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Changes in the Relationship between Particulate Matter and Surface Temperature in Seoul from 2002–2017

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Received: 19 March 2019; Accepted: 26 April 2019; Published: 1 May 2019

Abstract: This study focuses on the changes over time in the relationship between surface temperature and particulate matter (PM) concentration over Seoul using long-term observational data. Correlation coefficients between the daily mean PM_{10} concentration and surface temperature were calculated to investigate the relationship between the two. The PM_{10} and temperature displayed a strong positive correlation, suggesting the increase in PM was driven by large-scale synoptic patterns accompanying such high temperatures. It was found that the correlation coefficient in 2002–2009 was significantly higher than that of 2010–2017, indicating that the relationship between PM_{10} concentration and temperature has weakened over time in recent decades. Correlation coefficients between daily averaged temperature and the PM_{10} of each year were calculated to account for the decreased correlation in the most recent decade. We found that the correlation coefficients between surface temperature and PM of each year exhibited a clear negative correlation with the longitudinal position of the Siberian High, suggesting that the position of the Siberian High might affect the strength of the relationship between PM concentration and temperature over Seoul. We also found that the eastward shift of the Siberian High reduces the standard deviation of pressure over Seoul, indicating reduction of synoptic perturbation. These results imply that the eastward shift of the Siberian High in recent decades might weaken the relationship between the PM and surface temperature over Seoul. This study suggests that the relationship between PM and meteorological variables is changing over time through changes in large climate variability.

Keywords: particulate matter; climate change; air pollution meteorology; air quality

1. Introduction

Poor air quality as a result of particulate matter (PM) in Seoul, the largest city in South Korea, is a serious issue. This is exemplified by frequent haze events, which are particularly common in winter [1–3]. Although emissions over Seoul have decreased over the past few decades [4,5], haze events have still occurred in recent years [3,6,7]. Fully understanding these haze events is difficult, since PM is affected not only by emissions but also by meteorological and chemical environments [8–10]. Although previous studies have suggested that emission changes are the primary factor in determining the PM level over East Asia and Seoul [1,11,12], PM concentration is also significantly affected by meteorological conditions, since changes in emissions tend to occur slowly [13]. Indeed, a number of recent studies have reported that synoptic weather conditions affect the frequency and longevity of pollution episodes over East Asia [14–16].

More specifically, Kim et al. reported that the interannual variability of surface PM, with a diameter of ≤ 10 µm (PM_{10}), in South Korea was closely linked with the interannual variations of wind speed [1]. Their study also suggested that reduced regional ventilation was likely associated with more stagnant conditions in the past few years, which have caused severe pollutant episodes in South Korea. In addition, Lee et al. showed that higher air temperatures and weak lower/upper-level winds led to high PM episodes [15]. Previous studies have also reported that the strength of large climate variability, such as the East Asia monsoon, El Niño-Southern oscillation, and Arctic oscillation, has influenced PM variability over East Asia [17–19]. Furthermore, numerous studies have suggested that the impact of meteorological conditions on PM variability is not negligible [11,20,21], and so the mechanisms and contribution of the meteorological effect on PM should be elucidated.

As previous studies have employed long-term datasets to understand the relationship between PM variability and meteorological conditions [11,20,22], they have tended to focus on the averaged strength and contribution of meteorological conditions to variations in PM over long periods. However, as climate change shifts the synoptic system slowly over time [23], the mechanism involved in PM variations resulting from meteorological conditions may also change in line with climate change, as may the strength and contribution of meteorological conditions to such changes. Thus, evidence of a relationship change between PM variations and meteorological variables over time is reported here by using PM and surface temperature data over Seoul. Factors that potentially affect the relationship between PM and temperature are also explored by using long-term observational data and a re-analysis dataset.

2. Domain and Data

A dataset of PM_{10} concentrations and surface temperatures in Seoul was used to investigate the relationship between PM and meteorological variables. PM_{10} data were obtained from 25 air quality monitoring stations in Seoul (blue dots in Figure 1) over 16 years (December 2001 to February 2017) [24]. Measurement of PM_{10} used the SPM-613D beta gauge method, which utilized the fact that a portion of beta rays were absorbed and dissipated by a substance when the rays that irradiated PM collected on filter tape. PM data were reviewed comprehensively through comparison with previously reported observational data [25–27]. Previous studies concluded that this method was advantageous for high temporal resolutions, but it had an uncertainty of ≤10% because of the presence of moisture-containing particles.

