

# Recent recovery of surface wind speed after decadal decrease: a focus on South Korea

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**Abstract** We investigate the multi-decadal variability of observed surface wind speed around South Korea. It is found that surface wind speed exhibits decreasing trend from mid-1950s until 2003, which is similar with the trends reported for other parts of the world. However, the decreasing trend ceases and becomes unclear since then. It is revealed that decreasing wind speed until 2003 is strongly associated with the decreasing trend of the spatial variance in both atmospheric pressure and air temperature across the East Asia for the same period. On the contrary, break of decreasing trend in surface wind speed since 2003 is associated with increasing spatial variance in surface temperature over the East Asia. Ground observation shows that surface wind speed and air temperature exhibit highly negative correlations for both summer and winter prior to 2003. However, since 2003, the correlations differ between seasons. We suggest that mechanisms behind the recent wind speed trend are different between summer and winter. This is on the basis of an interesting finding that air temperature has decreased while surface temperature has increased during winter months since 2003. We hypothesize that such contrasting temperature trends indicate more frequent movement of external cold air mass into the region since 2003. We also hypothesize that increasing summer wind speed is driven by intrusion of warm air mass into the region which is witnessed via increasing spatial variance in surface temperature across East Asia and the fact that both air and surface temperature rise together.

**Keywords** Wind speed · Climate change · Temporal trends · Interannual variability · Stilling

## 1 Introduction

The Earth's atmosphere redistributes heat fluxes originated from incoming solar radiation through global and regional circulations. Atmospheric circulations involve movement of air mass, namely wind, which helps preventing dramatic changes in air and surface temperature across latitudes. It is important to estimate the speed of wind, especially surface wind which refers to the wind near the ground, in many respects. First, surface wind greatly influences all life on the Earth's surface including human, directly and diversely as shown through wind-related natural disasters. Further, surface wind is a key element for studying water cycles because surface wind speed dominantly controls evaporation (e.g., Penman 1948; Kohler 1959; Dunne and Leopold 1978). Surface wind is also important as a renewable energy source. A large number of wind farms have already been constructed, and more are planned in the near future. The total installed capacity of wind power generators worldwide has increased ten times from 24 GW in 2001 to 239 GW in 2011, and this capacity is forecasted to reach at least 1000 GW by 2020 (Gsanger and Pitteloud 2012).

Within the context of changing climate, surface wind speed possibly exhibits non-trivial trends over time (McVicar et al. 2012). Understanding temporal variations in surface wind speed, in particular for the human time scale, is vital to establish necessary plans with respect to wind-related natural disasters. This understanding is also critical in studying global environmental changes as variations in wind speed will bring changes in many other environmental quantities which shall provide complex

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feedbacks to mechanisms behind the changing wind speed. Variations in surface wind speed also serve as key information in planning wind energy facilities. Efficiency of wind turbine generators does not necessarily increase with wind speed. Once the efficiency reaches the maximum, usually in a range between 11 and 14 ms<sup>-1</sup>, further increase in wind speed often decreases efficiency of power generation (Burton et al. 2001). In addition, forces loaded by wind on such facilities should also be carefully examined to secure their structural stability (Bazeos et al. 2002). Therefore, future outlook on surface wind speed is critical in site selection, structural design, and management of wind energy facilities.

Earlier studies reported that, during the last decades, surface wind speeds have been gradually decreased at statistically significant levels in many parts of the world, the phenomenon often named as ‘stilling’ (Roderick et al. 2007). For example, decreasing trends of surface wind speed have been reported in most parts of China (Xu et al. 2006; Guo et al. 2010), western and southern Canada (Tuller 2004; Griffin et al. 2010; Wan et al. 2010), and the continental United States (Pryor and Ledolter 2010). Surface wind speeds over south-eastern Australia (McVicar et al. 2008), Arabian Sea (Kumar et al. 2009), and most of Europe including the Czech Republic (Brazdil et al. 2009), France (Najac et al. 2009), Germany (Bormann 2011), Iberian Peninsula (Azorin-Molina et al. 2014), and the Netherlands (Smits et al. 2005) have also shown decreasing trends. For further details about global trends of surface wind speed, refer to McVicar et al. (2012) where trends in observed surface wind speed during last decades across the world are summarized in depth.

Although these earlier studies have reported decrease of surface wind speed as a global trend, here we claim that this trend seems broken around the last decade. This hypothesis on recent trend in surface wind speed can be argued at least in some areas, through detailed investigations on observed data reported in literature. For example, Keyhani et al. (2010; Table 1) presented monthly and annual surface wind speed at Tehran, Iran. With a detailed look at their data, we can identify a likely increasing trend in surface wind speed at Tehran starting around year 1998. Similarly, through

a close examination of surface wind speed data in the Czech Republic and Tibetan plateau presented by Brazdil et al. (2009; Figure 11c) and You et al. (2010; Figure 3), respectively, we can suggest recent increase of wind speed at above areas. Such recent trend in surface wind speed is more directly stated in the case of China by Fu et al. (2011; Figure 6b) where the decreasing trend of surface wind speed has shifted to an increasing trend since 2000. However, such recent trends of recovering surface wind speed have received little attention.

Motivated by this background, we present in-depth investigation on multi-decadal variability of surface wind speed including data of very recent years. In this study, we take South Korea (SK) as the study area and investigate the observed surface wind speed across SK from 1954 to 2013. Our objectives are: (1) to understand whether surface wind speed across SK has shown significant decadal trends; (2) to compare the trends of SK to those found in other areas; (3) to examine whether the surface wind speed trends exhibit transitions in recent years; and (4) to provide geophysiological reasons for the observed surface wind speed variations. We organize the rest of this paper into four sections. In the next Sect. 2, we describe study area and pre-processing of observed wind data. In Sect. 3, trends in surface wind speed extracted from ground-observed data are described. In Sect. 4, drivers of multi-decadal variations in surface wind speed are discussed with extra analysis of geopotential as well as air and surface temperature. Finally, conclusions are given in Sect. 5.

