Arctic sea ice, Eurasia teleconnection pattern and summer surface ozone pollution in North China: in terms of climate variability

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Abstract. Summer surface O_3 pollution has rapidly intensified in China recently, damaging human and ecosystem health. In 2017, the summer mean maximum daily average 8 h concentration of ozone was greater than 150 μg/m³ in North China. Basing on the close relationships between the O_3 concentration and the meteorological conditions, a daily surface O3 weather index was constructed, which extends the study period to the historical period before 2007 and the projected future. Here, we show that in addition to anthropogenic emissions, the Eurasia teleconnection pattern (~~EUTP~~EU), a major globally significant atmospheric teleconnection pattern, influences surface O_3 pollution in North China on a time scale of climate. The local meteorological conditions associated with the ~~EUTP~~EU ~~-~~positive phase supported intense and efficient photochemical reactions to produce more surface O_3. The associated southerlies over North China transported surrounding O_3 precursors to superpose local emissions. Increased ~~S~~solar radiation and high temperature during the positive EU phase dramatically enhanced O_3 ~~photochemical reactions~~production. Furthermore, due to the close connection between the preceding May Arctic sea ice and summer ~~EUTP~~EU pattern, approximately 60% of the interannual variability of ~~summer surface~~ O_3 ~~-~~-related weather conditions~~pollution~~ was attributed to Arctic sea ice to the north of Eurasia. This finding will aid~~s~~ in understanding the interannual variation of O3 pollution, specially the related meteorological conditions.~~the seasonal prediction of O_3 pollution.~~

Keywords: ozone pollution, photochemical reaction, Eurasia teleconnection pattern, climate change, Arctic sea ice

1 Introduction

Along with social and economic development, air pollution has been ~~increasing~~ serious in China (Chen, 2013; Watts et al., 2018). The major air pollution types in China are haze pollution in winter (Yin et al., 2015; Wang, 2018) and surface ozone (O_3) pollution in summer (Ma et al., 2016; Tang et al., 2018). Due to drastic air pollution control in China since 2013,~~the low visibility it caused and its obvious unusual smell,~~ haze pollutions~~ easily causes warning and~~ are being controlled in recent years (The environmental statistics unit of stat-~~center~~centre in Pe~~r~~king University, 2018), appearing as sharp decreasing in fine particulate matter. However, surface O_3 pollution, which~~has~~ always occurred on clear and sunny days (Wang et al., 2017), ~~so~~

~~it is not visible to humans.~~ has not improved (Li et al., 2018). The negative effects of surface O_3 pollution was not weaker than those of haze (Liu et al., 2018), but ~~T~~the impacts of climate variability ~~features and causes of~~ on surface O_3 pollution in China~~,~~ ~~especially~~ (Yang et al, 2014) ~~the impacts of climate variability,~~ have not been sufficiently studied. ~~Europe has benefitted from its rigorous air protection act and maintained good air quality, but the surface ozone levels still showed significant increases during 1995–2012 (Yan et al., 2017). In the major urban areas in China, the surface O_3 concentrations have exceeded the ambient air quality standard by 100–200% (Wang et al., 2017), especially in the Yangtze River Delta (Tong et al., 2017) and Beijing-Tianjin-Hebei region in North China (Wang et al., 2006; Shi et al., 2015).~~ In the major urban agglomerations in China, such as Beijing-Tianjin-Hebei, Yangtze River delta and the Pearl River delta, the surface O_3 concentrations exceeded the ambient air quality standard of China (i.e., 100 μg/m³) by 100–200 % (Wang et al., 2017). In the Yangtze River delta, the inter-annual variations of NO and O_3 levels generally presented decreasing and increasing trends respectively, from 2012 to 2015 at both urban and suburban sites (Tong et al., 2017). Furthermore, the concentration of O_3 and its precursors in Beijing-Tianjin-Hebei was significantly larger than that in other regions of China (Wang et al., 2006; Shi et al., 2015). Revealed by the datasets from Shangdianzi Station, the long-term trend of O_3 concentrations in North China indicated that the O_3 pollution has undergone a significant increase in the period of 2005–2015, with an average rate of 1.13 ±0.01 ppb $year^{-1}$ (Ma et al., 2016).

~~There is rarely a direct discharge of s~~Surface O_3~~.~~ is a secondary pollutant. The precursors of O_3 (e.g. NOx and VOC) photochemically react to generate O_3 under suitable weather conditions, i.e., hot-day and sunny environments (An et al., 2009). ~~Sedimentation~~Surface deposition, dynamic transport and ~~attenuation~~ dispersion of O_3 are also closely related to atmospheric circulations. For example, ~~The North Atlantic Oscillation intercontinentally affects surface O_3 concentrations over Europe (Christoudias et al., 2012; Pausata et al., 2012)~~the prevailing positive phase of the North Atlantic Oscillation contributed to the increasing ozone concentration in western and northern Europe, through the anomalous atmospheric circulations to influence regional photochemical processes (Christoudias et al., 2012; Pausata et al., 2012). ~~-~~The summer surface O_3 variability in North America is significantly modulated by the position of the jet stream (~~Barnes and Fiore, 2013;~~ Lin et al., ~~2015~~2014). Barnes and Fiore (2013) pointed out jet position may dynamically modulate surface ozone variability in eastern North America and other northern mid-latitude regions. A strong positive correlation between the East Asian summer monsoon and summer mean ozone existed ~~during 1986–2006, based on numerical model results (Yang et al., 2014)~~. The model simulation by Yang et al. (2014) illustrated that the changes in meteorological parameters, associated with East Asian summer monsoon, lead to 2–5% interannual variations of surface O_3 concentrations over central eastern China. Focusing on the dataset in 2014, ~~A~~a significantly strong west Pacific subtropical high resulted in higher relative humidity, more clouds, more rainfall, less ultraviolet radiation and lower air temperatures, which were ~~unfavorable~~unfavourable for the formation of O_3 (Zhao and Wang, 2017). The photochemical reaction was the main local sources of O_3. The hot and dry environments and the violent solar radiation could accelerate the chemical conversion from the precursor to O_3 (An et al., 2009; Tong et al., 2017). ~~-~~In 2013, a severe heat wave~~,~~, with highest temperature 41.1 ℃, contributed to the high O_3 concentration in the Yangtze River Delta (Pu et al., 2017). The frequency of large-scale, extreme heat events is closely related to atmospheric patterns, such as the Eurasia teleconnection pattern (~~EUTP~~EU; Pu et al., 2017; Li and Sun, 2018) and aerosol effective radiative forcing (Liu and Liao, 2017). The winds from a polluted area also transport O_3 and its precursors downwind (Doherty et al., 2013). Due to the close relationship between surface O_3 and meteorological conditions, the impacts of climate change on O_3 have been projected by various numerical models (Doherty et al., 2013; ~~Nolte et al., 2008;~~ Melkonyan and Wagner, 2013; Zhu and Liao, 2016; Gaudel et al., 2018). Over eastern China, the surface ozone concentration and possibility of severe ozone pollution may both increase in the future (Wang et al., 2013).

However, previous studies mainly focused on observational analyses of several synoptic processes (e.g., Zhao and Wang, 2017), rather than long-term climate diagnostics, because of the lack of long-term surface O_3 observations. The goal of this study is to examine the large-scale atmospheric circulations associated with the interannual variation of summer surface O_3 pollution in North China based on long-term meteorological observations. The role of May Arctic sea ice, as a preceding and effective driver, ~~were~~ was also ~~analyzed~~analysed. The outcomes of our research, in terms of climate variability, may provide a basis for understanding the interannual variation of O_3 pollution, specially the related meteorological conditions.~~ and its seasonal-to-interannual prediction.~~

2 Data and Method

The observation duration of the surface O_3 concentration was much shorter than the meteorological measurements and could not support the climate analysis. The hourly O_3 concentration data from 2014 to 2017 in China were provided by the Ministry of Environmental Protection of China. As one of the three regional background air-monitoring stations in China, ~~T~~the hourly O_3 concentration data at the Shangdianzi station (SDZ: located at 40°39'N, 117°07'E and 293.3 m high) was continuously observed from 2006 to~~–~~2017~~ at the Shangdianzi station (SDZ: located at 40°39'N, 117°07'E and 293.3 m high)~~, ~~one of the three regional background air-monitoring stations in China,~~ and were ~~collected and~~ controlled by the National Meteorological Information Center, China Meteorological Administration. According to the Technical Regulation on Ambient Air Quality Index of China (the Ministry of Environmental Protection of China, 2012), the maximum daily average 8 h concentration of ozone (MDA8) was ~~calculated~~ used to represent the daily O_3 conditions. The MDA8 was calculated as the maximum of the running 8 h mean O_3 concentrations during 24 hours in the day. The monthly sea ice concentrations (1°×1°) were downloaded from the Met Office Hadley Center (Rayner et al. 2003), which are widely used in sea ice-related analysis.

The 1°×1° ERA-Interim data used here included the geopotential height (Z), zonal and meridional wind, relative humidity, vertical velocity, air temperature at different pressure levels, boundary layer height (BLH), surface air temperature (SAT) and wind, downward UV radiation, downward solar radiation, low and medium cloud cover and precipitation (Dee et al. 2011).

The daily mean and monthly mean ERA-Interim data were directly downloaded from the ERA-Interim websiteanalyzed in this study. Furthermore, the daily mean and monthly reanalysis datasets supported by the National Oceanic and Atmospheric Administration (NOAA) were also employed and denoted as NOAA NCEP/NCAR (National Center for Environmental Prediction and the National Center for Atmospheric Research) data. The 2.5°×2.5° geopotential height (Z), zonal and meridional wind, relative humidity, vertical velocity, air temperature at different pressure levels, SAT and wind, downward UV radiation, downward solar radiation, low and medium cloud cover were downloaded from the National Center for Environmental Prediction and the National Center for Atmospheric Research (Kalnay et al. 1996). The BLH of NCEP/NCAR dataset was only available from 1979 to 2014 in the NOAA data was derived fromthe website of the NOAA-CIRES 20th Century Reanalysis version 2c (Giese et al., 2016). The daily precipitation data was from the CPC global analysis of the daily precipitation dataset (Chen et al., 2008).