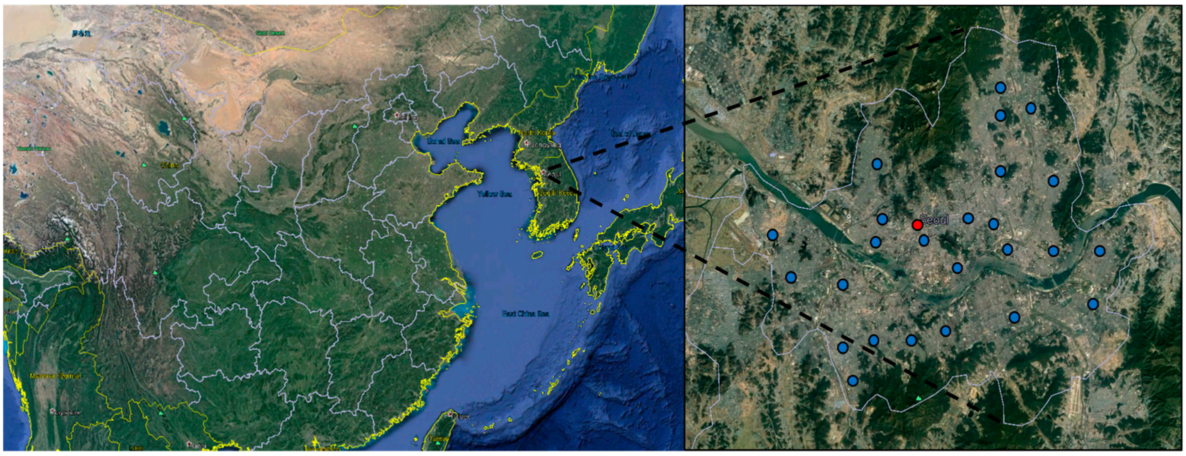

Figure 1. Monitoring sites of PM_{10} (blue dots) and temperature (red dot) in Seoul, Korea (map obtained from Google Earth).

Surface temperature, sea level pressure, surface wind, and relative humidity data were obtained from the Seoul station of the Korea Meteorological Administration [28] for the same period (red dot in Figure 1). We also employed a re-analysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis Interim (ERA-Interim) to investigate synoptic patterns relating to the changing relationship between PM and temperature [29]. We focused on the boreal winter season (December, January, and February) during which haze events frequently occur, owing to large emissions from heating activities in Korea and China [3,6,7].

The Siberian High has the most significant influence on winter climate over the Eurasian continent, including East Asia [30,31], as the position and strength of the Siberian High controls the synoptic systems over this area. Figure 2 displays the multi-year (2002–2017) averaged sea level pressure (shading) and wind at 850 hPa (vector) data of the ERA-Interim re-analysis dataset in winter. The Siberian High results in a strong northwesterly wind over western China and Korea as a result of a strong pressure gradient between the Siberian High and the Aleutian Low in winter. Thus, the intensity and the longitudinal center of the Siberian High of each year were calculated to investigate the status of the Siberian High. More specifically, the strength of the Siberian High was defined as the mean sea level pressure over Mongolia and southern Siberia between 80–120 °E and 40–65 °N (black box in Figure 2) [32]. Previous studies have shown that this definition successfully represented the strength of the Siberian High using not only climate studies but also air quality studies [33,34].

