Contribution of variations in Northern Hemisphere annular mode to the near-surface wind speed changes over Eastern China for 1979-2017

Jinlin Zha¹,², Cheng Shen³, Jian Wu²*, Deming Zhao¹†, and Cesar Azorin-Molina⁴,⁵

¹CAS Key Laboratory of Regional Climate and Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, People’s Republic of China

²Key Laboratory of Atmospheric Environment and Processes in the Boundary Layer over the Low-Latitude Plateau Region, Department of Atmospheric Science, Yunnan University, Kunming 650091, People’s Republic of China

³Gaochun Meteorological Bureau, Nanjing 211300, People’s Republic of China

⁴Centro de Investigaciones sobre Desertificación, Consejo Superior de Investigaciones Científicas (CIDE-CSIC), Moncada, Valencia, Spain

⁵University of Gothenburg, Department of Earth Sciences - Regional Climate Group, Gothenburg, Sweden

*Corresponding author: Jian Wu (wujian@ynu.edu.cn)

†Additionally corresponding author: Deming Zhao (zhaodm@tea.ac.cn)
Abstract

Studies have shown that large-scale ocean-atmosphere circulations (LOACs) played the major role to the near-surface wind speed (NWS) changes over China; however, the mechanisms whereby LOACs influences NWS to have received little attention. In this study, the processes of the Northern Hemisphere annular mode (NAM) influencing the NWS changes are revealed over eastern China for 1979-2017. The results showed a slowdown in NWS, at a rate of $-0.09\pm0.01$ m s$^{-1}$ decade$^{-1}$; meanwhile, this decline could be partly driven by the weakening of the zonal wind component. When the NAM exhibits positive phases, the zonal-mean westerly weakens at the low-to-mid-latitudes ($10^\circ$–$40^\circ$N); meanwhile, in the troposphere descending flows prevail near $40^\circ$N and ascending flows prevail near $65^\circ$N, and in the lower troposphere there are northerly anomalies at the low-to-mid-latitudes and southerly anomalies at mid-to-high latitudes ($40^\circ$–$70^\circ$N). The anomalous meridional flows transport heat from lower latitudes to higher latitudes and weaken the north–south air temperature gradient. The decreased air temperature gradient over East Asia reduces the pressure-gradient near the surface in eastern China, thereby decreasing the NWS. Furthermore, the effects of NAM on NWS changes are more significant at interannual scale than decadal scale. $32.0\pm15.8\%$ of the changes in the annual mean NWS are caused by the variations in NAM; meanwhile, the NAM contribution to the interannual changes in the zonal component of NWS reach $45.0\pm12.9\%$.

Keywords: near-surface wind speed, temperature gradient, pressure gradient, Northern Hemisphere annular mode

1 Introduction

Near-surface wind speed (NWS) partially governs the transfer of energy, water, and momentum between the land surface and the lower atmosphere (Azorin-Molina et al. 2014; Kim and Paik 2015). Changes in the NWS affect long-term wind energy production (Pryor and Barthelmie 2011; Tobin et al. 2015, 2016; Tian et
al. 2018), evapotranspiration (McVicar et al. 2012), aerosol dispersion (Lin et al. 2015; Segovia et al. 2017; Shi et al. 2019; Zhang et al. 2019a), among others. Consequently, understanding what causes the NWS to change is critical for addressing some regional environmental issues (Jacobson and Kaufman 2006; McVicar et al. 2007).

A long-term decrease in NWS has been discovered at global-scale (Berrisford et al. 2015; Dunn et al. 2016; Azorin-Molina et al. 2017; Zhang et al. 2019b), with an average linear trend of $-0.08 \text{ m s}^{-1} \text{ decade}^{-1}$ for 1979-2008 (Vautard et al. 2010). At regional-scale, the NWS exhibited decreasing trends of $-0.09$, $-0.16$, $-0.12$, and $-0.07 \text{ m s}^{-1} \text{ decade}^{-1}$ in Europe, Central Asia, East Asia, and North America, respectively (Vautard et al. 2010). In Europe, the decrease in NWS was discovered mainly in Turkey (Dadaser-Celik and Cengiz 2014), Portugal and Spain (Azorin-Molina et al. 2014, 2016), and Finland (Laapas and Venalainen 2018). In Asia, it was reported principally in South Korea (Kim and Paik 2015) and China (Liu et al. 2014; Wu et al. 2016, 2018a; Shi et al. 2015, 2019; Zha et al. 2017a, b; Zhang et al. 2019c). In North America, the NWS decrease was found in Canada (Wan et al. 2010) and America (Pryor et al. 2009; Pryor and Ledolter 2010; Malloy et al. 2015), and it has been discovered also in Australia (McVicar et al. 2008). Overall, decreased NWS is a global fact (McVicar et al. 2012; Wu et al. 2018b). Roderick et al. (2007) termed this decreasing trend in SWS “stilling”.

A terrestrial stilling has been revealed over the past several decades, but some studies also discovered that a weak increase in NWS over the past decades, termed “reversal” (Zeng et al. 2019). Yang et al. (2012) proposed that the annual mean NWS increased over southwestern China after 2000, with an increasing trend of $+0.55 \text{ m s}^{-1} \text{ decade}^{-1}$. The strengthening of NWS was also observed over northwestern China for 1993-2005, with a trend coefficient of $+0.04 \text{ m s}^{-1} \text{ decade}^{-1}$ (Li et al. 2018). Zha et al. (2019a) discovered that a weak increase in NWS over eastern China was detected only in winter since 2000. Zhang and Wang (2020) suggested that the original NWS time series increased over entire China after 1990s. Hence, the
turning point of stilling is not consistent among different regions. Zeng et al. (2019) highlighted the major role of the ocean-atmosphere oscillations in explaining the “stilling” vs. “reversal” phenomena.