The EU pattern is a major teleconnection pattern in the Northern Hemisphere and appears in all seasons. Wang and Zhang (20154) used the method defined by Wallace and Gutzler (1981) to calculate the EU pattern index in winter and pointed out that the positive EU phase is associated with a cold-dry climate in East China, *vice versa*. Meanwhile, Wang and He (2015) regarded the summer EU pattern as the main reason for the severe summer drought in North China in 2014. Considering the seasonal change of the EU pattern's location, Thethe calculation procedure for the Eurasia teleconnection pattern (EUTPEU) index here was consistent with that of in Wang et al. and He (2015).

$$\text{EUTP index} = [-1\times\overline{\text{H500}}_{(70-80°N,60-90°E)} + 2\times\overline{\text{H500}}_{(45-55°N,90-110°E)}$$

$$-1\times\overline{\text{H500}}_{(35-45°N,120-140°E)}]/4$$

$$\text{EU index} = [-1\times\overline{\text{H500}}_{(70-80°N,60-90°E)} + 2\times\overline{\text{H500}}_{(45-55°N,90-110°E)}$$

$$-1\times\overline{\text{H500}}_{(35-45°N,120-140°E)}]/4$$

where H500 represents the geopotential height at 500 hPa, and overbars denote the area average.

To verify the connection between the Arctic sea ice and the O_3 pollution, the Community Atmosphere Model version 5.3 (CAM5, Meehl and Washington 2013) was employed to design numerical experiments. The spatial resolution employed was 0.9°×1.25°, with 30 vertical hybrid sigma-pressure levels. The climatological mean sea surface temperature and sea ice taken from the Hadley Center were used to force the control run.

3 Summer ozone pollution and associated weather conditions

Due to increased surface O_3 pollution in China, the number of O_3 measurement stations has dramatically increased since 2014 (Figure S1 a, c, e, g). During 2006–2014, O_3 concentrations were only observed in the most developed regions in China, i.e., the Beijing-Tianjin-Hebei area, the Yangtze River Delta, and the Pearl River Delta. Since 2015, O_3 concentrations have been measured in most areas in eastern China. O_3 concentrations in the high-mid latitudes were higher than those in the lower latitudes, which appeared to be separated bordered by the Yangtze River. The O_3 concentrations in North China were rather already high in 2014; the summer mean maximum daily average 8 h concentration of ozone (MDA8) in North China was higher than 120 μg/m³. The observations, with maximum MDA8 higher than 265 μg/m³ (i.e., the threshold of the server surface O_3 pollution in China Since) existed in the south of Hebei Province and the north of Shandong Province (Figure 1a). Since that time, the O_3 polluted region has expanded approximately yearly. In 2017, the areas with summer mean MDA8 > 120 μg/m³ were visibly enlarged. In North China, the summer mean MDA8 observations were larger than 150 μg/m³, and the maximum MDA8 was almost higher thannearly 265 μg/m³ (i.e., the threshold of severe surface O_3 pollution). South of the Yangtze River, the O_3 concentrations were distinctly lower and decreased progressively towards the Pearl River Delta.

The time span of O_3 observations (i.e., 2015–2017 for most of the sites) limited the possibility of determining the role of climate variability in the interannual O_3 variations in North China. Thus, we examined the representativeness of the O_3 measurements at SDZ Shangdianzi station (SDZ: one of the three regional background air-monitoring stations in China, with observations from 2006–2017), with observations from 2006–2017. The correlation coefficients between SDZ MDA8 and the observed MDA8 at the other sites were calculated and are shown in Figure S1 (b, d, f, h). Similar to the O_3 concentrations, thesThe distribution of correlation coefficients is similar to the MDA8 on Figure 1 (a, c, e, g)were also oppositely distributed south and north of 30°N. The SDZ MDA8 significantly covaried with the MDA8 in the north of China., especially in North China in summer. Along with the increasing of the surface O_3 pollution, the covariation and the representativeness of SDZ MDA8 to the MDA8 in North China was strengthened. However, the correlation coefficients between SDZ MDA8 and MDA8 in the south of China were negative, indicating opposite variation (Zhao and Wang, 2017). The variation of summer SDZ MDA8 is presented in Figure S21. The diurnal daily difference in MDA8 was large, which contradicts the quasi-constant emission of ozone precursors. Therefore, we speculated the impacts of meteorological conditions were significant. According to the Technical Regulation on Ambient Air Quality Index in China (The Ministry of Environmental Protection of China, 2012), the thresholds of moderate surface O_3 pollution (MOP) and non-surface O_3 polluted ion (NOP) level and moderate surface O_3 polluted (MOP) level are 215 μg/m³ and 100 μg/m³ and 215 μg/m³, respectively. The upper and lower quartile of SDZ MDA8 was 188 μg/m³ and 114 μg/m³, indicating that more than 75% of summer days were not the NOP days even at the regional background air-monitoring station. During the years 2007–2017, there were 126 NOP days and 155 MOP days in summer at SDZ station. The maximum number of MOP days was 26 days in 2015, and the mean number of MOP days was

14 days (~~Figure~~ Table S1~~3~~). The interannual variation in MOP (NOP) days was significant at the 95% confidence level, without an obvious long-term trend.

Due to the significant covariation between the SDZ MDA8 to the MDA8 in North China, although ~~The~~ the meteorological conditions were composited for the MOP and NOP days in SDZ (Figure ~~1~~2), the results were also appropriate for those in North China. The local and surrounding weather conditions were significantly different. During calculating the correlation coefficients with the meteorological conditions, the averaging area for meteorological indexes were the regions with most significantly different elements in the composites of MOP and NOP events. The anomalous southerlies, higher ~~boundary layer height (~~BLH~~)~~, less rainfall, warmer surface air temperature, and cooler temperature in the high troposphere favored surface O_3 pollution and *vice versa*. Anomalous southerlies from the Yangtze River transported O_3 precursors (that were ~~discharged~~ emitted in the economically developed Yangtze River Delta) and superposed them with the local high emissions in North China (Figure ~~1a~~2a). When the anomalous winds reversed, i.e., northerlies, the O_3 precursors in North China was dispersed, and the surface O_3 concentration was reduced (Figure ~~1b~~2b). The correlation coefficient between the SDZ O_3 concentration and the area-averaged meridional wind at 10 m (35–~~50°N~~50 °N, 110–122.~~5°N~~5°E, denoted as V10mI) was 0.39, exceeding the 99% confidence level. The ~~moisture environment (i.e., high relative humidity) and~~ cloudy skies and ~~were essential conditions for~~ precipitation~~, which~~ weakened the photochemical reaction by influencing exposure to ultraviolet rays. In addition, precipitation was also an important indicator of the wet removal efficiency (Figure ~~1f~~2f). In summer, a day without rain represents efficient solar radiation, in favor of the occurrence of surface O_3 pollution (Figure ~~1e~~2e). The correlation coefficient between the area-averaged precipitation (37.5–42.5 °N, 112–127.5 ~~°N~~°E, denoted as PI) and the SDZ O_3 concentration was –0.35 (above the 99% confidence level), indicating that ~~sufficient~~ precipitation was connected with more NOP days.

In contrast, ~~the~~ high ~~temperature near the surface~~SAT enhanced~~d~~ the photochemical reactions and resulted in ~~a~~ higher surface O_3 concentrations (Figure ~~1~~ 2 g). ~~The sky without clouds not only provided strong solar radiation (i.e., warmer surface air temperature) but also resulted in weak absorption of long-wave radiation in the upper air (i.e., cooler temperature at 200 hPa).~~ The correlation coefficient between the area-averaged difference in the temperature at the surface and 200 hPa (~~surface air temperature~~SAT minus temperature at 200 hPa, 37.5–47.5 °N, 110–122.5 ~~°N~~°E, denoted as DTI) and the SDZ O_3 concentration was 0.49. Furthermore, due to the strengthening of solar radiation, the near-surface turbulence was enhanced, and the boundary layer was lifted (Figure ~~1c~~2c). The entrainment~~downwash~~ of atmospheric ozone from the upper air into the boundary layer enlarged the surface O_3 concentration (An et al., 2009). The correlation coefficient between the SDZ O_3 concentration and the area-averaged BLH (37.5–47.5 °N, 112.5–120 ~~°N~~°E, denoted as BI) was 0.40. Therefore, the anomalous southerlies, high surface temperature, above average BLH, and sunny skies were favorable environments for severe surface O_3 pollution. To confirm the robustness of the link between meteorological conditions and the MOP and NOP days over North China, the above composite analysis was repeated with ~~NOAA~~ NCEP/NCAR reanalysis data, and identical results were obtained (Figures S2~~4,~~, ~~5~~3).

To assess the interannual variation of surface O_3 pollution and its relationship with climate variability (Cai et al., 2017), we tried to fit an O_3 weather index (OWI) based on long-term meteorological observations. Here, we defined the OWI as OWI=normalized V10mI+normalized BI–normalized PI+normalized DTI. For comparison, the multiple regression equation was built between the MDA8 and associated weather indices (Figure ~~S6~~3). Our analysis indicated that the observed MDA8 was well fit by the multiple regression equation (Figure ~~S6~~3). The correlation coefficient was 0.61 between the fit and daily measured MDA8 during 2007–2017 (i.e., 92 days × 11 years). ~~In contrast, t~~The correlation coefficient between the observed MDA8 and daily OWI was also 0.61 for the 11 year period. Thus, the OWI was easily constructed by accumulating the normalized weather index and was selected to represent the variation in surface O_3 pollution. A total of 90.3% of the MOP events were in the range of OWI > 0, and correspondingly, 90.5% of the NOP events were linked with OWI < 0 (Figure ~~2~~4). The correlation coefficients between the OWI and observed MDA8 at the other sites were calculated (Figure ~~S7~~5). The significantly positive correlations were distributed in North China (Figure 5 b-d). Thus, it is reasonable to ~~analyze~~analyse the variation in surface O_3 pollution in North China using the OWI, which also extends the study period to the historical period before 2007 and the projected future.

4 Impacts of ~~EUTP~~EU pattern on the interannual variation of surface ozone

After the assimilation of satellite data, possible in 1979, the quality of the reanalysis data was improved ~~to support studies of climate variability and change~~. Here, the daily OWI was calculated with both ERA-Interim and NCEP/NCAR~~NOAA~~ reanalysis data from 1979.~~,~~ According to the above analysis, the daily OWI could largely represent the variation in MDA8 in North China. T~~and t~~he monthly ~~mean~~ OWI was computed as the monthly mean of the daily OWI. During 2007–2017, the constructed JJA (June-July-August) mean OWI varied similarly with the observed MDA8 and captured the extremes (Figure 6~~3~~). Although the range of the SDZ MDA8 was 2006–2017,~~In the above composite analysis and OWI construction processes,~~ only the data from 2007 to 2017 were used in the above OWI construction processes. ~~the range of the data used was 2007–2017; thus~~Thus, the datasets in 2006 were independent~~ly~~ samples (i.e., test set), and could verify the performance of the OWI~~ied samples~~. The JJA mean OWI in 2006 successfully reflected the variation in observed MDA8; even the MDA8 in 2006 was ~~a staged~~the minimum, confirming the robustness of the OWI. Derived from two different reanalysis datasets, the OWI-ERA and OWI-NCEP~~NOAA~~ varied consistently. The above independent verifications proved that the performance of the summer OWI did not depend on the kinds of reanalysis data~~, confirming the robustness of the monthly OWI~~. In the following study, the monthly OWI from ERA-interim data and associated physical mechanisms were ~~analyzed~~analysed. Before the mid-1990s, the OWI was below zero, with a slightly decreasing trend and insignificant interannual variation. Since then, the OWI has significantly increased; furthermore, the intensity of interannual variation has strengthened. The emissions of O_3 precursors increased persistently and linearly due to the steady economic development in China (Wang 2017). We speculated that Tthe strong interannual variation in the OWI, representing the impacts of meteorological conditions on O_3 concentrations, contributed to the interannual fluctuations of thein surface O_3 pollution was significantly related to climate variability. Thus, the impacts of the large-scale atmospheric circulations on the summer O_3 pollution, specially the related OWI, –were analyzed.