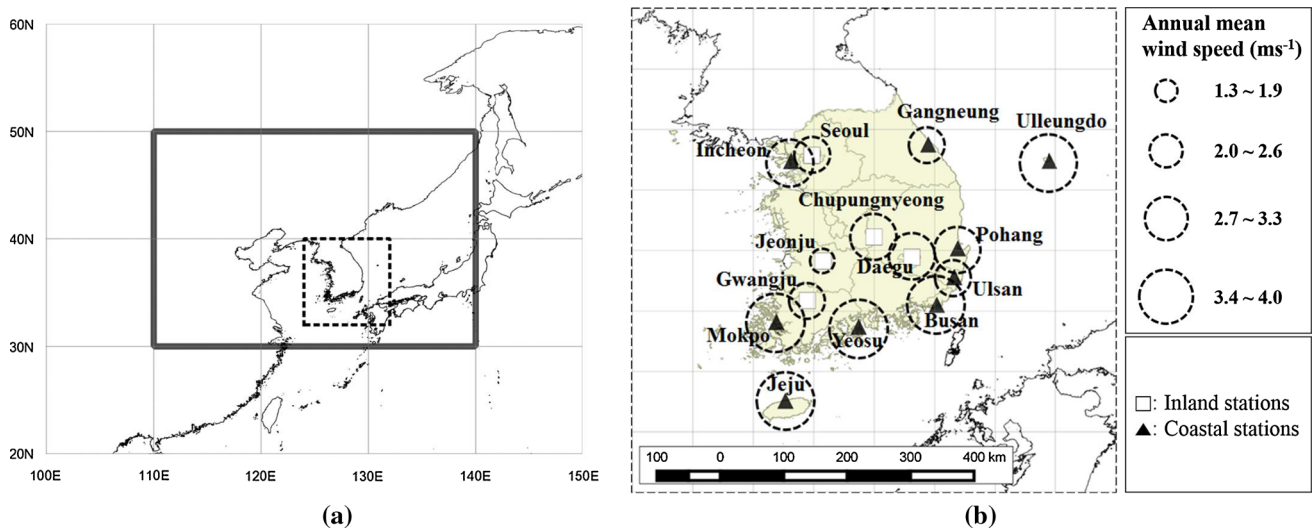
## 2 Study area and data processing

### 2.1 Study area and basic data

To analyze the variability of surface wind speed across SK, we use ground-observed daily data provided by the Korean Meteorological Administration. The number of ground stations in SK has gradually increased over the last century. Hence, we seek a reasonable compromise between the number of available stations and length of data period. Our goal

**Table 1** Datasets used in this study

Dataset	Source	Data period	Variables	Measuring height	Horizontal resolution (lat. × long.)	Temporal resolution
Ground measurements	Korean Meteorological Administration	1954–2013	Wind speed	10–20.8 m	–	24-hourly
			Air temperature	1.5–1.8 m		
ERA-40	European Centre for Medium-range Weather Forecasts	1958–2001	Geopotential Air temperature	1000 hpa	2.5 × 2.5°	24-hourly
MODIS	National Aeronautics and Space Administration	2003–2011	Surface temperature	Land or sea surface	1.0 × 1.0°	24-hourly



**Fig. 1** Study area definitions. **a** East Asia region (30–50N, 110–140E) (box illustrated with the solid lines) and SK (box illustrated with the dashed lines). **b** Ground observation stations across SK. In **b**, circle size indicates the magnitude of annual mean wind speed

is to investigate the long-term variations in surface wind speed and so we decide to utilize data over six decades (from 1 January 1954 to 31 December 2013, 60 years). Year 1954, just after Korean War (1950–1953), is chosen as the starting year to exclude large number of missing data during the war. For the study period (1954–2013), continuous data are available from 14 stations which are evenly distributed across SK (Fig. 1). These ground stations, located between 2 m (Pohang) and 245 m (Chupungnyeong) above sea level, can be divided into two groups: five inland stations defined here as being more than 40 km (direct distance) away from nearest coast, and the remaining nine coastal stations. The raw data we utilize is the daily wind speed which is average of 24 hourly measurements (from 00:00 to 24:00). Each hourly measurement is recorded over 10 min before every hour in Korean standard time.

To understand fundamental mechanisms associated with surface wind variations in SK, we analyze geo-physiological variables over a greater spatial scale. We use ERA-40 (European centre for medium-range weather forecasts' 40 year Re-Analysis) output (Uppala et al. 2005) for geopotential and air temperature over SK and surrounding areas. Brunke et al. (2011) examined 11 re-analysis products and identified ERA-40 as one of best products for both temperature and momentum fluxes. It is daily data from 1 September 1957 to 31 August 2002. To investigate surface temperature variations in recent years as supplementary information, we use data measured by MODIS (MODerate resolution Imaging Spectroradiometer) satellite instrument (for details of datasets used in this study, refer to Table 1). We analyze these datasets for the East Asia, a region defined here as a rectangular domain (30–50N, 110–140E) which covers entire SK and surrounding areas (Fig. 1).

## 2.2 Data processing

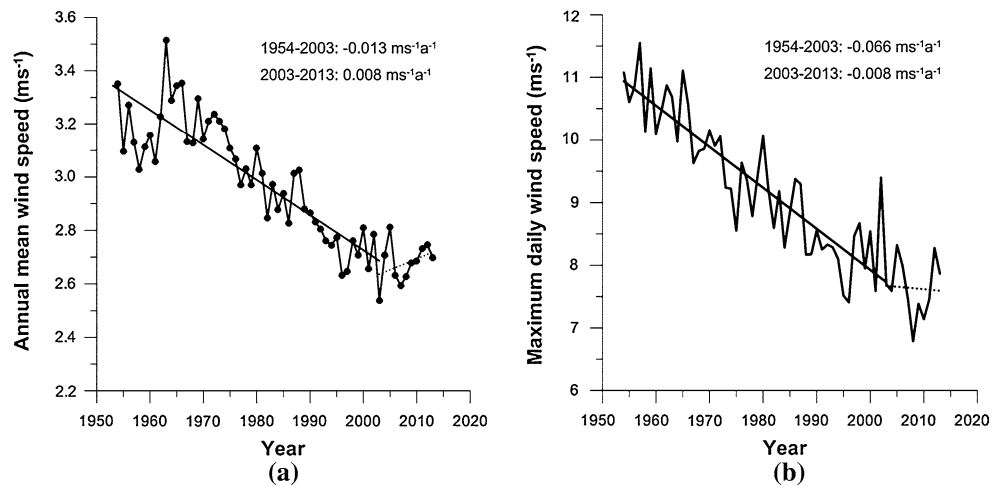
Wind speeds are measured at different heights above the ground, ranging between 10 and 20.8 m. At 5 of the 14 stations, wind speed has been measured at 10 m height which is often regarded as the standard level (Oke 2004). The remaining nine stations have anemometers at various heights. Coincidentally, most of these nine stations (eight stations except for Gwangju) are classified as coastal stations. Here, we adjust wind speed data observed at these nine stations to the standard 10 m above the ground. This is performed using a theoretical wind speed profile.

