

RESEARCH ARTICLE

10.1002/2014JD021958

Key Points:

- Highlight regional climate change affects visibility (Vis) and air quality
- Weakened wind and less cold wave contribute to winter Vis decline over China
- Link Vis with cold wave makes long-term prediction of low Vis more practical

Supporting Information:

- Texts S1 and S2, Figure S1, and Table S1

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Citation:

Qu, W., J. Wang, X. Zhang, Z. Yang, and S. Gao (2015), Effect of cold wave on winter visibility over eastern China, *J. Geophys. Res. Atmos.*, 120, 2394–2406, doi:10.1002/2014JD021958.

Received 28 APR 2014

Accepted 13 FEB 2015

Accepted article online 17 FEB 2015

Published online 18 MAR 2015

Effect of cold wave on winter visibility over eastern China

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Abstract Considerable concern has been raised on the severe wintertime haze episodes over eastern China (ECN) where visibility (Vis) decline in winter is identified from 1973 to 2012 (−0.68 km per 10 years or −26% in 40 years). Based upon the analysis of daily Vis and weather records, cold wave (CW) originating from high latitudes is found to increase Vis by 2.7 km on average because of its relatively stronger wind and drier, cleaner air mass compared with the typical, stable midlatitude air over ECN in winter. However, the lessening frequency of CW occurrence and cold air activity in recent years and the accompanied decrease of surface wind speed (−0.15 m/s per 10 years or −18% in the 40 years) may have amplified the effect of increased anthropogenic emissions on Vis and consequently resulted in more substantial Vis decline. A comparison of Vis trends on the “normal wind” days and on all days in winter implies that the emission increase has contributed to about 79% of the declining Vis trend, while the meteorology change contributed 21%. Furthermore, the diurnal cycle of the boundary layer height is found to have weakened or in some cases disappeared in the winters with less CW, which probably contributed to the long-lasting characteristic of the wintertime low Vis events in this region. Hence, the effect of climate change, such as the decrease of CW occurrence, should be accounted as part of the interpretation for the steady decrease of winter Vis over ECN in the past four decades.

1. Introduction

The severe wintertime air pollution episodes (fog and haze events) over eastern China (ECN) have received much attention lately [Tao *et al.*, 2012; Yang *et al.*, 2013; Zhao *et al.*, 2013; Boynard *et al.*, 2014]. These widespread and long-lasting fog and haze events, combined with the resultant low visibility (Vis), have a deleterious impact on the environment, human health, and economy. Past studies have attributed the cause of the increasing frequency of low Vis events to the continuous increase of anthropogenic emissions over China since the 1980s [Qian *et al.*, 2009; Wang *et al.*, 2009]. However, recently, a few studies also pinpointed the importance of the variation of synoptic systems in regulating the frequency of low Vis events. Zhu *et al.* [2012] highlighted the effect of the weakened East Asian summer monsoon on the increase of aerosol loading over China. Qu *et al.* [2013] found that the strengthening and westward extension of the western Pacific subtropical high have contributed to summer Vis decline over ECN since the 1970s. Indeed, the effect of regional climate change on the occurrence of haze and low Vis events is found not only in Asia but also in other parts of the world including North America [Tai *et al.*, 2010]. “How the shift of weather patterns (due to the climate change) may have affected and will affect air quality and visibility?” is an interesting question to be further investigated at interannual and regional scales. In this paper, we study the role of meteorology in the decreasing trend of winter Vis over ECN.

In comparison with other seasons, house heating in winter (including both the intensive central heating in the north and the presumably long durative air condition using or other types of heating ways in the south) is an additional important source of the anthropogenic emissions of the aerosol and its precursor gases [Hao *et al.*, 2005; Chan and Yao, 2008]. Meanwhile, multiyear (1973–2012) wintertime averages identify a general background of anticyclone accompanied with low wind speed (WDSP) over ECN (Figure 1a), which tends to result in a general stagnant air mass background over ECN in winter. Although needs further investigation, such a stable weather background should be presumably favorable (as will be briefly discussed in sections 3.1 and 4) for formation of the secondary aerosol, which was highlighted as the major contributor to Vis reduction during haze events in China [Tan *et al.*, 2009; Zhao *et al.*, 2013; Guo *et al.*, 2014; Sun *et al.*, 2014;

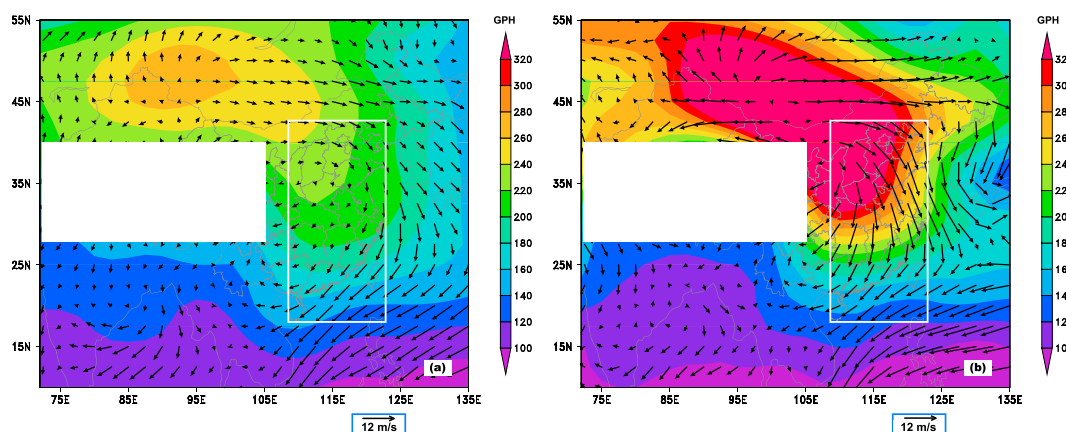


Figure 1. The NCEP reanalysis 1000 hPa geopotential height (GPH, m) and wind vector (m/s), (a) mean in winter during 1973–2012, (b) on a typical cold wave (CW) day, 21 December 2008. Eastern China (ECN) is defined in section 2 and Figure 2a; the white box shows the location of ECN, and only part of the continent within the box is included in ECN. Values over topography higher than 1500 m (mostly the Tibetan Plateau) were masked out. Here the station pressure extracted from the GSOD data is found to be greater than 1000 hPa for most of the stations over ECN (except several mountain stations); thus, 1000 hPa meteorology is physical over ECN.

Qu et al., 2015]. What makes the wintertime meteorology unique is the intrusion of cold air from high-latitude areas (i.e., the cold air activity). A typical strong cold air activity, cold wave (CW, cold surge termed by other researchers) is characterized by low temperature and intensive wind. It is associated with southeastward extension of the anticyclone over Siberia (or Mongolia and other high-latitude areas) into China (Figure 1b) and the passage of midlatitude synoptic waves, which results in a cold front and intensive wind through ECN. Because CW is a strong wind event, more CW occurrences should be related to more intensive East Asian winter monsoon in a specific winter, but our presentation in this study focuses on CW for simplicity. *Niu et al.* [2010] studied possible impacts of the weakening of East Asian monsoon and increasing aerosol loading on the increase of wintertime fog in China. A description of CW and its relationship with outflow of the Asian pollution can also be found in *Liu et al.* [2003]. In this context, the frequently occurring stable air due to the semipermanent anticyclone over ECN (Figure 1a) and the additional emission from house heating are two important causes for the increasingly severe air pollution over ECN in winter, and the stronger surface wind associated with CW is substantially important to the dilution/diffusion and downwind transport of pollutants. While analysis on the historic weather records has identified the decreased frequency of CW during the last five decades [*Wang and Ding*, 2006; *Qian and Zhang*, 2007; *Wei*, 2008], it remains unclear how the less frequent CW may have affected the trend of Vis after considering the effect of increased emissions during this period [*Qian et al.*, 2009; *Wang et al.*, 2009].

