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Variations of Haze Pollution in China Modulated by Thermal Forcing of the Western Pacific Warm Pool

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Abstract: In addition to the impact of pollutant emissions, haze pollution is connected with meteorology and climate change. Based on the interannual change analyses of meteorological and environmental observation data from 1981 to 2010, we studied the relationship between the winter haze frequency in central-eastern China (CEC) and the interannual variations of sea surface temperature (SST) over Western Pacific Warm Pool (WPWP) and its underlying mechanism to explore the thermal effect of WPWP on haze pollution variation in China. The results show a significant positive correlation coefficient reaching up to 0.61 between the interannual variations of SST in WPWP and haze pollution frequency in the CEC region over 1981–2010, reflecting the WPWP's thermal forcing exerting an important impact on haze variation in China. The anomalies of thermal forcing of WPWP could induce to the changes of East Asian winter monsoonal winds and the vertical thermal structures in the troposphere over the CEC region. In the winter with anomalously warm SST over the WPWP, the near-surface winds were declined, and vertical thermal structure in the lower troposphere tended to be stable over the CEC-region, which could be conducive to air pollutant accumulation leading to the more frequent haze occurrences especially the heavy haze regions of Yangtze River Delta (YRD) and Pearl River Delta (PRD); In the winter with the anomalously cold WPWP, it is only the reverse of warm WPWP with the stronger East Asian winter monsoonal winds and the unstable thermal structure in the lower troposphere, which could attribute to the less frequent haze pollution over the CEC region. Our study revealed that the thermal forcing of the WPWP could have a modulation on air environment change in China.

Keywords: haze pollution; interannual variation; sea surface temperature; Western Pacific Warm Pool

1. Introduction

Haze refers to an environmental phenomenon with a large number of fine particles suspending in ambient air, generally resulting in pervasive air turbidity with the horizontal visibility reducing to lower than 10 km [1]. In recent years, the occurrences of haze, as an anthropogenic air pollution in China have experienced an increasing trend [2,3]. The central-eastern China (CEC) region was climatologically identified as a large-scale "susceptible region" of haze pollution covering the North China Plain, the Yangtze River Delta (YRD), the Pearl River Delta (PRD) and the Sichuan Basin in China [4–6]. The haze pollution in the CEC region shifted seasonally between a peak in winter and a low in summer [7–9].

Variations in haze pollution are affected by both air pollutant emissions and meteorological conditions. It is generally accepted that air stagnation with low near-surface winds and stable vertical thermal structures in the lower troposphere could be a dominant meteorological condition for poor air diffusions leading to air pollutant accumulation for frequent haze occurrences in China [10,11]. Although the anthropogenic emissions dominated the increase in winter pollutant concentrations over Eastern China during the past decades, the variations in meteorological conditions contributed 17% of the increasing trend in wintertime air pollution from weakening East Asian Winter Monsoon [12]. In January 2013, the persistent air stagnation condition was an important meteorological factor controlling the severe haze pollution covered much of the CEC region [13,14]. In addition, haze pollution in China could be intensified by aerosol-meteorology interactions, such as radiation forcing of black carbon aerosols enhanced the haze pollution in China by suppressing the development of atmospheric boundary layer [15].

The East Asian monsoons are the primary climatic components in China [16], changing the atmospheric circulations and meteorological conditions with anomalies in winds, precipitation, air temperature and humidity [17,18]. Located in a typical East Asian monsoon region, air quality over the CEC with strong pollutant emissions has been a deteriorated by haze pollution over recent years [19,20]. Meteorological conditions could exert a significant impact on air quality by altering the transport, emission, formation, deposition and washout of aerosols [21,22]. East Asian monsoons has experienced a steady decrease trend in interannual variations of near-surface wind speed over past decades, which could redistribute the air pollutants for air quality in China [23,24]. The haze pollution is closely associated with climate change of East Asian monsoon, besides the large increases in emissions of anthropogenic aerosols in the last three decades [4,9,25]. The anomalies of Arctic sea ice, as well as sea surface temperature (SST) over the tropical Eastern Pacific and northwestern Pacific could also influence the interannual change of haze pollution over Eastern China [26–30].

