‘Warm Cover’- Precursory ‘Strong Signals’ hidden in the Middle Troposphere for Haze Pollution

Xiangde Xu[1], Wenyue Cai[1, 2, 3], Tianliang Zhao[4], Xinfa Qiu[5], Wenhui Zhu[6], Chan Sun[1], Peng Yan[7], Chunzhu Wang[8], and Fei Ge[9]

[1]State Key Laboratory of Severe Weather (LASW), Chinese Academy of Meteorological Sciences, Beijing, China.

[2]National Climate Center, China Meteorological Administration, Beijing, China.

[3]School of Geographical Science, Nanjing University of Information Science and Technology, Nanjing, Jiangsu Province, China.

[4]Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science and Technology, Nanjing, Jiangsu Province, China.

[5]School of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, Jiangsu Province, China.

[6]Beijing Institute of Applied Meteorology, Beijing, China.

[7]Meteorological Observation Center, China Meteorological Administration, Beijing, China.

[8]Training Center, China Meteorological Administration, Beijing, China.

[9]School of Atmospheric Sciences/Plateau Atmosphere and Environment Key Laboratory of Sichuan Province/Joint Laboratory of Climate and Environment Change, Chengdu University of Information Technology, Chengdu, Sichuan Province, China.

Correspondence: Wenyue Cai (caiwy@cma.gov.cn) and Tianliang Zhao (tlzhao@nuist.edu.cn)

Abstract. Eastern China (EC), located on the downstream region of Tibetan Plateau (TP), is a large area that has become vulnerable to frequent haze. In addition to air pollutant emissions, meteorological conditions were a key 'inducement' for air pollution episodes. Based on the study of the Great Smog of London in 1952 and haze pollution in EC over recent decades, it is found that the abnormal 'warm cover' (air temperature anomalies) in the middle troposphere, as a precursory 'strong signal', could connect to severe air pollution events. The convection and vertical diffusion in the atmospheric boundary layer (ABL) were suppressed by a relatively stable structure of 'warm cover' in the middle troposphere, leading to the ABL height decreases, which were favourable for the accumulation of air pollutants in the ambient atmosphere. The anomalous structure of the troposphere's "warm cover" not only exist in heavy haze pollution on the daily scale, but also provide seasonal and interdecadal 'strong signals' for frequently occurring regional haze pollution. It is revealed that a close relationship existed between interannual variations of the TP's heat source and the 'warm cover' strong-signal in the middle troposphere over EC. The warming TP could lead to the anomalous 'warm cover' in the middle troposphere from the plateau to the downstream EC region and even the entire East Asian region.

1 Introduction

In China, mainly over the region east of 100 °E and south of 40 °N (Tie et al., 2009), $PM_{2.5}$ (particulate matter with an aerodynamic diameter equal to or less than 2.5 μm) has become the primary air pollutant in winter (Wang, et al., 2017). Therefore，in September 2013, the Chinese government launched the China's first air pollution control action plan-'The Airborne Pollution Prevention and Control Action Plan (2013-2017)' (State Council of the People's Republic of China, 2013). By 2017, about 64% of China's cities are still suffering from air pollution, especially Beijing-Tianjin-Hebei region and surrounding areas (Wang et al., 2019; Miao et al., 2019). Then, in July 2018, the Chinese government launched the second three-year action plan for air pollution control, the "blue sky defense plan", which demonstrates China's firm determination and new measures for air pollution control (State Council of the People's Republic of China, 2018). After the implementation of air pollution control action plans, air quality in many regions and cities in China has been significantly improved.

Anthropogenic pollutant emissions and unfavorable meteorological conditions are commonly regarded as two key factors for haze pollution (Ding and Liu, 2014; Yim et al., 2014; Zhang et al., 2015). Air pollutants mainly come from surface emission sources, and most of air pollutants are injected from the surface to the atmosphere through the atmospheric boundary layer (ABL) (Quan et al., 2020). The ABL structures are the key meteorological conditions which influences the formation and maintenance of heavy air pollution episodes (Wang et al., 2015; Cheng et al., 2016; Wang et al., 2016; Tang et al., 2016; Wang et al., 2019).

Most of the previous studies focused on exploring the impact on the heavy air pollution in Eastern China (EC) for the meteorological conditions in ABL. However, the thermodynamic and dynamic structures of free troposphere can affect the meteorological conditions in ABL (Cai et al., 2020). The convection and diffusion in the ABL are suppressed by a relatively stable structure in the middle troposphere, leading to the ABL height decreases, which were favourable for the formation and persistence of heavy air pollution (Quan et al., 2013; Wang et al., 2015; Cai et al., 2020).

This study investigated whether the thermodynamic structure of the troposphere and its intensity changes can be used as a "strong warning signal" for the changes of $PM_{2.5}$ concentration in heavy air pollution, and whether this strong signal exists in the time scales of seasonal, interannual and interdecadal changes. In order to explore the interaction between the free troposphere and the ABL and the impact on the heavy air pollution in Eastern China (EC), this study extended the meteorological conditions for heavy air pollution from the boundary layer to the middle troposphere. We identify a precursory ‘strong signals’ hidden in the free troposphere for frequent haze pollution in winter in EC.

2 Data and methods

The data used in this study included NCEP/NCAR and ERA-Interim reanalysis data of meteorology, as well as data of surface $PM_{2.5}$ concentration measurement, air temperature observation and L-band sounding, as briefly described as follows:

The monthly NCEP/NCAR reanalysis data of meteorology with horizontal resolution of 2.5° for 1960-2019 were obtained from the U.S. National Center for Environmental Protection (NCEP, https://www.esrl.noaa.gov/).

