

Influence of springtime North Atlantic Oscillation on crops yields in Northeast China

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Abstract Forecasting grain production is of strategic importance in considerations of climate change and growing population. Here we show that the springtime North Atlantic Oscillation (NAO) is significantly correlated to the year-to-year increment of maize and rice yield in Northeast China (NEC). The physical mechanism for this relationship was investigated. Springtime NAO can induce sea surface temperature anomalies (SSTAs) in the North Atlantic, which display a tripole pattern and are similar to the empirical mode pattern in spring. The spring Atlantic SSTA pattern that could persist to summer, can trigger a high-level tropospheric Rossby wave response in the Eurasia continent, resulting in atmospheric circulation anomalies over the Siberia-Mongolia region, which is unfavorable (favorable) for cold surges that affect NEC. Weaker (stronger) cold surges can accordingly reduce (increase) cloud amount, resulting in an increase (a decrease) in daily maximum temperature and a decrease (an increase) in daily minimum

temperature, thereby leading to an increase (a decrease) in diurnal temperature range. And summer-mean daily minimum temperature and diurnal temperature range are most significantly related to the NEC crop yields.

Keywords NAO · Crop yields · Teleconnection · Year-to-year increment

1 Introduction

In the past 100 years, the global-average surface temperatures have increased by 0.74 °C (IPCC 2007) and more severe warming events have occurred from early 1980s to the present. However, warming is different in different regions and the cultivated land areas stand a good chance of faster rate (Lobell et al. 2011). Changes in the frequency and intensity of climatic extremes are usually associated with the advent of global warming, such as the increase in heat waves (Shabbar and Bonsal 2003; Meehl et al. 2000). So climate change will bring great uncertainty to surrounding agriculture production. Moreover, growing population could add pressure on agriculture (Parry et al. 1999). Hence, an accurate estimation of grain output is highly significant for guaranteeing food security and stabilizing the provision market.

For the purpose of predicting crop yields, local meteorological variables that are the direct environmental factors for crop growth must be predicted first. But seasonal prediction of the meteorological variables is difficult so far, particularly in the middle and high latitudes. Therefore, seeking antecedent large-scale signals from the climate system is very important (Stenseth et al. 2003). The North Atlantic Oscillation (NAO) refers to a large-scale seesaw in atmospheric mass between the subtropical high (centered

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on the Azores) and the polar low (centered on the Iceland) (Hu and Wu 2004; Hurrell et al. 2003; Yuan and Sun 2009). Previous work revealed that the NAO has a profound influence on the weather and climate over the North Atlantic and its surrounding regions (Rogers et al. 2004; Deser and Blackmon 1993; Pozo-Vázquez et al. 2004). In addition, the NAO has important implications for the climate in China and East Asia (Wang and Shi 2001; Li and Li 2000; Sun et al. 2008; Xin et al. 2006).

Recent investigations have also aimed at the impact of NAO on ecosystems (Ottersen et al. 2001). For example, the NAO may alter oceanic ecosystems by changing winds, sea surface temperatures, and ocean currents (Drinkwater et al. 2003; Richardson and Schoeman 2004). Many animals and plants have an advanced growing season as a response to the fluctuation of NAO (Forchhammer et al. 1998; Post and Stenseth 1999). It has been revealed that vegetation productivity could be attributed to the natural climatic variability represented by NAO (Orlandini et al. 2011). However, previous studies have mainly focused on the relations of NAO with yields statistics without explaining the responsible physical mechanisms and survey regions have mainly been in Europe and North America (Gouveia and Trigo 2008; Kim and McCarl 2005; Stige et al. 2006).

Wang (2004) found a significant correlation between wintertime NAO index and yield of certain crops in China, with a lead of NAO by one and a half years. However, the relationship was based on short time series (<20 years) of raw data and there was no analysis of the physical mechanism for the remote linkage.