The causes of NWS decrease can be attributed to both global and regional scale factors (McVicar et al. 2012; Wu et al. 2018b). Significant reductions in NWSs have been observed in many global regions as mentioned above, thereby indicating that large-scale ocean-atmosphere circulations (LOACs) played a considerable role to the stilling and reversal (Earl et al. 2013; Jerez et al. 2013; Azorin-Molina et al. 2014, 2016; Zhang and Wang 2020). In China, Yang et al. (2012) indicated that the NWS changes in southwestern China were affected by LOACs. Lin et al. (2013) strongly proposed that the spatial gradients of warming or cooling might change the NWS significantly at regional-scale through atmospheric thermal adaption. Xu et al. (2006) proposed that the decreased NWS could be attributed to the steady decline in the East Asia monsoons during 1969–2000. Fu et al. (2011) pointed out that the temporal variations in NWS over China corresponded well with the positive and negative phases of the interdecadal Pacific oscillation. Chen et al. (2013) revealed that the warm and cold Arctic Oscillation (AO) phases have distinct influences on the NWS probability distribution; thus, they proposed the internal climate variability as a major source of both interannual and long-term NWS changes. Accordingly, the LOACs impact on the NWS changes showed large uncertainty over China (Jiang et al. 2010a; Fu et al. 2011; Lin et al. 2013; Wu et al. 2018a).

Variations in LOACs can alter air temperature gradient and pressure gradient (Wu et al. 2017, 2018b; Li et al. 2018). Guo et al. (2017) indicated that the NWS and the air temperature showed negative correlations over and around the Tibetan Plateau in China. You et al. (2010) proposed that the most likely cause of the decreased NWS over Tibetan Plateau was the asymmetric reduction of latitudinal surface air temperature gradient. Guo et al. (2011) quantified the influence of pressure gradient on the weakening of NWS over China for 1969-2005. In the former study, we calculated the pressure-gradient force from the surface to 300 hPa and discovered the changes in NWS over eastern China might be due primarily to the
These abovementioned studies hypothesized that the air temperature gradient and pressure gradient play the predominant roles. However, how the changes of LOACs impact on the air temperature and pressure gradients and, therefore, on NWS changes are rarely analyzed in the scientific literature (You et al. 2010; Guo et al. 2011; Lin et al. 2013).

The dominant circulation pattern in Northern Hemisphere is the Northern Hemisphere annular mode (NAM), also known as AO (You et al. 2010; Lin et al. 2013). The NAM has been revealed to have played a prominent role in the changes of NWS in eastern China over the past several decades (Wu et al. 2018a); nevertheless, the processes whereby the NAM affects NWS were not revealed systematically. Therefore, the novelty of this manuscript over previously published work lies in two key points: 1) the processes of NAM influencing the NWS changes are revealed and 2) the relative contributions of NAM to variations in NWS are estimated.

2 Datasets and Methods

2.1 Datasets

We selected eastern China (15°–55°N, 105°–135°E) as the study region, due to its dense meteorological stations and mostly flat topography. We used the observed NWS (in m s\(^{-1}\)) at 10 m to investigate the spatiotemporal characteristics and changes. The wind speed dataset was obtained from China Meteorological Administration (CMA) (http://www.nmic.cn/site/index.html; last accessed 14 November 2020). The site selection of the observation stations, the anemometer installation, and the observation process were all done according to the standards of the World Meteorological Organization’s guide to the Global Observing System and the CMA’s technical regulations on weather observation (CMA 2003; Feng et al. 2004; Guo et al. 2011). Based on the introduction of CMA, the correct data, questionable data, and incorrect data was labeled with the quality control code ‘0’, ‘1’, and ‘2’, respectively. Spatial pattern of total stations in Eastern China
are shown in Fig. 1. The quality control and homogenization of observed NWS is explained in section 2.2.

To investigate the changes in LOAC pattern, the variables including the daily mean zonal wind (in m s\(^{-1}\)), meridional wind (in m s\(^{-1}\)), air temperature (in K), sea-level pressure (in Pa), and surface pressure (in Pa) in the ERA5 reanalysis data at a spatial resolution of 0.75°×0.75° over the Northern Hemisphere from 1979-2017 were used, which were produced by European Centre for Medium-Range Weather Forecasts (ECMWF; Hersbach and Dee (2016)). ERA5 data released covers the period from 1979 and continues to be extended forward in near real time, which was produced using 4D-Var data assimilation in CY41R2 of ECMWF’s Integrated Forecast System (IFS) and was operational at ECMWF in 2016. Relative to the ERA-Interim dataset (Simmons et al. 2007, 2010, 2014), the ERA5 reanalysis dataset benefits from a decade of developments in model physics, core dynamics and data assimilation. In addition to a significantly enhanced horizontal resolution, ERA5 has a number of innovative features. These include hourly output throughout and an uncertainty estimate (Copernicus Climate Change Service (C3S) 2017). Compared with the other global reanalysis datasets, the ERA5 reanalysis dataset shows better performance in describing the regional mean climate at a seasonal scale and representing the spatiotemporal variations of the wind speed (Ramon et al. 2019). The ERA5 dataset includes 137 hybrid sigma/pressure (model) levels in the vertical, with the top level at 0.01 hPa. The daily mean surface pressure, sea-level pressure, 10 meter \(U\) and \(V\) wind component (in m s\(^{-1}\)) were used; meanwhile, the \(U\) and \(V\) wind components and air temperature at 27 vertical levels from 1000 to 100 hPa were also used.

To explore the process whereby the NAM affects the NWS changes over eastern China, the NAM index derived from Li and Wang (2003) is employed (http://ljp.gcess.cn/dct/page/65540; last accessed 14 November 2020), which is one measure of the hemispheric-wide fluctuations in surface air pressure occurring at the mid-to-high-latitude annular belt of actions. Compared to other zonal indices, the NAM index better reflects the zonal hemispheric fluctuation in air mass, and therefore it has been extensively used
to investigate the variations of the atmospheric circulation (Baldwin and Thompson 2009; You et al. 2013; Rotstaln et al. 2014; Liu et al. 2016; He et al. 2018).

2.2 Methods

To improve the quality of NWS data, the stations used in this study were selected based on the following criteria: 1) the station must be the national meteorological station; 2) there is no missing data in a whole year after 1979; meanwhile, there is no missing data in a whole season and month in a year; 3) the total days of missing data accounted for less than 1% of the length of the total data series; 4) the wind speed must be accompanied by the quality control code ‘0’ in the datasets. Finally, 587 stations during the period from 1979-2017 were selected for analysis (Fig. 1, green dots). The standard normal homogeneity test (SNHT) method was further used to test the homogenization of selected stations, which has been extensively used in the former studies (Alexandersson 1986; Liu 2000; He et al. 2012; Azorin-Molina et al. 2014; Zhang et al. 2020). Firstly, the reference function is defined, named as Eq. (1).