The daily and monthly ERA-Interim reanalysis data of meteorology with horizontal resolution of 0.75° were derived from the European Center for Medium-range Weather Forecasts (ECMWF, https://www.ecmwf.int/), including air temperature, geopotential height, humidity, wind field and vertical velocity, etc.

The hourly $PM_{2.5}$ concentration data during 2013-2019 were collected from the national air quality monitoring network operated by the Ministry of Ecology and Environment the People's Republic of China (http://www.mee.gov.cn/). In addition, we categorized air pollution levels with the surface $PM_{2.5}$ concentrations based on the National Ambient Air Quality Standards of China (HJ633-2012) released by the Ministry of Ecology and Environment in 2012 as shown in Table 1.

We also used the monthly air temperature of surface observation data during 1960-2014 from 58 meteorological observation stations in the plateau area with an altitude above 3000 meters, which were archived from the China Meteorological Information Center (http://cdc.cma.gov.cn/).

Furthermore, the L-band sounding 'seconds-level' data of the site Beijing from 2010 to 2019 to were used to calculate the height of ABL (Liu and Liang, 2010). The height of ABL top is characterized by the L-band sounding observations at 20:00 (local time is used for this paper). The L-band sounding 'seconds-level' data has been undergone the quality control before analysis (Zhu et al., 2018), and interpolation was implemented in a vertical direction at an interval of 2 hPa. The L-band detection data provided by the Meteorological Observation Network (http://cdc.cma.gov.cn/) contains several automatic observation meteorological elements with time resolution of 1.2 s and vertical resolution of 8 m. More detail information can be found in Li et al. (2009) and Cai et al. (2014).

Table 1. Air pollution degrees categorized with surface $PM_{2.5}$ concentrations

Air pollution degrees	$PM_{2.5}$ concentration ranges
'less-serious' pollution	$75 \mu g \cdot m^{-3} < PM_{2.5} \leqslant 115\ \mu g \cdot m^{-3}$
'serious' pollution	$115\ \mu g \cdot m^{-3} < PM_{2.5} \leqslant 150\ \mu g \cdot m^{-3}$
'more-serious' pollution	$150\ \mu g \cdot m^{-3} < PM_{2.5} \leqslant 250\ \mu g \cdot m^{-3}$
'most-serious' pollution	$PM_{2.5} > 250\ \mu g \cdot m^{-3}$

3 Results

3.1 A precursory 'strong signal' of 'warm cover' in the middle troposphere

In February 2014, a rarely persistent air pollution weather process occurred in EC, this process had caused severe air pollution in more than 50 cities, with an impact area of 2.07 million square kilometers. In the Beijing area during February 20–26, 2014 the regional average $PM_{2.5}$ concentration exceed the 'most-serious' air pollution level, and with a peak value of up to 456 $\mu g\ m^{-3}$. In addition, the Great Smog of London in 1952 was attributed to the long-lasting and heavy haze pollution under the influence of certain weather systems (Whittaker et al., 2004). To find the precursory 'strong signals' hidden in meteorology for heavy air pollution events, we retrieved the three-dimensional atmospheric dynamic and thermal structure during December in 1952 as well as February in 2014 by analyzing vertical anomalies of meteorology. There were high-pressure systems moved to London as well as Beijing and stagnated over the area at 500 hPa geopotential height anomalies, as shown in Figs. 1a and 1b. Prior to the heavy-pollution events, a high-pressure system over London as well as Beijing gradually strengthened (Figs. 1c and 1d), and the middle troposphere was characterized by a 'warm cover', i.e. a 'upper warming and bottom cooling' anomalies in vertical structure of air temperature (Figs. 1e and 1f).

By comparing Fig. 1a and Fig. 1b, we found that two persistent heavy air pollution events occurred during the maintenance stage of stable high pressure system. During stagnation of the blocking high pressure system, the strength of the center of the geopotential height anomalies in the stable maintenance region of the blocking exhibited a synchronous response to the ‘warm cover’ above areas (Figs. 1c–1f). It can be seen that the local atmospheric thermal structure is significantly modulated by the persistent large-scale anomalous circulation. The ‘subsidence (temperature) inversion’ effect of the blocking high pressure system continuously strengthened the ‘warm cover’ structure in the middle troposphere, which suppressed the vertical diffusion capacity in the atmosphere (Cai et al., 2020). Moreover, it was obvious that ‘strong signals’ arising from the thick ‘warm cover’ persisted during the abnormal air-pollution episode during December 5–9, 1952 in London as well as February 21-26, 2014 in Beijing. It is worth pointing out that the bottom edge of ‘warm cover’ in the free troposphere declined day-by-day. During the heavy pollution incident, the ‘warm cover’ dropped to 900 hPa (Figs. 1g and 1h). The above analysis shows that in the ABL over London during December 5–9, 1952 and Beijing during February 21–26, 2014, the inversion layer height decreased, which made the ABL structure stable for accumulation of air pollutants. The deep ‘warm cover’ structures in the middle troposphere acted as a precursory ‘strong signal’ of the Great Smog of London and Beijing’s heavy air pollution.