Wind speed profile is usually represented as either logarithmic (Rossby 1932) or power-law (Köhler 1933) profile. Both theoretical profiles have been widely used in previous studies and so it is difficult to claim an absolute advantage of one over the other. Note that our goal is to capture the long-term trends in wind speed. Although adjusted wind speed is probably different depending on the choice of velocity profile, this choice shall give little effect on the trends in the wind speed time series as long as one theoretical profile is consistently used (McVicar et al. 2008). Therefore, any profile can be used for our purpose.

One noticeable point is that logarithmic profile requires an extra parameter, associated with surface roughness, compared to the power-law profile. While the utilization of the extra parameter may provide further flexibility for better fitted profile, this necessitates a pre-requisite investigation for appropriate value of this parameter. Therefore, practical difficulty exists to use the logarithmic profile for areas where surface roughness information is limited.

On this basis, we use the power-law profile which gives the wind speed at 10 m level as:

**Fig. 2** **a** Annual mean and **b** annual maximum series of surface wind speed averaged over 14 ground stations for SK. *Solid linear fit line* indicates statistically significant trend whereas *dashed line* is statistically insignificant trend at 90 % confidence level (here after in all figures)



$$V_{10} = \left(\frac{10}{h}\right)^{\alpha} V_h \quad (1)$$

where  $V_h$  is the wind speed ( $\text{ms}^{-1}$ ) at anemometer height  $h$  (m) above the ground level. In this study, the parameter  $\alpha$  is fixed as  $1/7$  following a wide range of literature (e.g., Frost 1948; Haltiner and Martin 1957; Peterson and Hennessey 1978). The parameter value of  $\alpha = 1/7$  is also found appropriate by Hsu et al. (1994) who have studied wind velocity profile for coastal stations. In that most of our stations where wind speeds are adjusted to the standard height are coastal, similar to Hsu et al. (1994), our choice of  $\alpha = 1/7$  is regarded appropriate.

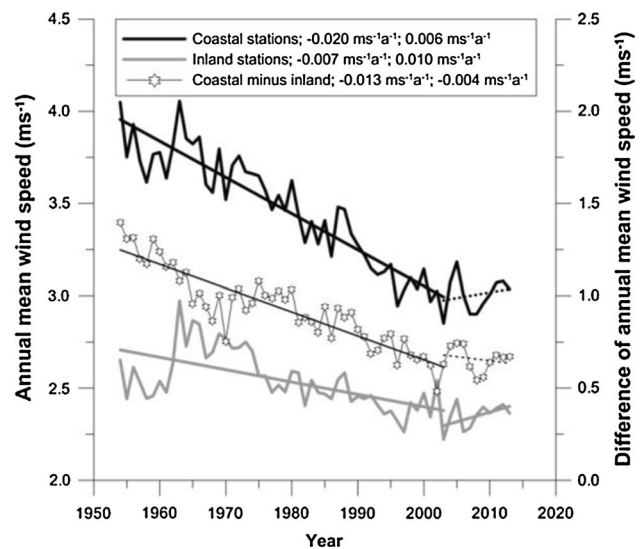
### 3 Wind speed trends around South Korea

Here we report annual mean and annual maximum series of daily surface wind speed. Annual mean series is an annual series where each entry in the series is average of daily  $V_{10}$  over 14 stations and an entire year. For the annual maximum series, spatially-averaged daily  $V_{10}$  is first obtained and then the greatest daily value over a year becomes an entry for the given year.

This study reveals two important trends in surface wind speed around SK. First, we find that the surface wind speed had decreased from 1954 until early 2000s. This can be found in both annual mean and annual maximum series (Fig. 2). Second, we report change in wind speed trends beyond early 2000s. To figure out the transition point in the time series, we implement three methods and follow the result from the two-phase regression technique (Elsner et al. 2000) which gives year 2003 as the transition point, commonly for annual mean and annual maximum series (see Appendix 1 for details). Decreasing trend which had dominated in previous years has disappeared (annual mean series) or has become significantly weakened (annual

maximum series) from 2003 onwards (Fig. 2). The previous decreasing trend of annual mean wind speed has reversed into the increasing trend at both the coastal and inland stations (Fig. 3).

For the stilling period (prior to 2003), it is noteworthy that decreasing rate is greater where the wind speed used to be greater, i.e., greater decrease for annual maximum than annual mean series and greater decrease for coastal than inland stations. Decreasing rate of annual mean wind speed, evaluated as the slope of a fitted linear regression line between 1954 and 2003, is  $-0.013 \text{ ms}^{-1} \text{ a}^{-1}$  which is close to the value reported by Vautard et al. (2010) ( $-0.012 \text{ ms}^{-1} \text{ a}^{-1}$ ; linear trend over 30 years between year 1979 and 2008 for a domain of 30–75N and 100–160E).



**Fig. 3** Annual mean wind speeds spatially averaged over coastal and inland stations, respectively. Figure also shows differences between them. *Numbers in the legend* are trends from 1954 to 2003 and from 2003 to 2013, respectively

Annual maximum series shows a greater decreasing rate ( $-0.066 \text{ ms}^{-1} \text{ a}^{-1}$ ) for the same period. Annual mean surface wind speed at the coastal stations had decreased until 2003 at a rate of  $-0.020 \text{ ms}^{-1} \text{ a}^{-1}$ , much greater than the rate for the inland stations for the same period ( $-0.007 \text{ ms}^{-1} \text{ a}^{-1}$ ) (Fig. 3). The significance of the simple linear regression fitted in this study is tested within 90 % confidence level by student's *t* test using Spearman's rank correlation (1904) (all trends reported in this paper are tested for statistical significance, which is described in Appendix 2).

Greater decrease rate of coastal stations compared to inland stations implies that the difference between surface wind speeds at the coastal and inland stations had become reduced. To investigate this further, annual mean value is obtained for each of 14 stations and then we calculate standard deviation between these 14 values, a measure of 'spatial variance,' for each year. Spatial variance over the 14 stations follows trends resembling those of surface wind speed (Fig. 4). Spatial variability in surface wind speed had decreased until 2003, explaining that the difference in surface wind speeds between the coastal and inland stations had become smaller. Since 2003, the decreasing trend of spatial variance ceases.

