Decadal Relationship between the North Atlantic Oscillation and Cold Surge Frequency in Taiwan

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Abstract

The close decadal relationship between the North Atlantic Oscillation (NAO) and the cold surge frequency in Northern Taiwan is identified. The cold surge frequency was higher (lower) in 1957-1977 (1981-2001), which corresponded to the negative (positive) phase of the NAO. The teleconnection pattern associated with the NAO suggests that the Siberian high, the ridge upstream of Lake Baikal and the East Asian trough, which are well-known circulation characteristics favorable for cold surge occurrences, were enhanced in the negative NAO phase. A weakened upper-level convergence over the Mediterranean-Sahara occurring in the negative NAO phase was associated with a wave-like pattern spreading toward East Asia along the subtropical jet stream.

Barotropic modeling results suggest that the suppressed upper-level convergence in the Mediterranean-Sahara region may force a wave train emanating toward East Asia along the subtropical jet stream, which acts as a Rossby waveguide. The barotropic wave pattern may result in a stronger low-level northerly over subtropical East Asia and create a favorable background for the further southward penetration of cold air, and therefore more frequent cold surge occurrence. The same process may be applied to the period when the NAO is in the positive phase.

1. Introduction

Cold surge is one of the most prominent weather events in the East Asian winter monsoon (Chang et al. 1979). During strong cold surge events, cold air from Siberia often penetrates southward all the way to Southern China, Taiwan and the South China Sea (Chang et al. 2006). This means that the cold surge in Taiwan, an island off the southeastern coast of China, can be seen as an indication for cold surge occurrence, which has a stronger influence in subtropical East Asia.

Cold surge, like many severe weather systems exhibits significant interannual variation in frequency (Chen et al. 2004, Jeong and Ho 2005). This characteristic is likely due to the interannual variability of large-scale circulation, which creates a favorable/unfavorable background for the development and occurrence of cold surges. For example, a recent study by Jeong and Ho (2005) showed that the interannual cold surge occurrence variation is well correlated with the Arctic Oscillation (AO). Besides the interannual variability, the present study identifies a clear decadal signal in the cold surge frequency (CSF) in Taiwan. More interestingly, this fluctuation is strongly correlated with the North Atlantic Oscillation (NAO), which is known for its strong decadal variation (Hurrell 1995) and downstream influence on winter climate (Branstator 2002, Watanabe 2004). The intriguing relationship between the CSF in Taiwan and the NAO, and the corresponding large-scale circulation linking the two phenomena are reported. A possible mechanism explaining how the NAO affects the cold surge is also explored using a linearized perturbation barotropic model.

2. Data and definitions

The boreal winter (December to February of next year) is the focused period in this study. Data retrieved from the European Centre for Medium-range Weather Forecast reanalysis (ERA40, Uppala et al. 2005) in 1957-2002 are used to characterize the circulation variation. The SH index, following Wu and Wang (2002), is defined as the averaged SLP anomaly over (40°-60°N, 80°-120°E). The winter NAO index is defined according to Hurrell (1995). The definition of cold surge in Taiwan is: (i) the daily maximum temperature of Taipei (25°N, 121.5°E, located in Northern Taiwan) drops at least 4°C within 24 to 48 hours, and (ii) the daily minimum temperature in Taipei is less than 10°C. The CSF is defined as the number of cold surge events per winter.

3. Decadal oscillation of cold surge frequency and NAO Data and

The 7-year running means of the CSF anomaly in Taiwan, the NAO index and the SH index, exhibit a clear decadal oscillation (Fig. 1a). The CSF anomaly and SH index underwent a sharp phase reversal from positive to negative value around 1976/77, while the corresponding NAO index underwent a reversal around the same time but with opposite sign. During the NAO negative phase, the cold surge is more frequent, and the SH is stronger than in the positive NAO phase. The correlation coefficients between the SH index/the NAO index and the CSF are 0.86/-0.86, respectively, which exceed 99% confidence level. The decadal variation in the CSF and the NAO changed signs almost simultaneously around 1977. This year is therefore chosen as the reference year to investigate the changes in the atmospheric circulation between the two twenty-year periods before and after 1977.