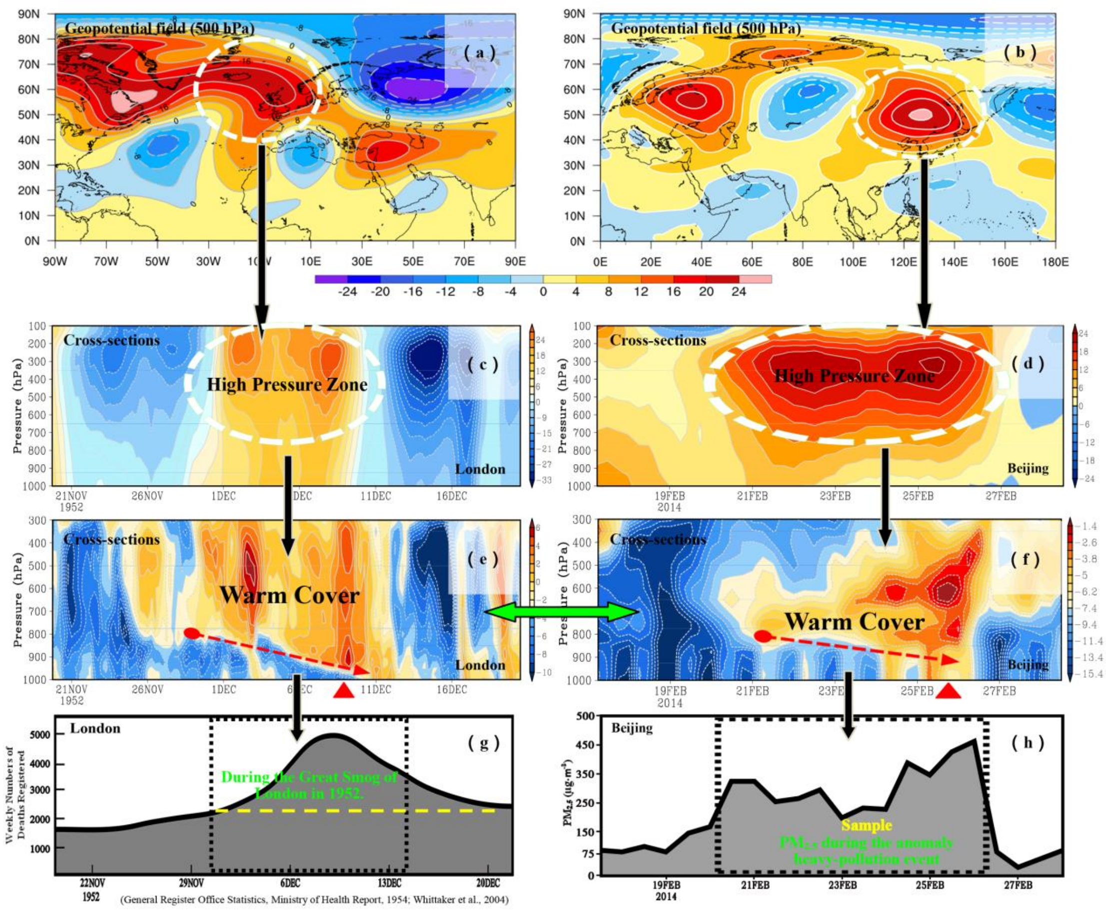

Figure 1. Dynamical and thermodynamical structures and air pollution variations: (a) geopotential height anomalies (unit: dagpm) at 500 hPa during December 5-9, 1952 for the Great Smog of London, (b) the same as (a) but during February 21-26, 2014. Time-vertical cross-sections of (c) the geopotential height anomalies (unit: dagpm) in the high pressure area (50-70 °N; 20 °W -10 °E) during November 20 to December 20, 1952，(d) the same as (c) but in the high pressure area (40-63 °N; 115-138 °E) during February 17-28, 2014. (e) Time-vertical cross-sections of air temperature anomalies (unit: ℃) over London (the Red dotted arrow shows the bottom edge of the 'warm cover' during the Great Smog in London) during November 20 to December 20, 1952, (f) the same as (e) but during the heavy pollution in February 2014 over Beijing. (g) Weekly death rate in London prior to, during and after the 1952 pollution episode (General Register Office Statistics, Ministry of Health Report, 1954; Whittaker et al., 2004). (h) The variation of surface $PM_{2.5}$ concentrations (units: $\mu g \cdot m^{-3}$) during the heavy pollution in February 2014 over Beijing.

3.2 Effect of 'Warm Cover' in the free troposphere on ABL and surface $PM_{2.5}$ variations

During five heavy air pollution episodes over Beijing in December 2015 and 2016 the vertical structures of air temperature anomalies presented the 'warm cover' structure in the free troposphere (see Fig. S1).

During winter 2014-2017, Figs. 2a and 2b demonstrated the significant negative correlations passing 0.001 confidence degree between the height of the ABL and air temperature anomalies over same period and 24 hours ahead in Beijing, reflecting that the ‘warm cover’ structure hidden in the middle troposphere with significant ‘strong-signal’ features is of persistent premonitory significance for the heavy pollution episodes. Figs. 2c–2e presented the significant positive correlation passing 0.001 confidence degree between $PM_{2.5}$ concentrations and air temperature anomalies over same period and 24, 48 hours ahead in Beijing. Based on the above mentioned results, air temperature anomalies over 24 and 48 hours ahead could also be reflected that ‘warm cover’ hidden in the middle troposphere could be regarded as the precursory ‘strong-signal’ for air pollution change. Furthermore, such a ‘stable’ structure also restricted the transport of moist air from the lower to the middle troposphere for forming secondary aerosols, which could dominate $PM_{2.5}$ concentrations in air pollution over China (Huang et al., 2014; Tan et al., 2015).