Here, we primarily address the quantitative relationship between springtime NAO index and yield in Northeast China (NEC) and provide physical explanations for the far-reaching non-simultaneous relationship. The following two issues are solved: what are the local summer meteorological variables that are most relevant to the NEC crop yields (simultaneous local relationship) and why are these summer meteorological variables connected to antecedent NAO anomalies (non-simultaneous remote relationship).

2 Data and methods

In the following analysis, we focus the research on regional scales. The analysis domain is limited to NEC (Heilongjiang, Jilin, and Liaoning provinces) (see Fig. 1), which contains a total area of 1.82×10^5 km² of farmland (Chen et al. 2012) and is characterized by long cold winters and short warm summers. The annual rainfall is 400–1,000 mm, concentrated in the growing season of crops from May to September. NEC has a short frost-free period and is vulnerable to frost disasters. Due to the limit of temperature spring maize is cultivated widely. Also, as a

result of inadequate heat the single rice whose growing season is extended from April to September is popular in the region. Wheat varieties include spring and winter wheat, but spring wheat is mainly planted in Liaoning province. At present, the cultivate areas of maize is more than 50 % of the NEC farmland and the production accounts for 30 % of countrywide output (Ma et al. 2008). Rice is the second important grain crop and the production of japonica rice is more than 40 % of the production of the whole country (Sun et al. 2010).

The data used for this analysis are as follows. Daily average temperature (T_{avg}), minimum temperature (T_{min}), maximum temperature (T_{max}), total cloud cover (T_{cc}), and precipitation (Pre) for 514 stations throughout China were obtained from the Chinese Meteorological Administration (CMA). Diurnal temperature range (DTR) is the difference between daily maximum and minimum temperatures. Average T_{avg} , T_{min} , T_{max} , and DTR and total Pre and T_{cc} for summer were computed for each weather station. Seasonal fields of variables on 0.5 grids for 1968–2008 were derived by crossman interpolations. Regional-level time series of meteorological factors in summer were obtained by computing a weighted average of grid data. The monthly atmospheric reanalysis dataset acquired from the US NCEP/NCAR (Kistler et al. 2001), with a horizontal resolution of $2.5^\circ \times 2.5^\circ$, are used for the circulation analysis. SST data is obtained from the National Ocean and Atmospheric Administration (NOAA) monthly extended reconstructed version 3 (ERSST V3) dataset, with a horizontal resolution of $2.0^\circ \times 2.0^\circ$. The NAO index used in the study is from the website <http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>.

Province-level data of crop area and production for 1968–2008 were from China Agricultural Yearbooks. Because of the adjustment of public policy and other factors, there is a large shift in crop area of NEC. With the aim of verifying the relationship between climate and crop production more precisely at regional scale, yields were selected as the response variables, which were computed by dividing production by crop area. Spring NAO index was defined as the average value for March, April, and May. The summer season in this study refers to the mean of June, July, and August.

To minimize the influence of long-term changing factors on the yield, such as development of science and technology, we adopt the year-to-year increment approach (Fan and Wang 2007), which was proposed for studies of climate variability and predictability. The year-to-year increment approach has provided more accurate forecasts in climate prediction such as the summer rainfall over the Yangtze River in North China (Fan et al. 2009), the number of typhoon generated over the Western North Pacific (Fan and Wang 2009) and so on. All variables in the form of