Figure 1b presents the sea level pressure (SLP) and the 500-hPa height (H500) difference by subtracting the 1981-2001 mean from the 1957-1977 mean. The SLP difference exhibits a spatial pattern resembling the NAO pattern (Hurrell 1995). Besides the perturbation in the North Atlantic, a large-scale SLP pattern in the middle-high latitudes of the Eurasian continent is evident. The SLP north of the 60°N was higher in 1957-1977 than in 1981-2001. There was a negative SLP anomaly between 30°N and 60°N in the North Atlantic and also in the Mediterranean. This anomaly pattern indicates the weakened Icelandic low, subtropical anticyclone and westerly in the Atlantic in 1957-1977. A similar pattern but with a more wave-like structure is also seen in the H500, reflecting an equivalent barotropic vertical structure. These patterns also reveal the deepened upper-level trough over the East Asian coast, the enhanced upper-level ridge upstream of Lake Baikal and the stronger SH during 1957-1977. These are the common features that are often observed prior to the cold surge occurrence (Ding 1994, Takaya and Nakamura 2005). The similarity suggests that the NAO and the associated decadal change in the large-scale circulation provide a favorable background for the development and occurrence of East Asian cold surge.

There are other decadal variations in the Northern Hemisphere, e.g. the AO, the Pacific Decadal Oscillation (PDO), the North Pacific (NP) pattern, and the El Niño/Southern Oscillation (ENSO), which are probably well correlated with the CSF. Particularly, the PDO was found to be well correlated with the decadal fluctuation of the spring rainfall in Taiwan (Hung et al. 2004). To investigate how unique the decadal fluctuation of CSF in Taiwan was associated with the NAO, we calculated the correlation coefficients between the CSF and the indices that represent the fluctuation of large-scale circulation patterns such as the NAO, AO, PDO, ENSO and NP in the decadal time scale. As shown in Table 1, the correlation coefficients with the NAO and AO are as high as -0.86 and -0.82, respectively, which are much higher than those for the PDO, ENSO, and NP. The high correlation for both the NAO and AO is expected, because of the close association between the NAO and AO (Wallace 2000). The correlation coefficients between the AO and other variables in Table 1 are almost the same as those for the NAO. The following discussion will therefore focus on the NAO only. Although the PDO, ENSO and NP are significantly correlated with the SH, the correlation with the CSF is much weaker compared with the NAO (Table 1). It has been noted that a strong SH is not necessarily corresponding to a strong surge and the southward penetration of the cold air, because the latter was primarily associated with the low level northerly anomaly over southeast China (Compo et al. 1999). A calculation of the correlation coefficients between the 850hPa meridional wind anomaly over southeast China (105°-120°E,25°-35°N) and the above indices indicates that only the NAO was significantly correlated with northerly anomaly over the southeast China (Table 1), suggesting that the stronger downstream influence of the NAO on the decadal fluctuation of the CSF in Taiwan may be through its effect on the meridional wind in southeast China.

The longitude-height cross section of the meridional wind difference between 1957-1977 and 1981-2001 (Fig. 1c) shows that the low-level anomalous northerly in East Asia is associated with a upper-level wave train, emanating from the Mediterranean-Sahara region to southern East Asia along the subtropical jet, which has been identified as a Rossby waveguide in previous studies (e.g., Hsu and Lin 1992, Hoskins and Ambrizzi 1993, Branstator 2002). Figure 1c also reveals the equivalent barotropic vertical structure of the wave-like pattern. Particularly interesting is the upper-troposphere-to-surface northerly anomaly over the East Asian coast where cold surges occur. This result implies that the decadal fluctuation in the CSF in Taiwan is likely affected by the phase change of the upper-level wave train. It was shown in Hong et al. (2008) that the upper-level Rossby wave excited from the Mediterranean-Sahara region may help trigger the southward advance of cold surge. Watanabe (2004) demonstrated that the downstream impact on the East Asian weather, through the subtropical jet stream waveguide, was often stronger when the Rossby wave source (RWS, Sardeshmukh and Hoskins, 1988) over the Mediterranean-Sahara region was associated with the NAO. This effect is explored in the next section using a barotropic model to investigate how the decadal variability of the RWS associated with the NAO modified the low-level meridional wind in East Asia.