The Western Pacific Warm Pool (WPWP), located in the equatorial western Pacific region with the SST perennially maintained over 28 °C, is one of the primary sources of atmospheric heat for climate change of East Asian monsoons [28,31,32]. As an important thermal forcing on East Asian monsoon climate system [33,34], the SST anomalies of WPWP could modify East Asian winter monsoon [35–37]. The abnormal increase of SST in the WPWP could lead to declining East Asian winter monsoon [38]. The thermal anomalies of WPWP have the significant impacts on wintertime weather in the CEC region [2,39,40]. However, under the circumstances of high anthropogenic pollutant emissions, climatic modulation of WPWP thermal forcing on haze pollution over the CEC has been poorly understood.

Based on the interannual change analyses of environmental and meteorological observation data from 1981–2010, this study attempted to explore the modulation of WPWP thermal forcing on haze pollution over the CEC and the underlying mechanism in associated with the interannual variations of East Asian monsoons to more comprehensively understand the atmospheric environment changes in China.

2. Data and Methods

In this study, we used the surface observational records from total 2408 stations over China of visibility, weather phenomenon, relative humidity and 10 m wind archived at the China Meteorological Administration (CMA),the reanalysis data of wind speed, relative humidity, geopotential heights and air temperature generated by the US National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP/NCAR), and the global SST data from the NOAA (http://www.cpc.ncep.noaa.gov/data/indices/). This study adopted a widely-used comprehensive haze definition using surface in-situ observations of visibility, relative humidity and weather phenomenon. The observed relative humidity of less than 90% is used to distinguish haze from fog under the visibility <10 km [4–6], and a haze day is defined as the average of four measurements of relative humidity and visibility each day. This definition of haze day has been used for analyzing the tempo-space variations in haze over China in many previous studies [4,41,42].

In order to analyze the thermal forcing effect of WPWP on haze variation in China, we conducted the correlation analysis and composite anomalies to investigate the relationship between the interannual anomalies of SST in WPWP and haze pollution over the CEC region in the past 30 years and its mechanism. In this study, the CEC region as the study area covers 106°–123° E and 20°–42° N in mainland China. Because the haze pollution occurred mostly in winter [4], we focused all the analyses on boreal wintertime (December, January and February) in this study, and all the climatic mean values were averaged over winters of 1981–2010.

3. The Relationship between Haze Variations and SST Anomalies in WPWP

3.1. A Key Pacific Area Affecting CEC Haze

Winter is a frequent haze pollution season in the CEC region in terms of climatology [4]. As depicted in Figure 1a, the wintertime haze pollution over the CEC region during 1981–2010 was concentrated at the east of 106° E and the south of 42° N in China. The severe haze areas included the Pearl River Delta (PRD), the Yangtze River Delta (YRD) and the North China Plain, where the average number of wintertime haze days exceeded 10 days per winter averaged over 1981–2010 (Figure 1a). Therefore, the CEC region was selected as the target area in this study (the black rectangles area in Figure 1a). Haze pollution in the CEC region showed a significantly interannual variation over 1981–2010. From the 1980s to the early 1990s, the trend in the interannual haze variation was relatively mild, while since late 1990s the obvious oscillations and the increasing trend in the interannual haze variation have occurred (Figure 1b). In order to investigate the relationship between the interannual variations of wintertime SST in WPWP and the number of days with haze in the CEC region, we calculated the spatial distribution of correlation coefficients between the haze days averaged over the CEC region and the SST in western Pacific during winters of 1980–2010. As shown in Figure 2, the significant high correlations with the positive correlation coefficients reaching 0.55 (passing the 99% confidence level) were centered in the WPWP region over the western equatorial Pacific region, reflecting a close connection of thermal forcing in the WPWP region with the haze pollution change over the CEC region. This climate analysis revealed that the WPWP is a key area over the Pacific Ocean affecting the variation of haze pollution in the CEC region, and the warm (or cold) SST anomalies in the WPWP could lead to more (or less) frequent haze occurrences in the CEC region.