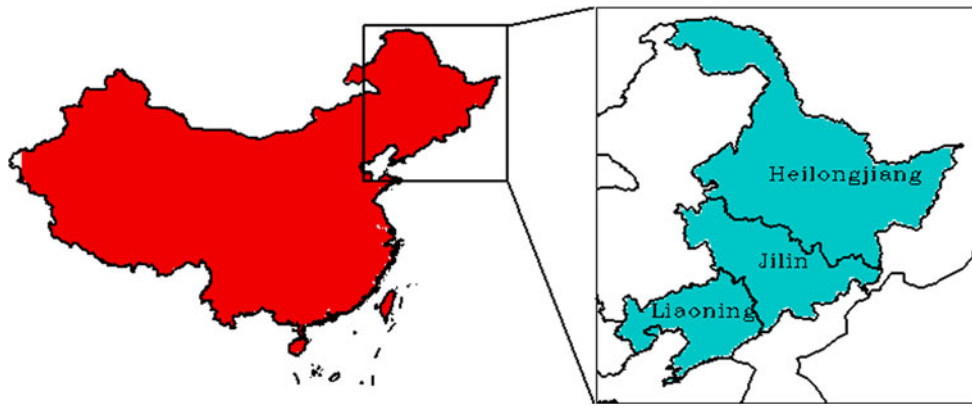


Fig. 1 Map of domain of interest

year-to-year increment are expressed as Δ (such as Δ yield). The time span of the actually available dataset is 40 years, covering 1969–2008.

3 Results

3.1 Spring NAO and yields

We computed the coefficients of correlation between springtime NAO index (SNAOI) and different crop yields (including maize, rice, and wheat) in NEC, using year-to-year increment data and raw data, respectively. Results show that correlation is significant only when year-to-year increments are adopted and insignificant for original data (Table 1; Fig. 2a). Thus all the discussions in the following sections refer to year-to-year increments. Both maize yield and rice yield are negatively correlated with spring NAO index at the 95 % confidence level. However, the relationship between wheat yield and spring NAO index is very weak. The possible reason is that the wheat yield analyzed here is the weighted average of winter wheat and spring wheat. Winter wheat and spring wheat may respond to the NAO differently, which weakens the correlation.

To understand what local meteorological variables are most relevant to crop yields, we focus on the following five

meteorological factors: summer-average daily air temperature (T_{avg}), minimum temperature (T_{min}), maximum temperature (T_{max}), diurnal temperature range (DTR), and total precipitation (Pre). The individual impact of each factor on yield is analyzed by simple linear correlation. It is shown that maize yield is influenced by T_{avg} , T_{max} , DTR, and Pre, but the primary impacting factor is DTR (Table 2; Fig. 2b). When DTR increase by 1 °C, the maize yield decreases by 5.8 % relative to the yield in 2008. As shown in Table 2, a negative response to DTR is coupled with a negative response to T_{avg} , which demonstrates that the day-time temperature increases are more harmful than nighttime temperature. For a given T_{avg} , an increase in T_{max} could increase water stress and damage the activity of photosynthetic protease, resulting in depressed photosynthesis rates. Meanwhile, high temperature in summer makes pistil and staminate flowering asynchronism, which leads to inadequate pollination and increases in the number of kernel abortion. In addition, warmer temperature tends to shorten growth duration and consequently decrease the length of time that crops intercept radiation indirectly (Bennett et al. 1990). Furthermore, the requirement of water for maize in NEC largely depends on precipitation, and the combination of high DTR and low precipitation could aggravate the losses of maize yields.

The prominent meteorological variables that affect rice yield are the diverse temperatures while rainfall has little influence on rice yield because most rice field in NEC is irrigated by human being (Table 2; Fig. 2c). Table 2 shows that T_{min} is the main impacting factor for rice yield. When it increases by 1 °C, rice yield increases by 7.6 % relative to the yield in 2008, since the summer heat is the chief environmental stress that affects the productivity of crops in NEC. The suitable high temperature in NEC cuts down the incidence of delayed-type and sterile-type cooling damage for rice and ensures the development of pollen grain. Rice is a thermophilic crop. Warmer night temperature can contribute

Table 1 Correlation between yield and spring NAO index based on year-to-year increments of variables and raw data, respectively, for 1969–2008

	Δ SNAOI	SNAOI (Raw)
Maize	−0.3698**	0.0674
Rice	−0.3419**	−0.0348
Wheat	−0.0005	−0.0160