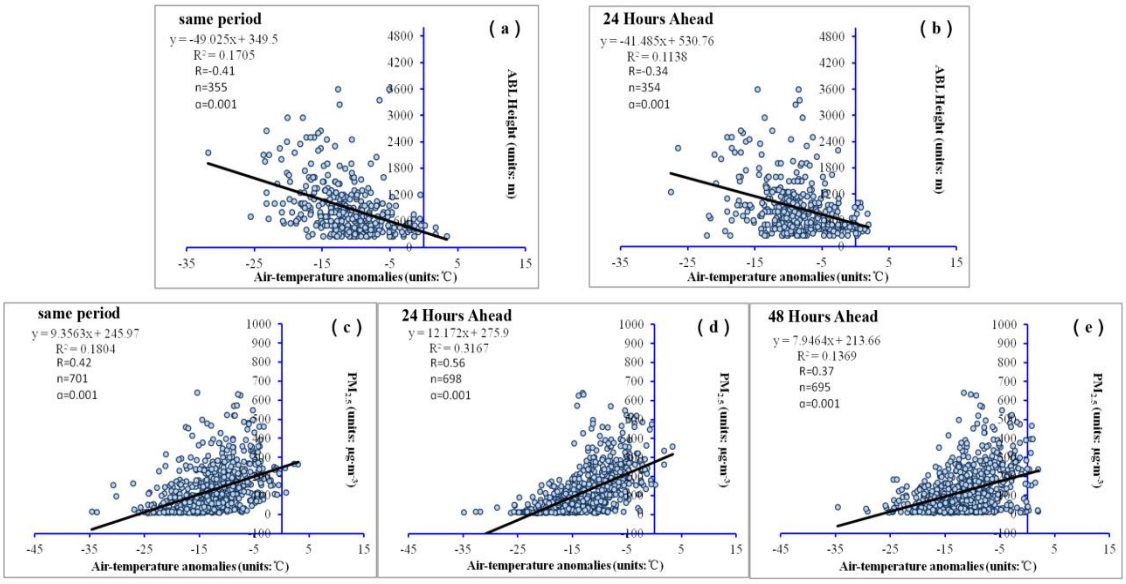

Figure 2. (a) The correlations between ABL height and air temperature anomalies, at 800 hPa. (b) 24 hours ahead at 650 hPa in Beijing during winter 2014–2017. The correlations between $PM_{2.5}$ concentration and air temperature anomalies, (c) at 850 hPa; (d) 24 hours ahead, at 800 hPa; (e) 48 hours ahead, at 724 hPa in Beijing during winter 2014–2017.

3.3 Changes of the 'warm cover' structure in the middle troposphere

The 'warm cover' structure of air temperature anomalies in the middle troposphere indicated the intensification of heavy air pollution. The 'warm cover' structure is a precursory 'strong signal' for the frequent occurrence of regional haze events. The air pollution in EC exhibited the significant seasonal variations. Our study revealed that existed seasonal differences of the thermal structures in the atmosphere over EC. In spring (Figs. 3a and 3e) and summer (Figs. 3b and 3f), the middle troposphere was characterized by a 'upper cooling and bottom warming' vertical structure for less air pollution. When the autumn (Figs. 3c and 3g) and winter (Figs. 3d and 3h) arrived, the middle troposphere was characterized by a 'upper warming and bottom cooling' vertical structure, which intensified the air pollution. In autumn, atmospheric thermal structure over EC was marked with a transition between summer and winter (Fig. 3c). The atmosphere condition reversed in winter, a large-scale anomalous air temperature pattern of 'upper warming and bottom cooling' in the middle troposphere appeared from the plateau to downstream EC region and even the entire East Asian region (Fig. 3d). The structure of 'warm cover' in winter was much stronger than that in autumn, and its height of the former was much lower than that of the latter. Therefore, the intensity of air pollution over EC during winter is significantly higher than other seasons (Fig. 3h).

From the perspective of interdecadal variations, our study revealed a close relationship between the frequent occurrence of haze events in EC and the atmospheric thermal structure in the eastern Tibetan Plateau (TP). Furthermore, the thermal structures of the troposphere exhibited the distinct interdecadal variations (Figs. 4a-4c). A cooling structure was identified in the wintertime air temperature anomalies over the east region of TP during 1961–1980 (Fig. 4a); the upper level of the eastern TP during 1981–2000 showed a 'upper cooling and bottom warming' vertical structure (Fig. 4b). The interdecadal changes of vertical structure reversed during 2001–2018 with a significant 'warm cover' (Fig. 4c). The years of 2001–2018 witnessed the highest frequency of haze days (Fig. 4f), and 1981–2000 saw a middle-level occurrence of haze days (Fig. 4e), while the lowest frequency of haze days occurred during 1961–1980 (Fig. 4d).