The atmospheric circulation associated with summer mean OWI, indicated by the correlation coefficients, are displayed in Figure 74 5. In the mid-upper troposphere, cyclonic and anticyclonic anomalies were alternately distributed over the north-central Siberian Plateau (–), North China and Mongolia (+), and the Yellow Sea and Japan Sea (–) (Figure 74a). These three atmospheric centers, propagated from the polar region to the mid-latitudes, appeared to be the positive phase of EUTPEU pattern. This Rossby wave-like train, i.e., the EUTPEU pattern, could also be recognized in the surface air temperature. The correlation coefficient between the EUTPEU pattern index and OWI was 0.44 (after detrending and above the 99% confidence level), indicating that the strengthening of the EUTPEU –positive phase contributed to the severe surface O_3 pollution in North China.– More precisely, the positive phase of EUTPEU pattern could modulate the local meteorological conditions to enhance the photochemical reactions. The EUTPEU pattern is considered to be the main reason for the variability of the severe drought in North China, i.e., resulting in hot and dry climate extremes (Wang and He, 2015). To a certain extent, the severe drought environment promoted the formation of surface ozone. After 2007, the EUTPEU –index and the observational SDZ MDA8 synchronously changed (Figure S8). More than 80% of the SDZ MDA8 anomalies showed the same mathematical sign as the anomalous EUTPEU pattern index. Furthermore, the intensified EUTPEU pattern anomalies (i.e., the |EUTPEU pattern index| > 0.8 × its standard deviation) always induced homodromous surface ozone pollution.

Under barotropic anticyclonic circulation over North China, i.e., one of the active centers of the positive EUTPEU pattern, the significant descending air flows indicated efficient adiabatic heating (resulting in high temperatures near the surface) and dry air (i.e., less cloud cover) below 300 hPa. Furthermore, over North China, the air temperature (relative humidity) anomalies were negative (positive) at 200 hPa but positive (negative) below 300 hPa (Figure 74c). The barotropic anticyclonic circulation associated with surface ozone pollution (Figure 74b) was similar to the positive EUTPEU pattern (Figure 74c) and led to sunny days, i.e., hot temperatures (Figure 74a), strong downwards solar radiation and UV radiation (Figure 95c–d), less low and medium cloud cover (Figure 95d), and dry conditions (Figure 95b–c). Without the cover of low and medium clouds, the short wave solar radiation, especially the UV radiation, penetrated straight to the land surface. The photochemical reaction of the O_3 precursor was enhanced, generating more O_3 near the surface. The dry atmosphere near the surface, i.e., less precipitation and lower relative humidity, accelerated the photochemical reaction but restricted the wet clearing of the stocked O_3 in the atmosphere. A higher BLH (Figure 95b), resulting from the strengthening of solar radiation, facilitated the downward transportation of O_3 from aloft. Near the surface, the western part of these anticyclonic anomalies manifested as significant southerlies (Figure 9~~5~~a), which transported the O_3 precursors from the economically developed Yangtze River Delta. The extraneous O_3 precursor, superposed with local emissions, supported a harsh and efficient photochemical reaction of O_3.~~ To confirm the robustness of the atmospheric circulation and associated physical mechanisms, the above analysis was repeated with the NOAA data, and identical results were obtained (Figure S9–S10).~~ To confirm the robustness of the atmospheric circulations and associated physical mechanisms, the above analysis was repeated by the NCEP/NCAR data and identical results were obtained (Figure S~~5~~4–S~~6~~5). The large-scale EU teleconnection, and anti-cyclonic circulations were clear. Local meteorological conditions, such as hot land surface (Figure S~~5~~4), violet solar radiation (Figure S~~6~~5c–d), clear sky (Figure S~~6~~5d), less precipitation (Figure S~~6~~5c) and lower relative humidity (Figure S~~6~~5b) were also clearly recognized. Thus, the impacts of the atmospheric circulations were confirmed by both the ERA-Interim and NCEP/NACAR data, i.e., the analyse and conclusions were independent of data sets.

5 Roles of the Arctic sea ice

The positive ~~EUTP~~EU pattern enhanced the local anticyclonic circulation over North China and facilitated the photochemical processes leading to the formation of surface ozone. The ~~EUTP~~EU pattern originated from the Arctic region. The preceding sea ice anomalies could stimulate atmospheric responses like EU pattern in summer (Wang and He, 2015)~~;~~ ~~t~~Thus, the role of Arctic sea ice on the OWI was also ~~considered~~ explored in this study. The correlation between the sea ice and JJA OWI was monthly checked (Figure omitted), and we found ~~T~~the interannual variation of OWI was significantly correlated with May sea ice conditions to the north of Eurasia, especially near the Gakkel Ridge, the Canada Basin and the Beaufort Sea (Figure ~~6~~10a). The ~~area~~ averaged (green boxes in Figure ~~6~~10a) sea ice area in May was calculated as the SI index, whose linear correlation coefficient with JJA OWI was 0.67 (after detrending) from 1979 to 2017. During 2007–2017, 73% of the May SI anomalies may be followed by observational SDZ MDA8 anomalies with the same mathematical sign (Figure ~~6b~~10b). Furthermore, the linear and nonlinear relationships were both introduced using the generalized additive model (Figure ~~S11~~11), and the contribution of May sea ice to the interannual variability of OWI was approximately 60%.

These positive sea ice anomalies could induce ~~EUTP~~EU-like pattern~~-like~~ responses in the subsequent summer (Figure ~~6~~10c). The excited atmospheric and thermal centers were located over the Central Siberian Plateau, North China and Mongolia, and the Yellow Sea. Similarly, the local meteorological responses, such as anomalous southerlies and less precipitation (Figure ~~6~~10d), less cloud and strong solar radiation (Figure ~~6~~10e) were also closely connected with the positive sea ice anomalies in May. Thus, the preceding May sea ice positively modulated the ~~EUTP~~EU pattern, and then, this Rossby wave train transported the impacts from the polar region and strengthened the anti-cyclonic anomalies over North China. Finally, suitable meteorological conditions, including hot-dry air, anomalous southerlies and intense sunshine, were induced to intensify the photochemical production of surface ozone pollution. To confirm the roles of Arctic sea ice and associated physical mechanisms, the above analysis was repeated with the ~~NOAA~~ NCEP/NCAR data, and identical results were obtained (Figure S~~12~~6).

The causality, i.e., the preceding May sea ice anomalies contributed to the subsequent JJA OWI in North China, was also confirmed by CAM5. During the control experiment (CTRL), the CAM5 model firstly integrated 20 years with climate mean initial and boundary conditions, and then, integrated 10 years with each 1st September of the last 5 years (i.e., five slightly different initial conditions). The JJA mean results of the last 6 years (i.e., 6 years × 5 groups = 30 ensembles) were employed as the output of the CTRL. On the basis of CTRL, the May sea ice concentration in the two boxes of Figure 10a was separately reduced by 10% (denoted as LowASI experiments), i.e., totally 30 sensitive runs. Similarly, the JJA mean results of 30 sensitive ensembles were employed as the output of the LowASI. The differences (LowASI minus CTRL) were the responses of atmospheric circulations and meteorological conditions to the declining May sea ice.

It was evident that an EU-like Rossby wave train was induced on the mid-troposphere (Figure 12a), which propagated from the Taymyr Peninsula (–), Northeast China (+), to east of China and the west Pacific (+). Under such large-scale atmospheric anomalies, the anomalies of relative humidity were significantly positive and resulted in denser low and cloud cover in North China (Figure 12d). Furthermore, the cover of cloud efficiently prevented the solar radiation from reaching the land surface, meanwhile, cooled the air in the boundary layer (Figure 12b). Without hot-dry air and violent sunshine, the photochemical reaction was significantly decelerated and the generation of surface O_3 was rather weak. On the other side, sufficient moisture and clouds caused more rainfall (Figure 12c). The wet deposition effect was also significantly enhanced. Thus, corresponding to less Arctic sea ice in May, the photochemical process to generate O_3 was weakened, but the wet deposition effect to decrease O_3 was enhanced. That is, the positive relationship and associated physical mechanisms were causally verified.

6 Conclusions and discussions

Recently, the summer surface O_3 concentrations and the number of O_3 observation stations have steadily increased in China. Spatially, the O_3 concentrations in North China were substantially higher than those in South China. To reveal the climatic driver and improve the potential of seasonal prediction of summer surface O_3 pollution in North China, a daily OWI (i.e., surface O_3 weather index) was constructed based on long-term meteorological observations. The robustness of this index (i.e., OWI) was verified by the ERA-Interim and NOAA reanalysis datasets and surface O_3 measurements. May Arctic sea ice was found to be a preceding and efficient climatic driver. In the historical period, variation in Arctic sea ice can explain approximately 60% of the interannual variability of the summer ~~surface O_3 pollution~~OWI in North China, which was closely associated with the surface O_3 pollution. Currently, the Arctic region has been warming approximately twice as much as the global average (Huang et al., 2017; Zhou, 2017), indicating accelerated change in the sea ice. Thus, understanding the role of Arctic sea ice may contribute to the seasonal ~~forecasting~~ look of O_3 pollution.

The ~~EUTP~~EU pattern acted as an atmospheric bridge to link May Arctic sea ice and the summer surface O_3 pollution in North China. The accumulated sea ice in May could induce or enhance the positive ~~EUTP~~EU ~~-~~phase. The anticyclonic circulation over North China, i.e., one of the active centers of the ~~EUTP~~EU pattern, was connected with high surface temperature, strong downward solar radiation, less low and medium cloud cover, and drought over North China. Under such local meteorological conditions, the photochemical reaction to produce surface O_3 was accelerated. Generally, these anticyclonic anomalies over North China were barotropic and could persist for a long time; thus, the processes that produce surface O_3 were continuous to achieve a fairly high concentration. The connections revealed in this study were based on long-term meteorological measurements and ~~thus provide possibilities for the seasonal to interannual prediction of O_3 pollution. The seasonal outlook helps to determine whether extra stringent control measures on regional O_3 precursor emissions are needed to counteract the effect of climate variability~~ was casually verified by well-designed numerical experiments.