** Statistically significant with 95 % confidence levels

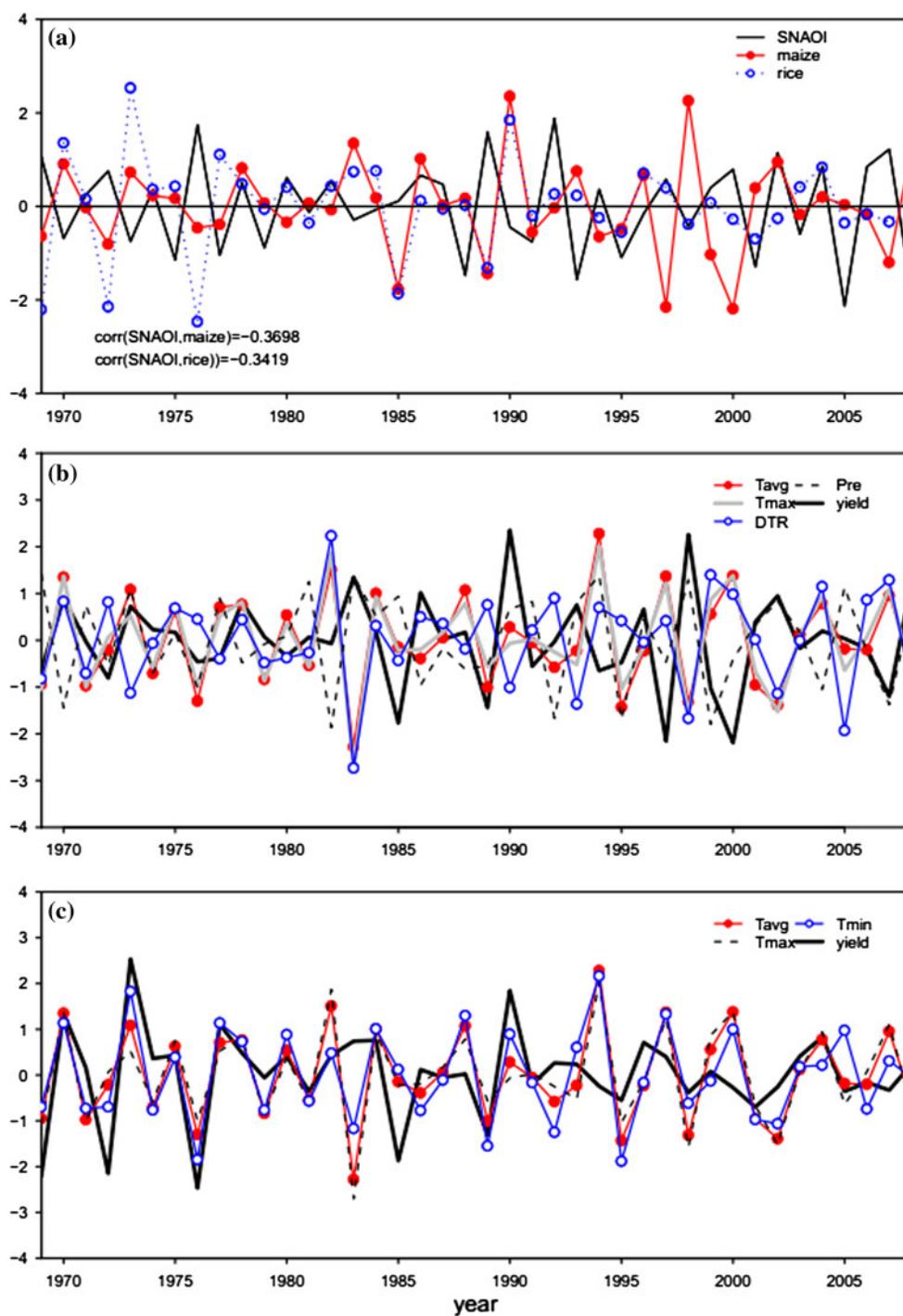


Fig. 2 Time series of normalized **a** Δ NAOI and Δ Yield, **b** Δ Yield for maize, Δ Tavg, Δ Tmax, Δ DTR, and Δ Pre, **c** Δ Yield for rice, Δ Tavg, Δ Tmin, and Δ Tmax, 1969–2008

to an increase in accumulated temperature and promote rice growth. Moreover, the elevated night temperature could improve the synthesis of chlorophyll and raise light utility efficiency (Shi et al. 2006). In the meantime, it can increase the activity of some certain enzymes, which could translocate the products of photosynthesis to grain effectively (Li et al. 1994).