The concept of interdecadal variations of the tropospheric ‘warm cover’ has been proposed in this work. Under the background of climate change, it is worth considering whether the variational tendency of the structure of the plateau’s heat source induces variations of the tropospheric thermal structure in downstream areas of the Plateau, leading to the interdecadal variations of the frequency of haze events seen in Eastern China since the 21th century. Thermal anomalies of the TP also play an important role in the variations of the frequency of haze events in EC apart from the anthropogenic pollutant emission related to the rapid industrialization of China. The observational and modeling studies have demonstrated that the interannual variations in the thermal forcing of TP are positively correlated with the incidences of wintertime haze over EC (Xu et al., 2016). The TP induced changes in atmospheric circulation, increasing atmospheric stability and driving frequent haze events in EC (Xu et al., 2016). In this study, the data analysis concerning the interannual variations of the TP’s apparent heat source and air temperature in wintertime at the TP with the altitudes above 3000 meters showed that since the 1960s the heat source in areas vulnerable to TP climate change strengthen continuously as the surface temperature increased (Fig. 5a). Furthermore, the TP’s apparent heat and air temperature of the middle troposphere over EC presented the significant positive, which is similar to ‘warm cover’ structure characteristic (Fig. 5b). Therefore, we considered that the ‘warm cover’ change in the middle troposphere over EC was closely related to TP’s apparent heat and the surface temperature. The TP induced changes in thermodynamic structure of atmospheric provided favorable climatic backgrounds driving air pollution events in EC.

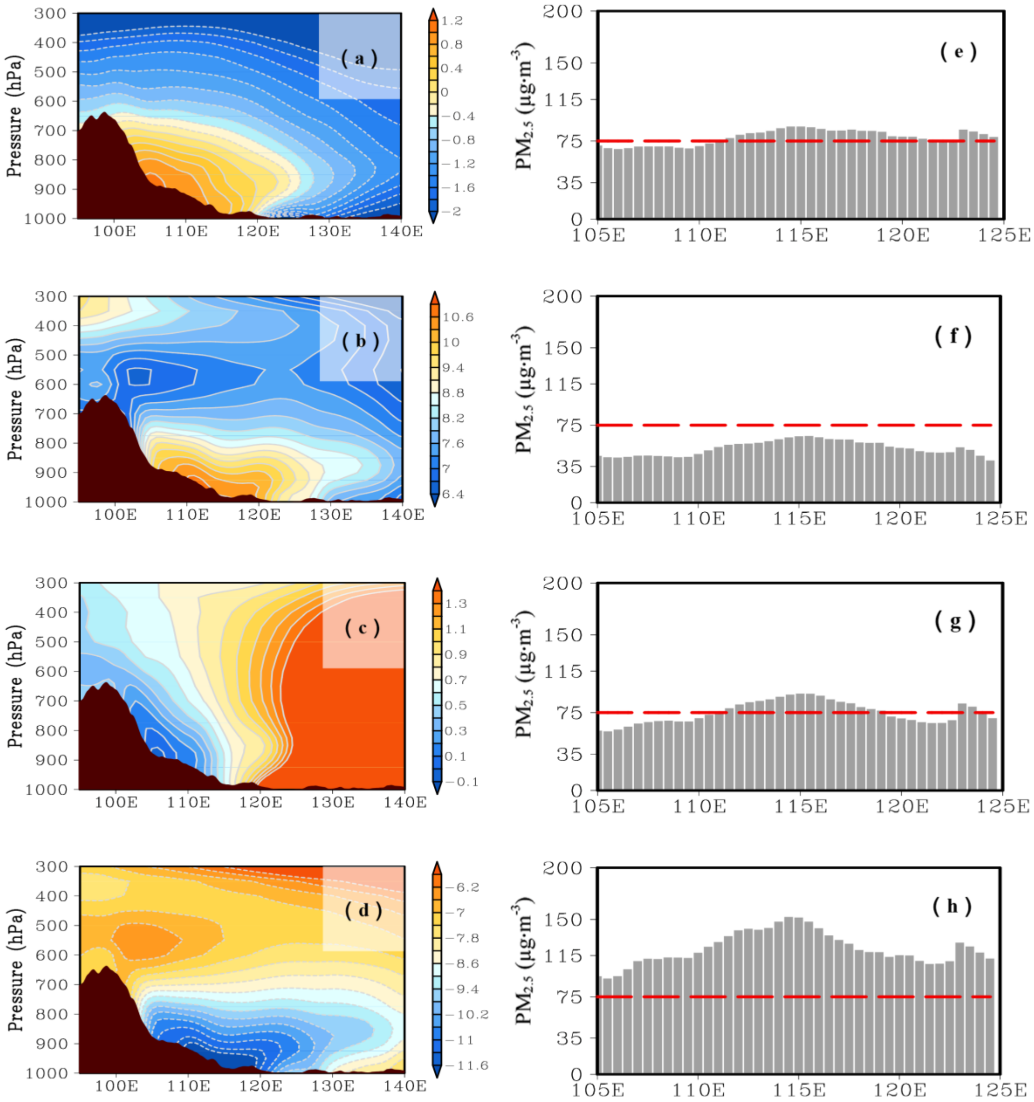

Figure 3. Vertical cross sections of (a-d) air temperature anomalies (unit: ℃) , and (e-h) the $PM_{2.5}$ concentrations (unit: μg·m^{-3}) averaged along 25-40 °N in spring (a, e), summer (b, f), autumn (c, g), winter (d, h) from 2013 to 2018.