In order to extend the time range of this study, the OWI was constructed in North China. Although the feasibility of the construction approach was strictly examined, the OWI was still a substitution focusing on the impacts of the weather conditions. When discussing the impacts of atmospheric circulations, the linear trend was removed to weaken the signal of anthropogenic emissions. Thus, the results in this study concentrated on and emphasized the meteorological and climate factors. However, there is no doubt that the polluted emissions are the fundamental inducement of the surface O3 pollution. The joint effects of the climate anomalies and the historical emissions should be lucubrated using the numerical models in the future. The processes how the weather conditions impacted the photochemical reaction were not deeply discussed here and have been analyzed in many previous studies by the atmospheric chemists. However, the reason why the cooler high troposphere contributed to the surface ozone pollution was still an open question and needed further attention. The EU pattern was a well-known continental Rossby wave train and could link the mid-high latitude climate with the change of the Arctic. Although the connection between the Arctic sea ice and the ozone pollution was revealed, the separate roles of the sea ice near the Gakkel Ridge, and the Canada Basin and Beaufort Sea should be intensively studied in the future.

Author contribution

Yin Z. C. and Wang H. J. designed the research. Yin Z. C., Li Y. Y. and Ma X. H. performed research. Yin Z. C. and Zhang X. Y. analysed data. Yin Z. C. prepared the manuscript with contributions from all co-authors.

The authors declare no conflict of interest.

Acknowledgments

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Table and Figures captions

Figure 1. The distribution of the JJA mean MDA8 (a, c, e, g) and the correlation coefficients (b, d, f, h) between the daily MDA8 and SDZ MDA8 from 2014 to 2017. The black cross in panels a, c, e, and g indicate that the maximum daily MDA8

was larger than 265 $\mu g/m^3$. The black cross in panels b, d, f, and h indicates that the CC was above the 95% confidence level. The green triangle in panel (a) illustrates the location of the Shangdianzi site.

Figure ~~1~~2. Composite of the meteorological conditions associated with different O_3 events during 2007–2017. Results for MOP (a, c, e, g) and NOP (b, d, f, h) events included (a–b) surface wind (arrow) and v-wind (shading), (c–d) BLH, (e–f) precipitation, (g–h) SAT, and temperature at 200 hPa. The black dots denote the composite results passed the 95% confidence level. The boxes represent the area used to calculate OWI. These composites were calculated using the ERA-Interim datasets.

Figure 3. The variation in the daily (a) observational SDZ MDA8 (black), (b) fitting SDZ MDA8 (red), and (c) OWI (blue) from June to August during 2007–2017. The numbers are the correlation coefficients between the observational SDZ MDA8 and fitting SDZ MDA8 (red) and OWI (blue).

Figure 4~~2~~. The OWI for MOP (red) and NOP (blue) events during 2007–2017.

Figure 5. The correlation coefficients between the daily MDA8 and OWI from 2014 to 2017. The black crosses indicate that the CC was above the 95% confidence level.

Figure ~~3~~6. The variation in the JJA mean observed SDZ MDA8 (green) from 2006 to 2017, OWI calculated from ERA-interim datasets during 1979–2017 (blue) and OWI calculated from NOAA datasets (red) during 1979–2014.

Figure ~~4~~7. The associated atmospheric circulation. (a) The correlation coefficients between the JJA mean OWI and surface air temperature (shading), wind (arrow) at 200 hPa and geopotential height at 500 hPa (contour) from 1979 to 2017. The black dots indicate that the CC with surface air temperature was above the 95% confidence level. The cross-section (110°–125°E mean) correlation coefficients between JJA mean OWI (a), ~~EUTP~~EU pattern index (b) and relative humidity (shading), temperature (contour), wind (arrow, vertical speed multiplied by 100) from 1979 to 2017. The black dots indicate that the CC with relative humidity exceeded the 95% confidence level (t test). The data used here are ERA-Interim datasets.

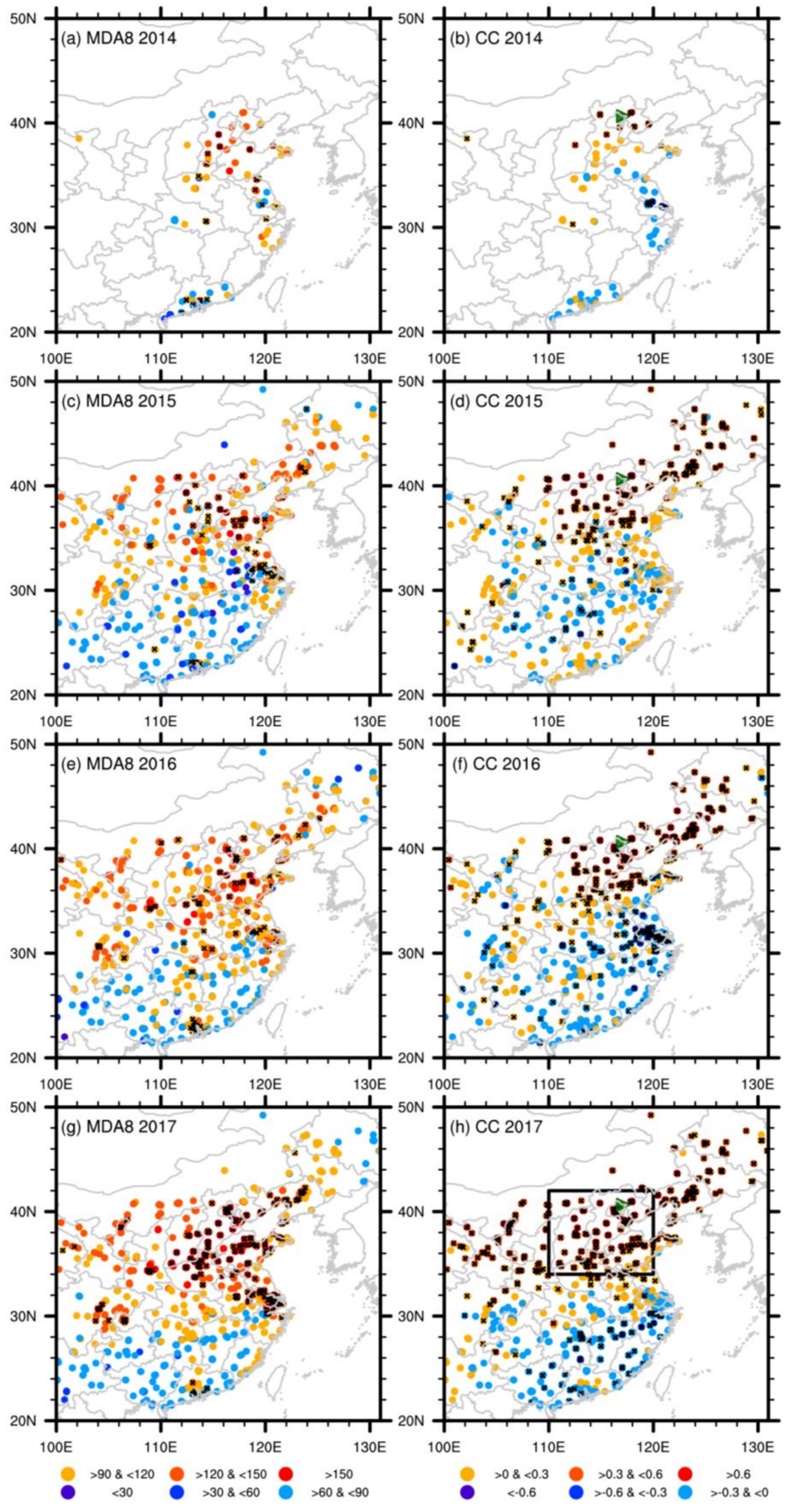
Figure 8. The variation in the JJA mean observational SDZ MDA8 (blue) and EU pattern index (red) from 2007 to 2017.

Figure ~~5~~9. The associated meteorological conditions. (a) The correlation coefficients between the JJA mean OWI and v wind at 10 m (shading), surface wind (arrow), (b) relative humidity near the surface (shading), boundary layer height (contour), (c) precipitation (shading), downward UV radiation at the surface (contour), (d) downward solar radiation at the surface (shading), sum of low and medium cloud cover (contour) from 1979 to 2017. The black dots indicate that the CC with temperature was above the 95% confidence level. The contours plotted in panel (b–d) exceeded the 95% confidence level. The data used here are ERA-Interim datasets.

Figure ~~6~~10. The role of the Arctic sea ice. (a) The correlation coefficients between the JJA mean OWI and May sea ice, (b) The variation of the May SI index (red bar, area-averaged sea ice of the green boxes in panel a), JJA mean ~~EUTP~~EU pattern index (blue bar) and JJA mean observational SDZ MDA8 (black bar) from 2007 to 2017. (c) The correlation coefficients between the May SI index and surface air temperature (shading), geopotential height at 500 hPa (contour) from 1979 to 2017. The black dots indicate that the CC with surface air temperature was above the 95% confidence level. (d) The correlation coefficients between the May SI index and precipitation (shading), surface wind (arrow), (e) downward UV radiation at the surface (shading) and sum of low and medium cloud cover (contour) from 1979 to 2017. The black dots indicate that the shading CC with precipitation (d) and downward UV radiation (e) was above the 95% confidence level. The data used here are ERA-Interim datasets.