3.2 Spring NAO and NEC meteorological variables

The spring NAO has significant impacts on summer minimum temperature and diurnal temperature range in NEC, which can be revealed by the correlation analysis shown in Fig. 3. Positive (negative) phases of spring NAO correspond to negative (positive) anomalies of summer

Table 2 Coefficients of correlation of Δ Yield with summer Δ Tavg, Δ Tmin, Δ Tmax, Δ DTR, and Δ Pre for 1969–2008

	Tavg	Tmin	Tmax	DTR	Pre
Maize	-0.2912*	-0.0504	-0.3813**	-0.5042**	0.2748*
Rice	0.3994**	0.5343**	0.2986*	-0.1156	0.0287

* Statistically significant with 90 % confidence levels
 ** Statistically significant with 95 % confidence levels

minimum temperature and positive (negative) anomalies of summer diurnal temperature range. To further understand the relationship between SNAO and summer climate in NEC, we analyze the pattern of correlation between SNAO and the summer total cloud amount (Fig. 4). An out-of-phase relationship is clearly demonstrated.

A reduction of total cloud cover can increase the daytime downward solar radiation at the surface, resulting in temperature increase. It can also increase the upward long-wave radiation during the nighttime, leading to temperature decrease. Thus, the connections of the summer daily minimum temperature and temperature diurnal cycle to SNAO can be attributed to the impact of the SNAO on the cloudiness over NEC during summer.

Here, we will further investigate why the SNAO can affect the summer cloudiness over NEC. The key issues are, first, whether the SNAO signal can persist from spring to summer in the Atlantic sector; and, second, how the SNAO—associated summer anomalies in the Atlantic sector affect the atmospheric circulation and cloudiness over NEC. To address the first issue, we analyze the patterns of correlation between SNAO and the SSTs in spring and summer (Fig. 5). Results reveal that the SNAO signal can be stored in the ocean in terms of SST anomalies, and that the spring SST anomalies can persist to summer. Such persistence of SST anomalies is demonstrated by the correlation between spring and summer time series of SST index for SST anomaly patterns in the Atlantic Ocean

(Fig. 6), with a coefficient of 0.58 for the period of 1969–2008. The SST index is defined to represent the primary feature of the Atlantic SST pattern as the weighted difference between the regional averaged SST in the positive correlation area (a weight factor of 1/2) and averaged SST in the two negative correlation regions (a weight factor of 1/4). To illustrate that the SST pattern in

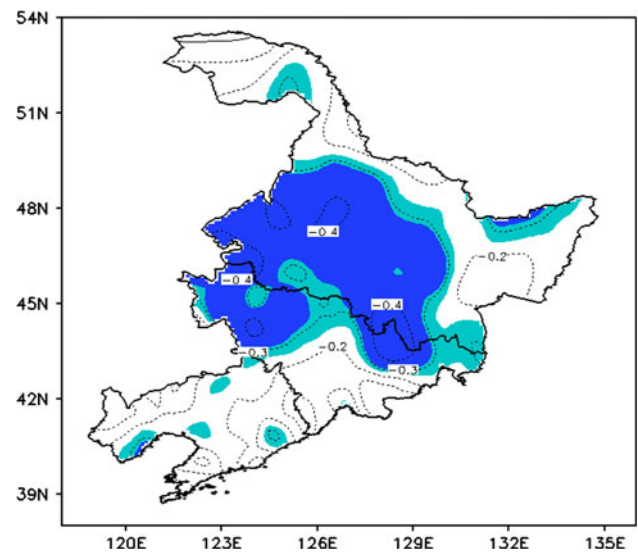


Fig. 4 Correlation between Δ SNAOI and Δ Tcc in summer. Dark (light) shadings indicate values significantly exceeding the 95 % (90 %) significance level