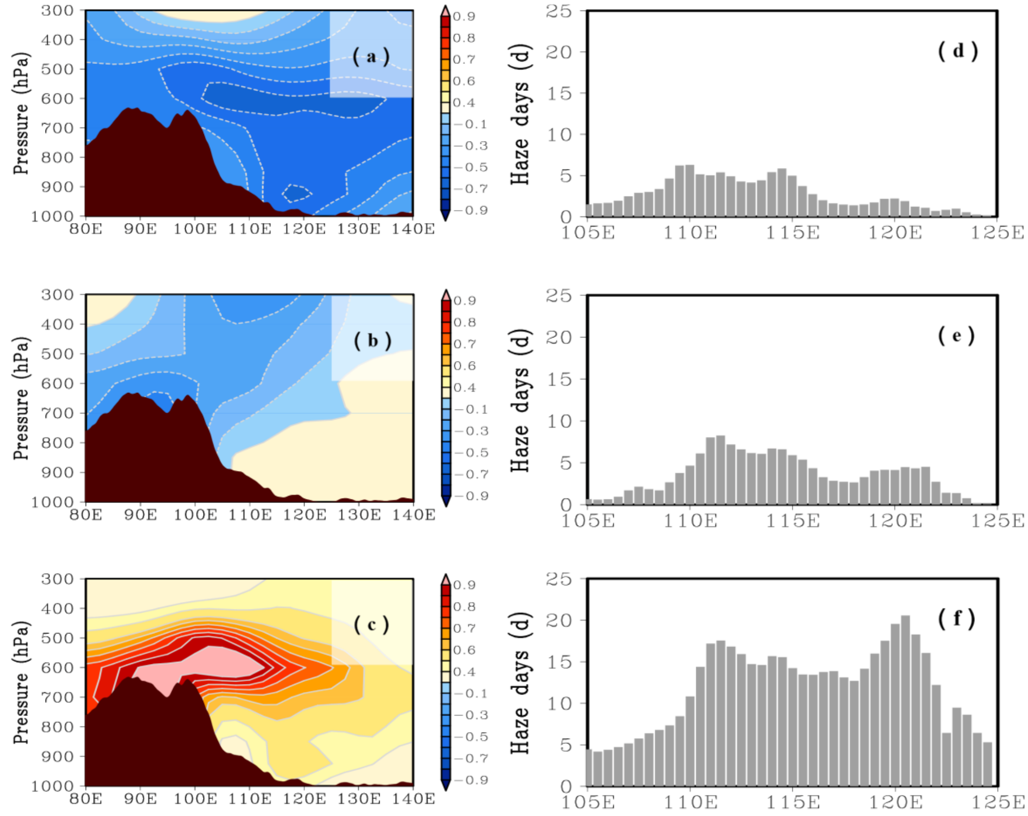

Figure 4. Vertical cross sections of (a-c) air temperature anomalies (unit: ℃) and (d-f) the number of haze days averaged along 25-40 °N in winter during 1961-1980 (a, d), 1981-2000 (b, e) and 2001-2018 (c, f).

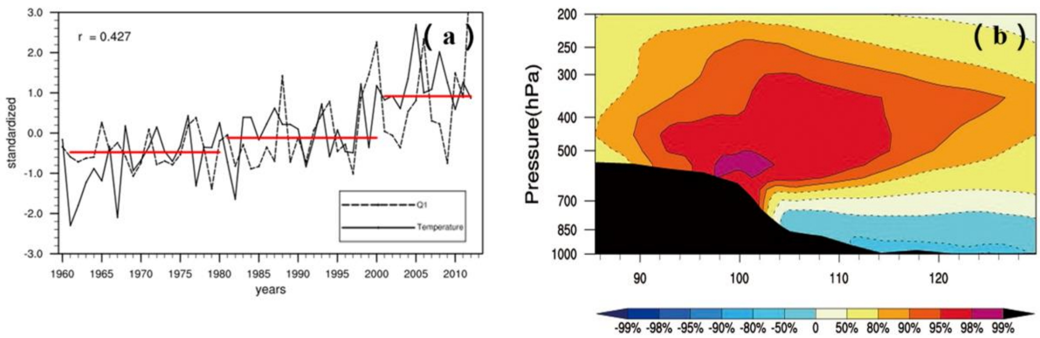

Figure 5. (a) TP's apparent heat source (Q1) and air temperature variations with interanual variations of TP's apparent heat source (Q_1) and air temperature of meteorological stations in the TP with the altitudes above 3000 meters in the winters during 1960-2014; (b) Vertical cross sections of the correlations between TP's apparent heat (Q_1) and air temperature latitude-averaged along 30-35 °N in the winters during 1960-2014.

4 Conclusions and discussion

Based on the study of the Great Smog of London in 1952 and Beijing's heavy air pollution in 2014, as well as $PM_{2.5}$ pollution over EC, the anomalous 'warm cover' in the free troposphere was identified as a precursory 'strong signal' for severe air pollution events, which could be attributed to climate change. A stable thermal structure in the middle troposphere, i.e. a 'warm cover', suppressed the ABL development, which was a key 'inducement' for the accumulation of air pollutants in the ambient atmosphere.

A large-scale anomalous air temperature pattern of 'upper warming and bottom cooling' in the troposphere appeared from the TP to the downstream EC region and even the entire East Asian region. The frequent haze pollution events in EC since the start of the 21st century happens to be within a significant positive phase in the interdecadal variations of 'warm cover' in the middle troposphere. A close relationship between the TP's heat and the thermal structure in the atmosphere in EC and even the entire East Asian region reflected an important role of TP's thermal forcing in environment change over China.

Data availability. The monthly NCEP/NCAR reanalysis data of meteorology are collected from the U.S. National Center for Environmental Protection (NCEP, https://www.esrl.noaa.gov/); the daily and monthly ERA-Interim reanalysis data of meteorology are collected from the European Center for Medium-range Weather Forecasts (ECMWF, https://www.ecmwf.int/); the hourly $PM_{2.5}$ concentration data are collected from the national air quality monitoring network operated by the Ministry of Ecology and Environment the People's Republic of China (http://www.mee.gov.cn/); the air temperature of surface observation data and L-band sounding data are obtained from the China Meteorological Information Center (http://cdc.cma.gov.cn/). All data presented in this paper are available upon request to the corresponding author (Wenyue Cai, caiwy@cma.gov.cn).

