investigation on the large-scale circulation associated with sea ice cover in the Pacific as a potential aid to seasonal prediction of TC activities in the WNP.

Prior to our current study, Wu et al.[28] suggest that positive winter sea ice extend anomalies in the Barents and Kara Sea may weaken the northerlies in East Asia, hence reducing the cold air invasion into China in winter. Zhao et al.[29] found that the reduced sea ice extent may lead to a reinforced summer monsoon rainfall in southeastern China via the stationary wave dynamics and land surface processes.

The dateset for the annual typhoon number over WNP (TNWNP) was obtained from the Joint Typhoon Warning Center (JTWC). Because most of typhoons are formed in June-July-August-September-October (JJASO), the interannual variability of the typhoon frequency in the JJASO is basically consistent with that of the annual results. Thus, we focus on the spring season (March—May) and a summer season (JJASO). Here, WNP is confined to the area of 5°—45°N, 105°—180°E including the South China Sea. The Hadley Center for Climate Prediction and Research (HC) monthly mean sea ice concentration with a horizontal resolution of 1°×1° was also employed[30]. The monthly mean sea surface temperature (SST) used in this research is the NOAA optimum interpolation (OI) SST dataset [31]. The National Center for Atmospheric Research (NCAR) and National Center for Environment Prediction (NCEP) atmospheric monthly reanalysis data with resolution of 2.5°×2.5° were also applied in our analysis. Above datasets used in this research cover the period of 1965—2004.

2 The sea ice cover in the northern Pacific and the TC activities

Sea ice covers the northern part of the Pacific, mainly in the Bering Sea and the Sea of Okhotsk (BOS). ISA is confined to the areas of 53.5°—66.5°N, 158.5°E—159.5°W and 44.5°—59.5°N, 140.5°E—155.5°E. To address the relationship between the TNWNP and ISA, the time series of annual typhoon number and ISA in

1) Wang H J , Sun J Q, Fan K. Relationship between North Pacific Oscillation and the typhoon and hurricane frequency, Sci China Ser D-Earth Sci, 2006, accepted

December-January-February (DJF) and ISA in March-April-May (MAM) are displayed in Figure 1. All the time series have been normalized and detrended. The correlation coefficient between ISA-DJF and ISA-MAM is 0.54 (above 99% significant level), suggesting that ISA has a good seasonal persistence from the boreal winter to spring. The correlation coefficients between the TNWNP and ISA are −0.42 and −0.49 respectively for DJF and MAM, indicating a close relationship between ISA and the TNWNP on interannual time scale. Considering that most of the typhoon activities in the WNP occur from June to October (JJASO) in a year, the ISA (MAM) may be used as a predictor for typhoon frequency.

To further identify the relationship between the TNWNP and ISA (MAM), the correlation coefficients of SLP-TNWNP and SLP-ISA (MAM) are analyzed for 1965—2004. The positive correlation at high latitudes and negative correlation at low latitudes in the North Pacific are quite pronounced, corresponding to the positive NPO pattern in MAM (Figure 2(a)). The negative correlation dominates the whole Arctic region in MAM and it becomes weaker in JJASO (Figure 2(b)). The negative correlation coefficients are also remarkable at low latitudes in the Pacific in JJASO, as shown in Figure 2(b). Thus, atmospheric circulations over the Pacific

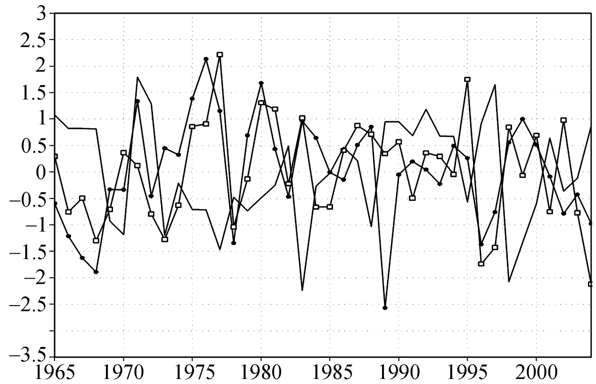

Figure 1 The interannual variation of ISA in MAM (solid line with dots), ISA in DJF (solid line with boxes) and TNWNP (solid line) during 1965—2004. All these time series have been normailized and detrended.

during MAM and JJASO are quite important for the typhoon genesis.