4. Effects of RWS over Mediterranean-Sahara

The 200-hPa velocity potential and RWS difference (Fig. 2a) show that the phase change of the wave train is associated with the decadal variation of the subsidence (i.e., upper-level convergence) over the Sahara and the Mediterranean. Two RWS can be seen clearly over the northeast Mediterranean and Sahara, respectively. The former can be attributed to the NAO induced rainfall anomaly over the Mediterranean (Hurrell 1995). Since the RWS over the Sahara is located to the south of the negative SLP and H500 anomalies associated with the NAO, where the upper-level divergence easily develops, the RWS can also be thought as a phenomenon induced by the NAO. This is consistent with the recent finding by Wang (2003).

Fig. 2b displays the observed 200-hPa streamfunction and wind difference. A wave train near the subtropical jet stream is clearly seen. The eastern end of this wave train is the anomalous northerly over south China and Taiwan, where the anomalous surface northerly and cold surges in Taiwan occurred. To further investigate the relationship between the upper-level divergence anomaly over the Mediterranean-Sahara and the decadal change of the wave train and the East Asian cold surge, three simulations forced by different RWS (i.e., Sahara only, Mediterranean only, and Sahara+Mediterrannean) were conducted to estimate the relative contribution of different RWS's shown in Fig. 2a in a linearized barotropic vorticity model as in Hoskins and Ambrizzi (1993). Here, the climatology (1958-2001) of 200-hPa streamfunction is used as the basic flow. The steady-state response to the Sahara only and Sahara+Mediterrannean forcing (shown in Fig. 2c-2d) is characterized by a wave train, which emanates from the forcing region to East Asia along the subtropical jet stream. The similarity between the observed and simulated wave pattern is evident. The response to the Sahara forcing exhibits larger amplitude in the lower latitude and seems to better mimic the observed perturbation in the tropics. A comparison between Figure 2c and 2d indicates that the response to the Mediterranean forcing give rise to larger perturbation in the extratropical Eurasia and better mimic the observed extratropical perturbation. . As the model is linear, a forcing associated with the convergent anomaly in the Mediterranean-Sahara region will produce a mirror image of the wave train. Since the wave train is barotropic in nature and the CSF is significantly correlated with the northerly anomaly over southeast China (Table 1), this numerical experiment suggested that the decadal variability of the NAO-related RWS over the Mediterranean-Sahara is correlated with the decadal variation of the CSF in Taiwan (and subtropical East Asia) by changing the phase of the upper-level Rossby wave and the associated upper-level meridional wind anomaly and the trough over subtropical East Asia.

5. Conclusions and Discussion

This study demonstrates the strong decadal relationship between the NAO and the CSF in Northern Taiwan, which can be viewed as an indication of the occurrence of subtropical-reaching cold surge in East Asia. The cold surges are more (less) frequent in 1957-1977 (1981-2001), when the NAO was in a negative (positive) phase. A correlation analysis reveals that the NAO is much better correlated with the CSF than other large-scale circulation patterns such as the PDO, ENSO and the North Pacific pattern. This demonstrates the uniqueness of the NAO in influencing the decadal fluctuation of cold surge events in Taiwan.