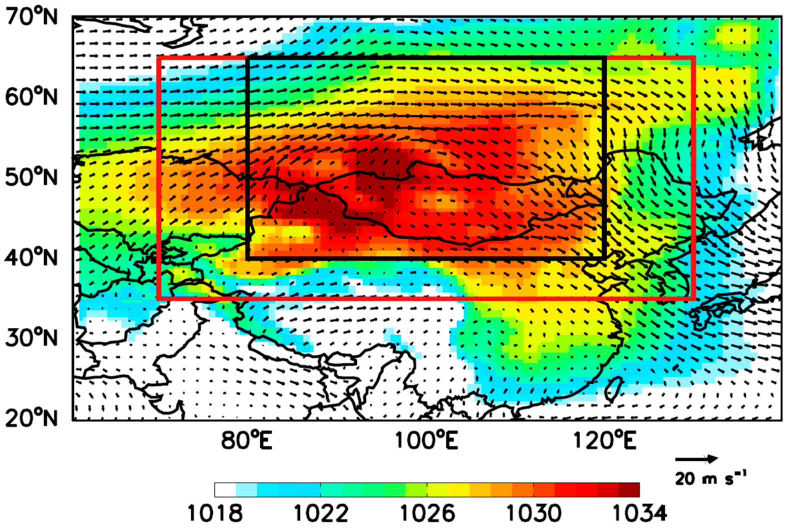

Figure 2. Multi-year (2002–2017) averaged sea level pressure (shaded) and 850 hPa wind fields (vectors) over Siberia and East Asia in winter. The black and red rectangles indicate the domains of the intensity and longitudinal center of Siberian High calculations, respectively. Units are hPa (sea level pressure) and m s^{-1} (wind).

The longitudinal center of the Siberian High was also calculated as the weighted mean of the longitudes of all grids within the 1026 hPa isobar over the Siberian region of 70–130 °E and 35–65 °N (red box in Figure 2), as presented in Equation (1).

$$\mathrm{SHCI} = \frac{\sum (P_i \times L_i)}{\sum P_i} \tag{1}$$

where L_i is the longitude of the grid point i within the 1026 hPa isobar and the definition domain, and P_i is the sea level pressure at i. This method was measured in degrees of longitude and was similar to the longitude index of the Siberian High defined by Hou et al. [35] and the Siberian High position index proposed by Jia et al. [36]. However, the current definition was slightly different, as previous studies defined the indices as the weighted mean longitude within the 1023 hPa isobar under a much wider area. In contrast, to prevent the current index being affected by high-pressure areas in the polar or other Asian regions, the spatial domain in which the 1026 hPa isobar was considered for the longitude center of Siberian High calculation was limited. The intensity and the longitude center of the Siberian High were calculated using the ERA-Interim dataset. The spatial domains of our calculation (black and red boxes in Figure 2, respectively) included the center of the Siberian High.

3. Results and Discussion

Figure 3a shows the time series of the seasonal averaged PM_{10} concentrations over Seoul in the winters of 2002–2017, where an average PM_{10} concentration of 63.6 µg m^{-3} was obtained. However, the PM_{10} concentration decreased continuously (i.e., −2.8 µg m^{-3} $year^{-1}$) as a result of a decrease in emissions in Korea between 2001 and 2017 [11]. Although the PM_{10} concentration showed a decreasing trend, it showed clear year-to-year variations. This might represent the effect of meteorological conditions on PM_{10} concentration, considering emission changes were relatively small compared to interannual variability.

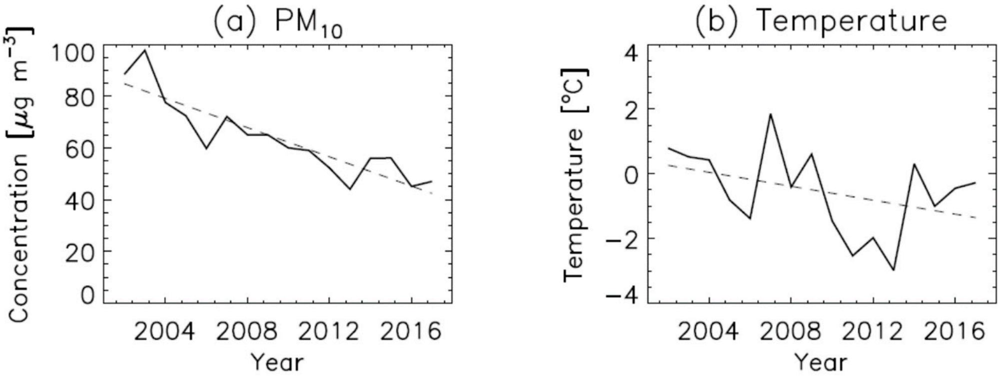

Figure 3. Seasonal averaged time series of (**a**) the surface PM_{10} (left panel) and (**b**) the surface temperature (right panel) over Seoul in winter. Units are µg m^{-3} and °C, respectively.