The correlation coefficients of ISA-SLP (MAM) and ISA-SLP (JJASO) patterns are shown in Figure 2(c) and (d), respectively. The spatial pattern of Figure 2(c) is basically reverse to that of TNWNP-SLP in Figure 2(a). The significant positive correlation is located in the tropical Pacific in Figure 2(d). Therefore, Figure 2 reconfirms that ISA (MAM) is negatively correlated with the annual typhoon frequency in the WNP, which suggests that large (small) sea ice cover in the North Pacific can potentially reduce (reinforce) the typhoon activ-

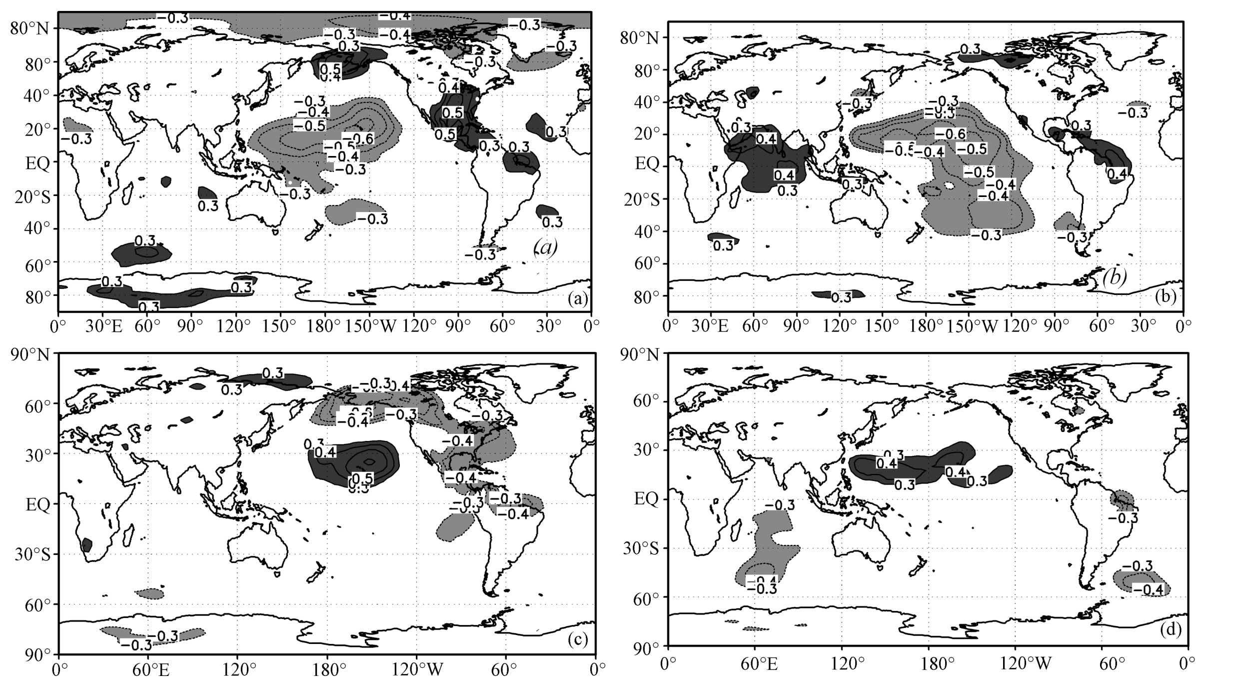

Figure 2 Correlations coefficients of TNWNP-SLP and ISA (MAM)-SLP during 1965-2004. Shaded areas indicate significant changes at 95% level, estimated by a local student's t-test. (a) TNWNP- SLP (MAM); (b) TNWNP- SLP (JJASO); (c) ISA (MAM)-SLP (MAM); (d) ISA (MAM)-SLP (JJASO).

ities in the WNP.