It is proposed that the change in large-scale circulation associated with the NAO alters the background flow for the cold surge and leads to the decadal variation in CSF. The major characteristics of the circulation in 1957-1977 are summarized in the schematic diagram presented in Fig. 4. The existence of a teleconnection pattern, which is observed to be associated with the NAO in the negative phase, over the middle/high latitudes of the Atlantic and the Eurasian continent resulted in a stronger and more active Siberian high. The latter was accompanied by an enhanced ridge upstream of Lake Baikal and deepened trough over coastal East Asia. These circulation characteristics are well known favorable conditions for the occurrence of cold surges. In addition, a wave train along the subtropical jet stream was observed in such a phase that a northerly anomaly, which extended vertically through the troposphere with little vertical phase tilt, existed over subtropical East Asia. The existence of the northerly anomaly seemed to provide a favorable background for the stronger cold surge activity in subtropical East Asia. Barotropic modeling results suggest that the suppressed upper-level convergence (or weaker subsidence) in the Mediterranean-Sahara region, as in 1957-1977, may force such a wave train emanating toward East Asia along the subtropical jet stream, which acts as a Rossby waveguide.

We also investigate the relative contribution of these two RWS by prescribing individual or both RWS to the model. The results presented in Fig. 2 (and also in Fig. 3) show that the Sahara RWS is the major forcing to induce the subtropical wave train and the northerly anomaly over southeast China. Both RWS also induce wave-like pattern over the northern Eurasian continent, but the Mediterranean RWS seems to contribute more to the enhancement of the ridge upstream of the Lake Baikal. The suppressed convergence in the Mediterranean-Sahara region, which was located to the south of the negative height anomaly of the NAO over the Europe, may be considered as the NAO's impact on the circulation in the region. While the middle/high latitude teleconnection associated the NAO seemed to result in the stronger SH, the indirectly induced subtropical wave train enhanced the northerly background favorable for the southward penetration of the cold surges.

It is suggested that the combination of both effects led to the close decadal relationship between the NAO and the cold surge frequency in Taiwan. The frequency change might occur not only in Taiwan but also in a larger area in subtropical East Asia, considering the characteristics of the strong cold surges. More studies are needed to confirm this. Since the composites for 1981-2001 are mirror images of those for 1957-1977 and the model simulation is linear, the physical interpretation discussed above is also applicable to 1981-2001 except in the reversed phase.

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Table and Figure

Table 1 Correlation coefficients between the decadal fluctuations of oscillation indices and the Siberian high, the cold surge frequency in Taiwan, and the northerly anomaly over southeast China. Correlations significant at 95% are marked in bold.

Catalog / Index	Siberian high (80°E-120°E,40°N-60°N)	Cold Surge Frequency	850hpa-V (105°E-120°E,25°N-35°N)	Cor. Coef. with NAO
NAO	**-0.76**	**-0.86**	**-0.52**	1
AO	**-0.72**	**-0.82**	-0.46	**0.9**
PDO[1]	**-0.7**	-0.47	-0.34	0.39
NP[2]	**0.52**	0.32	0.18	-0.29
Niño3.4	**-0.73**	-0.45	-0.22	0.25

[1] the leading principal component of North Pacific (north 20°N) SSTA
[2] sea level pressure over the region 30°N-65°N, 160°E-140°W

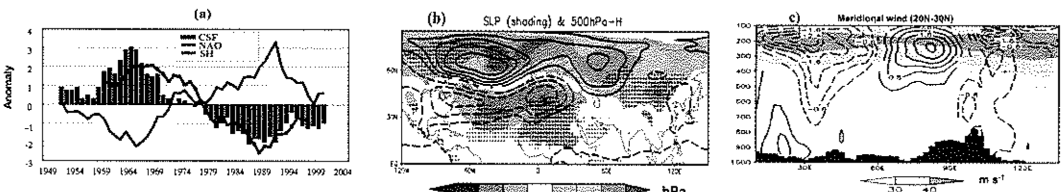

Fig. 1 a) The 7-year running means of the CSF anomaly in Taiwan, the NAO index and the SH index. The long-term mean CSF (4.1 times per year) was subtracted from the time series. b) SLP and the H500 difference by subtracting the 1981-2001 mean from the 1957-1977 mean, c) The longitude-height cross section of the anomalous meridional wind averaged over 20°-30°N. The contour interval is 10m/0.4 m s^{-1} for b)/ c). The unit of NAO index and SH index is hPa. The area marked by "+" in b) indicated the SLP anomaly exceeding 99% confidence level.