We also analyze wind speed trends for each season of DJF (December–February), MAM (March–May), JJA (June–August), and SON (September–November). Daily  $V_{10}$  is averaged over 14 stations and over each season, yielding a quantity named as seasonal mean wind speed. Seasonal mean wind speed is greatest during DJF, followed

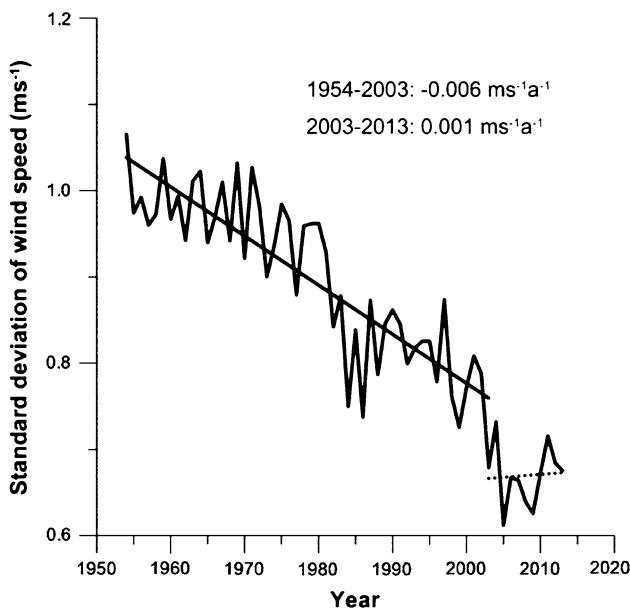


Fig. 4 Standard deviation in surface wind speed across 14 ground stations

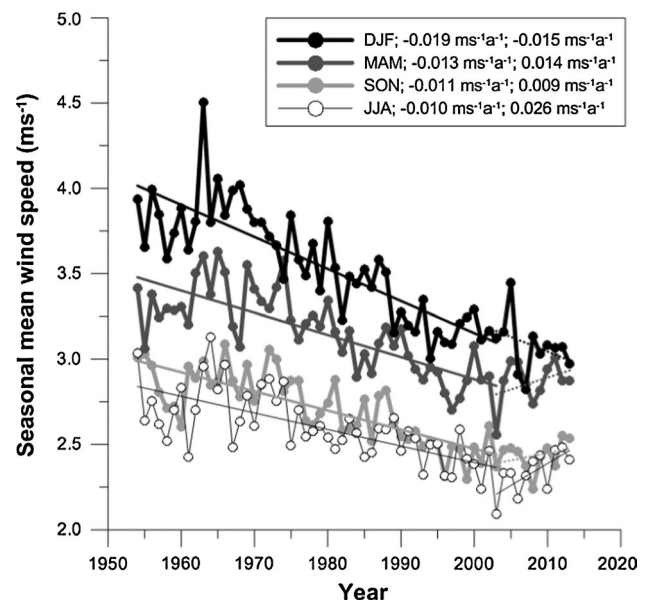


Fig. 5 Seasonal mean wind speed averaged over 14 stations. For DJF, December data is of its previous year. For 1954, DJF value is calculated as mean of January and February 1954. Numbers in the legend are trends from 1954 to 2003 and from 2003 to 2013, respectively

by MAM, while SON and JJA record lower wind speed (Fig. 5). This seasonal difference in wind speed agrees with results from an earlier study on SK by Kim and Kim (2013) but differs from a study on the neighboring country of China where wind speed during MAM stands out as the greatest (Guo et al. 2010). This difference between two countries is likely due to their geographical locations where SK is located further outskirts of Siberian High compared to most part of China (e.g., Gong et al. 2001; Figure 1).

Decadal trends of seasonal mean wind speed resemble those of annual mean and annual maximum series, i.e., decrease until 2003 and transition thereafter (Fig. 5). Linear rate of surface wind speed from 1954 to 2003 is greatest in DJF (winter), i.e.,  $-0.019 \text{ ms}^{-1} \text{ a}^{-1}$ . This also contrasts with the study on China (Guo et al. 2010) which reports MAM as the season of the greatest decline.

#### 4 Discussions on long-term variability of surface wind speed

Previous section presents two key findings regarding surface wind speed around SK. First, there are robust trends of decreasing surface wind speed from mid-1950s until 2003. Second, the decreasing trends become unclear since 2003. It would be of great scientific interest to understand physical mechanisms underlying these trends and the transition around 2003.



Many studies have associated changing wind speed with local factors such as urbanization. Bornstein and Johnson (1977) studied wind speed distribution around the New York area and attributed the low wind speed in the city compared to its surrounding areas to the increase of surface roughness. Tamura and Suda (1989) reported that the annual maximum series of surface wind speed had decreased since 1930s in Sapporo city, Japan and the decrease is reversely related to the increase of building density for the same period. Azorin-Molina et al. (2014) also considered urban roughness as one of causes for wind speed change in Spain. At a larger spatial extent, Vautard et al. (2010) claimed that surface roughness change has partially contributed global wind speed decrease. Similarly in Korea, decrease of observed surface wind speed has been attributed to the result of urbanization (Ryoo et al. 2006).