3 Atmospheric circulations and sea ice change in the North Pacific

We now analyze the atmospheric circulation associated with the variations of the sea ice cover in the North Pacific to understand how the sea ice affects the typhoon activities. Years 1977, 1979, 1980, 1981, 1988, 1994 (1965, 1967, 1972, 1978, 1982, 1997, 2004, 2002) are identified with positive (negative) ISA (MAM) anomalies years. In order to weaken the impacts of ENSO occurrence in different periods on typhoon, we exclude the years with the criteria that the mean SST anomalies averaged over 120°W－170°W, 5°S－5°N for lasting six months during the DJFMAM (from December to May) being greater (smaller) than +0.5℃ (–0.5℃).

The difference of the JJASO geopotential height at 850 hPa between positive and negative ISA years in MAM and JJASO is analyzed (Figures not shown). The apparent negative NPO anomalous pattern can be seen in MAM, with negative anomalies over the North Pacific and positive anomalies over the subtropical Pacific. It can be seen that positive anomalies dominate the WNP and the middle latitudes in southern Pacific in JJASO. Tropical atmospheric circulation over the Pacific is quite steady from the MAM to JJASO. Meanwhile, there is anticyclonic anomaly in the tropical Pacific in the positive phase of ISA, which is also unfavorable for enhancing the monsoon trough and the genesis of TC activities over WNP.

The vertical wind shear is defined here as the difference of zonal winds between 200 hPa and 850 hPa. Climatologically, The WNP contains a region with low vertical wind shear during JJASO and with the low-level convergences, positive vorticities as well as high SST. All these conditions are favorable for typhoon genesis and development. It is well known that stronger vertical wind shear inhibits tropical cyclogenesis while weaker vertical shear favors tropical cyclogenesis and possible typhoon development.

The composite differences of winds at 850 hPa as well as 200 hPa in JJASO between positive and negative ISA (MAM) years are shown in Figure 3. The easterly wind anomalies over WNP in low level indicate that the monsoon trough become weaker (Figure 3(a)). Another feature in Figure 3(a) is the twins systems with tropical anticyclonic anomalies on both sides of the equator, indicating the weaker cross equatorial flow along the 140°E from the Southern Hemisphere. The weaker cross-equatorial flow from the winter hemisphere is unfavorable to the genesis of typhoons in the summer hemisphere. The upper-level westerly anomalies over tropical Pacific and cyclonic anomalies over WNP are exhibited in Figure 3(b). Thus the vertical zonal wind shears are enhanced in the region, which is not favorable to the typhoon genesis and development.

To further analyze the impact of ISA (MAM) on the dynamic parameters for genesis of typhoon over WNP in JJASO, Figure 4 depicts the composite difference of the relative vorticity at 850 hPa and 200 hPa between the positive and negative ISA (MAM) years. The negative relative vorticity anomalies dominate the WNP at 850 hPa, which is consistent with anticyclonic anomalies in Figure 3(a), representing the weaker monsoon trough (Figure 4(a)). A large area with positive relative vorticity dominates the WNP in Figure 4(b). Therefore, by conducting the composite analysis, we find that positive