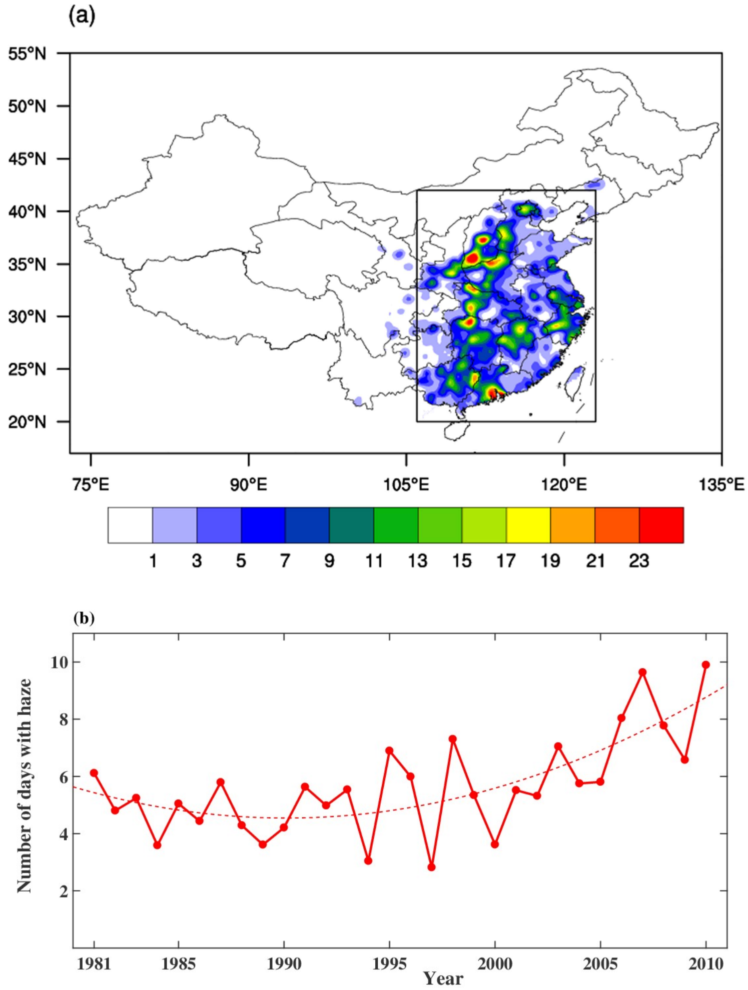

Figure 1. (**a**) Spatial distribution of the winter haze days averaged from 1981 to 2010 and (**b**) the interannual variation of winter haze days regionally averaged over the CEC region from 1981 to 2010. The CEC region (106°–123° E, 20°–42° N) is marked with the black rectangles in Figure 1a.