To quantitatively establish a linkage between the variation of Vis and change of CW frequency, we analyzed the data of Vis, surface wind speed, and relative humidity (RH) over ECN in winter (December–February). A method used in *Qu et al.* [2013] (which is briefly introduced in section 3.2) is modified to separate the effect of emission increase on Vis decline. We introduce the data and the identification method of CW in section 2; this is followed by investigation of the favorable meteorology for Vis decline (section 3.1), discussion of the effect of CW weather on Vis, the impact of the decreased CW occurrence and surface wind on Vis trend (section 3.2), comparison of Vis, RH and wind anomaly on the more and less CW-influenced years (section 3.3), and variation of boundary layer height (BLH) in the absence of CW and its relationship with Vis (section 3.4). The paper is concluded in section 4.

2. Data and CW Definition

The Vis, wind speed, temperature, and RH data are extracted from the Global Summary of Day (GSOD) database. Daily Vis is estimated by averaging the observations (for the day with at least four records) with an uncertainty of 0.1 km [*China Meteorological Administration*, 2003]. Detail of these data is described in *Qu et al.* [2013]. Here we use data from 354 stations in China during 1973–2012, where and when data sets are most complete.

The 25th percentile Vis, which better reflects the variation and trend of Vis [Qu *et al.*, 2013], is used to evaluate Vis level, because (1) low Vis values best reflect Vis degradation, which is the major focus, and (2) the visual range generally can be estimated more accurately under low Vis conditions [Zhu and Mei, 2010] as it is less influenced by artificial factors [Li, 2010]. On the other hand, as discussed at the beginning of paragraph 2 in section 1, weak surface wind is the normal conditions in winter over ECN. Therefore, the 75th percentile wind speed (WDSP) is used to evaluate the WDSP trend because the variation of the high values of WDSP can capture more variability of the surface wind speed in this weak wind context. NCEP (United States National Centers for Environmental Prediction) reanalysis data and ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis data are also used to supply the meteorological background and to make composite analysis of RH, wind, and BLH for the CW-influenced days.

CW occurrence at a certain station is identified by the criterion that the minimum temperature (T_{\min}) decreases by at least 8°C on a given day from the prior day, similar to the criterion of 8°C or 10°C used in Wang and Ding [2006], Qian and Zhang [2007], and Wei [2008]. Note that the number of CW-influenced days determined by the criterion of 8°C is greater in magnitude than that determined by the criterion of 10°C, but they follow a same variation in detail and show a good correlation ($R=0.90$, $P<0.0001$, $n=40$). As our focus here is the enhancement of surface wind speed (WDSP) due to the cold air activity rather than decrease of the air temperature, 8°C, the criterion selected in this study is adequate because it reflects *larger sampling* of the change of WDSP due to the cold air activity.

In addition, the PM₁₀ (particles with diameter $\leq 10\ \mu\text{m}$) concentration in 52 major Chinese cities, which are derived from the air pollution index from the Ministry of Environment Protection of China using the method in Qu *et al.* [2010], is used to analyze the CW-related aerosol concentration change. Note here that the PM₁₀ concentration represents the average PM₁₀ level measured at several air quality monitoring stations in each city, which can reflect the variation of aerosol in a given area of the city. Totally, 464 station-time of CW events are identified for these city stations in winter during 2000 to 2012; the related changes of PM₁₀ concentration are calculated for each individual CW event at each station, and their statistics are presented in section 3.2.

The results are discussed within eastern China (ECN) and southwestern China (shaded with yellow, Figure 2a). ECN is also further separated into a south part (shaded with green and dark green) and a north part (shaded with light green) to facilitate discussion. The partition of China into ECN and other regions is similar as in Qu *et al.* [2013].

3. Results

3.1. Trends and Relationship Between Vis and CW-Related Meteorology

Vis shows an overall declining trend in ECN ($-0.68\ \text{km}$ per 10 years or -26% in the 40 years, Figure 2d). For the total 136 stations over ECN (similar as one of the major haze areas identified by Zhang *et al.* [2012b]), 80 stations are found to have a significant ($P<0.05$ significance) decline in Vis (shown in red in Figure 2a), and 22 stations have a significant ($P<0.05$) Vis increase (shown in blue in Figure 2a); these 22 stations are mostly located near the north edge of ECN (i.e., the semiarid region of North China), where the natural mineral dust aerosol emission driven by strong winds could dominate the low Vis event, thus resulting in negative correlations between WDSP and Vis in contrast to other parts of ECN in winter. That is, the decreased WDSP leads to less dust release and subsequently an increase of Vis at these stations near the north edge of ECN.

Similar to Vis, WDSP shows an overall decreasing trend over ECN ($-0.15\ \text{m/s}$ per 10 years or -18% during the 40 years, Figure 2d). For the total 136 stations over ECN, 79 stations are found to have a significant ($P<0.05$) decrease in WDSP (shown in blue in Figure 2b) and 12 stations have a significant ($P<0.05$) WDSP increase (shown in red in Figure 2b). These 12 stations with WDSP increase are mostly located in the southeastern coast (10 stations) or scattered as inland mountain stations (i.e., Yushe in Shanxi Province and Enshi in Hubei Province); their different increasing WDSP trends probably could be attributed to localized meteorology difference due to station siting. The WDSP trend at the other 45 of the total 136 stations over ECN is insignificant ($P=0.05$ significance level) and not shown in Figure 2b. A positive correlation is also found between the area geometric mean Vis and WDSP over ECN for the 40 years ($R=0.78$, $P<0.0001$, $n=40$,