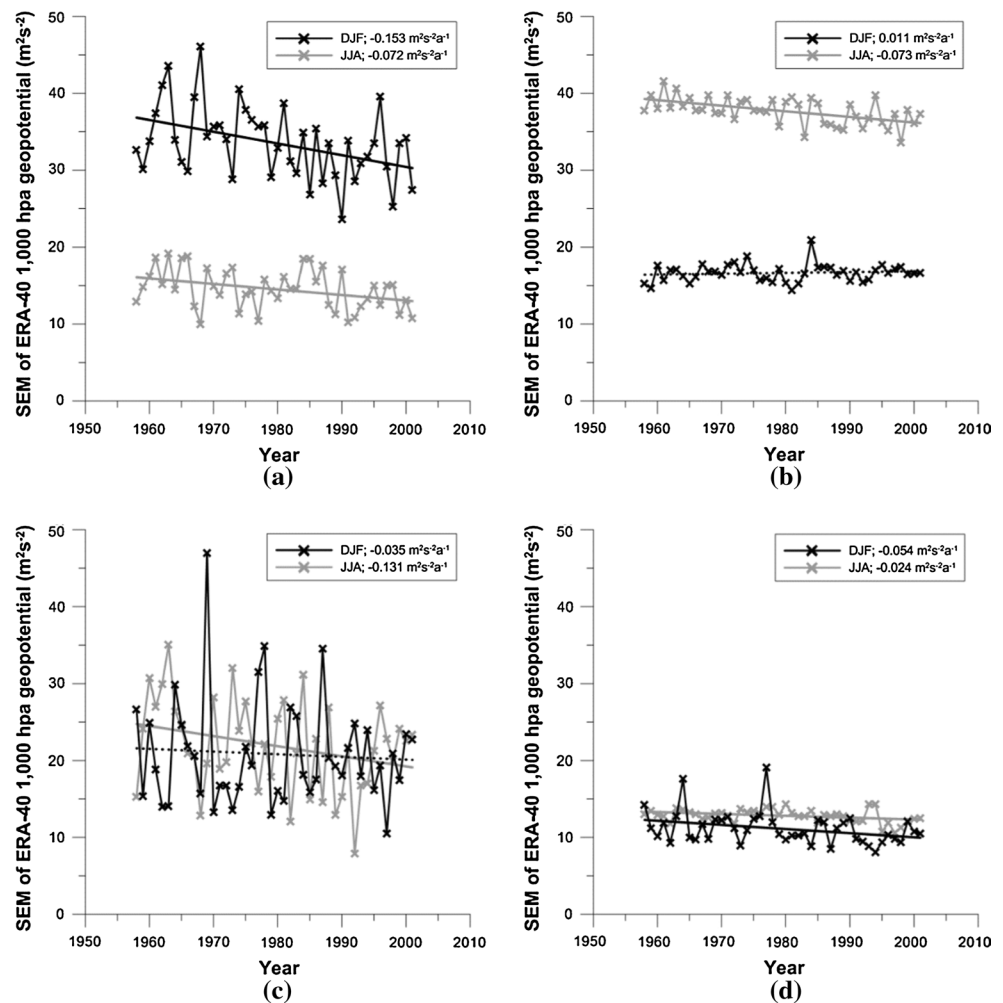
Nevertheless, local factors such as urbanization provide limited explanation for multi-decadal wind speed variations presented in our data. For example, decreasing wind speed trend of Ulleungdo site, which is a small remote island (Fig. 1) where no sign of urbanization has been

made, cannot be explained with local land use change. This is in line with findings in other countries including China where both urban and rural areas show similar decreasing trends (e.g., Guo et al. 2010). More importantly, increase of surface roughness due to urbanization cannot explain the reversed trend since 2003. In this sense, it is likely that the observed wind speed trends around SK are associated with varying climatic conditions over a greater spatial scale of East Asia. We present extra analysis below to discuss details behind the observed trends in this context.

#### 4.1 Decreasing trends in surface wind speed (1954–2003)

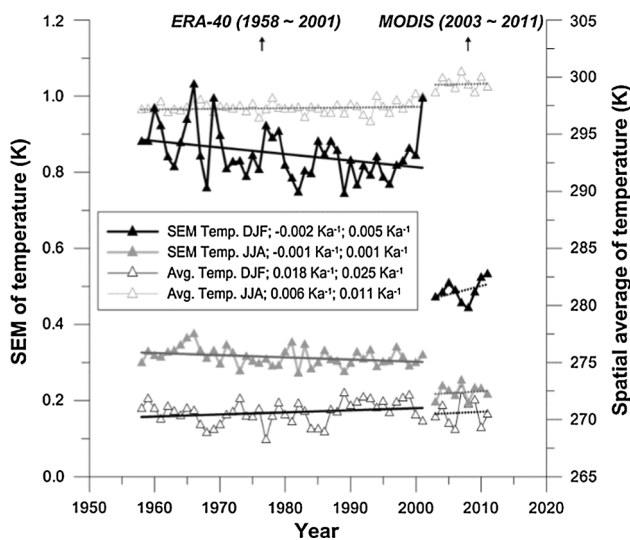
Because surface wind is initiated by pressure gradient force (Holton and Hakim 2013), surface wind speed over a region is closely associated with the spatial distribution of atmospheric pressure or geopotential height. To investigate the spatial variance in geopotential over the East Asia, here we calculate Standard Error of the Mean (SEM; standard deviation divided by square roots of observation number) of geopotential from ERA-40 at 1000 hpa over the East

**Fig. 6** SEM of ERA-40 1000 hpa geopotential in **a** East Asia (30–50N, 110–140E), **b** Arabian Sea (5–25N, 57.5–80E), **c** western Canada (50–60N, 110–135W), and **d** the continental United States (25–50N, 67.5–127.5W). The number in the legend indicates the trend from 1958 to 2001



Asia. It can be noticed that SEM had gradually decreased from 1958 to 2001 over the region (Fig. 6a). Smaller SEM of geopotential implies smaller variation in atmospheric pressure within the region which leads to lower surface wind speed. Therefore, the decreasing trend of SEM in geopotential accords to the decreasing trends of surface wind speed for the given period. The SEM and its decreasing rate are greater for DJF, compared to JJA (Fig. 6a). This agrees well with the seasonal difference in the mean wind speed and their decreasing rates (Fig. 5).

We also calculate SEM of ERA-40 at 1000 hpa geopotential in Arabian Sea, western Canada, and continental



**Fig. 7** SEM and spatial average of temperature in the East Asia for DJF and JJA. ERA-40 air temperature at 1000 hpa (from 1958 to 2001) and MODIS surface temperature (from 2003 to 2011) are used. Numbers in the legend are trends from ERA-40 and from MODIS, respectively

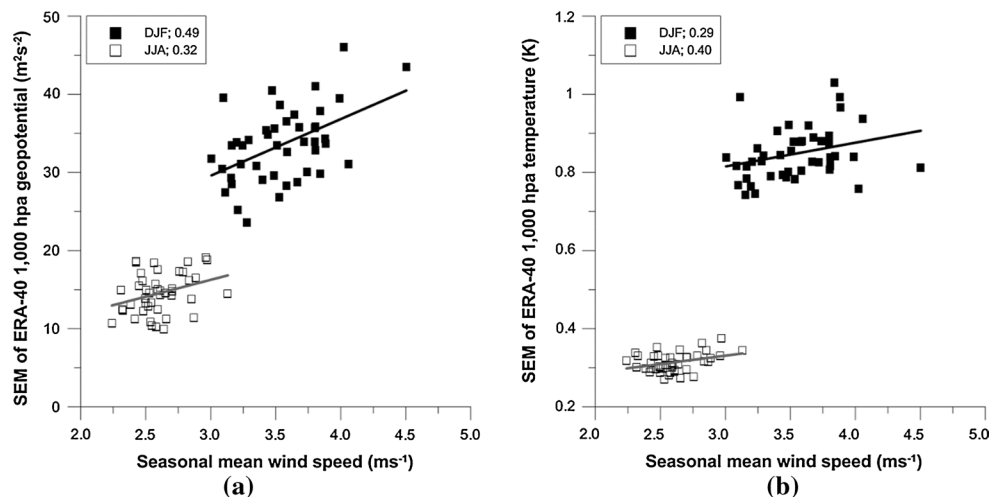
United States, respectively, where the decline of surface wind speeds has been reported (i.e., Tuller 2004; Kumar et al. 2009; Griffin et al. 2010; Wan et al. 2010; Pryor and Ledolter 2010). SEM of geopotential had generally decreased over all these regions from 1958 to 2001 (Fig. 6).