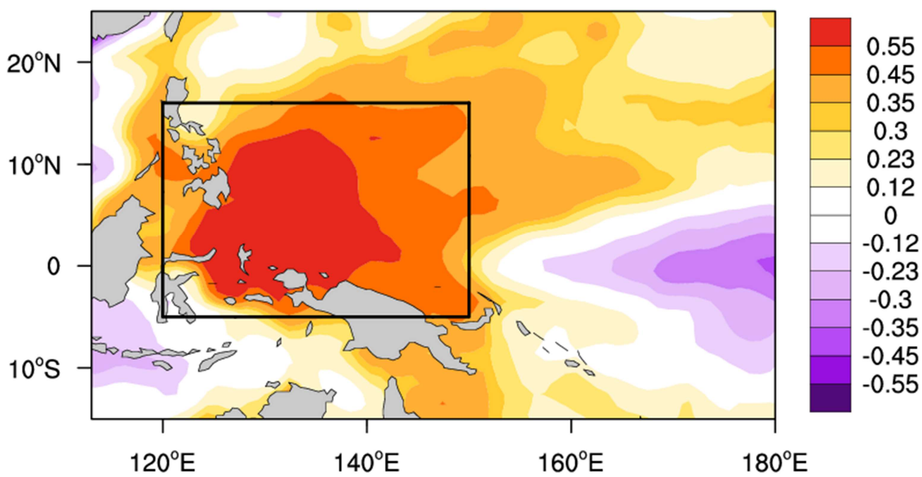

Figure 2. Spatial distribution of correlation coefficients between the winter haze days averaged over the CEC-region (marked with the black rectangles in Figure 1a) and the western Pacific SST from 1981 to 2010. The contour lines of 0.23 (−0.23), 0.30 (−0.30), 0.35 (−0.35) and 0.45 (−0.45) indicate the correlations at 80%, 90%, 95% and 99% confidence levels, respectively.

3.2. Interannual Variations of CEC Haze and the WPWP Thermal Forcing

As presented in Figure 2, the WPWP is a key Pacific area affecting the variation of haze pollution in the CEC region. Therefore, we averaged the SST over the WPWP region of 120°–150° E and 5° S–16° N (marked with black rectangles in Figure 2) as the regional SST values to represent the WPWP thermal forcing. In order to explore the effect of WPWP thermal forcing on the interannual variation of CEC haze pollution, we calculated the correlation coefficients between the interannual changes of WPWP regional SST averages and the haze days averaged over the CEC region (marked with black rectangles in Figure 1a). Figure 3 exhibits the relationship between the interannual changes of WPWP regional SST and the CEC regional averages of haze days during 1981–2010 with their correlation coefficients up to 0.61, passing the 99% confidence level. Furthermore, similarly to the interannual change pattern of haze in the CEC region, the variation of SST in the WPWP has shown an ascending tendency since late 1990s. This further indicates the significantly positive connection of the WPWP thermal forcing with the haze pollution events in the CEC region.

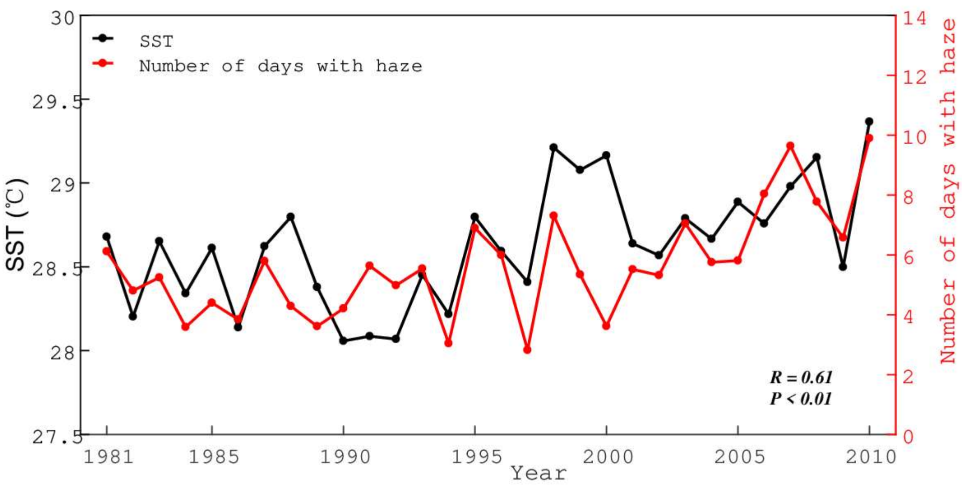

Figure 3. Interannual variations of winter haze days (red line) averaged over the CEC region (Figure 1a.) and SST (black line) averaged over the WPWP region (marked with the black rectangles in Figure 2) over winter from 1981 to 2010.