\[
Q_i = \frac{Y_i \cdot \sum_{j=1}^{n} \rho_j^2}{\sum_{j=1}^{n} (\rho_j^2 \cdot X_{ji} \cdot \bar{Y} / \bar{X}_j)}
\]

where \(Y_i\) denotes the mean wind speed of tested station in the \(i\) year. \(\bar{Y}\) denotes the mean value of tested station. \(X_{ji}\) denotes the mean wind speed of \(j\) reference station in the \(i\) year. \(\bar{X}_j\) denotes the mean value of \(j\) reference station from 1979-2017. \(\rho_j\) denotes the correlation coefficient between the tested station and reference station \(j\). The reference station is selected according to the followed criterion: if the stations are enclosed within a circle with radius of 1° latitude and longitude centered at middle of tested station, the stations are selected as the reference stations (Li et al. 2003). Based on Eq. (1), computing a new standardized series \(Z_i\) \((Z_i = \frac{Q_i - \bar{Q}}{S_Q})\). \(\bar{Q}\) and \(S_Q\) denote the mean value and standard deviation of \(Q_i\),
respectively. If \( \{Z_i\} \) has a breakpoint, which is occurred in \( K \) point (\( 1 \leq K \leq i \)), establishing the testing statistic \( T_K \):

\[
T_K = K \cdot \mu_1^2 + (i - K) \mu_2^2
\]  

(2)

where \( \mu_1 \) and \( \mu_2 \) denote the mean value of serial in prior and after breakpoint \( K \) (\( \mu_1 \neq \mu_2 \)). If maximum value of \( T_K \) is less than threshold (7.94, \( p<0.10 \)), the data passed the significance test at the 0.10 level (Liu 2000). Based on the SNHT method, the observed NWSs used in study are homogeneous.

To assess the consistency of the phases between two data series, the probability of an anomaly appearing at the same time point in the two data series are calculated (named as PAST) (Wu et al. 2018a; Zha et al. 2019a, b) (Eq. (3)).

\[
PAST = \frac{\sum_{i=1}^{m} (P_i + N_i)}{m} \cdot 100\%
\]  

(3)

where \( P_i \) and \( N_i \) denote the positive and negative anomalies of two data series at the same years, respectively. \( m \) denotes the whole study period (\( m = 39 \)).

To analyze whether the decrease in NWS is caused by the weakening of zonal or meridional circulations, the observed NWS is decomposed into zonal and meridional components based on the wind direction of the ERA5 reanalysis dataset, this being because the wind direction of the observed daily mean NWS is not available. Cressman objective analysis method is employed to interpolate the stations’ observational data to grid at a resolution of 0.75° (Cressman 1959). A Gaussian low-pass filter with a 9-yr window is used to extract the decadal signals in the data (Li et al. 2010, 2011; Zhu et al. 2012), then the inter-annual sequence of the data is obtained based on the raw sequence minus the decadal sequence (Wu et al. 2018a). The least-squares method (LSM) is used to calculate the linear trend coefficient (in m s\(^{-1}\) decade\(^{-1}\)). To compare the trend calculated based on LSM, a non-parametric Thiel-Sen approach (TSA) is used (Thiel 1950; Sen
Correlation analysis and two-tailed Student’s *t*-test are used to determine the significance of the data. Composite analysis is used to discuss the circulation differs between positive and negative NAM phases. The positive and negative values of NAMI were defined as the positive NAM phase (NAM+) and negative NAM phase (NAM−), respectively.

3 Results

3.1 Spatiotemporal characteristics of NWS

Spatiotemporal characteristics of NWS over eastern China have been presented in our former study (Wu et al. 2018a); therefore, herein we exhibited only the main NWS characteristics for completeness. The NWS decreased significantly at a rate of −0.09±0.01 m s⁻¹ decade⁻¹ (*p*<0.01) for 1979-2017, which mainly showed positive anomalies before 2000 and negative anomalies after (Fig. 2a). Compared with the previous studies in the other regions (Yang et al. 2012; Li et al. 2018, Zeng et al. 2019; Zhang and Wang 2020), a recovery of NWS after 2010 was also observed in eastern China, at a rate of +0.21±0.099 m s⁻¹ decade⁻¹ (*p*<0.10). The results exhibit that the zonal component of the observed NWS (denoted by *u*) had a decreasing trend, at a rate of −0.04±0.01 m s⁻¹ decade⁻¹ (*p*<0.01), which accounted for 44.4% of the decreasing trend of the NWS (Fig. 2b). The meridional component of the observed NWS (denoted by *v*) also exhibited a decreasing trend, at a rate of -0.005±0.014 m s⁻¹ decade⁻¹ (*p*>0.10). The decreasing trend of *v* accounted for only 5.6% of the decreasing trend of NWS (Fig. 2c). The trends were calculated based on LSM were consistent with that were computed based on TSA. Additionally, the correlation coefficients between the total wind speed and *u* and *v* were 0.60 (*p*<0.01) and 0.15 (*p*>0.10), respectively, the PAST between the NWS and *u* and *v* were 69.2% and 58.9%, respectively, and the values of the residual sum of squares of the linear fitting between the NWS and *u* and *v* were 0.13 and 0.39 m² s⁻², respectively. Consequently, the significant reduction in NWS was mainly caused by the reduction in *u*.
Spatial patterns of NWS and the corresponding trends are shown in Fig. 3. The regional mean values of NWS was 2.29 m s$^{-1}$. The highest values exceeding 2.4 m s$^{-1}$ were located in northeastern China, Inner Mongolia, Shandong peninsula, and coastal regions (Fig. 3a). The NWS has generally decreased for 1979-2017, with the trend coefficients exceeding the significance $t$-test at the 0.10 level in most regions. The strongest reduction in NWS was located in northeastern China and some regions of the middle and lower reaches of the Yellow River and Yangtze River, this being $-0.20$ m s$^{-1}$ decade$^{-1}$ ($p<0.01$), and the weakest decrease in NWS was located in central China, being less than $-0.05$ m s$^{-1}$ decade$^{-1}$ ($p<0.10$) (Fig. 3b). Previous studies have shown a significant slowdown in NWS over eastern China (Fu et al. 2011; Guo et al. 2011; Lin et al. 2013). The $u$ experienced a decreasing trend for 1979-2017, with most downward trends passed significance $t$-test at the 0.10 level. The most significant reduction in $u$ was found in northern China, with a trend coefficient exceeding $-0.10$ m s$^{-1}$ decade$^{-1}$ ($p<0.01$) (Fig. 3c). The decreasing trend of $v$ was not significant in southeastern China and North China plain, especially for southern China, the $v$ exhibited an increasing trend in some regions. Among all stations, 91.9% and 60.6% showed that $u$ and $v$ had a decreasing trend, respectively. These results mean that the decreasing trend of $u$ was more significant than that of $v$ during the study period 1979-2017, and that the observed decrease in NWS was mainly induced by the reduction of $u$.