Correlation coefficients between the daily mean PM_{10} concentrations and the meteorological variables (i.e., surface temperature, surface pressure, surface wind speed, and surface relative humidity) for the analysis period were calculated, using surface observation datasets over Seoul, to investigate the relationship between the meteorological conditions and the PM_{10} concentration (Table 1). Correlation between the PM_{10} value and temperature was found to be the highest (0.35) at a 99% confidence level, and this was supported by a previous study [37]. The relative humidity, surface pressure, and wind speed also showed clear correlations with the PM_{10} concentration (0.17, 0.25, and −0.13, respectively); however, the absolute magnitudes of the correlation coefficients were significantly lower than that of temperature. Considering that high temperatures can promote the evaporation of nitrate aerosols, which are a major pollutant in winter, the high positive correlation between temperature and the PM_{10} value suggests that the increase in PM is driven by large-scale synoptic patterns accompanying such high temperatures. It should be noted that sulfate concentrations were found to exhibit a relatively low contribution to the total PM_{10} in winter over East Asia [12]. Previous studies have reported that high surface temperatures occurred over Seoul along with high-pressure conditions over Seoul and Eastern China during high-PM_{10} episodes [17,37]. Therefore, surface temperature over Seoul might be a simple indicator for synoptic patterns relating to PM variations. Figure 3b shows the seasonally averaged temperatures over Seoul in winter. As the surface temperature over Seoul has decreased slightly over the past couple of decades because of the cooling of Eurasia [38], this decrease was only on a scale of −0.11 °C $year^{-1}$, which was a relatively small change compared to the year-to-year variation in temperature.

Table 1. Correlation coefficients between the daily mean PM_{10} concentration and the surface temperature, surface pressure, surface wind speed, and surface relative humidity for 2002–2017 in winter. ** denotes significance at the 99% confidence level.

Meteorology Variables	Surface Temperature	Surface Wind Speed	Surface Pressure	Surface Relative Humidity
PM_{10}	0.35 **	−0.13 **	0.25 **	0.17 **

Figure 4 shows a scatterplot of the daily averaged PM_{10} concentration against the daily averaged surface temperature of Seoul over the winter months between 2002 and 2017. The regression slope obtained over the whole period was 2.5 $\mu g\ m^{-3}\ {}^{\circ}C^{-1}$, indicating that an increase in temperature enhanced the PM_{10} concentration over Seoul. The red and blue diamonds indicated the data corresponding to the first and last eight years, respectively. The regression slope of the first eight years was two times higher than that of the last eight years (i.e., 3.1 and 1.5 $\mu g\ m^{-3}\ {}^{\circ}C^{-1}$, respectively), indicating that the sensitivity of PM_{10} to changes in temperature decreased in the last decade. Because this study only used observational data, the difference between the regression slopes in the former and latter periods included the effect from the large reduction in pollution above Seoul during the past few decades; therefore, it was decided to focus on changes in the correlation coefficients. More specifically, the correlation coefficient of the earlier period was significantly higher than that of the later period (i.e., 0.44 and 0.24, respectively), which implied that recent climate change had weakened the relationship between PM_{10} and surface temperature over Seoul. These results also suggested that contribution of weather systems to PM_{10} may have decreased in recent decades.