Figure 11. The variation in the observational OWI (black) and the fitted OWI by the generalized additive model (red) from 1979 to 201

Figure 12. Composite results of the LowASI experiments (LowASI minus Ctrl) by the CAM5 model: (a) geopotential height at 500 hPa, (b) preciptation, (c) net radiative flux at the top of the atmosphere (shading) and temperature at 925 hPa (contour), and (d) sum of low and medium cloud fraction (shading) and relative humidity at 925 hPa (contour). The black hatching denotes the differences with shading were above the 95% confiden**ce level (t-test).**



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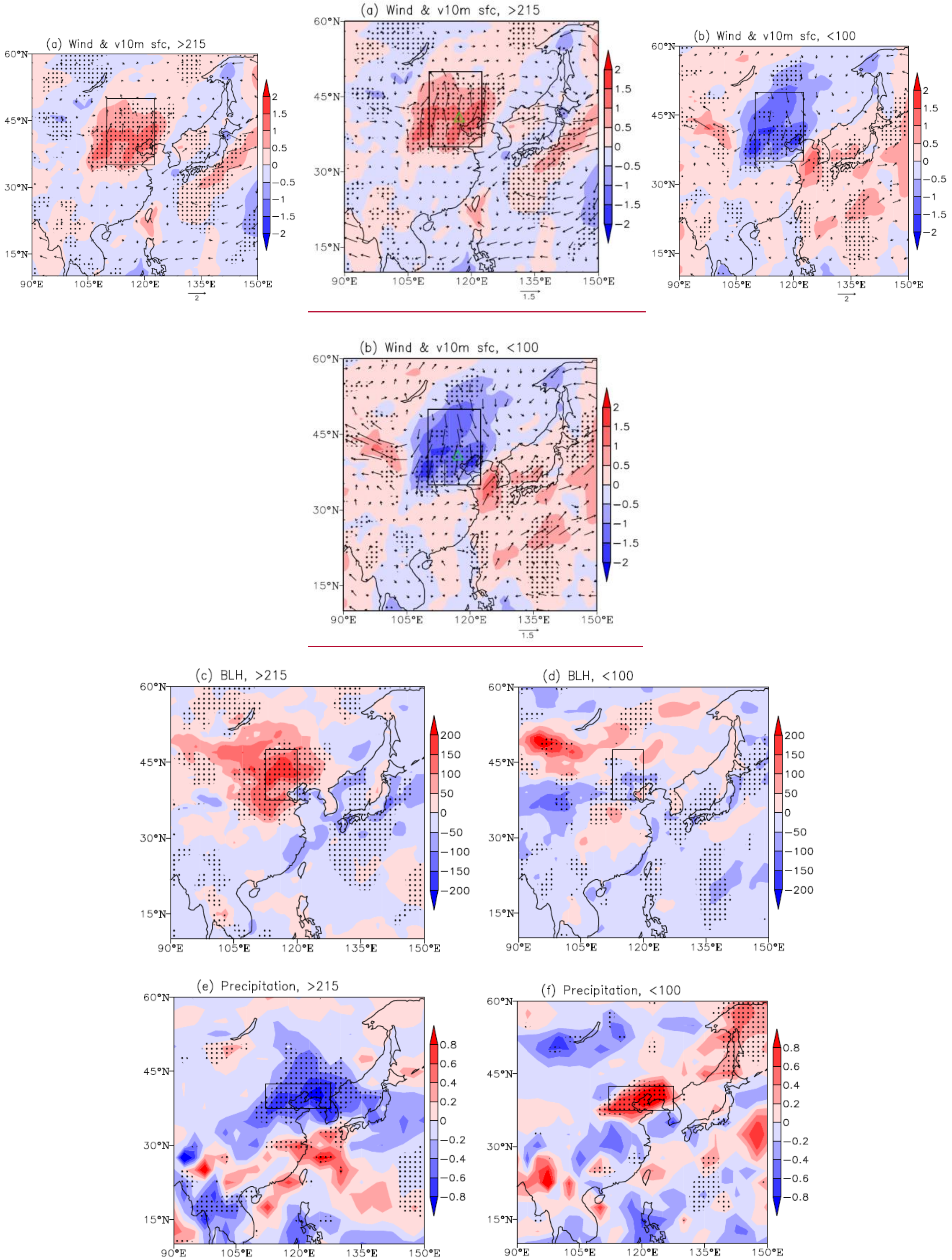
North China.


(a) Wind & v10m sfc, >215
(a) Wind & v10m sfc, >215
(b) Wind & v10m sfc, <100
(b) Wind & v10m sfc, <100
(c) BLH, >215
(d) BLH, <100
(e) Precipitation, >215
(f) Precipitation, <100

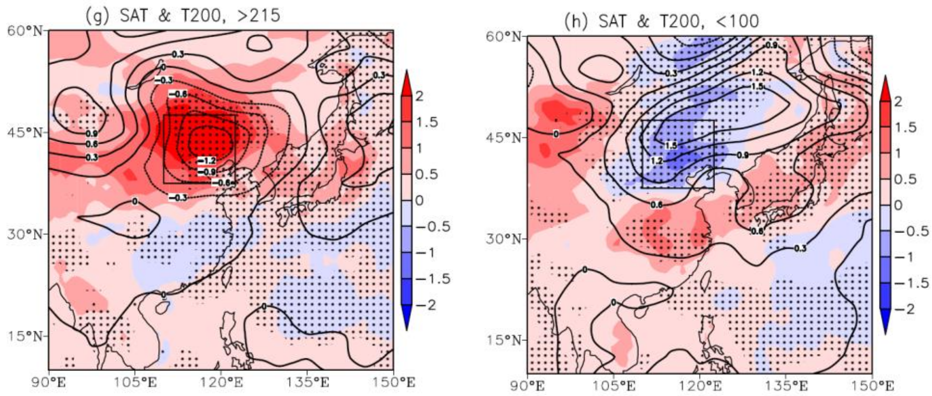
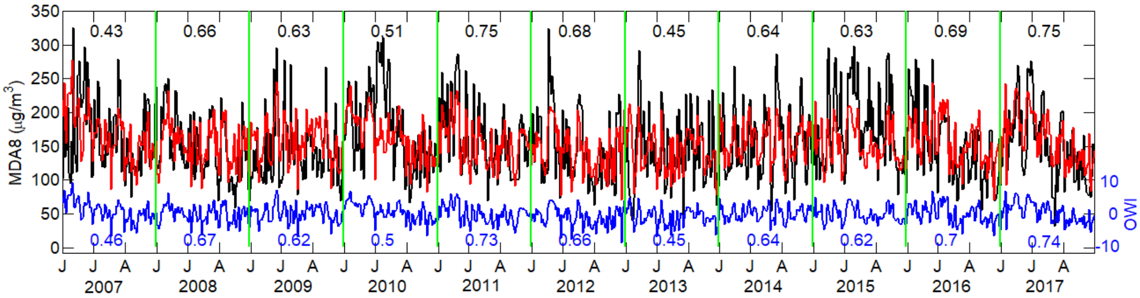


Figure 21. Composite of the meteorological conditions associated with different O_3 events during 2007–2017. Results for MOP (a, c, e, g) and NOP (b, d, f, h) events included (a–b) surface wind (arrow) and v-wind (shading), (c–d) BLH, (e–f) precipitation, (g–h) SAT (shading), and temperature at 200 hPa (contour). The black dots denote the composite results passed the 95% confidence level. The boxes represent the area used to calculate OWI. These composites were calculated using the ERA-Interim datasets. The green triangle in panel (a-b) illustrates the location of the Shangdianzi site.



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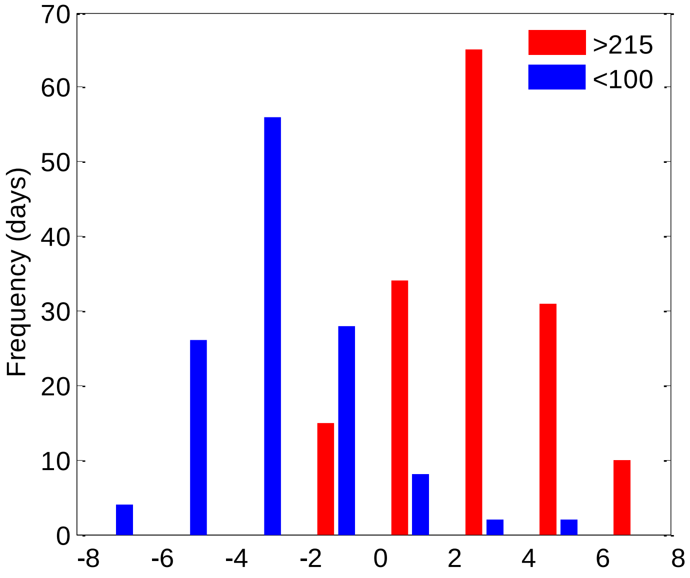

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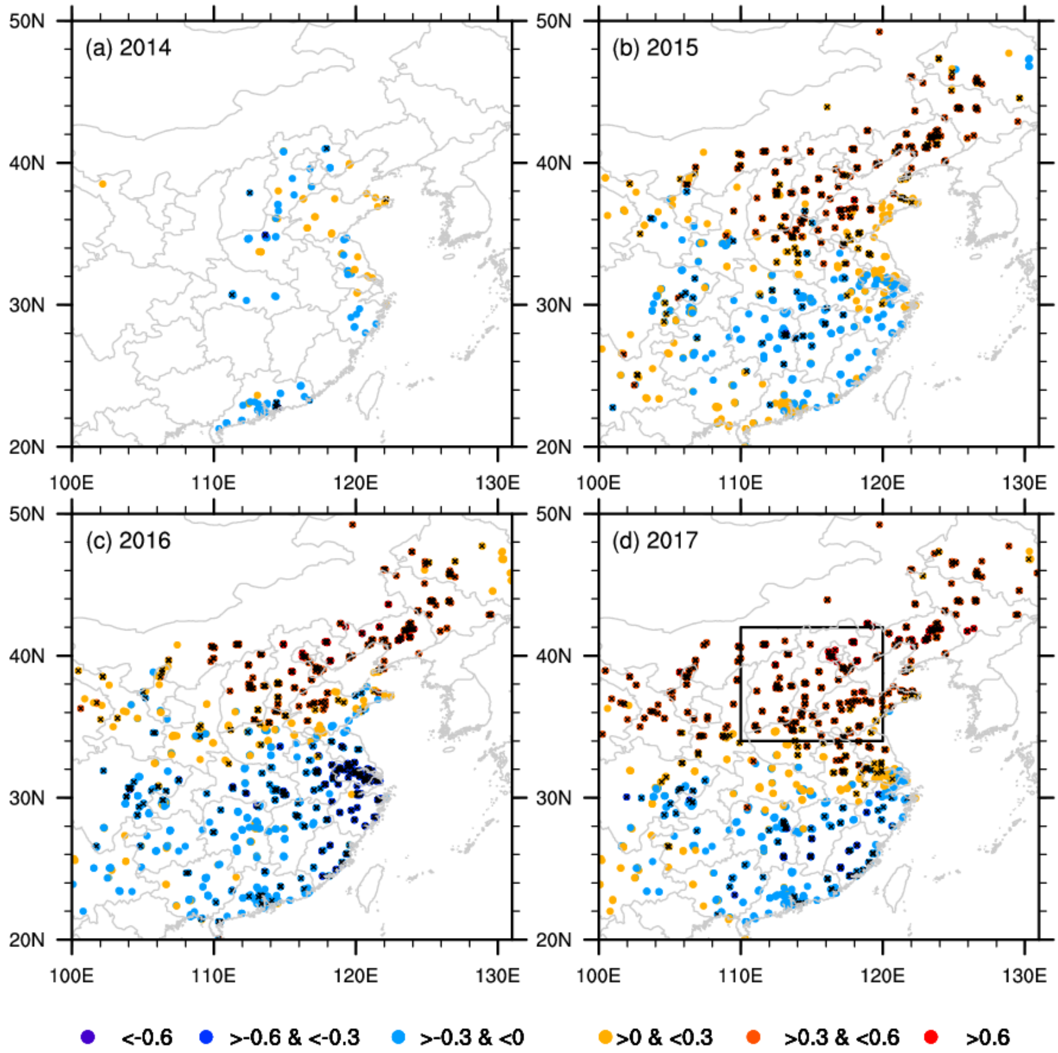