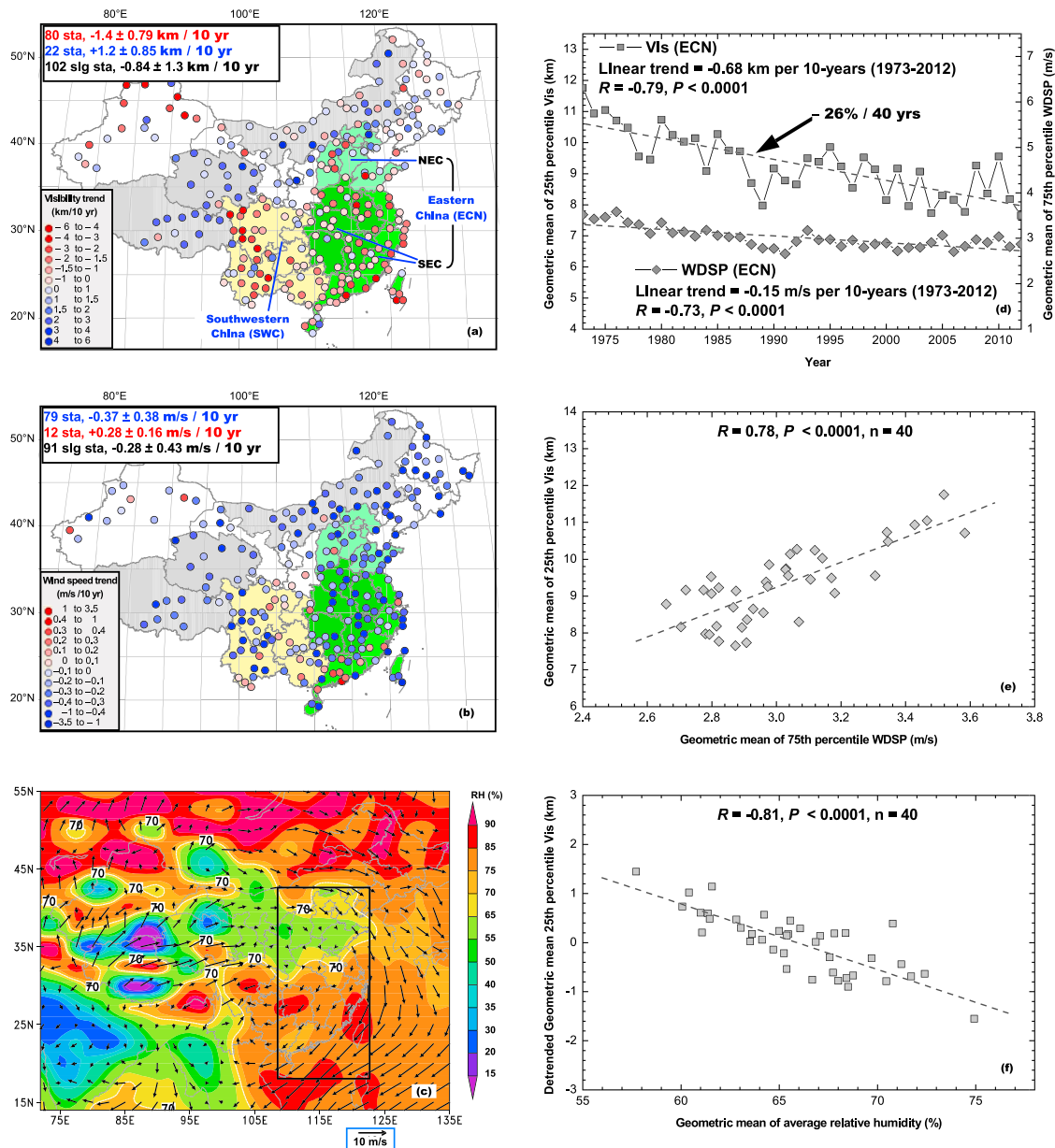


Figure 2. The trend of (a) 25th percentile Vis (km per 10 years) and (b) 75th percentile WDSP (m/s per 10 years) over eastern China (ECN) in winter from 1973 to 2012; all shown trends are significant at 95% confidence level. Partition of the study area can be found in section 2 and Qu *et al.* [2013]. (c) The NCEP reanalysis surface mean RH (%) and mean wind vector (m/s) in winter during 1973–2012; the black box shows the location of ECN (defined in section 2 and Figure 2a; note that only part of the continent within the box is included in ECN). (d) Time series of the geometric mean of 25th percentile Vis and the geometric mean of 75th percentile WDSP over ECN in winter. (e) Scatterplot of the geometric mean of the 25th percentile wintertime Vis (y axis) with the geometric mean of 75th percentile WDSP over ECN during 1973–2012; the best linear fitting line (dashed) between variables on the y axis and x axis is also shown. (f) Same as Figure 2e but for the linear detrended Vis and the geometric mean of the average RH.

Figure 2e). The similar trends of WDSP and Vis, as well as the positive correlation between them, suggest the low WDSP as one important factor for low Vis; it is clear that low WDSP is associated with less efficient diffusion/dilution, and accumulation of the pollutants then is favorable for Vis decrease. The decreasing trend in WDSP (Figures 2b and 2d) probably adds to the effect of increased emissions [Qian *et al.*, 2009; Wang *et al.*, 2009] and causes more substantial Vis decline in winter during 1973–2012. It is worthwhile to note that inspections on the maximal WDSP from the GSOD data and the NCEP reanalysis wind data also confirm the weakening wind over ECN in winter, although the short and anomalous “recovery” of WDSP in 1992 and 1993 (Figure 2d) should be further investigated in the future.

The negative correlation between the geometric mean of 25th percentile Vis and the geometric mean of average RH over ECN for the 40 years ($R = -0.49$, $P < 0.005$, $n = 40$, figure not shown) suggests higher RH as another factor of Vis decline. This can be understood because higher RH and more humid conditions are favorable for hygroscopic growth of the particles and subsequently Vis decline. While the effects from the presumably increased emissions and from the decrease of WDSP (Figure 2d) on Vis decline seem to increase continuously, RH generally shows a fluctuation with no significant trend; thus, a stronger correlation is found between the linear detrended Vis and RH over ECN for the 40 years ($R = -0.81$, $P < 0.0001$, $n = 40$, Figure 2f). This reveals that RH may be another factor that contributes to the variation of Vis. Here the linear detrended Vis is calculated through subtracting the linear trend, which mainly reflects the effect of the increased emissions and partially the effect of the decreased WDSP, from the original time series of Vis.

Composite analysis is also used to find meteorology associated with low Vis. Here 10 km, the minimal value for Vis to be graded as “fine” on a given day [China Meteorological Administration, 2010], is used to separate the poor and high Vis days. For the total 136 stations over ECN, 104 stations have significant $\Delta\text{WDSP}_{\text{max}}$ (the difference of maximal wind speed (WDSP_{max}) between the poor Vis days and the high Vis days, significant at 95% confidence level (t test)), among which 96 stations show a smaller WDSP_{max} on the poor Vis days (Figure 3b). Similarly, 133 of the total 136 stations have a significant positive ΔRH (95% confidence level (t test), Figure 3c) between the poor Vis days and the high Vis days over ECN. Quantitatively, WDSP_{max} (RH) on the poor Vis days is less (greater) than that on the high Vis days by 1.3 m/s (19%). The lower WDSP (stable weather) and higher RH (more humid) days are associated with Vis decline, same as discussed above. In contrast, higher WDSP (related to strengthened diffusion and dilution of the air pollutants) and lower RH (drier) days are associated with Vis increase, which usually happens under the influence of CW during winter over ECN (as will be discussed in section 3.2).

An interesting result is that T_{min} on the poor Vis days is found to be higher than that on the high Vis days by 2.8°C on average for 115 of the 125 stations with significant ΔT_{min} over ECN (Figure 3a). High temperature seems to be the third factor associated with low Vis, but they could be cooccurring results of the stable weather in winter, which is accompanied both by increase of temperature and by accumulation of pollutants in the more stagnant air. However, it is warranted to further investigate other potential effects of this warm and stable weather on low Vis in the future, such as strengthened photochemical process and increased reaction time of the precursor gases under this stagnant warm air, both of which should be more propitious to new particle formation and Vis degradation.

The NCEP reanalysis surface mean RH and mean wind vector in winter during 1973 to 2012 (Figure 2c) illustrate a general background of semipermanent anticyclone accompanied with weak wind over ECN, which tends to be favorable for accumulation of the pollutants. Moreover, in the southern part of ECN, RH is generally greater than 70%, a range within which Vis responds more sensitively to the change of RH [Qu *et al.*, 2013]; for the same value of RH increase, hygroscopic growth of particles becomes more efficient when $\text{RH} > 70\%$ (as compared to $\text{RH} < 70\%$) and thus is more favorable for Vis decline. The multiyear-averaged wind and RH (Figure 2c) reveal a general stable meteorology background that is favorable for the occurrence of low Vis events over ECN in winter. Yang *et al.* [2013] and Boynard *et al.* [2014] both highlight the importance of the high-pressure system which trapped the anthropogenic pollutants in the boundary layer (BL) and contributed to the severe pollution episode that occurred in Beijing, Tianjin, and Hebei provinces in January 2013. These results are consistent with our analyses above on the general stable meteorology background over ECN in winter.