### 3.2 Effects of NAM on large-scale atmospheric circulations

We discovered that changes in the near-surface and troposphere wind speeds over eastern China could be influenced by the NAM (Wu et al. 2018a); the NAMI exhibited a weak increasing trend during the study period. The NAM kept the strong positive phases, which were the strongest periods over the past 100 years (Li and Wang 2003; Li 2005). The NAM+ and NAM− accounted for 74.4% and 25.6% of all the years in the study period for 1979-2017, respectively (Fig. 4).

Before revealing the processes whereby the NAM influences the NWS changes over eastern China, we
first analyzed how NAM modulates the large-scale wind fields over the Northern Hemisphere. During a NAM+, a negative wind speed anomaly occurred over and around 30°N in the Northern Hemisphere, and a positive wind speed anomaly occurred over and around 60°N (Fig. 5a). The spatial pattern of the composite difference in the zonal-mean westerly between NAM+ and NAM− (Fig. 5b) is consistent with Fig. 5a. The correlation coefficient between the NAMI and wind speed exhibited a zonal pattern. The negative and positive correlation coefficients located at mid-latitudes and high latitudes, respectively, and that the significant correlations above a significance t-test at 0.10 level located around 30°N and 60°N, respectively, implying that accompanied by the variations of NAM, the wind speed decreased at mid-latitudes and increased at high latitudes (Fig. 5c). The spatial pattern of the correlation coefficient between the NAMI and zonal wind was consistent with that between the NAMI and wind speed, which also presented a zonal annular belt (Fig. 5d). These results implied that the continuously positive anomaly of NAM could induce the decrease of NWS at mid-latitudes of Northern Hemisphere (China lies in this region); moreover, the influence of the NAM on the NWS changes can be due to its modulation of zonal-mean westerlies.

3.3 Physical processes of NAM and its influence on NWS changes

The abovementioned results show that the effects of the NAM on the large-scale zonal flows are pronounced. Here, we investigate the processes behind the NAM that control the observed NWS changes. Vertical characteristics of the composite differences between NAM+ and NAM− are shown in Fig. 6. A negative zonal-mean zonal wind speed difference (denoted by ZWSD) between NAM+ and NAM− was found at 10°–40°N, and a positive zonal-mean ZWSD was found from 40°N to polar. The strongest negative ZWSD were found around 30°N and positive ZWSD were found around 55°N (contour). Accordingly, accompanied by the variations of NAM, the zonal westerly decreased over mid-latitudes and increased over high-latitudes. A negative zonal-mean meridional wind speed difference (denoted by MWSD) between NAM+ and NAM− was found at 5°–35°N in the lower troposphere, and a positive zonal-mean MWSD was
found at 40°–65°N in the lower troposphere (shaded). These results indicate that the northerly anomalies at 5°–35°N and the southerly anomalies at 40°–65°N in the lower troposphere accompanied by continuous NAM warm phases during the period from 1979-2017. The anomalous ascending flows occurred at 60°–72°N and the anomalous descending flows occurred over mid-latitudes at 30°–50°N (vector).

Consequently, the Ferrell cell at high latitudes enhanced along with the continuous NAM warm phases. Hence, the NAM had considerable effects on the vertical circulation field. Actually, these characteristics can also be produced at four seasons (Fig. S1).

The NAM caused the anomalies of meridional winds in the lower troposphere over the mid- and high-latitudes in Northern Hemisphere; meanwhile, the descending flows of Ferrell cell further increased the southerly in the low troposphere. The increased southerly in the lower troposphere transport heat from lower latitudes to higher latitudes near the surface; thus, the surface air temperature (SAT) at mid-to-high latitudes could rise. Consequently, the SAT difference between NAM+ and NAM− at the near-surface layer are investigated (Fig. 7a). The SAT was higher at mid-to-high latitudes between 30°N and 70°N during a NAM+ than it was during a NAM−; meanwhile, a significant SAT difference occurred at mid-to-high latitudes of East Asia, which exceeded +0.8°C ($p<0.10$). The SAT at subtropical and low latitudes was lower during a NAM+ than it was during a NAM−, although the SAT difference failed to exceed the significance $t$-test at the 0.10 level. These results indicate that the SAT increased at mid-to-high latitudes accompanied by the continuous NAM warm phases from 1979-2017, especially for East Asia. The north–south SAT difference between mid-to-high latitudes and low-latitudes over East Asia could decrease due to the significant positive SAT anomaly that occurred at mid-to-high latitudes in East Asia. Therefore, we investigated further the north–south SAT difference between mid-to-high latitudes (35°–60°N, 60°–140°E) and low latitudes (0°–20°N, 60°–140°E) over East Asia (denoted as SATD) (Fig. 7b). The temporal changes in SATD exhibited a downward trend, at a rate of $-0.21\pm0.066 \, ^\circ\text{C \, decade}^{-1}$ ($p<0.01$); meanwhile, the NAM and SATD
exhibited a negative correlation of $-0.60$ ($p<0.01$) (Fig. 7c). These results mean that NAM strengthening considerably reduced the SATD between mid-to-high latitudes and low latitudes of East Asia.

Looking into Fig. 7a, all parts of the east of 100°E showed a positive SAT difference, so the west-east SAT gradient could be influenced by variations of NAM. Consequently, the west-east gradient of SAT that over two regions 15°–50°N, 65°–105°E and 15°–50°N, 105°–138°E are analyzed. These two regions cover the entire China. The results show that the west-east SAT difference showed decreasing trend from 1979-1998, at a rate of $-0.27\pm0.079$ °C decade$^{-1}$ ($p<0.01$), and showed increasing trend from 1999-2017, at a rate of $+0.15\pm0.079$ °C decade$^{-1}$ ($p<0.10$) (Fig. S2). Compare to Fig. 7b, the temporal changes of west-east SAT difference were not consistent with that of north-south SAT difference. The correlation coefficients between west-east SAT difference and NWS, between west-east SAT difference and NAMI were $+0.21$ ($p>0.10$), and $-0.50$ ($p<0.01$), respectively. Compared to Fig. 2a, the temporal changes of west-east SAT difference were also not consistent with that of observed NWS. Consequently, the changes of west-east SAT difference could not be the primary factor that caused the NWS changes over eastern China.