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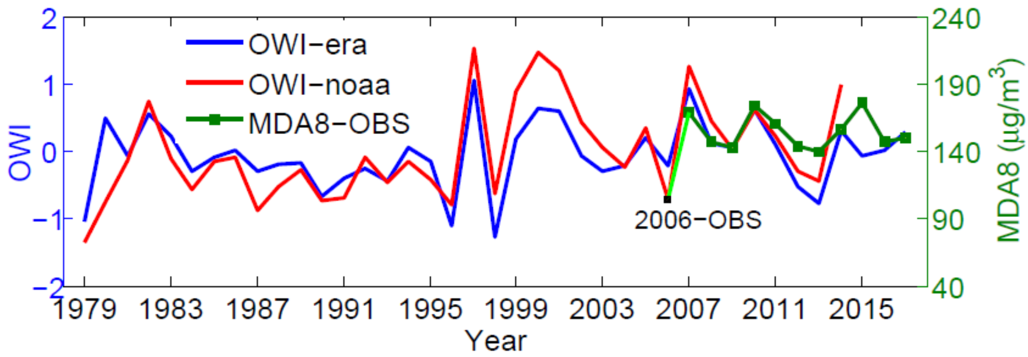


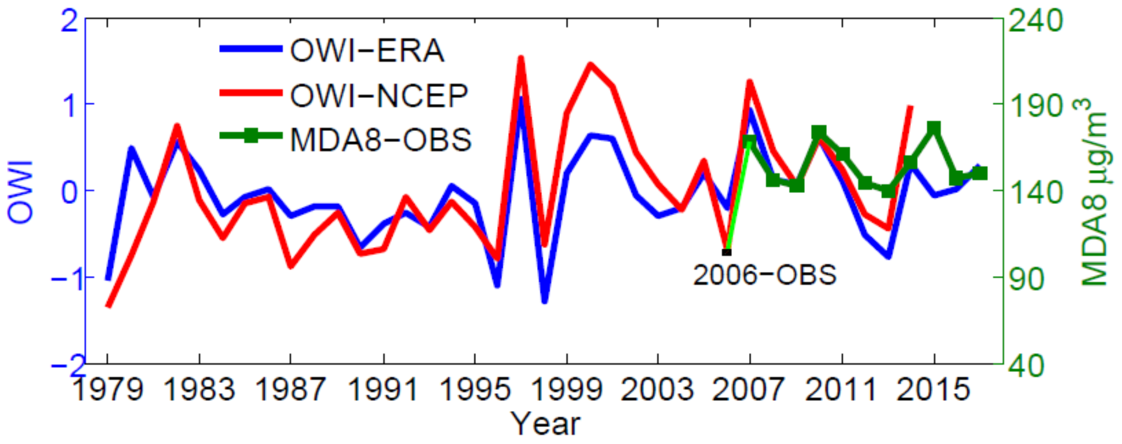
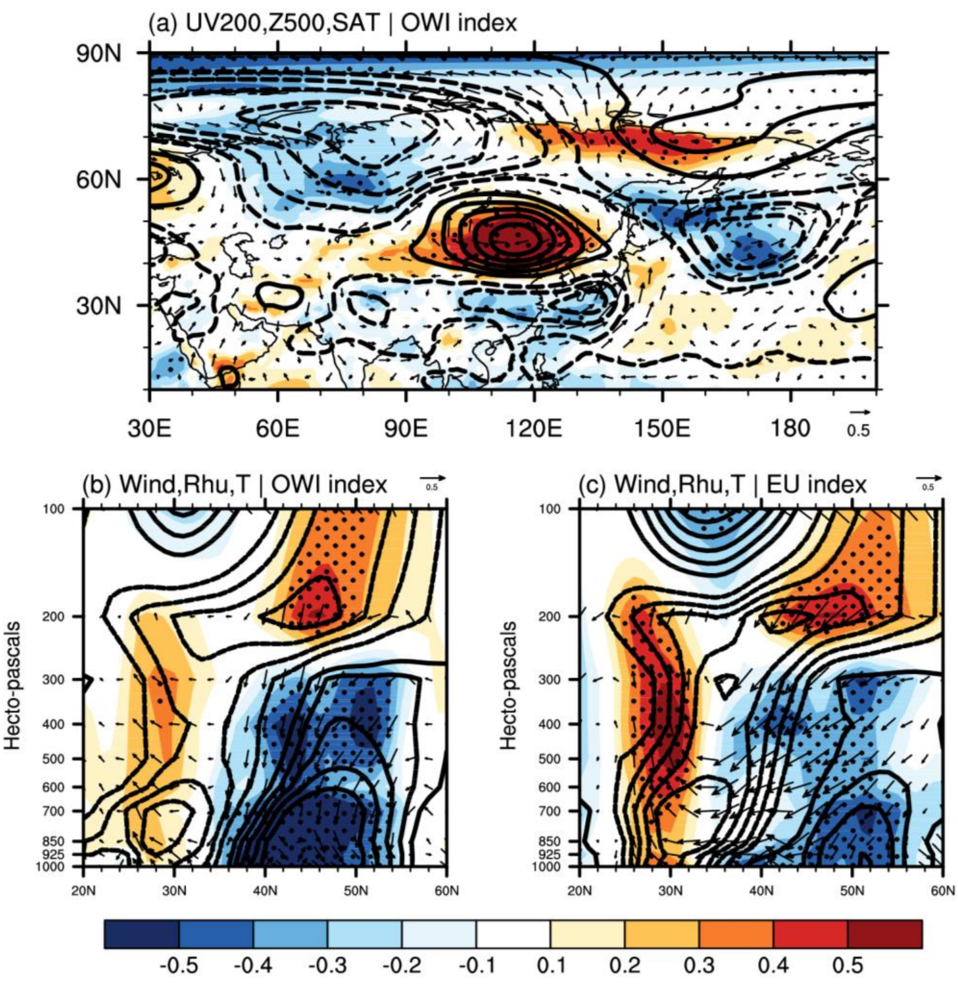
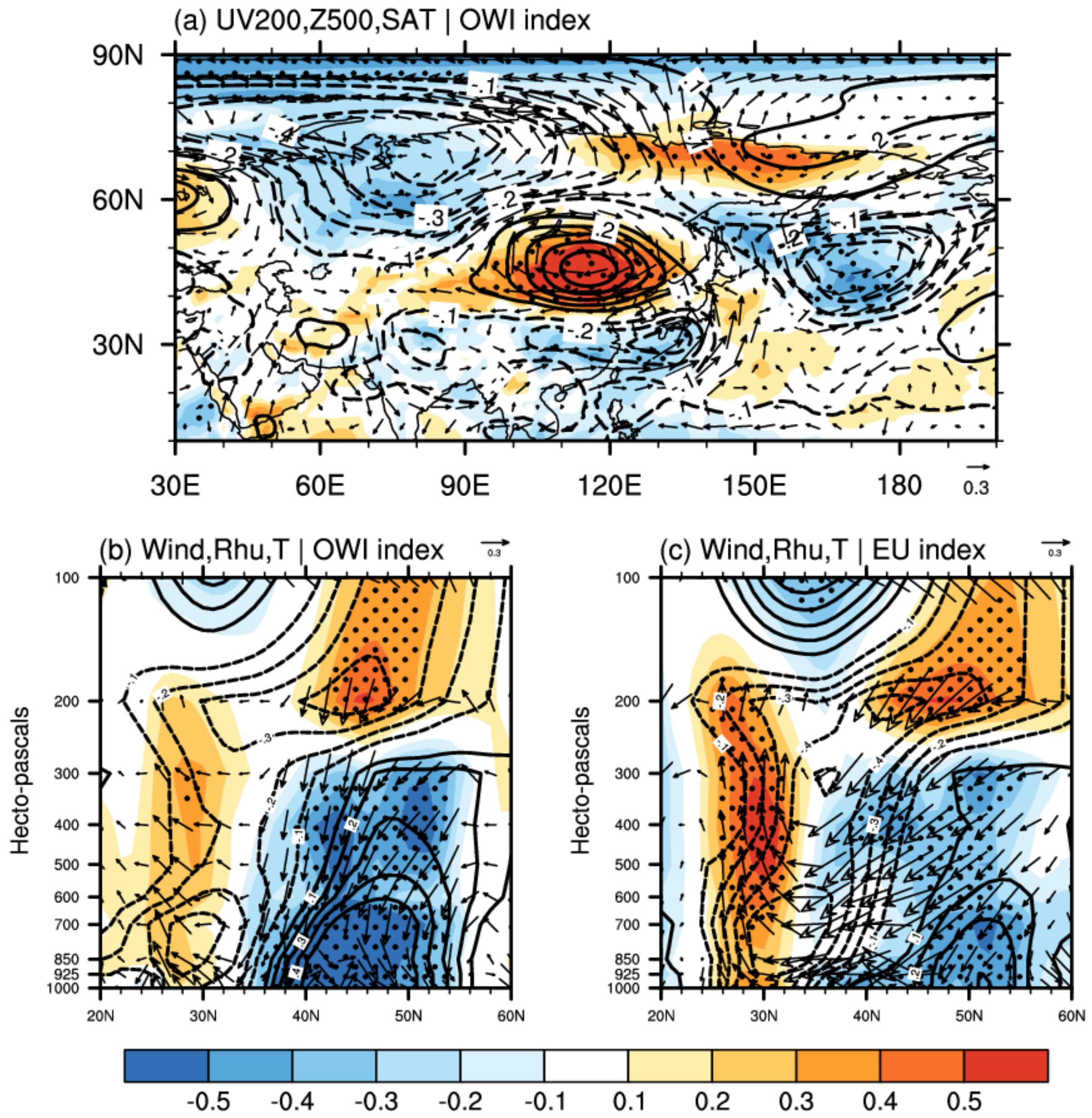


Figure ~~3~~6. The variation in the JJA mean observed SDZ MDA8 (green) from 2006 to 2017, OWI calculated from ERA-interim datasets during 1979–2017 (blue) and OWI calculated from ~~NOAA~~ NCEP/NCAR datasets (red) during 1979–2014.