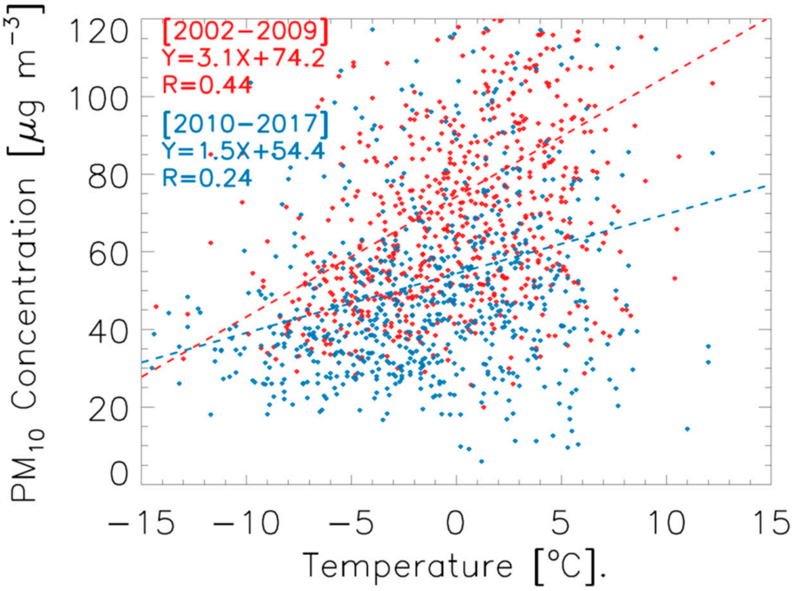

Figure 4. Scatterplot of the daily averaged surface PM_{10} versus the daily averaged surface temperature over Seoul. The red and blue diamonds indicate the data for 2002–2009 and 2010–2017, respectively. The red and blue dashed lines show the regression between the PM_{10} and temperature in 2002–2009 and 2010–2017, respectively. Units of PM_{10} concentration and temperature are $\mu g\ m^{-3}$ and °C, respectively.

The correlation coefficient between daily averaged temperature and PM_{10} of each year (hereafter CTP) was then calculated (Figure 5) to determine the cause of this decreased correlation. More specifically, CTP ranges of 0.13–0.64 were obtained for the majority of years, satisfying significance at a 95% confidence level (red dashed line in Figure 5). However, despite the considerable variation from year to year, the correlation coefficients clearly decreased over the 16 years during which the data were recorded. More specifically, the averaged CTP of the three most recent years (2015–2017) was only 0.22, which was not significant at a 95% confidence level, whereas the CTP between 2004 and 2006 was 0.53, and this value showed significance at a 99% confidence level.

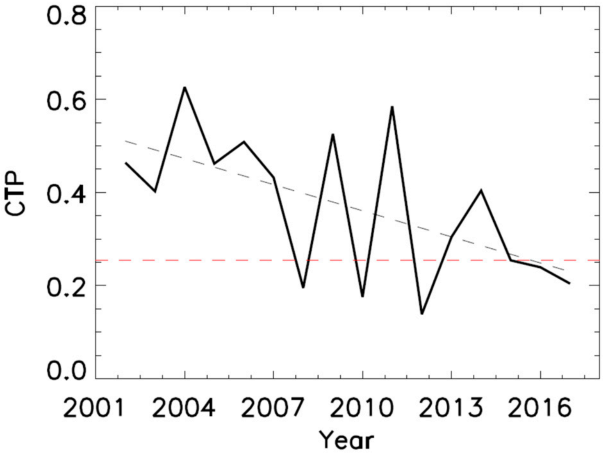

Figure 5. Time series of the correlation coefficient between daily averaged temperature and PM_{10} (CTP) during 2001–2017. The black dashed line indicates the regressed trend. The red dashed line is the 95% confidence level.

To understand the mechanism responsible for such a decrease in correlation, the regressed sea level pressure (Figure 6a) and wind field at 850 hPa (Figure 6b) were calculated against the CTP over East Asia using the ERA-Interim re-analysis dataset for 2002–2017. It was found that in the years of a high CTP, the sea level pressure decreased over Inner Mongolia and increased over western Mongolia and western China, thereby enhancing the pressure gradient over Mongolia. Regressed wind data showed that strong pressure gradients over Mongolia enhanced the northwestern wind over central and eastern China. These regressed patterns might imply that frequent ventilation over eastern China resulted in a high correlation between PM_{10} concentration and surface temperature over Seoul as a result of changes in the pressure system in the Siberian region. Regressed sea level pressure and wind patterns also suggested that there might be a relationship between changes in the Siberian High and the CTP.

