Reply to Referee #1

General comments:

The impact of external thermal forcing induced atmospheric circulation changes onair quality is an important issue in atmospheric environment study. Focusing this scientific issue, this manuscript presented an interesting finding on two pathways of thermal forcing sources in the North Atlantic region (R1) and the western North Pacific region (R2) drive the interannual variations of autumnal haze pollution in the air pollution region of North China via the tele-connection analysis and AGCM simulation, which could improve our understanding and prediction on air quality change in China, Asia and the Northern Hemisphere. This manuscript falls within the scope of ACP. I suggest the minor revisions before it is published as follows:

Reply: Thank you for your positive comments. We have revised the manuscript based on your comments/suggestions. Below is our point-by-point reply to these comments/suggestions (italic is for original comments and non-italic is our replies).

Specific comments:

1)*Please add the discussions on the tele-connection pattern from the R1 region to North China in connection with North Atlantic Oscillation, and the R2 region in association with Western Pacific Warm Pool.*

Reply: Thanks for your comment. We have added two relevant references and corresponding discussions. Please see Lines 220-223 and Lines 254-255 in the revised manuscript for the discussions.

(Lines 220-223) "Intriguingly, from the surface projection of the above quasi-barotropic teleconnection pattern, we can discern a positive phase of North Atlantic Oscillation-like mode in connection with this pattern (Hurrell and Deser, 2009)."

(Lines 254-255) "…with its southern portion belonging to the Western Pacific Warm Pool (You et al., 2018)."

Reference:

Hurrell, J. W., and Deser, C.: North Atlantic climate variability: The role of the North Atlantic Oscillation, J Marine Syst, 78, 28-41, 10.1016/j.jmarsys.2008.11.026, 2009.

You, Y. C., Cheng, X. G., Zhao, T. L., Xu, X. D., Gong, S. L., Zhang, X. Y., Zheng, Y., Che, H. Z., Yu, C.,Chang, J. C., Ma, G. X., and Wu, M.: Variations of haze pollution in China modulated by thermal forcing of the Western Pacific Warm Pool, Atmosphere, 9, 314, 10.3390/atmos9080314, 2018.

2)Please modify the lines 20-21: the joint impacts can greatly enhance the likelihood of a higher AHD_{BTH} Observational and simulation evidence suggests that SST anomalies can affect the variation……

Reply: Thanks for your comment. The modification was done. Please see Lines 22-24 in the revised manuscript.

Lines 22-24: "…When the autumnal SST warming in R1 and R2 are both significant, the likelihood of a higher AHD_{BTH} is greatly enhanced. Observational and simulation evidence demonstrated how SST anomalies over R1 and R2 influence variation of AHD_{BTH} via two different pathways."

3)Lines 191 and 193, please add "surface air" before "temperature".

Reply: Thanks for your suggestion. We have added "surface air" before "temperature". Please see Line 205 in the revised manuscript.

Line 205: "…and surface air temperature (Fig. 4b), …"

4)Please add the box outlines the research domain of the BTH region in Fig. 7.

Reply: Thanks for your constructive suggestion. We have added the blue dashed box outlining the research domain of the BTH region. Please see Fig. 7 in the revised manuscript.

Reply to Referee #2

General comments:

This paper provides a new possible signal source in the North Atlantic subtropical sector (R1) and the western North Pacific sector (R2) for autumnal haze days (AHD) inthe Beijing-Tianjin-Hebei region (BTH region) via the tele-connection mode. The effect sequence of the warm phase of these two oceanic sources on the AHD in BTH is basically reasonable, leading to depressed planetary boundary layer and subsidence of the atmosphere. These changing meteorological conditions are the favorable background for the higher AHD in BTH. The methodology used in this paper is correct (i.e. Rossby wave train). The findings obtained by this paper may be useful to make the seasonal outlook of the air pollution condition in autumn.

Reply: Thank you for your positive comments. We have revised the manuscript based on your comments/suggestions. Below is our point-by-point reply to these comments/suggestions (italic is for original comments and non-italic is our replies).

Specified corrections:

(1) For the SST of the North Atlantic, why only the middle oceanic region is selected? The representative signal source of the AMO should be the triple-pole SST pattern, with high-latitude and the tropical poles being more important.

Reply: Thanks for your comment. The AMO is known as the SST in the North Atlantic varying on the basin scale and at period of around 65–80 years. Since our study concentrated on the interannual variability, the AMO is not relevant to our research target.

We chose subtropical North Atlantic region (22°–32°N, 90°–40°W) as the key SSTA region for the following two reasons. Firstly, the subtropical North Atlantic SSTA is the only region over North Atlantic that highly correlated with the AHD_{BTH} on interannual timescale. Although the regression SSTA pattern over North Atlantic looks like a tri-pole SST pattern (NAT SST pattern for short) which has profound impacts on Eurasian climate, the relationship between AHD_{BTH} and simultaneous NAT SST pattern is insignificant. The correlation coefficient between AHD_{BTH} and NAT SST triple-pole index (Deser and Michael, 1997) is only 0.17. Therefore, we chose the middle oceanic region of North Atlantic as the key region for $AHD_{BTH.}$

Secondly, the positive correlated SSTA over that region can induce positive rainfall anomaly (diabatic heating). Therefore, the SSTA should play an active role in local air-sea interaction and in turn influence the large-scale circulation through inducing teleconnection.

To sum up, we chose subtropical North Atlantic region (22°–32°N, 90°–40°W) as the key driving region from both statistical diagnosis and physical basis.