According to the state equation, $P = \rho RT$ ($P$ is the pressure, $\rho$ is air density, $R$ is air constant, and $T$ is the air temperature), changes in air temperature can influence changes in surface pressure; therefore, changes in north-south SATD could cause the changes in the north–south pressure difference. Hence, the pressure difference between mid-to-high latitudes (35°–60°N, 60°–140°E) and low latitudes (0°–20°N, 60°–140°E) is calculated (Fig. 8a). A downward trend in the surface pressure difference was observed, at a rate of $-1.87\pm0.69$ Pa yr$^{-1}$ ($p<0.01$). Furthermore, the pressure difference and SATD exhibited a significant correlation, with a correlation coefficient of $+0.60$ ($p<0.01$) (Fig. 8b). Because the meridional pressure gradient changes can affect the zonal wind changes, the relationship between the meridional pressure gradient and $u$ of the observed NWS is also investigated. These exhibited a significant positive correlation, with a correlation coefficient of $+0.60$ ($p<0.01$) (Fig. 8c). To summarize, variations in NAM reduced the
SATD, which in turn weakened the meridional pressure gradient over East Asia and, thus, resulted in the decreased NWS in eastern China.

4 Discussion

4.1 Effects of NAM on the interannual variability of NWS

In a previous study, the correlation coefficient between the NAM and the observed NWS is more significant at interannual scale than that at decadal scale (Wu et al. 2018a). Therefore, we investigate here whether the physical processes of NAM on the NWS could be better presented at interannual scale and estimate the potential contribution of the NAM to interannual fluctuations of NWS. To estimate whether the interannual variability of NWS are influenced by the freedom of Gaussian low-pass filter, the interannual sequence of NWS is also extracted based on the raw sequence minus the linear fitting (Gong et al. 2014). The results showed that the year-by-year variability is similar based on two methods, with a correlation coefficient reaching 0.73 ($p<0.001$). The probability of the extremes appearing at the same time point in the two data serials reaching 100.0% (Fig. S3). Consequently, the extracted interannual signals based on the method used in this study are credible.

Before considering how the NWS and LOACs are related, the effects of NAM on the interannual variations of the circulation fields are analyzed first. The NAM index is defined based on the sea level pressure (SLP); therefore, the relationships between the NAM and the SLP at different timescales are investigated. The results show that significant positive correlation between NAMI and SLP was found at the belt of 30°N, and negative correlation was found at the belt of 60°N, with correlation coefficients exceeding ±0.4 ($p<0.05$) (Fig. 9a and 9b). Collectively, these spatial patterns of correlation coefficients present the typical NAM pattern. The mean values of the negative and positive correlations over the significant region (the blue and red rectangles in Fig. 9a and 9b) were also pronounced at interannual scale (Tab. 1), although
the percentage differences for the grid with the significant negative and positive correlations were not significant. Compared to Fig. 5d, the annular belt pattern of the correlation coefficient between the NAMI and zonal wind was reproduced well at interannual scale, and significant negative and positive correlations exceeding a confidence level of 0.10 were also located around 30°N and 60°N, respectively (Fig. 9c). The correlations between the NWS over eastern China and the SLP field over Northern Hemisphere were also analyzed (Fig. 9d). Compared to Fig. 9a, Fig. 9d shows the reverse spatial pattern of the correlation coefficient between the NWS over eastern China and the SLP, especially for the center of the significant correlation exceeded the 0.10 level. However, a similar spatial pattern was not presented when the decadal signals in the NWS were not excluded (Fig. 9e). The quantitative results show that the mean values of the negative and positive correlations over the significant region as shown by the blue and red rectangles in Fig. 9d were +0.30 (p<0.10) and -0.27 (p<0.10), respectively. The percentages of the grid with significant positive and negative correlations over the significant region were 80.2% and 78.6% at interannual scale, respectively, but these reached only 11.40% and 3.13% when the decadal signals of the NWS were not excluded, respectively (Tab. 1). The zonal pattern of the correlation coefficient between the NWS in eastern China and the zonal wind was more evident at interannual scale (Fig. 9f). Accordingly, the annular belt pattern of the correlation coefficient between the NWS and the zonal wind was more significant at interannual scale, especially for the annular belts around 30°N and 60°N.

The vertical characteristics of the circulation pattern associated with the NAM at interannual scale are also compared (Fig. 10). The NAM and zonal-mean meridional wind exhibited negative and positive correlations at 10°–40°N and 45°–70°N in the lower troposphere, respectively (Fig. 10a). Significant ascending flow was found around 65°N and descending flow was found around 40°N in the troposphere (Fig. 10b). Quantitatively, the percentages of grids with negative (positive) correlation coefficient based on raw and interannual sequences over the region with descending (ascending) flows at 30°–50°N (60°–72°N)
were 92.0% (84.7%) and 93.6% (82.4%), respectively (Tab. 2). Compared to Fig. 6, the Ferrell cell at high latitudes was well reproduced in Fig. 10a; consequently, the effects of NAM on vertical circulations can be reproduced well at interannual scale. If the effects of the NAM on the interannual variations of NWS in eastern China are more significant, the NWS should respond well to the changes in vertical circulation caused by the variations in NAM. Therefore, the relationships between NWS in eastern China and vertical circulations are compared at different timescales. Compared to Fig. 10a, the correlation coefficient between NWS and zonal-mean meridional wind exhibited a similar vertical structure (Fig. 10c). Negative correlation at 10°–40°N in the lower troposphere corresponded to reduced NWS over eastern China accompanied by weakening meridional wind, namely an enhanced northerly. Positive correlation at 45°–70°N in the lower troposphere corresponded to reduced NWS over eastern China accompanied by strengthening meridional wind, namely an enhanced southerly. The similar vertical characteristics of correlation coefficient between NWS and zonal-mean meridional wind as shown in Fig. 10e were consistent with those shown in Fig. 10c, but the more significant correlations were found at the interannual scale (Fig. 10c). At interannual scale, the significant positive correlation exceeded the 0.10 level between NWS and descending flow mainly located around the latitude belt of 40°N and negative correlation between the NWS and ascending flow mainly located around the latitude belts of 65°N, in particular for the region of the Ferrell cell (Fig. 10d). These results cannot be well presented when the decadal signals of the NWS were not excluded (Fig. 10f).