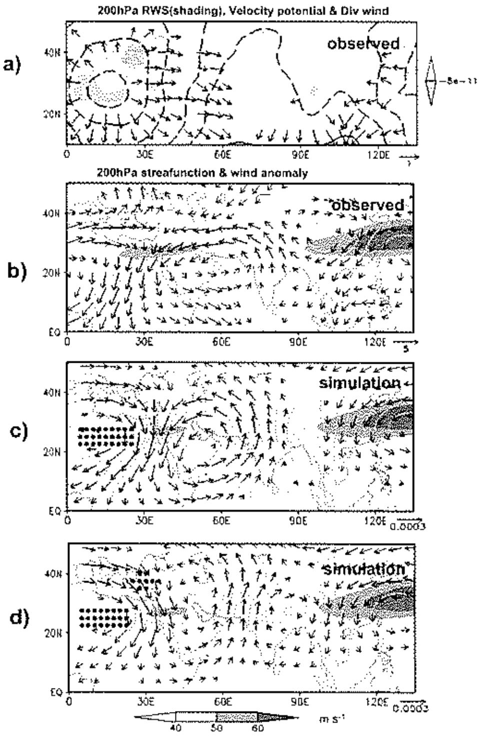

Fig. 2 The same as in Fig. 1b, but for a) the observed 200hPa RWS (shading, only less than $-8\times10^{-11}s^{-1}$ is plotted) and velocity potential-divergent wind anomalies, b) the 200hPa streamfunction and wind anomalies and climatological zonal wind (shading), c)/d) same as in b), but for the steady response of a linear barotropic model to the prescribed RWS in the region marked by "•". The contour interval is 5×10^{6} $m^2 s^{-1}$, 10^{6} $m^2 s^{-1}$, 50 $m^2 s^{-1}$and 50 $m^2 s^{-1}$ for panels a-d, respectively. The unit of wind vector is $m s^{-1}$.

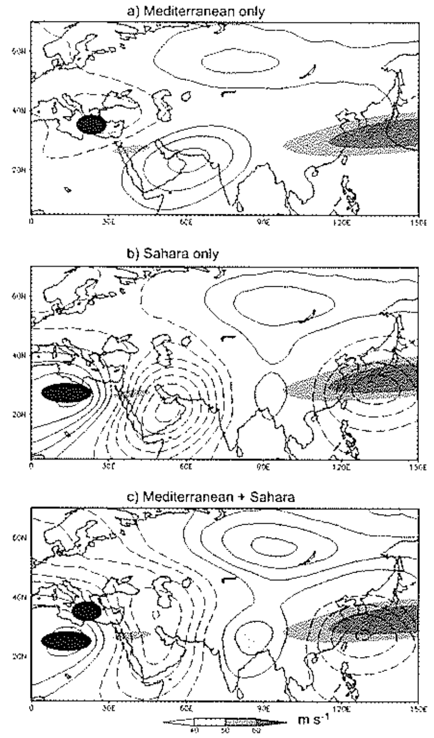

Fig. 3 The steady response (streamfunction) of a linear barotropic model to the prescribed RWS marked by blue closed ellipse. The contour interval is 30 $m^2 s^{-1}$. Shading indicates the climatological zonal wind.

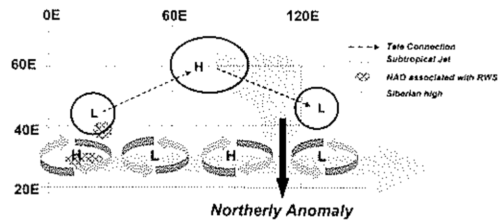

Fig. 4 Schematic diagram illustrating the circulation characteristics resulting in the decadal relationship between the NAO and the cold surge.