In summary, this section demonstrates that wintertime Vis impairment over ECN often occurred during meteorological conditions characterized by weak WDSP, high RH, and warm temperature. Such favorable meteorology for low Vis days may have occurred more often as the frequency of CW, an important synoptic system which can interrupt the usually stable weather during winter in the region, has decreased in recent years [Wang and Ding, 2006; Qian and Zhang, 2007; Wei, 2008]. This conjecture is analyzed in the next section.

3.2. Effect of CW and Relationship Between Decrease of CW Occurrence, Surface Wind, and Vis Decline

The average of meteorological variables during 2 days before and after CW is compared to evaluate the effect of CW on meteorology and Vis (also see supporting information). As expected, during and after CW, WDSP increase is identified for 119 of the total 136 stations over ECN (in average +1.1 m/s over ECN, Figure 3e), and

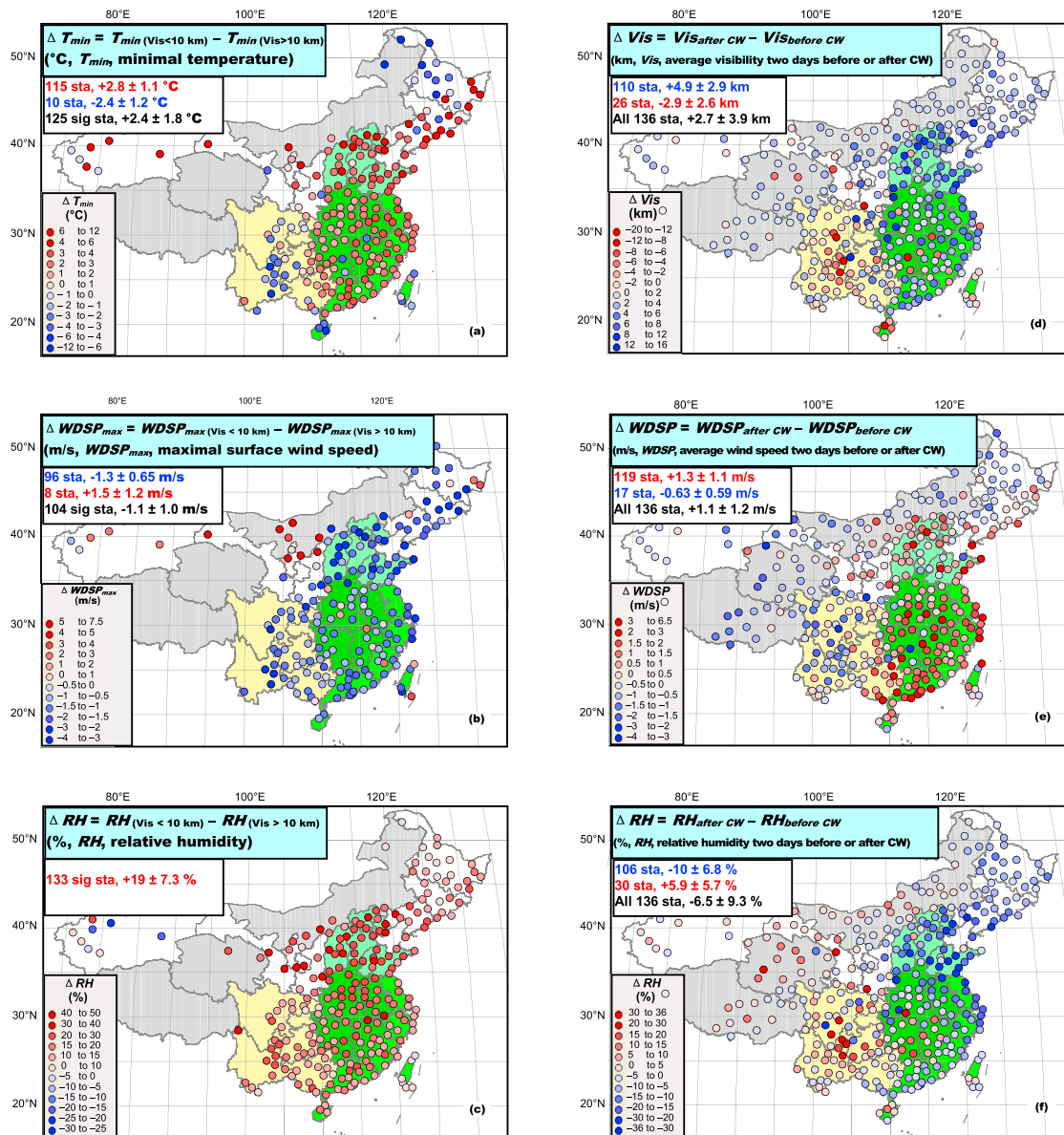


Figure 3. Composite analysis of (a) minimal temperature ($\Delta T_{min} = T_{min}(Vis < 10 \text{ km}) - T_{min}(Vis > 10 \text{ km})$, $^{\circ}\text{C}$), (b) maximal wind speed ($\Delta WDSP_{max} = WDSP_{max}(Vis < 10 \text{ km}) - WDSP_{max}(Vis > 10 \text{ km})$, m/s), and (c) RH ($\Delta RH = RH(Vis < 10 \text{ km}) - RH(Vis > 10 \text{ km})$, %) for the poor Vis days ($Vis < 10 \text{ km}$) and high Vis days ($Vis > 10 \text{ km}$) in winter during 1973–2012. All the calculated differences are significant at 95% confidence level (t test). The CW resulted (d) Vis improvement ($\Delta Vis = Vis_{after \text{ CW}} - Vis_{before \text{ CW}}$, km), (e) WDSP change ($\Delta WDSP = WDSP_{after \text{ CW}} - WDSP_{before \text{ CW}}$, m/s), and (f) RH change ($\Delta RH = RH_{after \text{ CW}} - RH_{before \text{ CW}}$, %) in winter during 1973–2012. All the differences are calculated based on an average of data during 2 days before or after CW. CW occurrence is identified by the criterion that T_{min} decreases by at least 8°C on a given day from the prior day. Statistics of the interesting variables over ECN are also shown in the top left of each panel where necessary.

RH decrease is identified for 106 of the stations (in average -6.5% over ECN, Figure 3f), both of which are favorable for Vis improvement. Indeed, Vis increased at 110 of the 136 stations (in average $+2.7 \text{ km}$ over ECN, Figure 3d) during and after CW event. CW (and associated cold front) can carry drier, colder, and cleaner air from high latitudes to pass over and substitute for the general stable and humid air mass over ECN in winter; this can result in an increase of WDSP, a decrease of RH and air temperature, as well as a cleaner air. Statistics on the ΔPM_{10} concentration for the 464 station-time of CW events at the 52 major Chinese city stations in winter during 2000–2012 show that the average PM_{10} concentration after CW occurrence is less than that before CW occurrence by $12 \pm 49 \mu\text{g m}^{-3}$. It also should be noted here that the precipitation effect on Vis is not considered separately, as a preliminary inspection shows that it does not significantly influence the overall result about the CW effect on Vis.