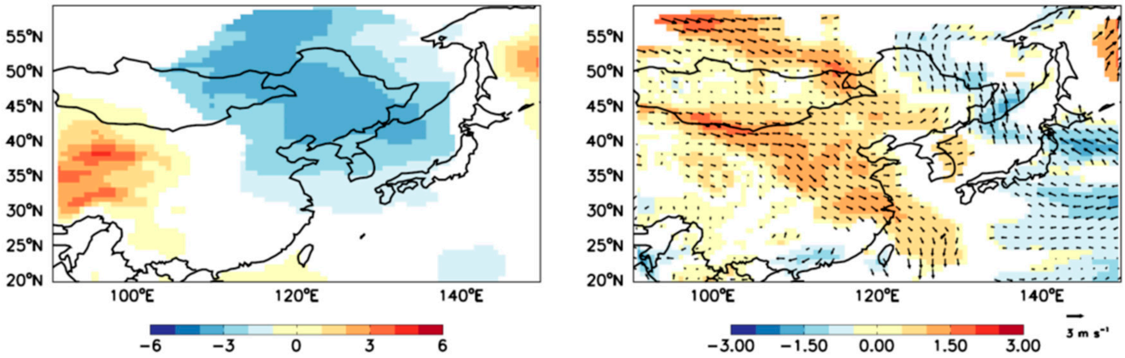

Figure 6. Regressed (**a**) sea level pressure (left panel) and (**b**) wind (shading: wind speed; vector: wind; right panel) at 850 hPa against the CTP for 2002–2017. The shading and vector only are plotted at the 90% confidence level. Units are hPa and m s^{-1}, respectively.

Previous studies have suggested that the state of the Siberian High significantly affected not only the climate but also the PM_{10} levels over Korea and nearby regions, thereby altering wind speed and relative humidity over eastern China [39,40]. In addition, Jeong et al. reported that development of the Siberian High resulted in a strong east–west gradient over the Eurasian continent in winter [17], which generated northerly winds that enhanced the transport of aerosols over northeastern China and Korea. Development of the Siberian High was accompanied by high temperatures over Korea owing to the winter monsoon system, and Jia et al. suggested that the PM concentration was affected by not only the strength of the Siberian High but also its location over East Asia [36].

The intensity and longitudinal center of the Siberian High were compared with the CTP to examine the potential effect of the Siberian High on the decreasing trend of correlation. As shown in Figure 7a, no relationship was observed between the intensity of the Siberian High and the CTP, indicating that the strength of the Siberian High did not alter the correlation between temperature and PM_{10}. To examine the effect of zonal shift of the Siberian High on the correlation, we also investigated the relationship between the longitudinal center of the Siberian High and the CTP (Figure 7b). Strikingly, a negative correlation of −0.55 was obtained, which was significant at a 95% confidence level. Furthermore, a trend of 0.21 °E year^{-1} was obtained for the longitudinal center of the Siberian High between 2002 and 2017, indicating a clear eastward shift over the analysis period. This shift might suggest that the decreasing trend of correlation between temperature and PM_{10} concentration over Seoul was related to the eastward shift of the Siberian High in recent decades.