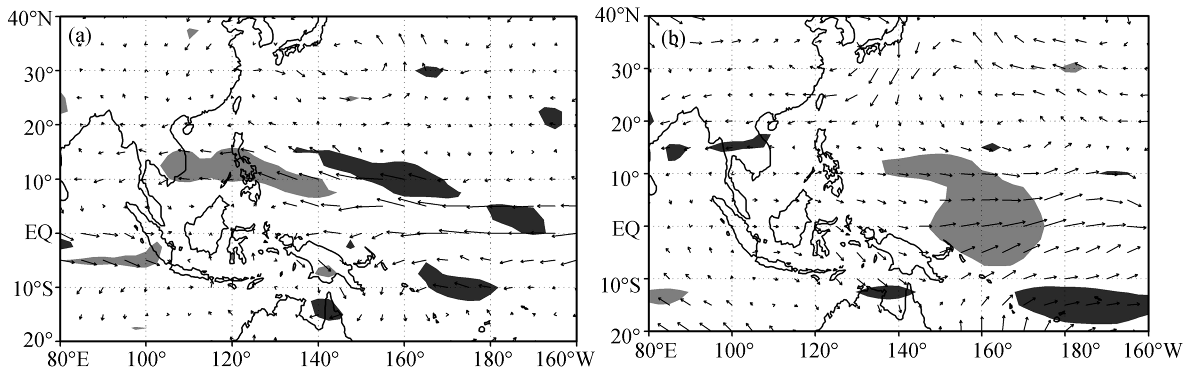

Figure 3 Composite differences of winds (in m/s) in JJASO between positive and negative ISA (MAM) years, with shading as Figure 2. (a) for 850 hPa and (b) For 200 hPa.

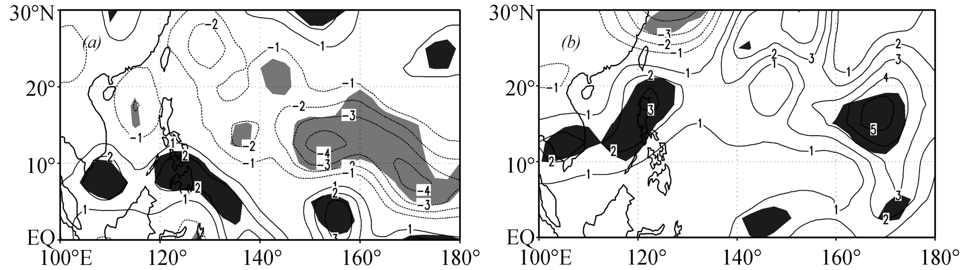

Figure 4 Composite differences of vorticities (in $1e^{-6}$ s^{-1}) in JJASO between positive and negative ISA (MAM) years, with shading areas as in Figure 2. (a) For 850 hPa; (b) for 200 hPa.

(negative) phase of ISA in MAM is associated with enhanced (weakened) vertical zonal shear, negative (positive) low-level relative vorticities and weakened (enhanced) monsoon trough in WNP, thus unfavorable (favorable) to the typhoon genesis and development. In the following section, we will discuss the possible physical mechanism.

4 Further explanation

How does sea ice cover in the North Pacific in boreal winter-spring affect the typhoon activities over WNP? The composite analysis suggests that changes of the atmospheric circulation over the tropical Pacific related to ISA (MAM) have a good seasonal persistence from MAM to JJASO. The atmospheric circulations anomalies at high latitudes over the North Pacific are substantially weaker in JJASO than in MAM, suggesting a weak seasonal persistence at high latitudes. However, the seasonal persistence of the circulation anomaly is much stronger in WNP (see Figure 2). Therefore, strong seasonal persistence of tropical Pacific atmospheric circulation may play an important role in the relationship between the ISA (MAM) and typhoon activities over WNP. To further testify our speculation, the correlation coefficient between the zonal wind at 200 hPa in MAM and that in JJASO during 1965—2004 is depicted in Figure 5. As can be seen, the significant positive correlations are distributed over the tropical and the subtropical Pacific, indicating the seasonal persistence of the circulation anomalies from MAM to JJASO. Such good seasonal persistence can be found in other atmospheric circulation components as well.

How about the simultaneous relationship between the sea ice cover in the North Pacific and tropical circulation in MAM? It has been found that TNWNP-associated SLP anomaly in MAM well displays a positive NPO anomaly pattern, with the weaker Aleutian Low and weaker subtropical high over the Pacific. In contrast, SLP variations in MAM related to ISA (MAM) show a negative NPO pattern, accompanied by the deeper Aleutian Low and stronger subtropical high over the North Pacific. Therefore, sea ice cover in the North Pacific may have impact on the tropical atmospheric circulation over the Pacific in terms of NPO and the atmospheric teleconnection between the North Pacific and WNP. The correlation between the SLP at (65°N, 170°E) and the global 200 hPa zonal wind in MAM is shown in Figure 6, exhibiting a well-organized teleconnection wave pattern, along with alternative positive and negative values from the polar region to tropical region over the Pacific. Positive SLP anomaly at point (65°N, 170°E) is corresponding to the upper-level easterly wind anomaly in MAM over the tropical Pacific. This is favorable to the increase of typhoon genesis because the tropical circulation over Pacific has good seasonal persistence from the MAM to JJASO (see Figure 5). Therefore, the teleconnection wave train plays a key role in the interaction between the extratropical and tropical atmospheric circulations in the context of typhoon-North Pacific sea ice relationship.