In order to more comprehensively understand the WPWP thermal forcing effects on the haze pollution over the CEC region, this study further calculated the spatial distribution of correlation coefficients between the SST regional average over the WPWP and the number of haze days in the CEC region over 1981–2010 (Figure 4). As shown in Figure 4, the significantly positive correlations existed over most of the CEC region with the highest correlation coefficients over the PRD and YRD in the southern and eastern CEC region (Figure 4), reflecting that the interannual variation of haze pollution over the areas of PRD and YRD had the strongest response to the thermal forcing of WPWP.

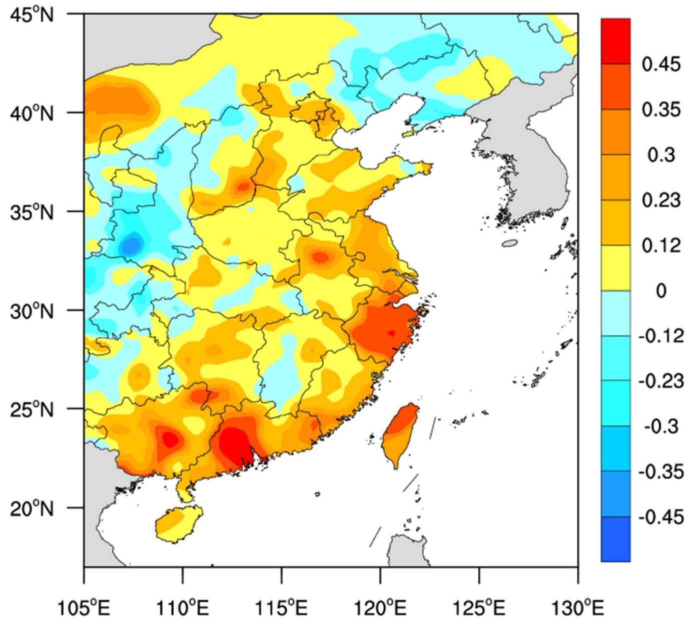

Figure 4. Spatial distribution of correlation coefficients between the interannual variations of SST averaged in the WPWP region (Figure 2) and the haze days over CEC region over winters from 1981 to 2010. The contour lines of 0.23 (−0.23), 0.30 (−0.30), 0.35 (−0.35) and 0.45 (−0.45) indicate the correlation coefficients at 80%, 90%, 95% and 99% confidence levels, respectively.

4. The Mechanism on Thermal Forcing of WPWP Influencing CEC Haze Pollution

4.1. Response of the Near Surface Wind Fields

Based on the interannual variation of the WPWP regional SST detrended anomalies over 1981–2010 (Figure 5), we computed the standard deviations σ of the SST detrended anomalies during the 30 years. The winter SST detrended anomalies beyond of the standard deviations σ could be identified as the extreme wintertime anomalies of WPWP thermal forcing. Accordingly, the extremely warm winters were selected in 1981, 1983, 1988, 1999, 1998, 2000 and 2010, and the extremely cold winters in 1990, 1991, 1992, 1994 and 2009, as the SST anomalies were larger (or smaller) than the positive (or negative) values of standard deviations σ. (Figure 5).

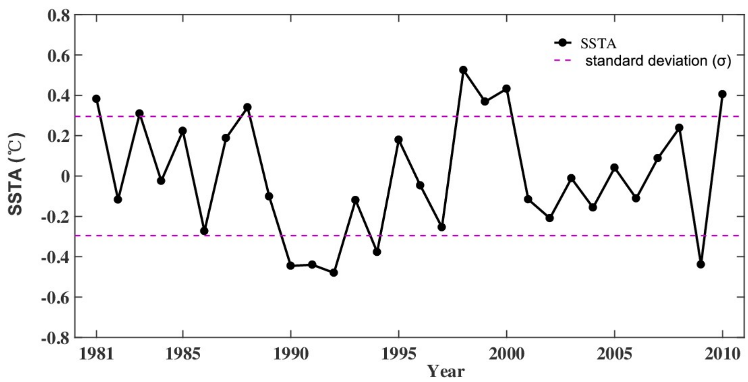

Figure 5. Interannual variations of the wintertime SST detrended anomalies (SSTA) averaged over the WPWP region (Figure 2) and the standard deviations σ from 1981 to 2010.