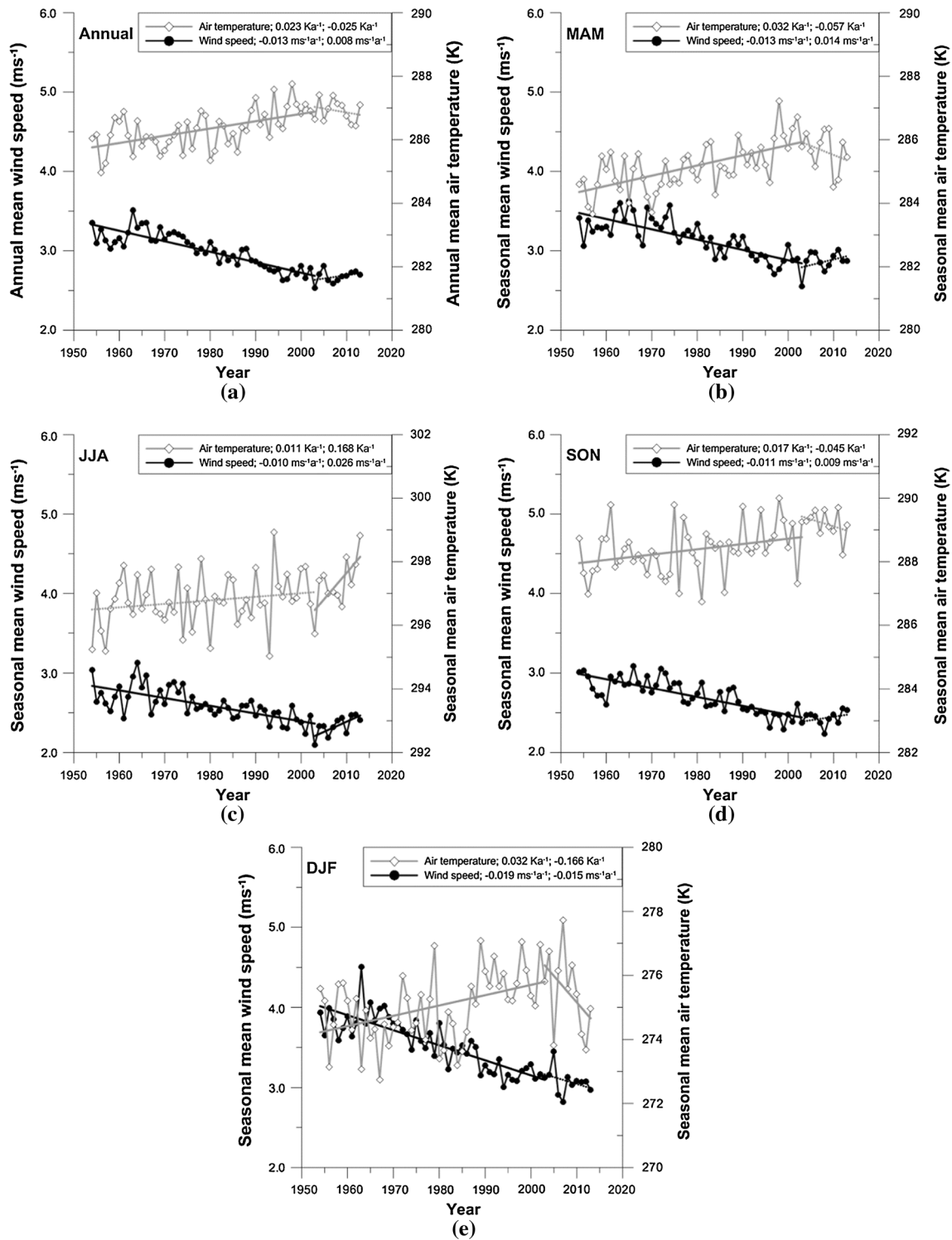
To understand mechanism behind this stiling, we also analyze ERA-40 air temperature at 1000 hpa from 1958 to 2001 (Fig. 7) over East Asia. Near-surface atmospheric temperature averaged over the region had risen for both DJF and JJA over the period. In contrast, SEM of near-surface atmospheric temperature had decreased for the same period. Such reduction of spatial variance in air temperature is likely responsible for more uniform spatial distributions of geopotential, and that leads to the decline of surface wind speed. To illustrate this plausible driving mechanism more directly, we present the relationship between SEM of ERA-40 1000 hpa geopotential in East Asia and seasonal wind speed (Fig. 8). The relationship between SEM of ERA-40 air temperature at 1000 hpa in East Asia and seasonal wind speed is also presented. Both relationships show positive correlations which further support our argument. Because our definition of East Asia here covers a large portion of China, we claim that the same explanation is also applicable for decadal decrease in wind speed reported for China.

#### 4.2 Recent trend in surface wind speed (2003–2013)

As shown in Figs. 6 through 8, decreased spatial variance in air temperature is associated with decreased spatial variance in geopotential, and eventually with the decreasing trend in surface wind speed prior to 2003. On the basis of these relationships, we hypothesize that the reversed wind speed trend since 2003 is associated with the opposite, i.e., the increase of the spatial variation in air temperature and geopotential. We test this by analyzing surface (land or sea)

**Fig. 8** Correlations between **a** SEM of geopotential in East Asia and seasonal mean wind speed; and **b** SEM of temperature in East Asia and seasonal mean wind speed. ERA-40 geopotential, air temperature at 1000 hpa (from 1958 to 2001) and seasonal mean wind speed over 14 ground stations (from 1958 to 2001) are used. Numbers in the legend are correlation coefficients





**Fig. 9** Trends of air temperature and wind speed averaged over 14 ground stations generally showing a negative correlation (except for JJA and DJF from 2003 to 2013). Figures show **a** annual mean wind speed and air temperature, as well as seasonal mean wind speed

and air temperature for **b** MAM, **c** JJA, **d** SON, and **e** DJF. Numbers in the legend are trends from 1954 to 2003 and from 2003 to 2013, respectively



temperature observed by MODIS satellite instrument over the East Asia. For the SK, we also analyze air temperature measured at the 14 ground stations. Note that ERA-40 products are not available beyond 2001.