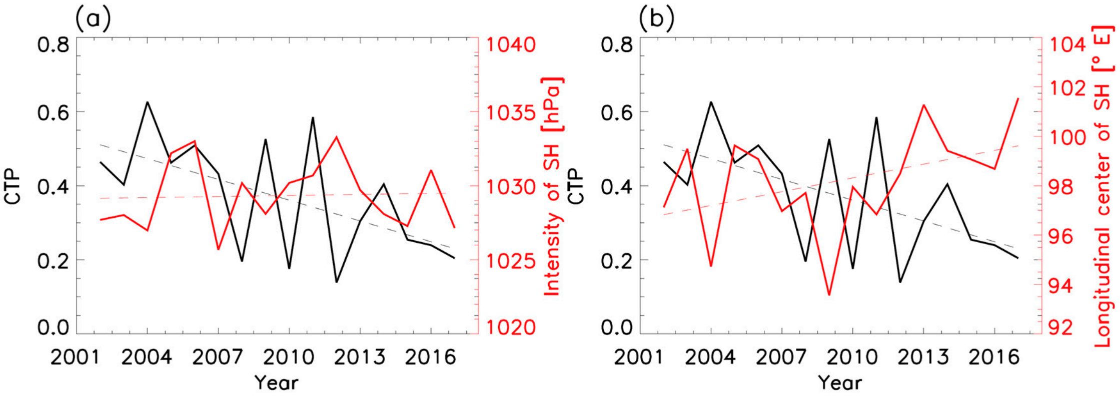

Figure 7. Time series of the (**a**) intensity (left panel) and (**b**) longitudinal center (right panel) of Siberian High against the CTP for 2002–2017. The red lines indicate the intensity and longitudinal center of the Siberian High, and the black line shows the CTP. The units of the intensity and longitudinal center of the Siberian High are hPa and °E, respectively.

To explore how the eastward shift of the Siberian High might influence the relationship between PM_{10} and surface temperature, the regressed sea level pressure and wind against the longitudinal center of the Siberian High were calculated using the ERA-Interim dataset for 1979–2017 (Figure 8). It was found that the eastward shift of the Siberian High induced a sea level pressure increase over Inner Mongolia and a decrease over western Mongolia. Regressed wind data showed that these pressure patterns reduced the northwestern wind over central and eastern China. These regressed pressures and winds showed an opposite pattern from that shown in Figure 6, indicating that the eastward shift of the Siberian High drove stagnant atmospheric conditions over Seoul. Previous studies have also reported that an eastward extension of the Siberian High reduced the wind speed over Eastern China and the Yellow Sea, causing stagnant atmospheric conditions over Seoul and increasing the PM concentration [36].

Stagnant conditions from the eastward shift of the Siberian High might reduce variability of synoptic patterns, giving a lower correlation between PM and surface temperature. To investigate this, the longitudinal center of the Siberian High was compared to the standard deviation of the surface pressure and temperature over Seoul for 1979–2017 (Figure 9). The correlations between the longitudinal center of the Siberian High and standard deviation (−0.41 and −0.22, which were significant at the 99% and 95% confidence levels, respectively) displayed a negative relationship. The clear negative correlation between the longitudinal center of the Siberian High and the standard deviation of the surface pressure suggested that the eastward shift of the Siberian High drove not only stagnant conditions over Korea but also a reduction of the frequency of synoptic perturbations over Korea. These results consistently suggested that the shift in the position of the Siberian High might have changed the relationship between PM_{10} and temperature over Seoul in recent decades.

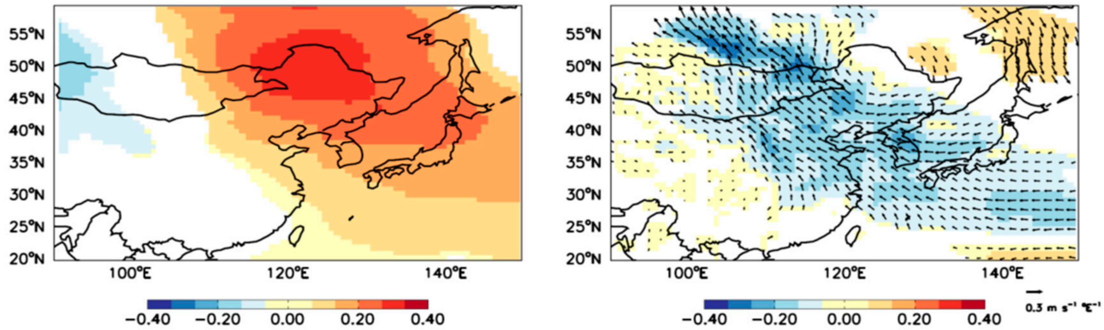

Figure 8. Regressed (**a**) sea level pressure (left panel) and (**b**) wind (shading: wind speed; vector: wind; right panel) at 850 hPa against the longitudinal center of the Siberian High for 1979–2017. The shading and vector only are plotted at the 90% confidence level. Units are hPa °E^{-1} and m s^{-1} °E^{-1}, respectively.