East Asian winter monsoon is characterized with the continental cold high pressure in the lower troposphere on the East Asian continent. The monsoonal winds are closely related to the strength and extension of the cold high pressure. The magnitude of the East Asian continental cold high pressure can be an indicator of the East Asian winter monsoon intensity [16,43,44]. Figure 6a,b show the composite anomalies in near-surface wind speeds and geopotential height field at 850 hPa in the extremely warm SST winters and extremely cold SST winters over the WPWP region, respectively.

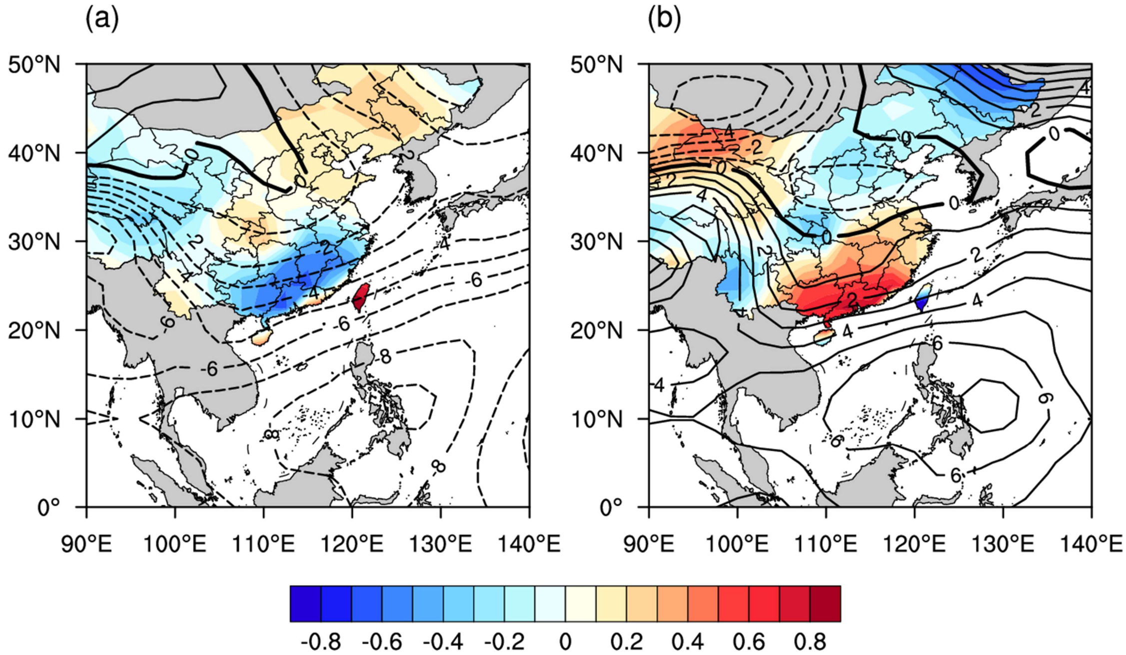

Figure 6. The anomalies of wind speeds (ms^{-1}) (color contours) and geopotential heights (contour lines) at 850 hPa averaged over (**a**) the extremely warm SST in winter WPWP of 1981, 1983, 1988, 1999, 1998, 2000 and 2010 as well as (**b**) the extremely cold SST in winter WPWP of 1990, 1991, 1992, 1994 and 2009.