MODIS data shows that SEM of surface temperature over the East Asia has increased since 2003 (Fig. 7), the trend opposite to those of ERA-40 air temperature for its earlier period. Our analysis of 14 ground stations shows that spatial variance in near-surface air temperature within SK has also increased since 2003. This serves as an evidence for the plausible relationship between increased spatial variance in temperature and increased surface wind speed. To more clearly understand the mechanism that links temperature and wind speed, we analyze ground measurements on SK in a more detail below.

Ground measurements over the entire period present an interesting point; spatially averaged temperature and wind speed exhibit clear negative correlations (Fig. 9). From 1954 to 2003, near-surface temperature follows increasing trends, exactly opposite to those of surface wind speed for all seasons. Annual near-surface temperature shifts to the decreasing trend since 2003. It is interesting to witness that wind speed also shifts its trend in accordance with temperature trend. This seesaw phenomenon (trends of surface wind speed and temperature move in opposite directions) is consistently found for all seasons prior to 2003. For post 2003 period, the seesaw phenomenon is also found for MAM and SON. However, for JJA and DJF, recent trends in surface wind speed and temperature are in the same direction. This implies that mechanisms associated with recent changes in surface wind speed are more complicated than those for prior 2003.

For post 2003 period, we notice that winter (DJF) air temperature from ground observation (Fig. 9e) has decreased while average surface temperature (MODIS data) in East Asia has increased (Fig. 7). MODIS winter surface temperature for cells corresponding to SK also shows the increasing trend since 2003. This inconsistency between air and surface temperature implies intrusion of external air mass, colder than surface, to SK in recent winter months. This winter movement of air mass indicates potential change in the extent of the Siberian High and jet stream paths. It is likely that penetration of cold air mass in winter months is associated with variations in the trends of tropical belt width. Many studies have actively tried to figure out robust trends in tropical belt width (e.g., Ao and Hajj 2013; Lucas et al. 2014) but there exist no definite trends reported yet (Birner 2010) which otherwise could help explain the phenomenon described in our study.

For summer months (JJA), recent trends show that surface temperature (MODIS data), air temperature, and wind speed increase together in SK (Figs. 7, 8c). Air temperature

increase has strengthened since 2003 which implies appearance of an extra contributor for warmer air. We postulate that this phenomenon reflects the intrusion of warm air system into East Asia in recent summer months. Partial intrusion of warmer air mass to the region, which can be captured by increased local air temperature, is supposed to raise the spatial variance of temperature within the region and accordingly of geopotential, which eventually contributes increase of surface wind speed. This idea warrants further investigation.

## 5 Conclusion

We investigated multi-decadal trends in surface wind speed around SK with various meteorological data from ground stations, ERA-40, and MODIS. It is found that surface wind speed had consistently decreased since mid-1950s until 2003. However, the decreasing trend in surface wind speed was broken in the last decade.

On the basis of careful examination on data reported in other literature and our analysis of climate variables over the East Asia, we argue that the recent recovery of surface wind speed may occur beyond the spatial extent of SK. Most studies on wind speed trends, covering various areas, have focused on decadal wind speed decrease but little has been studied about such recent trend. One rarely documented case on the recent reversal trend of wind speed is China where decreasing trend of surface wind speed is reported broken in 1990s (Guo et al. 2010; Fu et al. 2011). In comparison with these previous studies, our study indicates that the wind speed trend also changed in SK yet at later time than the nearby country of China.

In this study, we investigated geo-physiographic reasons that explain the observed trends by associating trends in other measures such as geopotential, air temperature, and surface temperature, at two scales of SK and East Asia, respectively. For the regional domain of East Asia, we analyze the spatial variance in ERA-40 at 1000 hpa geopotential and air temperature. For post 2003 period, MODIS surface temperature data is analyzed instead. The trends in spatial variance of these measures are closely related with wind speed trends, e.g., if spatial variance of geopotential and temperature decrease, the surface wind speed also decreases.

In terms of ground-observed data in SK, near-surface air temperature and surface wind speed generally exhibit 'seesaw' phenomenon, i.e., if air temperature increases, surface wind speed decreases and vice versa. Exceptions are summer and winter of post 2003 period when both air temperature and wind speed rose or fell together. Recent decrease of air temperature in winter months is likely attributed to more frequent intrusion of cold air into the region. This

hypothesis stems from the contrasting trends between air and surface temperature since 2003. We also hypothesize that recent increase of both surface temperature and wind speed in summer months is driven by greater influence of warm air mass, which raises both the mean and spatial variance of summer temperature in the region.

This finding of greater seasonal disparity raises further questions on its basic causes, which should be investigated in the context of changing regional climate. Some existing studies on this line provide noteworthy clues. For example, Hadley circulation intensity anomalies, which represent the extent of the wind speed and high pressure belt in subtropical regions, for the Northern Hemisphere are reported to switch its phase from negative to positive in the early 2000s (Nguyen et al. 2013); the timing matches the observed transition year of wind speed. In association, inter-decadal Pacific Oscillation Index (POI) was reported to have shifted its phase from positive to negative in 2000 (Parker et al. 2007). Fu et al. (2011) suggested possible relationship between POI shift and temporal variation of wind speed in China. Anomalies of global sea surface temperature also have changed their trends around early 2000s (Merchant et al. 2012).

Despite all these studies, nothing is conclusive at our current knowledge. This warrants future study on understanding inter-relationships between climate variables with regards to recent global environmental changes. The effect of urbanization over highly urbanized countries like SK on counter-acting regional surface wind speed increase shall need to be quantified as well. For a greater domain of East Asia, other factors such as marine upwelling for surface wind speed change would also need to be investigated. Recent changes of wind speed presented in this paper and our hypotheses on different geophysical reasons between summer and winter may help promote future studies in this direction.