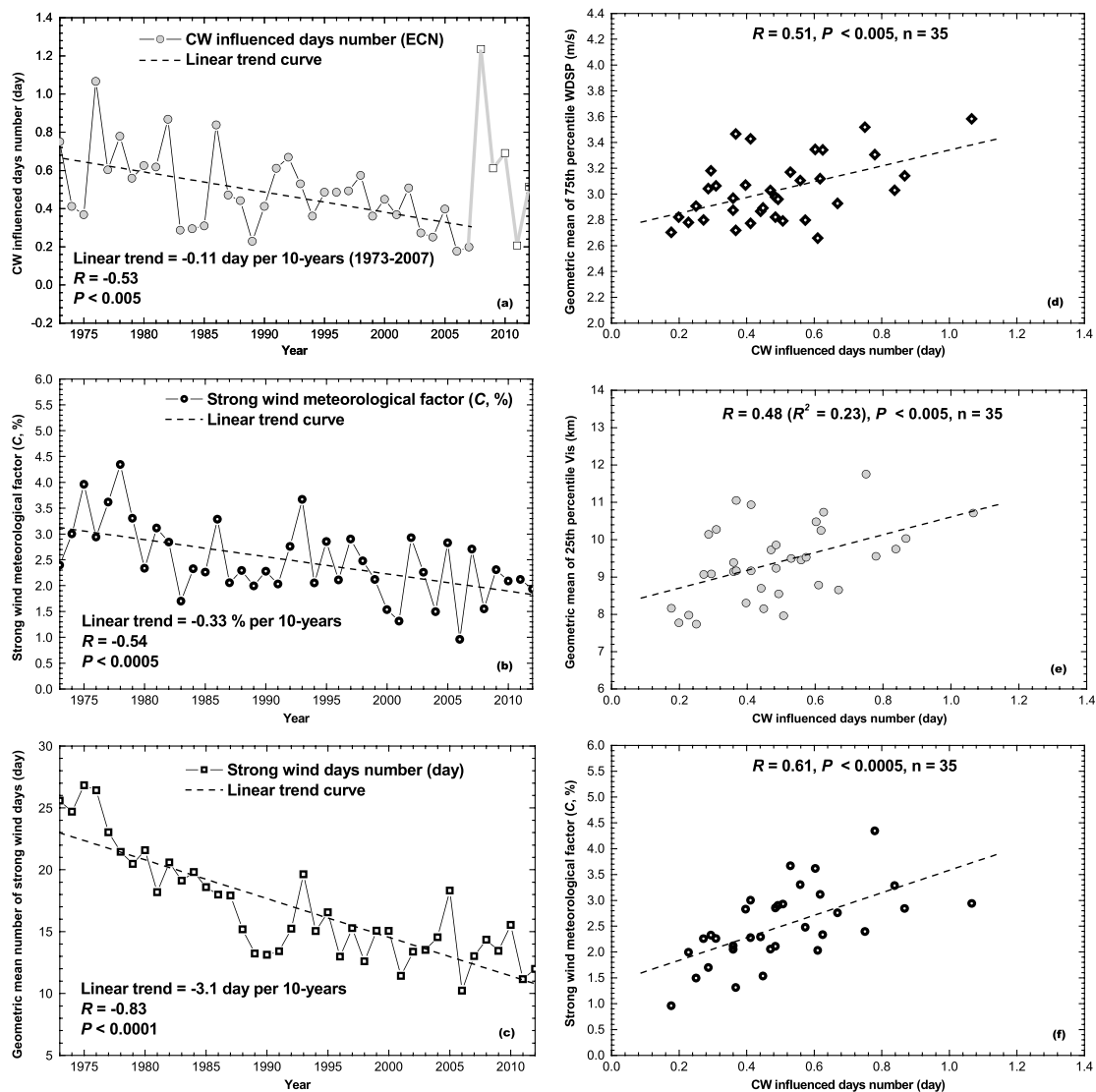


Figure 4. Time series of (a) the geometric mean number of CW-influenced days (counted as described in section 3.2), (b) the strong wind meteorological factor (C, defined in formula (3) in section 3.2), and (c) the geometric mean number of strong wind days over eastern China (ECN) in winter. (d) Scatterplot of the geometric mean of wintertime 75th percentile WDSP (y axis) with the number of CW-influenced days over ECN during 1973–2007; the best linear fitting line (dashed) between variables on the y axis and x axis is also shown. (e) Same as Figure 4d but for the geometric mean of 25th percentile Vis and the number of CW-influenced days. (f) Same as Figure 4d but for the strong wind meteorological factor (C) with the number of CW-influenced days.

To evaluate the trend of CW occurrence and its relationship with Vis, the number of CW-influenced days is calculated for each CW event from the day T_{\min} decreases significantly (at least by 8°C) to the day T_{\min} continues to decrease (i.e., the day that T_{\min} does not increase again or does not remain the same); inspections of the data found that after CW occurrence the improved Vis persists at a comparatively high level during the above defined period of the CW-influenced days. As high temperature is always associated with stable weather and low Vis in winter (discussed in section 3.1), warming after CW occurrence tends to be the beginning of another period (or round) of stable weather associated with accumulation of air pollutants and Vis degradation.

Similar to the decreasing trends of WDSP and Vis (Figure 2d), the number of CW-influenced days during winter (December to February) also shows a decreasing trend over ECN from 1973 to 2007 (-0.11 day per 10 years, Figure 4a) but anomalously increased in winter 2008. Here the trend of -0.11 day per 10 years from 1973 to 2007 is comparable with -0.01 to -0.02 times per year for the CW during September to May over the general ECN region from 1951 to 2003 (reported in the Figure 3 of Wang and Ding [2006]); this is also comparable with -0.17 times per 10 years for the CW during October to April over North China (the area in

China to the north of 35°N latitude) from 1960 to 2005 (reported in the Figure 8a of *Qian and Zhang* [2007]) and -0.0218 times per year for the CW during November to April over China (based on the records from 160 stations) from 1955 to 2004 (reported in the Figure 3 of *Wei* [2008]). Note that the results from the latter two studies include northeastern China and northwestern China, the area with higher CW frequency but not included in the ECN area of interest in this study. Hereinafter, the CW data from 1973 to 2007 are used to find its relationship with meteorology and Vis; also note that these results are similar to the analysis based on the whole data set, except that the better correlations for the data set eliminated the abnormal variation of CW after 2008. While the cause of the abnormal increase of the number of CW-influenced days in winter 2008 needs further study, one possibility is intensification of the northeasterly East Asian winter monsoon resulting from the increased differences in temperature and atmospheric pressure between the Indo-Pacific Oceans and the Asian continent due to the mature phase of La Niña event from winter 2008 to 2009 [*Gao and Yang*, 2009].

The number of CW-influenced days in each winter is positively correlated with the WDSP over ECN during 1973–2007 ($R=0.51$, $P<0.005$ significance, $n=35$, Figure 4d) and negatively correlated with the geometric mean of average RH (although insignificant, $R=-0.28$, $P=0.08$, $n=35$, figure not shown). These analyses suggest an increased WDSP and a lower RH during the winter with more CW-influenced days, when the cold front swept through ECN and the drier air mass introduced from high latitudes (as illustrated by the typical CW example of Figure 1b) increased. The increase of WDSP and decrease of RH after the occurrence of CW (Figures 3e and 3f) also support our analyses here.