Author contributions. XDX and WYC designed the study. XDX, WYC and TLZ performed the research. WYC performed the statistical analyses. XDX, WYC and TLZ wrote the initial paper. TLZ, XFQ, WHZ, CS, PY, CZW and FG contributed to subsequent revisions.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This study is supported by the Atmospheric Pollution Control of the Prime Minister Fund (DQGG0104), the National Natural Science Foundation of China (91644223) and the Second Tibet Plateau Scientific Expedition and Research program (STEP, 2019QZKK0105).

Financial support. This research has been supported by the Atmospheric Pollution Control of the Prime Minister Fund (DQGG0104), the National Natural Science Foundation of China (91644223) and the Second Tibet Plateau Scientific Expedition and Research program (STEP, 2019QZKK0105).

References

Cai, M., OU, J. J., Zhou, Y. Q., Yang Q., and Cai, Z. X.: Discriminating cloud area by using L-band sounding data (in Chinese), Chin. J. Atmos. Sci., 38, 213–222, https://doi.org/10.3878/j.issn.1006-9895.2013.12193, 2014.

Cai, W. Y., Xu, X. D., Cheng, X. H., Wei, F. Y., Qiu, X. F., and Zhu, W. H.: Impact of “blocking” structure in the troposphere on the wintertime persistent heavy air pollution in northern China, Sci. Total Environ., 741, 140325, https://doi.org/10.1016/j.scitotenv.2020.140325, 2020.

Cheng, Y. F., Zheng, G. J., Wei, C., Mu, Q., Zheng, B., Wang, Z. B., Gao, M., Zhang, Q., He, K. B., Carmichael, G., Poschl, U., and Su, H.: Reactive nitrogen chemistry in aerosol water as a source of sulfate during haze events in China, Sci. Adv., 2, e1601530, https://doi.org/10.1126/sciadv.1601530, 2016.

China Ministry of Environmental Protection: Technical Regulation on Ambient Air Quality Index (On Trial) (HJ633-2012), China Environmental Science Press, Beijing, China, 2012.

Ding, Y. H. and Liu, Y. J.: Analysis of long-term variations of fog and haze in China in recent 50 years and their relations with atmospheric humidity, Science China: Earth Sciences, 57, 36-46, https://doi.org/10.1007/s11430-013-4792-1, 2014.

Huang, R. J., Zhang, Y., Bozzetti, C., Ho, K. F., Cao, J. J., Han, Y. M., Daellenbach, K. R., Slowik, J. G., Platt, S. M., Canonaco, F., Zotter, P., Wolf, R., Pieber, S. M., Bruns, E. A., Crippa, M., Ciarelli, G., Piazzalunga, A., Schwikowski, M., Abbaszade, G., Schnelle-Kreis, J., Zimmermann, R., An, Z. S., Szidat, S., Baltensperger, U., Haddad, I. E., 11, and Prevot, A-S. H.: High secondary aerosol contribution to particulate pollution during haze events in China, Nature, 514, 218–222, https://doi.org/10.1038/nature13774, 2014.

Li, W., Li, F., Zhao, Z. Q., Liu, F. Q., Li, B., Li, H.: L-Band Meteorological Observation System Construction Technology Assessment Report (in Chinese), China Meteorological Press, Beijing, China, 2009.

Liu, S. Y. and Liang, Z. X.: Observed diurnal cycle climatology of planetary boundary layer height, J. Climate, 23, 5790-5809, https://doi.org/10.1175/2010JCLI3552.1, 2010.

Miao, Y. C., Li, J., Miao, S. G., Che, H. Z., Wang, Y. Q., Zhang, X. Y., Zhu, R., and Liu, S. H.: Interaction Between Planetary Boundary Layer and $PM_{2.5}$ Pollution in Megacities in China: a Review. Current Pollution Reports, 5, 261–271, https://doi.org/10.1007/s40726-019-00124-5, 2019.

Quan, J. N., Gao, Y., Zhang, Q., Tie, X. X., Cao, J. J., Han, S. Q., Meng, J. W., Chen, P. F., and Zhao, D. L.: Evolution of planetary boundary layer under different weather conditions, and its impact on aerosol concentrations, Particuology, 11(1), 34-40, https://doi.org/10.1016/j.partic.2012.04.005, 2013.

Quan, J. N., Xu, X. D., Jia, X. C., Liu, S. H., Miao, S. G., Xin, J. Y., Hu, F., Wang, Z. F., Fan, S. J., Zhang, H. S., Mu, Y. J., Dou, Y. W., and Cheng, Z.: Multi-scale processes in severe haze events in China and their interactions with aerosols: Mechanisms and progresses (in Chinese). Chin Sci Bull, 65, 810–824, https://doi.org/10.1360/TB-2019-0197, 2020.

State Council of the People's Republic of China: Notice of the General Office of the State Council on Issuing the Air Pollution Prevention and Control Action Plan, State Council of the People's Republic of China website. Available at: http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm, 2013.

State Council of the People's Republic of China: Notice of the General Office of the State Council on Issuing the Air Pollution Prevention and Control Action Plan, State Council of the People's Republic of China website. Available at: http://www. gov.cn/zhengce/content/2018-07/03/content_5303158.htm. 2018.