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MODIS data is from the website: <http://neo.sci.gsfc.nasa.gov/> and we retrieved ERA-40 products from the website of the Asia-Pacific data-research center of the International Pacific Research Center (<http://apdrc.soest.hawaii.edu/>). We thank the editor and anonymous reviewers for their constructive comments.

## Appendix 1: Transition point

To determine the transition point in the time series, yearly difference time series are first obtained from annual mean and annual maximum series, respectively. Then, transition points are calculated from the yearly difference time series. We implemented three methods of two-phase regression technique (Elsner et al. 2000), tabular cumulative summation test (Montgomery 2009), and commercial program based on combination of cumulative summation charts and bootstrapping (Taylor 2000). These methods yield different transition points (Table 2). Here, we follow the result from Elsner et al. (2000)'s method in that this method gives the same year (2003) as the transition point for both annual mean and annual maximum series.

When we implement the same methods with the original annual mean and annual maximum series and transition points are less clearly identified. Using yearly difference time series enhances clarity in determining transition points.

## Appendix 2: Statistical significance of trends

All trends reported in this paper, i.e., not only those of wind speed but also of geopotential and temperature, are tested for statistical significance. The significance of linear regression trends is tested within 95 and 90 % confidence levels by student's *t* test using Spearman's rank correlation (1904). Most trends prior to 2003 are found statistically significant at 90 % confidence level (Table 3). Not all trends are found significant and we distinguish statistically significant trend and the rest by using solid or dashed line in all linear regression lines.

**Table 2** Transition points in difference time-series of wind speed

Methods	Two-phase regression technique (Elsner et al. 2000)		Tabular cumulative summation test (Montgomery 2009)		Combination of tabular cumulative summation test and bootstrapping (Taylor 2000)	
	Annual mean series	Annual maximum series	Annual mean series	Annual maximum series	Annual mean series	Annual maximum series
Difference time series						
Transition points	1963, 2003	1963, 2003	1965, 2004	1966, 2002	1962, 1965, 1971, 1993, 2004	1964, 1979, 1997, 2001

**Table 3** Statistical significance of trends reported in this study

Time-series	Pre-2003 (in case of ERA-40, pre-2001)				Post-2003			
	Slope of linear fit	t-value	95 % confidence level (t = 1.960)	90 % confidence level (t = 1.645)	Slope of linear fit	t-value	95 % confidence level (t = 1.960)	90 % confidence level (t = 1.645)
Annual mean wind speed (Fig. 2a)	-0.013	12.36	--	--	0.008	-1.14	+	+
Daily maximum wind speed (Fig. 2b)	-0.066	12.91	--	--	-0.008	0.44	-	-
Wind speed over inland stations (Fig. 3)	-0.007	5.55	--	--	0.010	-1.77	+	++
Wind speed over coastal stations (Fig. 3)	-0.020	16.83	--	--	0.006	-0.82	+	+
Difference of wind speed between coastal and inland (Fig. 3)	-0.013	14.27	++	++	-0.004	0.47	-	-
Standard deviation of wind speed (Fig. 4)	-0.006	11.66	--	--	0.001	-0.38	-	-
Seasonal (MAM) wind speed (Fig. 5)	-0.013	8.78	--	--	0.014	-0.73	+	+
Seasonal (JJA) wind speed (Fig. 5)	-0.010	6.59	--	--	0.026	-3.02	++	++
Seasonal (SON) wind speed (Fig. 5)	-0.011	8.88	--	--	0.009	-1.45	+	+
Seasonal (DJF) wind speed (Fig. 5)	-0.019	11.50	--	--	-0.015	1.38	+	+
Seasonal (DJF) SEM of geopotential in East Asia (Fig. 6a)	-0.152	2.83	--	--				
Seasonal (JJA) SEM of geopotential in East Asia (Fig. 6a)	-0.072	2.39	--	--				
Seasonal (DJF) SEM of geopotential in Arabian Sea (Fig. 6b)	0.011	-0.70	+	+				
Seasonal (JJA) SEM of geopotential in Arabian Sea (Fig. 6b)	-0.073	4.11	--	--				

**Table 3** continued

Time-series	Pre-2003 (in case of ERA-40, pre-2001)				Post-2003			
	Slope of linear fit	t-value	95 % confidence level (t = 1.960)	90 % confidence level (t = 1.645)	Slope of linear fit	t-value	95 % confidence level (t = 1.960)	90 % confidence level (t = 1.645)
Seasonal (DJF) SEM of geopotential in western Canada (Fig. 6c)	-0.035	-0.22	-	-				
Seasonal (JJA) SEM of geopotential in western Canada (Fig. 6c)	-0.131	1.71	-	-				
Seasonal (DJF) SEM of geopotential in United States (Fig. 6d)	-0.054	2.22	--	--				
Seasonal (JJA) SEM of geopotential in United States (Fig. 6d)	-0.024	2.67	--	--				
Seasonal (DJF) SEM of temperature in East Asia (Fig. 7)	-0.002	2.31	--	--	0.005	-1.04	+	+
Seasonal (JJA) SEM of temperature in East Asia (Fig. 7)	-0.001	2.06	--	--	0.001	-0.18	+	+
Seasonal (DJF) mean temperature in East Asia (Fig. 7)	0.018	-1.75	+	++	0.025	-0.36	+	+
Seasonal (JJA) mean temperature in East Asia (Fig. 7)	0.006	-0.83	+	+	0.012	-0.13	+	+
Annual mean temperature (Fig. 9a)	0.023	-4.50	++	++	-0.025	0.79	-	-
Seasonal (MAM) air temperature (Fig. 9b)	0.032	-5.62	++	++	-0.057	0.64	-	-
Seasonal (JJA) air temperature (Fig. 9c)	0.011	-1.30	+	+	0.168	-2.00	++	++
Seasonal (SON) air temperature (Fig. 9d)	0.017	-2.43	++	++	-0.045	0.85	-	-

**Table 3** continued

Time-series	Pre-2003 (in case of ERA-40, pre-2001)				Post-2003			
	Slope of linear fit	t-value	95 % confidence level (t = 1.960)	90 % confidence level (t = 1.645)	Slope of linear fit	t-value	95 % confidence level (t = 1.960)	90 % confidence level (t = 1.645)
Seasonal (DJF) air temperature (Fig. 9e)	0.032	-3.38	++	++	-0.166	1.77	-	--

++, significantly increase; +, insignificantly increase; --, significantly decrease; -, insignificantly decrease

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