In summary, the positive correlation between Vis and the number of CW-influenced days over ECN during 1973–2007 ($R=0.48$, i.e., $R^2=0.23$, $P<0.005$, $n=35$, Figure 4e) indicates that the decreased occurrence of CW-influenced weather over ECN (Figure 4a) has resulted in a decrease of WDSP (Figures 2d and 4d) and more stable air mass, conditions favorable for Vis decline. Quantitatively, variation in the number of CW-influenced days can explain about 23% of the variance of Vis over ECN in winter (Figure 4e).

The following part of this section will focus on separation of the effects from emission increase and from meteorology change on Vis decline. Numerous studies indicated that strong wind in winter is accompanied with intrusion of the cold air from high latitudes and the occurrence of CW [*Shang*, 1975; *Wang and Ding*, 2006; *Qian and Zhang*, 2007]. CW, as a typical significant event of a strong East Asian winter monsoon [*Wang et al.*, 2010], is associated with the largest decrease in air temperature and increase of surface WDSP. The cold air activity and its accompanied meteorology change (increase of wind speed, shift of wind direction, and decrease of RH) are important to the wintertime Vis improvement. To quantitatively evaluate the contribution of variation in the cold air activity to Vis, the average Vis in a given winter is described as the sum of Vis on “normal wind” days and “strong wind” days, weighted by the number of their total days in that winter (see formula (1) below). Here the 75th percentile WDSP, based on all the 40 years winter records at a given station, is used as the criterion to separate the “normal” and “strong” wind days in a specific winter, i.e., the days when WDSP at that station is less or greater than the criterion are defined as the normal and strong wind days, respectively. Note that the strong wind days can be considered actually reflecting the days with the influence of cold air activity.

$$\text{Vis} = \text{Vis}_{\text{normal}} \times (N - N_{\text{strong}})/N + \text{Vis}_{\text{strong}} \times N_{\text{strong}}/N. \quad (1)$$

In formula (1) Vis is the visibility in a specific winter and $\text{Vis}_{\text{normal}}$ and $\text{Vis}_{\text{strong}}$ are the 75th percentile Vis on the normal and strong wind days, respectively. Note here that the 75th percentile Vis can better reflect the difference of Vis between the strong and normal wind days ($\Delta\text{Vis} = \text{Vis}_{\text{strong}} - \text{Vis}_{\text{normal}}$) than the 25th percentile Vis or the average Vis; ΔVis derived from the 25th percentile Vis or the average Vis is smaller. N_{strong} is the count of strong wind days, and N is the count of the total days that winter. Further arrangement of formula (1) gives

$$\text{Vis} = \text{Vis}_{\text{normal}} + (\text{Vis}_{\text{strong}} - \text{Vis}_{\text{normal}}) \times N_{\text{strong}}/N = \text{Vis}_{\text{normal}} \times (1 + C) \quad (2)$$

where

$$C = (\text{Vis}_{\text{strong}} - \text{Vis}_{\text{normal}})/\text{Vis}_{\text{normal}} \times (N_{\text{strong}}/N) \times 100\%. \quad (3)$$

The two terms on the right side of formula (2) reflect the different effects on Vis. The trend of $\text{Vis}_{\text{normal}}$ (i.e., Vis on normal wind days) largely reflects the effect of emissions. In contrast, by normalizing the difference of $\text{Vis}_{\text{strong}}$

and Vis_{normal} with respect to Vis_{normal} (formula (3)) in the same winter (in which emissions on each day can be assumed as same), term C minimizes the complicating effect of the variation of emissions from year to year and thus mainly expresses the effect of strong wind days occurrence on Vis ; term C is referred to as strong wind meteorological factor hereinafter. Computing C in each winter and then calculating its trend are helpful to understand how the change of strong wind days occurrence influences the Vis trend. The trend of C might actually reflect the effect of the changed frequency of CW and cold air activity on Vis variation, because under an overall background of usually stable weather over ECN in winter, the strong wind is always accompanied with the occurrence of CW [Shang, 1975; Wang and Ding, 2006; Qian and Zhang, 2007].

Indeed, the number of CW-influenced days is positively correlated with the number of strong wind days over ECN during 1973–2007 ($R = 0.64$, $P < 0.0001$, $n = 35$, figure not shown) and the strong wind meteorological factor ($R = 0.61$, $P < 0.0005$, $n = 35$, Figure 4f), implying that the decreased occurrence of CW (Figure 4a) is closely related to the decreased strong wind days (Figure 4c) and subsequently decrease of the strong wind days effect on Vis improvement (i.e., term C , Figure 4b).

The number of strong wind days in winter decreases from 1973 to 2012 (-3.1 days per 10 years, Figure 4c). Consequently, the effect of the strong wind days on Vis improvement (i.e., term C) decreases from about $+3.1\%$ in the early 1970s to about $+1.8\%$ in the early 2010s (-0.33% per 10 years, Figure 4b). Note here that the effect of the strong wind days on Vis improvement reflects the composite effect of all the meteorological factors (such as the increased WDSP, the decreased RH, and the decreased air temperature) rather than the sole influence from WDSP; the influences from the above mentioned meteorological factors might interact with each other and contribute jointly to the improvement of Vis on the strong wind days. Figures 4b and 4c imply that the decreased occurrence of strong wind days could be at least a partial cause of the declining Vis trend in winter.

To more intuitively quantify the contributions from change in meteorology and from change in emission on Vis , the Vis trend on the normal wind days was also calculated, which is -0.54 km per 10 years ($R = -0.71$, $P < 0.0001$); further comparison with the Vis trend in winter over ECN on all days (-0.68 km per 10 years, $R = -0.79$, $P < 0.0001$, Figure 2d) implies that the emission increase has contributed to about 79% ($= (-0.54)/(-0.68) * 100\%$) of the declining Vis trend in winter from 1973 to 2012, while the effect of the decreased occurrence of the strong wind days has further contributed to about 21% ($= [(-0.68) - (-0.54)]/(-0.68) * 100\%$) of the declining Vis trend.

In the context of weakened wind and presumably increased emissions in recent years, the occurrence of CW and strong wind days, although decreasing, becomes more crucial compared with the 1970s for its effect on the improvement of air quality and Vis , because the CW that cause favorable weather for efficient dilution/diffusion and downwind transport of the air pollutants becomes more scarce.

3.3. RH and Wind Anomalies for More and Less CW-Influenced Years

To further confirm the effect of CW on Vis improvement, NCEP reanalysis data are used to make comparisons of RH and wind for six typical years selected. First, as expected, higher Vis (9.5 ± 0.24 km) is identified in three more CW-influenced years (1986, 1998, and 2008) and lower Vis (7.8 ± 0.16 km) is identified in three less CW-influenced years (1989, 2007, and 2012) (see supporting information for detail).