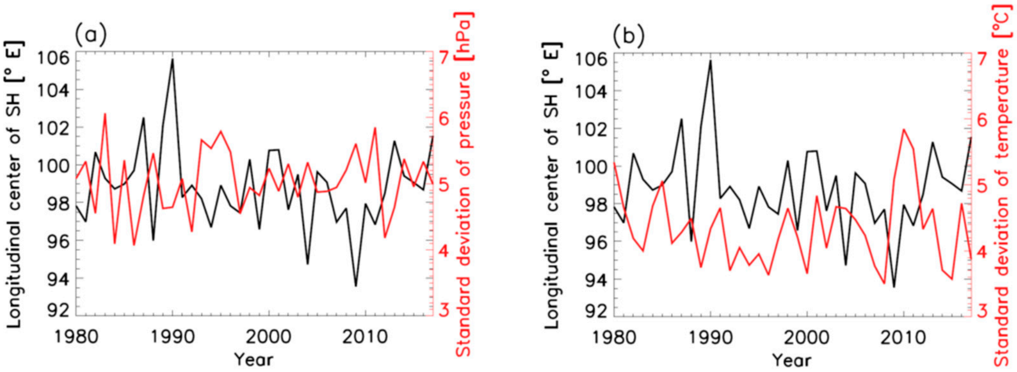

Figure 9. Time series of the standard deviation of daily averaged (**a**) surface pressure (left panel) and (**b**) temperature (right panel) against the longitudinal center of Siberian High for 1979–2017. The red lines indicate the standard deviation, and the black line shows the longitudinal center of the Siberian High. The units are hPa and °C, respectively.

4. Conclusion

The changing relationship between surface temperature and PM concentration over Seoul was investigated using long-term observation (2002–2017) and re-analysis datasets. PM_{10} concentration was found to have continuously decreased between 2002 and 2017 as a result of overall reductions in emissions in Korea during this period. The correlation coefficients between daily mean PM_{10} concentration and surface temperature were calculated to examine how the relationship between surface temperature and PM concentration changed over time. A strong positive correlation was obtained between PM concentration and temperature, with the correlation coefficient over the period 2002–2009 being significantly higher than that over the period 2010–2017. This change suggests that recent climate change has weakened the relationship between the PM_{10} value and the meteorological conditions over Seoul. The CTP was then calculated to determine the cause of this reduced correlation. Interestingly, despite the large variation from year to year, the CTP clearly decreased over the study period. In addition, sea level pressure and wind fields at 850 hPa were regressed against the CTP over East Asia to understand the mechanism responsible for this reduced correlation. It was found that in the years of high CTP values, strong pressure gradients over Mongolia enhanced the northwestern wind over central and eastern China. These results, therefore, suggest that there might be a relationship between CTP and changes in the Siberian High. CTP was then compared with the longitudinal center of the Siberian High to examine the effect of the shift of the Siberian High on the relationship between temperature and PM_{10}. A correlation of −0.55 was obtained, showing a clear negative relationship. This negative correlation suggests that the weakened relationship between temperature and PM_{10} in recent decades might relate to the eastward shift of the Siberian High. To explore how the eastward shift of the Siberian High might influence the relationship between PM_{10} and surface temperature, the regressed sea level pressure and wind against the longitudinal center of the Siberian High were calculated for 1979–2017. These regressed pressure and wind data showed a clear opposite pattern to the regressed patterns against CTP, indicating that the eastward shift of the Siberian High drove stagnant atmospheric conditions over Seoul. Then, the longitudinal center of the Siberian High was compared with the standard deviation of the surface pressure. Correlation between the longitudinal center of the Siberian High and standard deviation was clearly negative, suggesting that the eastward shift of the Siberian High drove a reduction of the frequency of synoptic perturbations over Korea. These results showed that the shift of the Siberian High might have changed the relationship between PM_{10} and temperature over Seoul in recent decades. This study suggests that the relationship between PM and meteorological variables varies over time via changes in large climate variability, which might be important for investigating the long-term effects of meteorological variables on PM.

This study, based on observational data, focused on the linear relationship between PM and temperature. However, many factors affect PM_{10} pollution, including nonlinear factors. Modeling studies should be conducted to elucidate the relationship change between PM and meteorological variables.

Funding: This work was funded by the 2017 Research Fund of Myongji University.

Acknowledgments: This work was supported by the 2017 Research Fund of Myongji University.

Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest."

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