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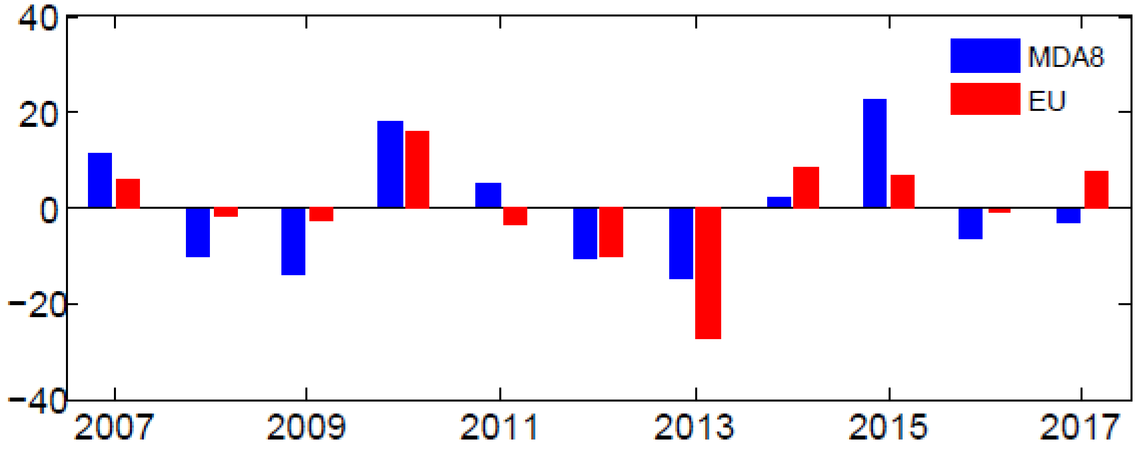

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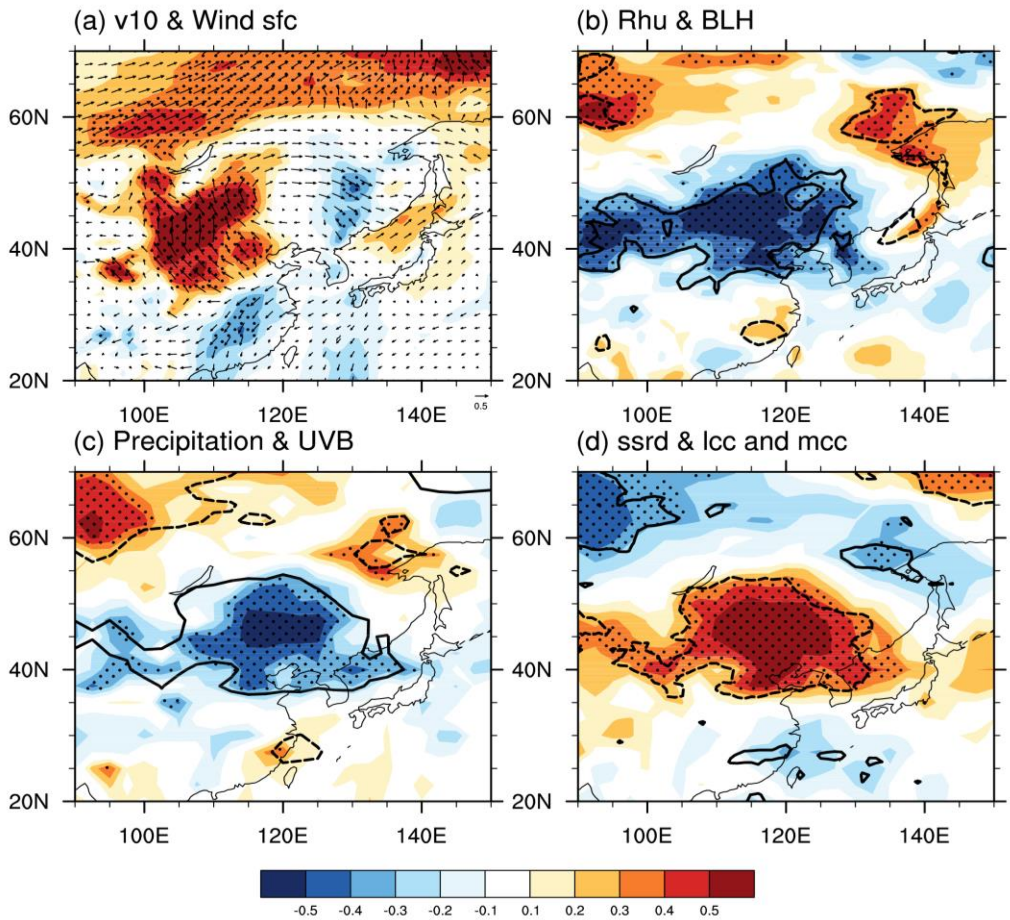

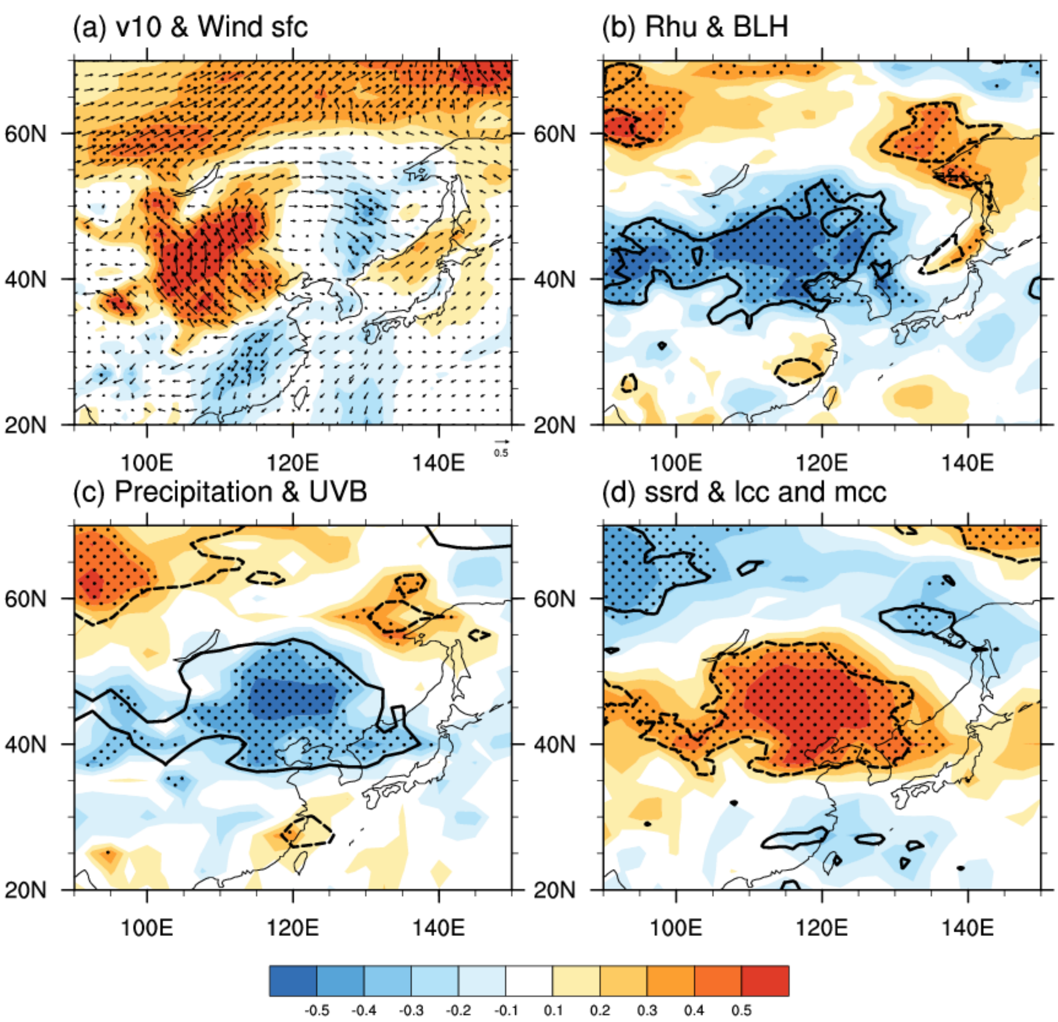

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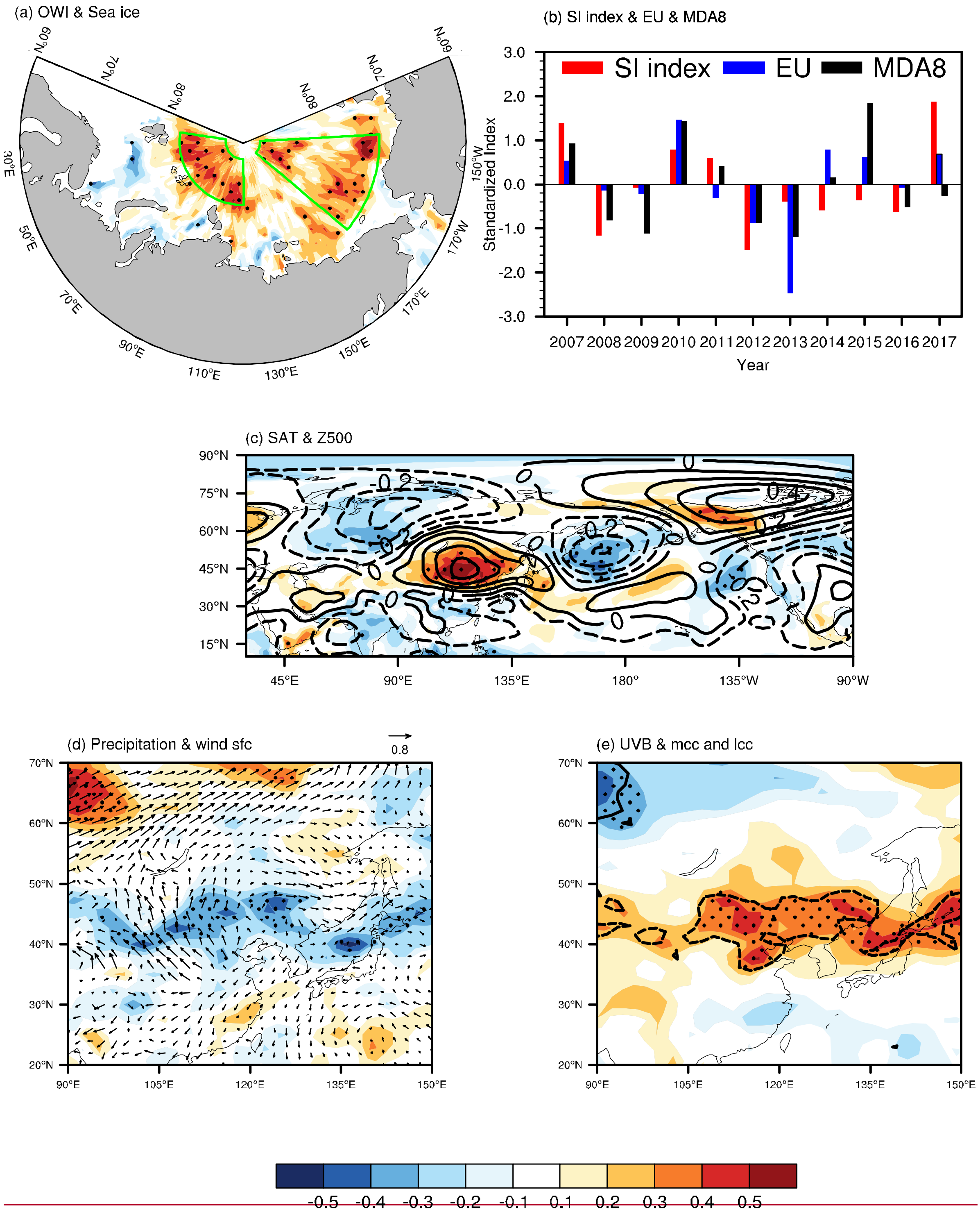
(a) OWI & Sea ice
(b) SI index & EU & MDA8
SI index
EU
MDA8
Standardized Index
Year
2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
(c) SAT & Z500
90°N
75°N
60°N
45°N
30°N
15°N
45°E
90°E
135°E
180°
135°W
90°W
(d) Precipitation & wind sfc
0.8
(e) UVB & mcc and lcc
70°N
60°N
50°N
40°N
30°N
20°N
90°E
105°E
120°E
135°E
150°E
-0.5 -0.4 -0.3 -0.2 -0.1 0.1 0.2 0.3 0.4 0.5