Figure 5a illustrates an anticyclone anomaly over ECN, which is associated with a negative RH anomaly over ECN and an obviously offshore anomaly of wind vector over the China coast in the more CW-influenced years. The lower RH (probably due to introduction of the drier air mass from high latitudes) can restrain hygroscopic growth of the particles; meanwhile, the offshore wind anomaly indicates enhancement of the outflow of continental pollutants and subsequently strengthened dilution/diffusion. All these processes result in lower RH and strengthened offshore wind, which are favorable for Vis improvement in the more CW-influenced years. Our result here is consistent with Liu *et al.* [2003], which reported that the outflow of Asian pollution is related to CW events. On the contrary, in the less CW-influenced years (Figure 5b), there is a cyclone anomaly over ECN, associated with a generally positive RH anomaly over ECN (probably resulted from the increased water vapor supply due to the enhanced easterly and southeasterly winds from the Pacific Ocean, as well as the enhanced southwesterly wind from the Indian Ocean) and an inshore anomaly of wind vector over the China coast (associated with a weakened outflow of Asian pollution); all these processes vary inversely and may lead to a decrease in Vis compared with the more CW-influenced years. Such discrepancy

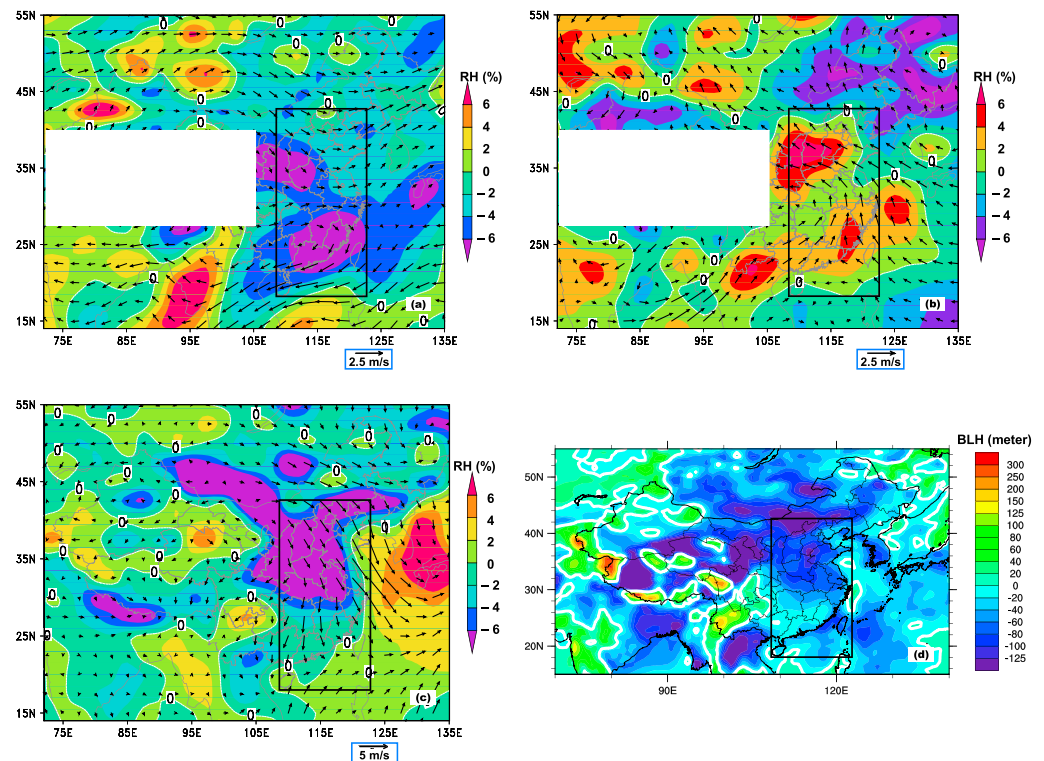


Figure 5. Comparison of the NCEP reanalysis 850 hPa RH anomaly and wind vector anomaly in winter (December–January–February) for (a) the years with more CW-influenced days (1986, 1998, and 2008) and (b) the years with less CW-influenced days (1989, 2007, and 2012). Values over topography higher than 1500 m (mostly the Tibetan Plateau) were masked out in Figures 4a and 4b. (c) Difference of the NCEP reanalysis surface RH and wind vector for the typical CW-influenced days over ECN (defined as the day with 10 or more than 10 stations over ECN identified as the CW-influenced day) and the rest of the days in winter during 1973–2012 ($\Delta RH = RH_{CW \text{ day}} - RH_{non-CW \text{ day}}$, %; $\Delta wind = wind_{CW \text{ day}} - wind_{non-CW \text{ day}}$, m/s). (d) The ECMWF reanalysis 2:00 P.M. LT (local time) boundary layer height (BLH, meter) anomaly in winter for the years with less CW-influenced days (1989, 2007, and 2012); white line illustrates the zero contour which divided the negative and positive anomaly. The black box shows the location of eastern China (ECN, defined in section 2 and Figure 2a); note that only part of the continent within the box is included in ECN.

in the meteorology is probably the essential reason leading to Vis difference in the more or less CW-influenced years. Statistics based on the GSOD data also show lower RH in the more CW-influenced years ($63 \pm 3.6\%$) and higher RH in the less CW-influenced years ($70 \pm 4.8\%$), consistent with analysis above.

Comparison of the NCEP reanalysis daily meteorological data between the typical CW-influenced days over ECN (defined as the day with 10 or more than 10 out of the 136 stations over ECN are identified as the CW-influenced day) and the rest of the days (non-CW-influenced days) further confirmed our analysis above. ΔRH ($RH_{CW \text{ day}} - RH_{non-CW \text{ day}}$) is clearly negative over ECN (Figure 5c), confirming a lower RH on the CW-influenced days. Meanwhile, the difference of the wind vector between the CW-influenced days and the non-CW-influenced days is generally offshore (southeastward or southward) over ECN and the coastal area, consistent with our analysis above that the downwind transport and outflow (associated with the dilution and diffusion) of the pollutants are enhanced on the CW-influenced days because the offshore wind vector increases.

Furthermore, there is a typical topography basin (with mountains to the north and mountains to the west as boundaries and open to the east) over the major anthropogenic emission region of ECN. Therefore, the easterly and southeasterly winds (i.e., the inshore winds from the Pacific Ocean, which are also associated with increased water vapor supply and RH increase) that collaborate with this typical eastward opening basin are more favorable for the pollutants to be accumulated within the basin over ECN, resulting in Vis impairment. It is also worth noting that compared with the prevailing offshore winds of northwesterly and northerly in winter (shown by the multiyear mean in Figures 1a and 2c), the wintertime inshore easterly and

southeasterly winds are generally weaker in intensity and cannot intrude deeply into inland China; therefore, their effects on diffusion/dilution of the air pollutants are quite limited. In contrast, the wintertime northwesterly and northerly winds are always associated with passage of the cold front (which can sweep the pollutants out of ECN) and increase of BLH (will be discussed next); all these are favorable for Vis improvement.

3.4. CW-Related BLH Change and Impact on Vis

Generally, due to the strong wind accompanied with the CW occurrence in winter [Shang, 1975; Wang and Ding, 2006; Qian and Zhang, 2007], the air becomes unstable, favoring an increase of BLH. Therefore, besides RH and wind, other meteorological parameters affected by CW and relevant to the surface Vis are low-level temperature profile and BLH. Temperature inversion and lower BLH are important factors leading to accumulation of the pollutants and Vis impairment over ECN in winter. For example, Boynard *et al.* [2014] found that the nighttime BLH is mostly lower than 100 m during the continuous haze episode from 3 to 13 January 2013 over Beijing, Tianjin, and Hebei provinces. Normally, BLH experiences a clear diurnal cycle with the minimum in the night and the maximum (associated with the most intensive convection) in the afternoon (generally 2:00 P.M. local time, LT) [Sheng *et al.*, 2003]. Here we use BLH extracted from the ECMWF ERA-Interim reanalysis data (0.125° grid) to investigate the relationship between BLH change and Vis.