The quantitative results show that the mean correlation coefficients computed based on raw and interannual sequences over the region with descending (ascending) flows at 30°–50°N (60°–72°N) were –0.13 (+0.11) and –0.27 (+0.17), respectively; therefore, all the correlation coefficients calculated based on raw sequences failed to exceed the significance t-test at 0.10 level (Tab. 2). Over the regions as shown using the blue and red rectangles in Fig. 10d, the percentage of grids exhibiting a significant negative and positive correlation between NWS and vertical velocity based on the interannual sequences accounted for 21.3% and
38.2% of all grids, respectively. However, based on the raw sequence, over the regions as shown using the blue and red rectangles in Fig. 10f, the percentage of grids exhibiting a significant negative and positive correlation between NWS and vertical velocity just accounted for 5.0% and 6.1% of all grids, respectively. (Tab. 2). The results are compared in detail in Tab. 2. Consequently, the more significant descending and ascending flows were found at interannual scale, which means that the effects of changes in vertical cell caused by the variations in NAM on NWS were stronger at interannual scale. To quantify the effects of NAM on the NWS changes, we normalized both the NAMI and NWS, and performed regression analyses at different timescales. We considered that the regression coefficients between NAMI and NWS as the relative contribution of the NAM to the NWS changes. At interannual scale, 32.0±15.8 % of the changes in the observed annual mean NWS over eastern China could be attributed to the NAM changes; however, the NAM contribution on interannual variations of $u$ of the observed NWS over eastern China could be more significant, which reached 45.0±12.9 %. Nevertheless, the NAM contribution to the annual mean NWS and $u$ over eastern China based on raw sequence only reached 23.5±15.2 % and 35.6±13.1 %, respectively. All these results at interannual scale passed the significance $t$-test at 0.05 level. Therefore, the NAM contribution to the $u$ of the observed NWS over eastern China is stronger than that to the observed total wind speed at the same timescale.

4.2 Other potential drivers of NWS changes

Terrestrial stilling changes include the effects of large and regional scale factors. In this study, we mainly focused on the role of NAM. Actually, except for the NAM, some studies also reported that NWS reduction might be attributed to other LOACs. Chen et al. (2013) hypothesized that the warm and cold ENSO phases have significant influence on probability distribution of wind speeds, thus internal climate variability could be a major source of both interannual and long-term variability; however, the processes of ENSO influencing the NWS were not analyzed in detail. Fu et al. (2011) showed that a negative Pacific Decadal
Oscillation (PDO) phase did not show a decreasing trend of NWS, and a positive PDO phase was associated with a statistically significant decreasing trend of NWS. Nevertheless, the PDO mainly influenced the decadal variability of NWS (Wu et al. 2018a). Xu et al. (2006) proposed that the slowdown of NWS could be attributed to East Asian monsoons circulations. The winter decline might be attributed to increase greenhouse gas emission, and the summer decline over south-central China may result from air pollution. However, Wu et al. (2016) found no significant wind speed difference between strong and weak monsoon years. Therefore, there is large uncertainty regarding how the East Asian monsoons influence the NWS. It is worth noting that the potential effects of LOACs on the NWS constitute a complex process. The interaction and modulation of different LOACs are evident; therefore, it is difficult to isolating and estimating the contributions of different LOACs to variability in NWS. These issues might be examined and identified using numerical simulations with a global climate model coupled to a regional climate model in near future.

Except for the variations of LOACs can induce the variability in NWS, some studies have observed that NWS reduction could also be attributed to other factors. For instance, land use and cover change (LUCC) can cause the changes in surface roughness, and which is likely the principal contributor to the reduction of NWS over China over the last several decades. It is note that the uncertainty of estimation results of LUCC impact on variations in NWS is considerable based on different methods (Tab. 3). The most distinctive manifestation of anthropogenic LUCC is urbanization (Zha et al. 2016; Wang et al. 2020). Effects of urbanization on NWS were revealed by both observation and numerical simulation (Tab. 3). Global warming also can induce significant changes in the large-scale meridional circulation and thus lead to changes in NWS over China (Jiang et al. 2009, 2010b). The greenhouse gases could alter the thermodynamic and dynamic processes of the atmosphere, and these changes can induce the variability in NWS (Zhang et al. 2016a). However, isolating the effects of greenhouse gases on the changes of NWS is difficult using the observation datasets. This aspect could be estimated based on the Coupled Model Intercomparison Project
(CMIP) (e.g., CMIP5/6) in the future work. Additionally, some former studies hypothesized that an increase in air stability due to aerosol interactions with radiation reduces vertical mixing which in turn, reduces the vertical flux of horizontal momentum. Because winds are generally higher aloft than at the surface, reduced vertical mixing decreased the transfer of fast winds aloft to the surface, and thereby slowing NWS (Jacobson and Kaufman 2006; Zhao et al. 2006; Li et al. 2016). The anthropogenic heat release reduces the boundary layer stability and enhances the vertical mixing, and thereby the anthropogenic heat release could lead to increase of the NWS (Zhang et al. 2016b). However, the real mechanisms of the aerosol emissions and anthropogenic heat release affecting NWS were not systematically revealed in current work. These issues might be examined and identified using numerical simulations with a global climate model coupled to a regional climate model in near future.

5 Conclusions

In this study, the potential process whereby the NAM affects the NWS over eastern China are revealed; meanwhile, the quantitative contribution of the NAM to interannual variations of NWS are estimated. The main conclusions are summarized as follows.

The NWS in eastern China mainly exhibited a decrease, with a linear trend of $-0.09 \pm 0.01$ m s$^{-1}$ decade$^{-1}$. The strongest reduction was found in northeastern China and some regions of the middle and lower Yellow River and Yangtze River, reached $-0.2$ m s$^{-1}$ decade$^{-1}$. The weakest slowdown was in central China, it being less than $-0.05$ m s$^{-1}$ decade$^{-1}$. The zonal component of the observed NWS also exhibited a significant reduction, with a linear trend of $-0.04 \pm 0.01$ m s$^{-1}$ decade$^{-1}$; however, no significant reduction was found in the meridional component of the observed NWS. Hence, the decrease in the observed NWS could be mainly caused by the weakening in the zonal component of the wind speed.