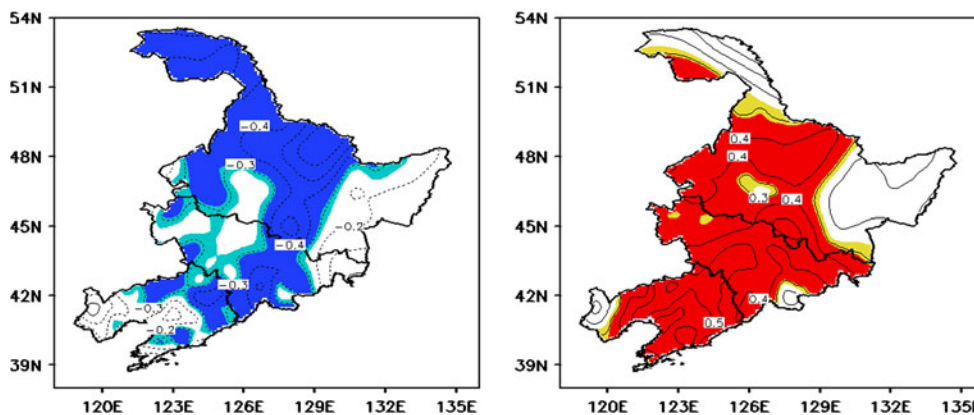


Fig. 3 Patterns of correlation of Δ SNAOI with Δ Tmin (left panel) and with Δ DTR (right panel) in summer. Dark (light) shadings indicate values significantly exceeding the 95 % (90 %) significance level

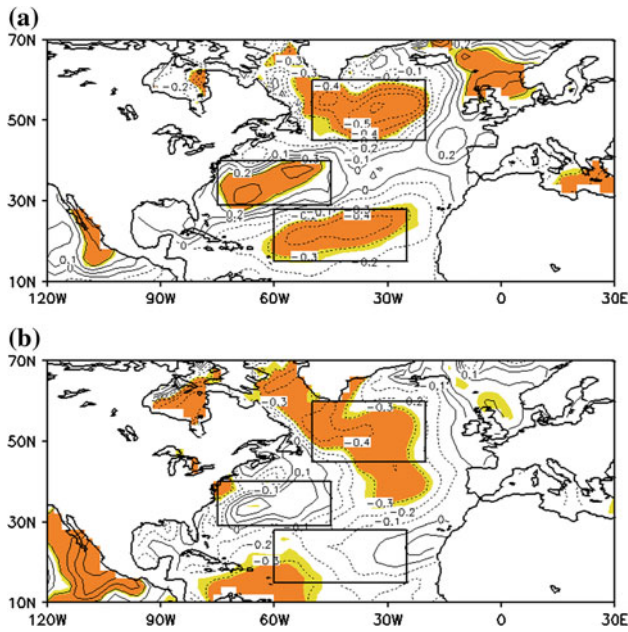


Fig. 5 Geographical distribution of coefficients of correlation: **a** between Δ SNAOI and spring Δ SST, and **b** between Δ SNAOI and summer Δ SST. Dark (light) shadings indicate values significantly exceeding the 95 % (90 %) significance level. The rectangular areas are the selected key regions

Fig. 6 is the most dominant mode, an EOF analysis is performed for the SSTs in spring and summer. The spatial pattern (see Fig. 7) shows a consistent distribution as shown in Fig. 5 and the time series of the first EOF mode is significantly correlated with the SST index, with a coefficient of 0.8 for summer. Therefore, the signal of SNAO can persist from spring to summer in the Atlantic sector via the associated SST anomalies.