Figure 5d illustrates the anomaly of the 2:00 P.M. LT BLH for the winters with less CW-influenced days (i.e., winters 1989, 2007, and 2012) relative to the mean wintertime 2:00 P.M. LT BLH during 1973–2012; a negative anomaly is clear over ECN, demonstrating an obviously smaller afternoon BLH in winters 1989, 2007, and 2012. Accumulation of the pollutants within such a shallower BL associated with less CW occurrence is more favorable for Vis impairment. Furthermore, the nighttime BLH anomaly (figure not shown) is not as explicit as that at 2:00 P.M. LT, suggesting an indistinguishable difference in the most developed stable BL during the winter night for the more and less CW-influenced years. Therefore, in contrast to the indistinctive stable nighttime BL (for the more and less CW-influenced years), the lower *daytime* BLH (at 2:00 P.M. LT) in the less CW-influenced winters with respect to the climatology mean during 1973–2012 (Figure 5d) suggests that the diurnal cycle of the BL might become unclear or in some cases disappear during much of the days in the winter with less CW influence.

It is worthwhile to note that the diurnal cycle of BL resulted from increase of the daytime BLH is important because it contributes significantly to dissipation of the fog and haze formed in the nighttime. Therefore, the unclear diurnal cycle of BLH in the winters with less CW influence might contribute to the long-lasting characteristic of the air pollution and low Vis episodes over ECN. Moreover, the lower daytime BLH during such stable weather probably also reflects part of the semidirect radiative effect of the aerosol, i.e., more stable daytime BL resulting from less solar radiation reaching the surface due to extinction of the fog and haze. This positive feedback (increased aerosol loading → more stable BL → more increased aerosol loading) is favorable for long-lasting air pollution and low Vis episodes [Wang and Christopher, 2006].

4. Conclusions and Discussions

Regional climate change, such as the weakened surface wind and decreased CW occurrence, may have combined with the increase in aerosol and its precursor emissions and amplified the effect of emissions on wintertime Vis decline during 1973–2012. CW is an important weather affecting air quality over ECN in winter. Under the influence of CW, the increased offshore wind enhances the outflow and dilution of the continental pollutants; moreover, a decrease of RH due to introduction of the drier air mass from high latitudes restrains hygroscopic growth of the particles; all are processes favorable for Vis improvement when CW occurs. However, the decreasing CW trend in recent years may have resulted in decrease of WDSP, increase of RH, and weakened outflow/dilution, consequently contributing to Vis decline. Quantitatively, variation in the number of CW-influenced days can explain about 23% of the variance of Vis over ECN in winter. Accompanied with decrease of the strong wind days (−3.1 day per 10 years), the effect of the strong wind days on Vis improvement (defined as term C in section 3.2) has decreased from +3.1% in early 1970s to +1.8% in early 2010s.

Although the decrease of WDSP, increase of RH, decrease of BLH, and change of synoptic systems (such as CW and other factors) have influences on the winter Vis over ECN, the major contribution from the increased emissions should be carefully considered. Furthermore, the change of the atmospheric aerosol with regard to its chemical composition, optical property, and size distribution should also be taken into account. For example,

the increase of the fine PM (particulate matter) loading is considered one important reason for the increase of aerosol optical depth over China from 1992 to 2011 [Wang *et al.*, 2012]. Moreover, numeric modeling should be helpful in the future to more accurately quantify the individual contributors to wintertime Vis decline over ECN.

Four aspects are important for further understanding the effects of the weakened surface wind and the stable weather on Vis decrease and air quality degradation over ECN in winter, including (a) enhanced accumulation of pollutants, increased stagnant time as well as more photochemical reaction time of the precursor gases (staying in the air) for nucleation; (b) increased temperature and intensification of the photochemical activity; (c) enhanced hygroscopic growth due to more humid/stable air; and (d) feedback such as “haze/fog → decreased solar radiation reaches to the surface → more stable atmosphere (profile) → further enhancement of pollutants accumulation → more severe haze/fog.” It is also worthwhile to note the important impacts from the changed aerosol burden on monsoon intensity and precipitation, as well as the complicated feedbacks between them [Sajani *et al.*, 2012; Zhang *et al.*, 2012a; Wu *et al.*, 2013]. Interactions between the increased aerosol burden and the weakening of East Asian winter monsoon will be a topic under debate and need further investigation in the future.

While a clear linkage exists between a decrease of wintertime Vis and a decrease of CW frequency over ECN, the causes resulting in variation of the CW occurrence over ECN in winter are more complicated and remain an open question. Although the decreasing CW trend since the early 1970s changed in winter 2008, the presumably continuous increase of emissions and the following decrease of the number of CW-influenced days after 2008 (Figure 4a) suggest that the low Vis event and severe air pollution over ECN in winter might not improve substantially in the near future. Moreover, the change of the cold wave duration might vary in northern and southern China in a warming climate [Jiang *et al.*, 2012]. As many dynamic processes are found to be related to the variability of East Asian winter monsoon and CW frequency [Wang *et al.*, 2010], further study is undoubtedly necessary to better understand the relationship between wintertime Vis and CW occurrence with the related climate factors. Investigations on the mechanisms of how variation of the complicated climate factors influence the CW frequency and subsequently affect the weather, air quality, and Vis over ECN in winter are potentially valuable with respect to long-term prediction of Vis as well as formulating strategies to regulate and improve the wintertime air quality and Vis in the region. The ground-based data analysis should combine the sensitivity experiments with chemical transport models in the future to study the response of Vis (as well as the photochemical reaction and the hygroscopic growth of aerosol) to the change of WDSP and RH due to CW frequency variation.

In addition to finding influences of the weakened circulation and increased aerosol loading on low Vis events (as in Niu *et al.* [2010]), this study further quantifies the contributions from meteorology change and emission to Vis decline over ECN in winter (section 3.2). Furthermore, the weakened diurnal variation of BLH identifying in less CW-influenced winters provides an important insight into how the increasingly stable BL contributes to the long-lasting characteristic of the wintertime fog and haze events (section 3.4). RH and wind differences for the more and less CW-influenced winters (section 3.3), in collaboration with the unique eastward opening topography basin, give better interpretation to the favorable meteorology related to downwind transport (and dilution/diffusion) of East Asian pollutants, RH change, and Vis variation in the region.

This study focuses on how the decreased CW occurrence influences Vis over ECN. However, the shift of the weather patterns has implications outside of the region. Accompanied by weakening of the East Asian monsoon [Chang *et al.*, 2000; Xu *et al.*, 2006; Ding *et al.*, 2008] (and decrease of the CW occurrence), PM concentration may increase over the source region [Zhu *et al.*, 2012]. On the other hand, outflow of the pollution (which influences PM loading and air quality downwind [Cheung *et al.*, 2005]) might weaken concurrently. Reevaluating the impact of East Asian emission, both on the source region and on the downwind area, is warranted as downwind outflux, and redistribution of the pollutants changed due to alteration of the atmospheric circulation.

Acknowledgments

We thank Chun Li from Ocean University of China for discussions and Rachel Phinney from University of Nebraska–Lincoln for language editing. The GSOD data are available at <ftp://ftp.ncdc.noaa.gov/pub/data/gsod>, the NCEP and ECMWF reanalysis data are available at <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html> and <http://apps.ecmwf.int/datasets/>, and the air pollution index data for the Chinese cities are available at <http://datacenter.mep.gov.cn>. This research is supported by National Basic Research Program of China (2011CB403401), NSFC 41276009, and Chinese Ministry of Education’s 111 Project (B07036).

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