The thermal condition is also an important factor for the typhoon genesis and development. The composite

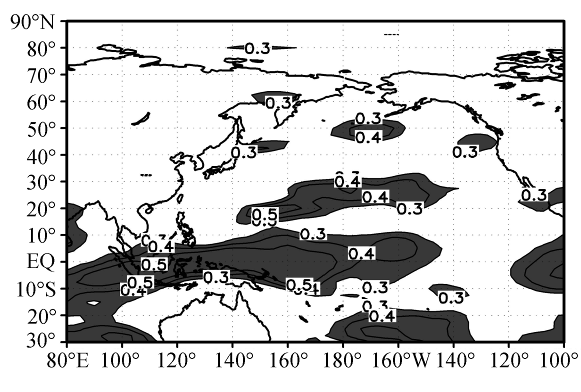

Figure 5 Correlation coefficients between the zonal winds in MAM and in JJASO at 200 hPa, with shading areas as in Figure 2.

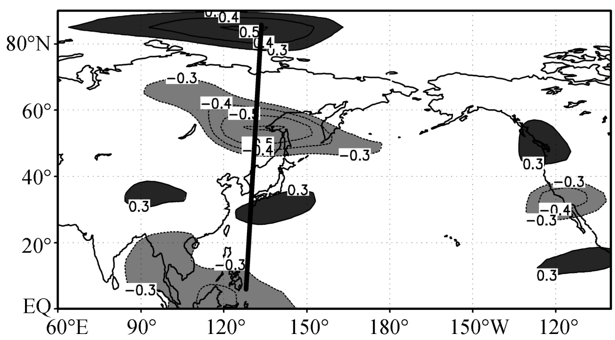

Figure 6 Correlation coefficients between SLP at grid point (65°N, 170°E) and zonal wind at 200 hPa in MAM. Shading area as in Figure 2. The black line indicates the wave train from the Artic to tropical.

differences of SST in MAM and JJASO between positive and negative ISA are displayed (Figure not shown). Negative SST anomalies in MAM are located along east of 140° E in the tropical Pacific and the Aleutian Low region. The SST anomalies in JJASO resemble those of MAM, except for that the Aleutian region. This is consistent with Ding[20] who note that the warming eastern to central tropical Pacific and western coast of North America are related to more typhoons over WNP. Thus, the ISA (MAM) associated with SST anomalies has good seasonal persistence in the WNP from MAM to JJASO. The cold equatorial central Pacific SST supresses the convective activities east of 140° E, which is consistent with Rossby wave-like response associated with anomalous twin anticyclonic anomaly systems over the tropical Pacific. It is also consistent with a large positive divergence anomaly at 850 hPa (figure not shown). The cold equatorial central Pacific SST anomaly associated with heating change tends to decrease the annual typhoon activities in the WNP.

5 Conclusion

In this paper, we define an index for the sea ice cover in the North Pacific (ISA) and found that ISA both in DJF and in MAM has significant signals in the typhoon frequency over WNP and discussed the possible mechanisms.

To sum up, positive (negative) ISA (MAM): (1) is highly correlated with the decreased (increased) the sea-level pressure and the local atmospheric circulation at high latitude over the north Pacific, (2) can potentially modulate the tropical circulation via the teleconnection wave train, (3) may change the tropical atmospheric circulation in JJASO, which tends to unfavor (favor) the typhoon genesis because of strong seasonal persistence. From the thermal perspective, positive (negative) ISA (MAM) is associated with the cold (warm) SST anomaly along the east of 140°E which weaken (increased) the convective activities, resulting in favorable thermal conditions for decreasing (increased) typhoon activities. However, our research is preliminary, the analysis based on more datasets as well as the state-of-the-art climate models is needed in the future work.

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