The NAM had a pronounced effect on the changes of the NWS over eastern China. During NAM+, the
zonal-mean westerly decreased over mid-latitudes, while the vertical movement was prevailingly descending
flow at mid-latitudes (30°–50°N) and ascending flow at 60°–72°N in the troposphere. Consequently, the
Ferrell cell enhanced accompanied by the continuous warm phases of NAM from 1979-2017. The
strengthening of the Ferrell cell induced northerly anomalies at mid-latitudes and southerly anomalies at
mid-to-high latitudes in the lower troposphere. The anomalous meridional flows transported heat from lower
latitudes to higher latitudes, thereby reducing the meridional SATD, which in turn decreased the driving
force of NWS changes over eastern China and caused a reduction of NWS.

32.0±15.8 % of the changes in the observed annual mean NWS over eastern China could be attributed to
the variations in NAM at interannual scale; however, the NAM contribution on interannual variations in $u$ of
the observed NWS was more significant, reaching 45.0±12.9 %. Nevertheless, the NAM contribution to the
annual mean NWS and $u$ based on raw sequences over eastern China reached only 23.5±15.2 % and
35.6%±13.1 %, respectively.

In this study, we investigated the processes whereby the NAM affects the variations of NWS and obtained
several interesting results. The mechanisms whereby LOACs influence NWS variations constitute a
challenging scientific issue; hence, the results shown here could help to promote future work on this topic.
Some limitations and drawbacks also must be mentioned. The NWS presented seasonal characteristics, so
the variations in NAM could not explain all changes in NWS during different seasons. How the LOACs
influence seasonal NWS changes is a next logical step in our future work. Actually, the effects of LOACs on
the NWS constitute a complex process, and the interaction and modulation of different LOACs must be
examined by using numerical simulations with a global climate model coupled to a regional climate one.

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Table 1. Correlation coefficients between Northern Hemisphere annular mode (NAM) and sea level pressure (SLP), and between near-surface wind speed (NWS) and SLP at different timescales. Top: correlation coefficients computed based on raw sequences of NAM (NWS) and SLP; bottom: same as top but for interannual sequences. *, **, and *** denote correlation coefficient ($R$) exceeding significance t-test at 0.10, 0.05, and 0.01 levels, respectively. Regions 1 and 2 are shown in Fig. 9 by blue and red rectangles, respectively.

|                  | Mean value of negative $R$ over region 1 | Percentage of the grids with the significant negative $R$ over region 1 | Mean value of positive $R$ over region 2 | Percentage of the grids with the significant positive $R$ over region 2 |
|------------------|------------------------------------------|------------------------------------------------|------------------------------------------|------------------------------------------------|
| NAM and SLP      | -0.56***                                 | 92.55%                                         | 0.51***                                  | 93.22%                                         |
|                  | -0.50***                                 | 88.36%                                         | 0.46***                                  | 86.40%                                         |
| NWS and SLP      | 0.21                                     | 11.40%                                         | -0.006                                   | 3.13%                                          |
|                  | 0.30**                                   | 80.02%                                         | -0.27*                                   | 78.56%                                         |
Table 2. Correlation coefficients between NAM (NWS) and vertical velocity ($w$) at different timescales, and percentages of grids with negative (positive) correlation coefficients. Top: correlation coefficients computed based on raw sequences of NAM (NWS) and $w$; bottom: same as top line but for interannual sequences. *, **, and *** denote correlation coefficient ($R$) exceeding significance *t-test* at 0.10, 0.05, and 0.01 levels, respectively. $R^-$: negative correlation coefficient. $R^+$: positive correlation coefficient. **Percentage** represents the percentage of grids with negative correlation coefficient ($R^-$), positive correlation coefficient ($R^+$), significant $R^-$, or significant $R^+$ over regions 1 and 2, which are the regions with descending and ascending flows at 30°–50°N and 60°–72°N, respectively, as shown in Fig. 10 by the blue and red rectangles, respectively.

|          | Mean value of R over region 1 | Mean value of R- over region 1 and Significant R- value of region 1 | Mean value of R+ over region 2 and Significant R+ value of region 2 | Percentage |
|----------|-------------------------------|--------------------------------------------------------------------|-------------------------------------------------------------------|-------------|
| NAM      | -0.29*                        | -0.32**                                                             | 0.32**                                                            | 0.41***     |
| and $w$  |                               |                                                                     |                                                                   | 0.51***     |
|          | (91.96%)                      | (93.57%)                                                            |                                                                   | (55.53%)    |
| NWS      | -0.10                         | -0.12                                                              | 0.11                                                              | 0.14        |
| and $w$  |                               |                                                                     |                                                                   | 0.28*       |
|          | (86.25%)                      | (71.96%)                                                            |                                                                   | (5.0%)      |

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Table 3. Other potential drivers of variability in NWS. AHR: anthropogenic heat release. BHT: Beijing-Hebei-Tianjin. CRU: comparison of rural and urban NWS. FWM: friction wind model. GHGs: greenhouse gases. LUCC: land use and cover change. OMR: observation minus reanalysis. PRD: Pearl River delta. SDM: statistical downscaling method. YRD: Yangtze River delta.