In the extremely warm SST winters, the anomalous negative geopotential height at 850 hPa was located in most of the CEC region with the negative center over the Philippines Islands (Figure 6a), which could be resulted from the stronger thermal forcing effect over the WPWP leading to the enhanced convection activities [37,45]. With the negative anomalies of geopotential height, East Asian continental cold high pressure of East Asian winter monsoon narrowed to the north of CEC, and the activity of cold air flows in the south of China had weakened, leading to a decrease in near surface wind speed in the eastern and southern CEC region (Figure 6a). The changes of wind speed and geopotential height field at 850 hPa were opposite to those in the extremely warm SST winters (Figure 6a,b). The East Asian continental cold high pressure of East Asian winter monsoon extended to the southern CEC with the stronger near surface winds (Figure 6b). The anomalies of the WPWP thermal forcing could exert a significant impact on the cold airflows of East Asian winter monsoon over the CEC region, influencing the haze pollution for regional air quality change.

4.2. The Changes of Atmospheric Thermal Structures

The stable stratification of atmospheric vertical thermal structure contributes to the local accumulation of haze pollution, while the unstable stratification is conducive to the strong vertical diffusion for less haze pollution [10,13]. To understand the relationship between the SST anomalies in WPWP and the changes of atmospheric thermal structure over the CEC region, we analyzed the vertical structures of air temperature over the CEC region in the winters with WPWP extreme SST anomalies (Figure 7a,b). The opposite patterns of atmospheric vertical thermal structure could be found in Figure 7a,b. In the WPWP extremely warm SST winter, the warmer (colder) air temperature in the upper (lower) troposphere tended to be a stable stratification in atmospheric vertical thermal structure over the CEC region (Figure 7a); in the WPWP extremely cold SST winter, the vertical structure of tropospheric temperature anomalies with colder (warmer) air temperature in the upper (lower) troposphere was beneficial to a unstable stratification over the CEC region (Figure 7b). These patterns of tropospheric vertical temperature in the extremely warm and cold SST winters may lead to a "warm shield" or a "cold shield" in the troposphere over the CEC region [4]. The "warm shield" could easily build an inversion layer in the atmosphere over the polluted CEC region, which could result in a more stably stratified atmosphere in this region (Figure 7a). The "cold shield" could provide the unstable background in the troposphere for the diffusion of haze pollutants (Figure 7b).