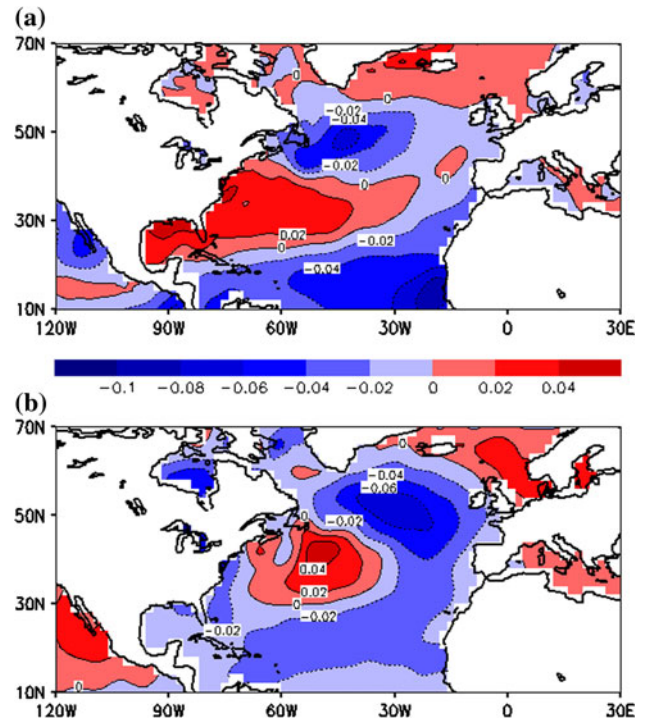


Fig. 7 Spatial display of the first eigenvector of the EOF analysis of Δ SST in **a** spring and **b** summer for 1969–2008. The first eigenmode explains 21.6 % of the total variance

To address the second issue, we examine the features of linear regression of summer geopotential height at 500 hPa against the SST index for 1969–2008. A Rossby wave pattern from the Atlantic to East Asia is apparently exhibited in Fig. 8. With the in-phase interrelationship, positive SNAO anomalies correspond to positive spring-summer SST index and positive geopotential height

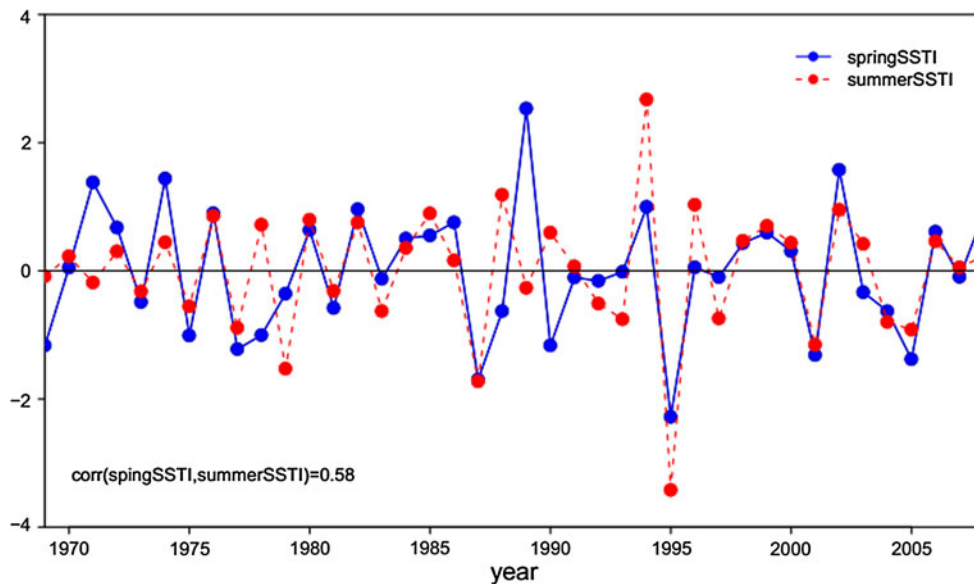


Fig. 6 Time series of normalized Δ SST index in spring and summer, 1969–2008

Fig. 8 Pattern of linear regression of summer geopotential height at 500 hPa against summer SST index for 1969–2008. Values significantly exceeding the 95 % (90 %) confidence level are shaded darkly (lightly)