Tan, C. H., Zhao, T. L., Cui, C. G., Luo, B. L., and Bai, Y. Q.: Characterization of haze pollution over Central China during the past 50 years, Science in China (in Chinese), China Environ. Sci., 35, 2272–2280, 2015.

Tang, G. Q., Zhang, J. Q., Zhu, X. W., Tao, S., Munkel, C., Hu, B., Schaefer, K., Liu, Z. R., Zhang, J. K., Wang, L. L., Xin, J. Y., Schaefer, P., and Wang, Y. S.: Mixing layer height and its implications for air pollution over Beijing, China, Atmos. Chem. Phys., 16, 2459–2475, https://doi.org/10.5194/acp-16-2459-2016, 2016.

Tie, X. X. and Cao, J. J.: Aerosol pollutions in eastern China: Present and future impacts on environment, Particuology, 7, 426–431, https://doi.org/10.1016/j.partic.2009.09.003, 2009.

Wang, G. H., Zhang, R. Y., Gomez, M. E., Yang, L. X., Zamora, M. L., Hu, M., Lin, Y., Peng, J. F., Guo, S., Meng, J. J., Li, J. J., Cheng, C. L., Hu, T. F., Ren, Y. Q., Wang, Y. S., Gao, J., Cao, J. J., An, Z. S., Zhou, W. J., Li, G. H., Wang, J. Y., Tian, P. F., Marrero-Ortiz, W., Secrest, J., Du, Z. F., Zheng, J., Shang, D. J., Zeng, L. M., Shao, M., Wang, W. G., Huang, Y., Wang, Y., Zhu, Y. J., Li, Y. X., Hu, J. X., Pan, B., Cai, L., Cheng, Y. T., Ji, Y. M., Zhang, F., Rosenfeld, D., Liss, P. S., Duce, R. A., Kolb, C. E., and Molina, M. J.: Persistent sulfate formation from London Fog to Chinese Haze, P. Natl. Acad. Sci., 113, 13630–13635, https://doi.org/10.1073/pnas.1616540113, 2016.

Wang, H., Li, J. H., Peng, Y., Zhang, M., Che, H. Z., and Zhang, X. Y.: The impacts of the meteorology features on $PM_{2.5}$ levels during a severe haze episode in central-east China, Atmospheric Environment, 197, 177–189, https://doi.org/10.1016/j.atmosenv.2018.10.001, 2019.

Wang, H., Xue, M., Zhang, X. Y., Liu, H. L., Zhou, C. H., Tan, S. C., Che, H. Z., Chen, B., and Li, T.: Mesoscale modeling study of the interactions between aerosols and PBL meteorology during a haze episode in Jing–Jin–Ji (China) and its nearby surrounding region – Part 1: Aerosol distributions and meteorological features, Atmos. Chem. Phys., 15, 3257–3275, https://doi.org/10.5194/acp-15-3257-2015, 2015.

Wang, J. J., Zhang, M. G., Bai, X. L., Tan, H. J., Li, S., Liu, J. P., Zhang, R., Wolters, M. A., Qin, X. Y., Zhang, M. M., Lin, H. M., Li, Y. N., Li, J., and Chen, L. Q.: Large-scale transport of $PM_{2.5}$ in the lower troposphere during winter cold surges in China, Sci. Rep., 7, 13238, https://doi.org/10.1038/s41598-017-13217-2, 2017.

Wang, Y. S., Li, W. J., Gao, W. K., Liu, Z. R., Tian, S. L., Shen, R. R., Ji, D. S., Wang, S., Wang, L. L., Tang, G. Q, Song, T., Cheng, M. T., Wang, G. H., Gong, Z. Y., Hao, J. M., and Zhang, Y. H.: Trends in particulate matter and its chemical compositions in China from 2013–2017. Science China Earth Sciences, 62: 1857–1871, https://doi.org/10.1007/s11430-018-9373-1, 2019.

Whittaker, A., Berube, K., Jones, T., Maynard, R., Richards, R.: Killer smog of London, 50 years on: particle properties and oxidative capacity, Science of the Total Environment, 334-335, 435–445, https://doi.org/10.1016/j.scitotenv.2004.04.047, 2004.

Xu, X. D., Zhao, T. L., Liu, F., Gong, S. L., Kristovich, D., Lu, C., Guo, Y., Cheng, X. H, Wang, Y. J., and Ding, G.: Climate modulation of the Tibetan Plateau on haze in China, Atmos. Chem. Phys., 16, 1365–1375, https://doi.org/10.5194/acp-16-1365-2016, 2016.

Yim, S-Y., Wang, B., Liu, J., and Wu, Z. W.: A comparison of regional monsoon variability using monsoon indices, Climate Dynamics, 43, 1423-1437, https://doi.org/10.1007/s00382-013-1956-9, 2014.

Zhang, X. Y., Wang, J. Z., Wang, Y. Q., Liu, H. L., Sun, J. Y., and Zhang, Y. M.: Changes in chemical components of aerosol particles in different haze regions in China from 2006 to 2013 and contribution of meteorological factors, Atmos. Chem. Phys., 15, 12935–12952, https://doi.org/10.5194/acp-15-12935-2015, 2015.

Zhu, W. H., Xu, X. D., Zheng, J., Yan, P., Wang, Y. J., and Cai, W. Y.: The characteristics of abnormal wintertime pollution events in the Jing-Jin-Ji region and its relationships with meteorological factors, Sci. Total Environ., 626, 887-898, https://doi.org/10.1016/j.scitotenv.2018.01.083, 2018.