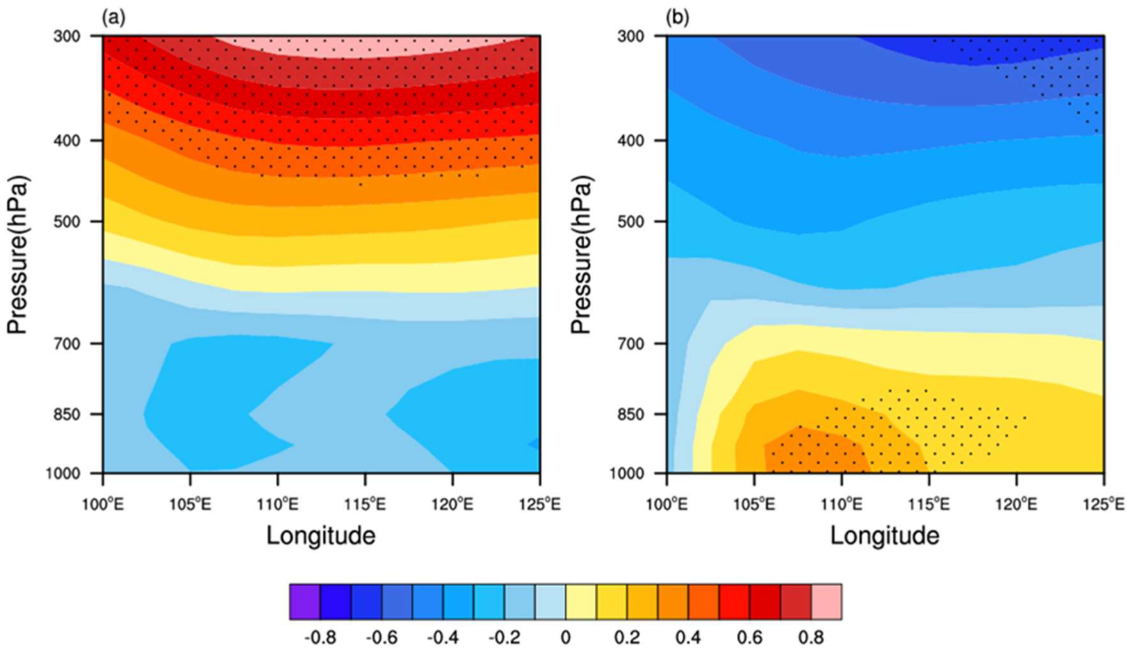

Figure 7. The vertical distribution of air temperature anomalies (color contours) averaged from 20° N to 42° N over (**a**) the extremely warm SST in winter WPWP of 1981, 1983, 1988, 1999, 1998, 2000 and 2010 as well as (**b**) the extremely cold SST in winter WPWP of 1990, 1991, 1992, 1994 and 2009 with passing statistical significance level of 0.1 (black dots).

5. Conclusions

Based on the meteorological and environmental observation data from 1981 to 2010, this study analyzed the relationship between the interannual variations of SST anomalies over WPWP and the number of haze days over the CEC region to explore the WPWP thermal forcing effect on the haze pollution in CEC region and the underlying mechanism.

The interannual change analyses demonstrated that the thermal forcing of WPWP could modulate the interannual variations of haze pollution in the CEC region, especially the YRD and PRD regions with high correlation coefficients up to 0.61 passing the 99% confidence level. The WPWP was identified as a key Pacific area with the thermal forcing affecting the variation of haze pollution in the CEC region, and the warm (or cold) SST anomalies in WPWP could lead to more (or less) frequent haze occurrences in the CEC region.

The interannual variation of thermal forcing in WPWP could lead the anomalies of East Asian winter monsoon circulation with cold airflows and change the tropospheric vertical thermal structure over the CEC region. In the WPWP extremely warm winter, the decreasing near surface wind speed and the more stable stratification in lower troposphere were beneficial to the frequent haze pollution over the CEC region. In the WPWP extremely cold winter, the East Asian winter monsoon in the CEC region was enhanced, and the vertical thermal structure tended to be unstable, which could attribute to less haze occurrences.

Based on the long-term observation data, this study revealed the relationship between the number of days with winter haze in China and variations of SST in WPWP through changing stagnation meteorological conditions of near-surface winds and vertical thermal structure in the lower atmosphere. This correlation study is further complicated by the fact that relative humidity is influenced by both temperature and water vapor mixing ratio fluctuations. Further insight would be gained by looking at correlations with haze and air temperature, haze and water vapor mixing ratio for these haze days. The impact of the thermal forcing of WPWP on air quality in China would be further studied in respects of changes of air pollutant emissions, changes of atmospheric chemistry and physics in changing climate.

The changing air temperature and relative humidity could be the main physics mechanism modulating the number of haze days, which is the omission in this study with being focused on the variations of stagnation weather with weak near-surface winds and stable vertical thermal structures in the lower troposphere to explore the underlying mechanism on the WPWP thermal forcing effect on the haze pollution in CEC region. Additionally, it is generally accepted that stagnation weather is a dominant meteorological condition for poor air diffusions leading to air pollutant accumulation for frequent haze occurrences in China, the comprehensive understanding on the impact changing climate on haze pollution should consider the role of air temperature and relative humidity in modulating the number of haze days in further study with data of longer than 30-year meteorology and environment observations.

Author Contributions: Y.Y., X.C. and T.Z. conceived and designed the experiments and analyzed the data as well as wrote the article; X.X., S.G., X.Z. and H.C., conceived and designed the experiments, Y.Z., C.Y., J.C., G.M. and M.W. helped in the statistical analysis.

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