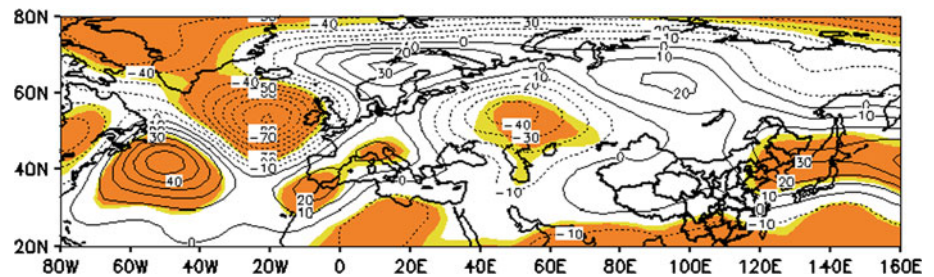
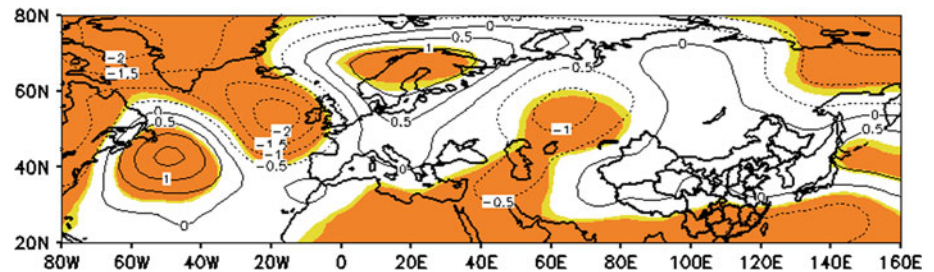


Fig. 9 Linear regression pattern of summer geopotential height at 500 hPa against the time series of first mode of EOF analysis for 1969–2008. Values significant at the 95 % (90 %) confidence level are shaded darkly (lightly)



anomalies over northeastern Asia, and vice versa. Positive geopotential height anomalies over northeastern Asia could lead to a weaker East Asian Trough, weaker cold air advection to East Asia, weaker convection, and hence reduced cloud amount (see Fig. 4). We also plot the linear regression of the geopotential height at 500 hPa against the time series of first EOF of summer SST in the Atlantic (Fig. 9). The pattern is similar to that shown in Fig. 8, particularly for northeastern Asia. Such a remote relationship between the Atlantic signal and East Asian climate during summer has been recently investigated (Sun et al. 2008; Sun and Wang 2012), which can be the specific evidence for our current analysis.

4 Conclusions

This paper documents the role of spring NAO in the yields of maize and rice in NEC for the 40 years of 1969–2008, with all variables in the form of year-to-year increment. NEC is prone to experience a lower nighttime temperature and larger diurnal temperature cycle during the years of positive spring NAO index. Large DTR limits the increase in maize yield while low nighttime temperature retracts a good annual rice yield, leading to a reduction in grain yield during positive-phase SNAO years. Our investigation on the physical mechanism for the SNAO–crop yield relationship suggests that the SNAO signal can be reserved in the Atlantic SST from spring to summer. In addition, summer SST anomalies in the Atlantic could influence the atmospheric circulation over NEC via a Rossby wave pattern, resulting in anomalies of the East Asian Trough,

cloudiness, nighttime temperature, and diurnal temperature cycle, leading to changes in crop yields.

It is interesting to note that the relationship between SNAO and the crop yields appears significantly only in the form of year-to-year increments but not in the original form. There is an increasing trend in the crop yield (including maize, rice, and wheat) from 1968 to 2008 and the use of the year-to-year increment approach in the paper tends to remove this trend, which can partly explain why the original NAO index has a insignificant correlation with crops. The finding of this work is potentially applicable to the prediction of crop yields in NEC. The remaining questions are whether the preceding anomalies in the Indo-Pacific sector are indicative to the crop yields in NEC, among others.

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