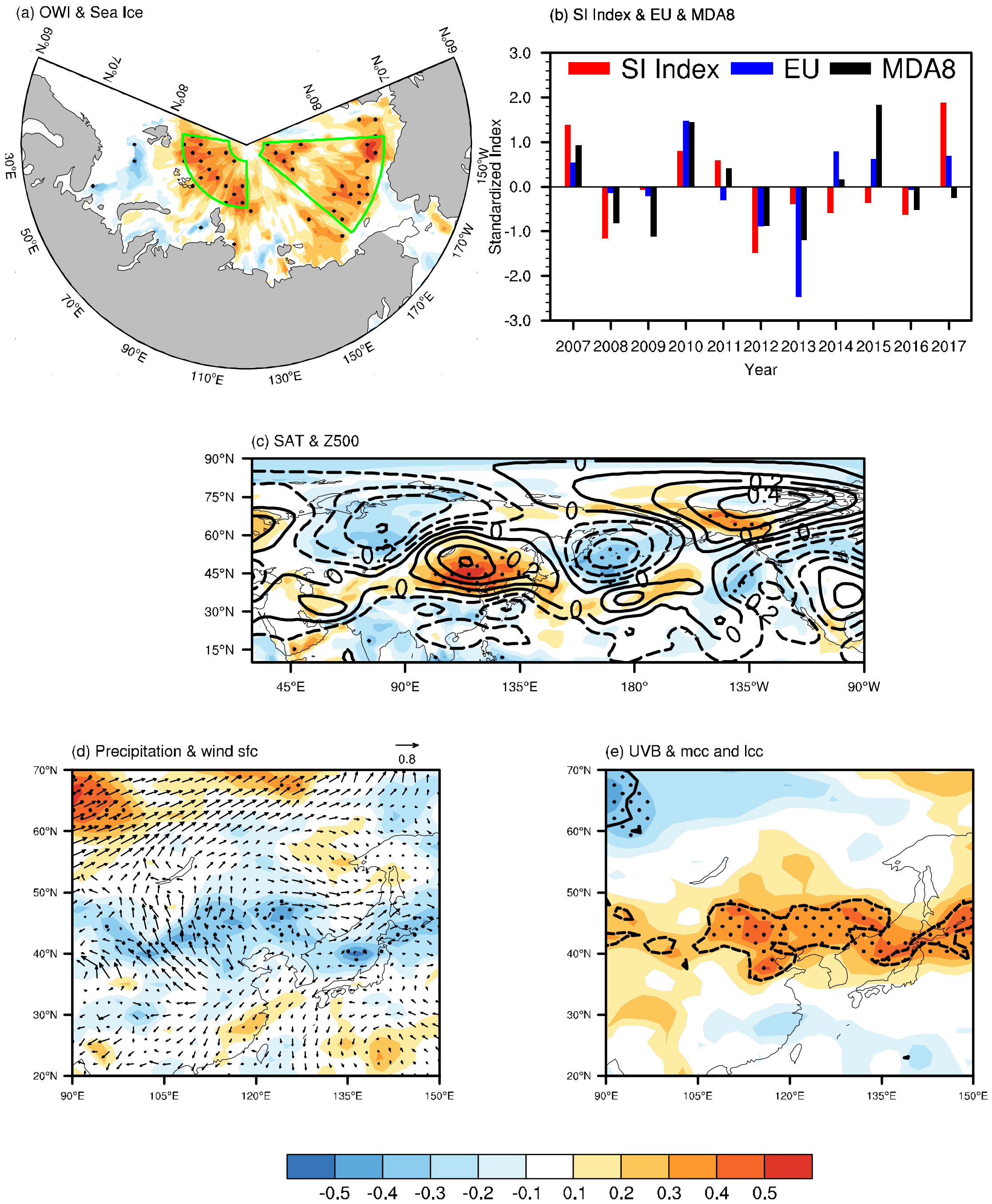

Figure ~~6~~10. The role of the Arctic sea ice. (a) The correlation coefficients between the JJA mean OWI and May sea ice, (b) The variation of the May SI index (red bar, area-averaged sea ice of the green boxes in panel a), JJA mean ~~EUTP~~EU pattern index (blue bar) and JJA mean observational SDZ MDA8 (black bar) from 2007 to 2017. (c) The correlation coefficients between the May SI index and surface air temperature (shading), geopotential height at 500 hPa (contour) from 1979 to 2017. The black dots indicate that the CC with surface air temperature was above the 95% confidence level. (d) The correlation coefficients between the May SI index and precipitation (shading), surface wind (arrow), (e) downward UV radiation at the surface (shading) and sum of low and medium cloud cover (contour) from 1979 to 2017. The black dots indicate that the shading CC with precipitation (d) and downward UV radiation (e) was above the 95% confidence level. The data used here are ERA-Interim datasets.

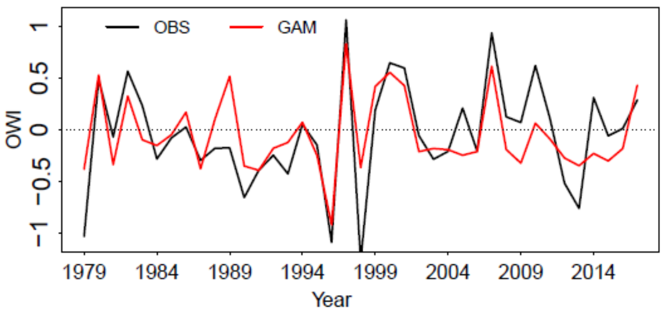

Figure 11. The variation in the observational OWI (black) and the fitted OWI by the generalized additive model (red) from 1979 to 2017

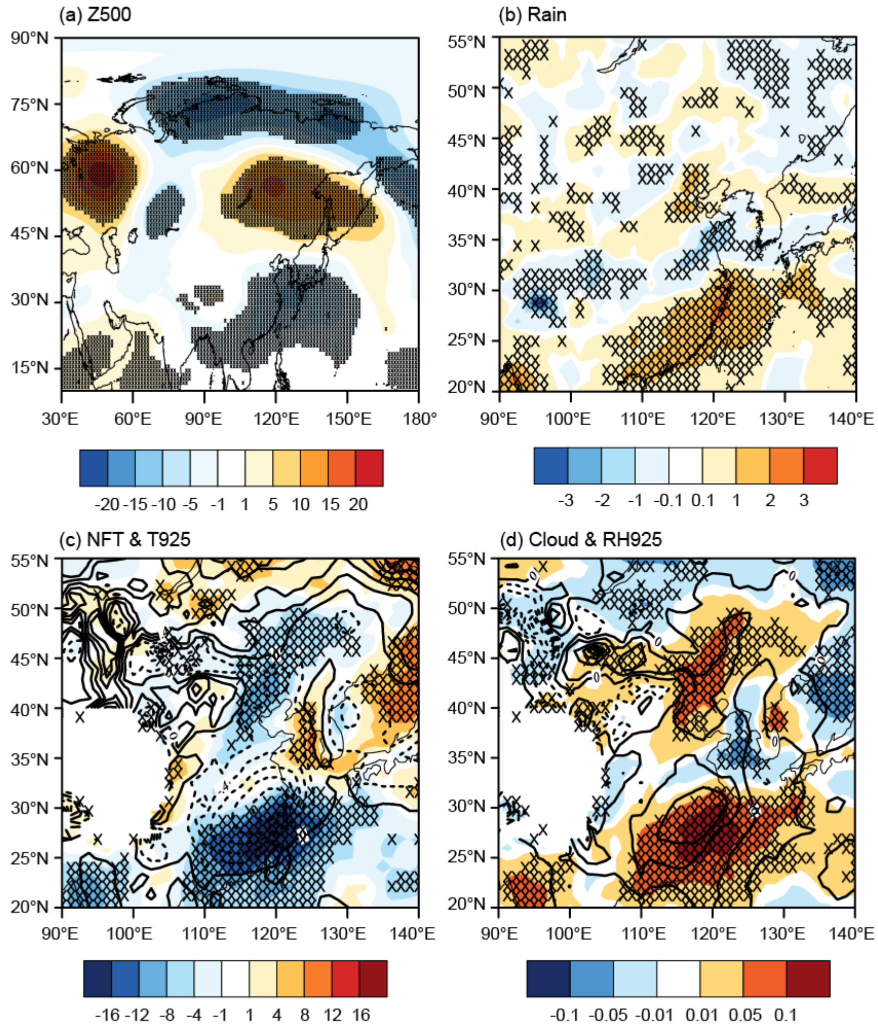

Figure 12. Composite results of the LowASI experiments (LowASI minus Ctrl) by the CAM5 model: (a) geopotential height at 500 hPa, (b) preciptation, (c) net radiative flux at the top of the atmosphere (shading) and temperature at 925 hPa (contour), and (d) sum of low and medium cloud fraction (shading) and relative humidity at 925 hPa (contour). The black hatching denotes the differences with shading were above the 95% confidence level (t-test).