| Order | Region        | Driver factor | Method          | Role                                      | Study period | Original paper |
|-------|---------------|---------------|-----------------|------------------------------------------|--------------|----------------|
| 1     | China         | Urbanization  | CRU             | Large city: -0.02 m s⁻¹ a⁻¹               | 1969-2000    | Xu et al. (2006) |
|       |               |               |                 | Small city: -0.018 m s⁻¹ a⁻¹             |              |                |
| 2     | YRD, China    | Urbanization  | Numerical simulation | Urban expansion caused a 50% NWS decrease | 2003-2007    | Zhang et al. (2010) |
| 3     | BHT, China    | Urbanization  | Numerical simulation | Urbanization caused a decrease of annual NWS approximately -0.37 m s⁻¹ | 1980-2018 | Wang et al. (2020) |
| 4     | China         | LUCC          | OMR             | Inducing the reduction in NWS: -0.12 m s⁻¹ decade⁻¹ | 1979-2010 | Zha et al. (2017a) |
| 5     | Eastern China | LUCC          | SDM             | LUCC caused a downward trend of 0.17 m s⁻¹ decade⁻¹ in NWS | 1980-2011 | Wu et al. (2017) |
| 6     | Eastern China | LUCC          | FWM             | Inducing the reduction in NWS: -0.2 m s⁻¹ decade⁻¹ | 1980-2011 | Wu et al. (2016) |
| 7     | Eastern China | LUCC          | Numerical simulation | LUCC caused a decrease of 0.17 m s⁻¹ in NWS | 1980-2010 | Zha et al. (2019b) |
| 8     | Taiwan, China | GHGs          | Correlation analysis | -1.4 m s⁻¹ per century primarily attributed to GHGs, rather than quantitative estimation | 1871-2010 | Zhang et al. (2016a) |
| 9     | PRD, China    | AHR           | Numerical simulation | Leading to increase in the NWS | 2010 | Zhang et al. (2016b) |
| 10    | China         | Aerosol emissions | Numerical simulation | May reduce NWS by up to 8% locally | 2002-2004 | Jacobson and Kaufman (2006) |
| 11    | China         | non-climate-related factors | Statistical analysis | Quantitative results are not shown | 1951-1990 | Liu (2000) |
Figure 1. Terrain height (shading) (unit: meters above sea level) and spatial pattern of total meteorological stations (red circles) over eastern China in the dataset, as well as the location of eastern China (inset). Green dots: 587 stations that are selected to use in this study. Red dots: the stations that are removed out.
**Figure 2.** Temporal changes of (a) NWS anomaly, (b) zonal component of observed NWS, and (c) meridional component of observed NWS during the period 1979-2017 (unit: m s$^{-1}$). Green lines denote linear fitting curves, and black dotted lines denote Gaussian low-pass filter with a 9-yr moving window. The linear trends of wind speeds are presented in insets (unit: m s$^{-1}$ decade$^{-1}$). In the inset, the vertical black bars indicate the standard errors of slopes. The significances of trends are as follows: *** Significance at the 0.01 level, and blank indicates a trend is not significant.
Figure 3. Spatial patterns of (a) mean near-surface wind speed (NWS) (unit: m s\(^{-1}\)), (b) linear trend of NWS, (c) linear trends of zonal component of observed NWS and (d) meridional component of observed NWS over eastern China during the period from 1979-2017 (unit: m s\(^{-1}\) decade\(^{-1}\)). Shades in (b), (c) and (d) denote the trend coefficients passed the 90%, 95% and 99% significance t-test, respectively.
Figure 4. Temporal changes in NAMI during the period from 1979 to 2017. Black dotted line denotes a Gaussian low-pass filter with a 9-yr window, and green line denote the linear fitting.
Figure 5. Spatial patterns of (a, b) composite difference in near-surface wind speed (NWS) between positive and negative NAM phases (positive NAM phases minus negative NAM phases), and (c, d) the correlation coefficients between NAM and NWS over Northern Hemisphere during the period from 1979-2017. (a) and (c) denote the total wind speed, (b) and (d) denote the zonal-mean westerly. Contour in (c) and (d) denotes the correlation coefficient exceeding the 90% confidence level \( t \)-test.
Figure 6. Vertical structures of composite difference of zonal-mean meridional wind (shade), zonal-mean zonal wind (contour), and meridional circulation (vector) between positive NAM phases (NAM+) and negative NAM phases (NAM-) (NAM+ minus NAM−) during the period from 1979 to 2017. The vector is that of wind speed difference, whose two components are the zonal mean meridional wind speed difference and the zonal mean vertical velocity difference between NAM+ and NAM−.
Figure 7. (a) Spatial pattern of surface air temperature difference between positive NAM phases (NAM+) and negative NAM phases (NAM−) in Northern Hemisphere (NAM+ minus NAM−) (unit: °C) from 1979-2017, (b) temporal changes of surface air temperature (SAT) difference between mid-to-high latitudes (35°–60°N, 60°–140°E) and low latitudes (0°–20°N, 60°–140°E) over East Asia (denoted by SATD) from 1979-2017, and (c) regression analysis between SATD and NAM between 1979 and 2017. The contours in (a) denote the SAT difference exceeding 0.10 level. Green lines denote linear fitting, and dotted line denotes Gaussian low-pass filter with a 9-yr window. The insets in (b) and (c) denote the linear trend of SATD and correlation coefficient between NAMI and SATD, respectively. In the inset, the vertical red bars indicate the standard error of slope, and *** denotes the significance at the 0.01 level. Bars in (c) denote the regular residual of linear fitting.
Figure 8. (a) Temporal changes of anomaly of north–south pressure difference (NSPD) between mid-to-high latitudes (35°–60°N, 60°–140°E) and low latitudes (0°–20°N, 60°–140°E) over East Asia for 1979-2017, and regression analysis between NSPD and SATD ($u$ of observed NWS) during the period from 1979-2017 (b, c). Green lines denote linear fitting, and dotted line denotes Gaussian low-pass filter with a 9-yr window. The inset in (a) denote the linear trend of NSPD, and which denote the correlation coefficients between NSPD and SATD ($u$ of observed NWS) in (b) and (c). In the inset, the vertical red bars indicate the standard error of slope, and *** denotes the significance at the 0.01 level. Bars in (b) and (c) denote the regular residual of linear fitting.
Figure 9. Correlation coefficients between (a, b) NAM and SLP, (c) NAM and zonal wind, (d, e) observed NWS over eastern China and SLP, and (f) observed NWS over eastern China and zonal wind in Northern Hemisphere during the period from 1979 to 2017. (a), (c), (d), and (f) are calculated based on interannual sequences; (b) and (e) are calculated based on raw sequences. The threshold for the correlation coefficient exceeding the 90% confidence level is 0.27. The contours in (c) and (f) denote the correlation coefficient exceeding the 0.10 significance level.
**Figure 10.** Vertical structures of correlations between NAM and zonal-mean meridional wind (a: shade), vertical velocity (b: shade), and meridional circulation (vector) based on interannual sequences from 1979-2017. (c) and (d) are the same as (a) and (b), respectively, but for the NWS in eastern China. (e) and (f) are the same as (c) and (d), respectively, but for the raw sequences. Contours denote the correlations exceeding 0.10 level. The vector is a vector of correlations whose two components are the correlation coefficients between NAM (NWS) and zonal-mean meridional wind and between NAM (NWS) and zonal-mean vertical velocity, respectively. Because NWS and NAM exhibit negative correlation, the NWS is added a negative sign when the correlation coefficient is calculated. Descending and ascending flows are with the arrow pointing down and up, respectively.
Figure 11. Quantitative contributions of variations in Northern Hemisphere Annular mode (NAM) to visibility in near-surface wind speed (NWS) and zonal component of NWS (u) during the period from 1979-2017. Red bars denote the standard error of estimation results. The significances of estimation results are as follows: *** Significance at the 0.01 level, ** Significance at the 0.05 level. Blank indicates an estimation result of NAM affects variations in NWS is not significant.