We have added this discussion in the revised manuscript (Lines 256-265).

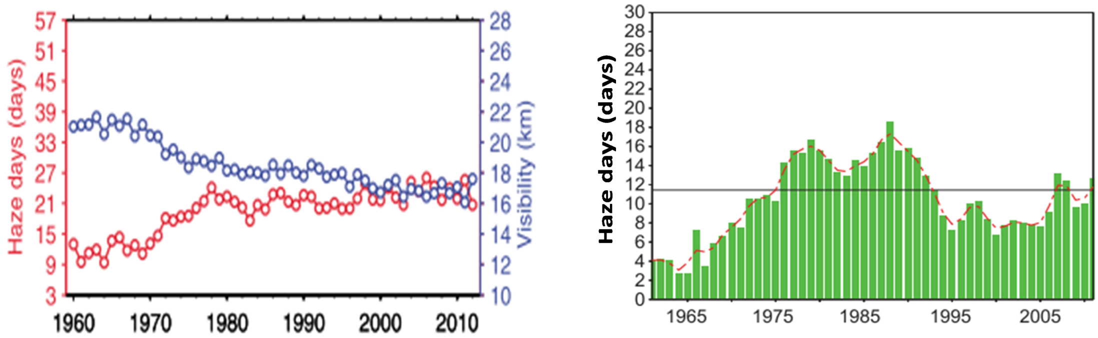
Reference:.

Deser, C. and Michael S.T., 1997: Atmosphere-ocean interaction on weekly timescales in the North Atlantic and Pacific. Journal of Climate, 10(3): 393-408.

***(2)** From Figure 2, one can see the rapid increase of AHD in BTH. However, other studies have shown that the rapid increase in AHD started from the mid-ninety of 20 century or early in this century. Please compare the difference between them and explain why.*

Reply: Thanks for your constructive comments. After checking many related literatures (e.g., **Figure 6b** in Fu and Dan, 2014), we found that the annual total haze days indeed showed the rapid increasein the BTH region since the early 21st century, but it is not materialized for the case of autumn season.

For the autumn season, from the previous studies, we found that the rapid increase in AHD over North China did not start from the mid-ninety of 20 century or early in this century (R-**Figure 1**). Our results are quite consistent with the previous studies.



R-Figure 1. Time series of AHD in North China. (left) Adapted from ***Chen and Wang* (2015)**. (right) Adapted from ***Ding and Liu* (2014)**. The red dashed line is 9-point smooth curve.

Reference:

Chen, H. P., and Wang, H. J.: Haze Days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012, J Geophys Res Atmos, 120, 5895-5909, 10.1002/2015JD023225, 2015.

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, Sci China Earth Sci, 57, 36-46, 10.1007/s11430-013-4792-1, 2014.

Fu, C. B., and Dan, L.: Spatiotemporal characteristics of haze days under heavy pollution over central and eastern China during 1960–2010, Climatic and Environmental Research (in Chinese), 19 (2), 219-226, 2014.

(3) *For Figure 6, please indicate the significance level for the correlation coefficient.*

Reply: Thanks for your suggestion. We have added the significance level for the correlation coefficient as suggested. Please see Figure 6 in the revised manuscript.

(4) *The anticyclonic circulation over Northeast China-Okhotsk Sea at 850 hPa is a critical system. Please check if it only takes place in autumn (or/and winter)? Whether or not it already exists in summer?*

Reply: Thanks for your good comment and suggestion. As you indicated, the 850-hPa anomalous anticyclonic circulation over Northeast China-Okhotsk Sea is indeed a critical system that having significant impacts upon the interannual variability of AHD_{BTH}. In addition to autumn season, this system also takes place in winter (e.g., **Figure 4b** in Yin et al., 2017; **Figure 3a** in Zhong et al., 2018), which greatly influences the interannual changes of wintertime haze pollution.

However, this anticyclonic circulation does not exist in the prior summer based on our correlation analysis (figures omitted). Therefore, we could infer that this anticyclonic circulation anomaly over Northeast Asia is only occurred in the simultaneous autumn and winter.

Reference:

Yin, Z. C., Wang, H. J., and Chen, H. P.: Understanding severe winter haze events in the North China Plain in 2014: roles of climate anomalies, AtmosChemPhys, 17, 1641-1651, 10.5194/acp-17-1641-2017, 2017.

Zhong, W. G., Yin, Z. C., Wang, H. J., and: The Relationship between the Anticyclonic Anomalies in Northeast Asia and Severe Haze in the Beijing–Tianjin–Hebei Region, AtmosChem Phys, Discuss., 10.5194/acp-2018-782, in review, 2018.

(5) *From Figure 10(a), the descending motion seems to be out of BTH region. Please explain it.*

Reply: Thanks for your comment. Except for a small portion of upward motion over the southern BTH region, most of the BTH region is indeed dominated by air subsidence from mid-to-upper troposphere (700-300 hPa in Figure 10a).

The significant descending motion is tied to strong ascending motion over south of the BTH region. Because the ascending motion is so strong, it makes the descending motion farther to the north. Nevertheless, this subsidence could enhance Northeast Asian anticyclonic anomaly.

(6) *The warm R2 should be associated with the El Nino event. Therefore, according the EAP pattern, it could be "- + -" meridional circulation pattern. Please attention to this point and further properly modify the position A in Figure 13.*

Reply: Thanks for your insightful suggestion. The El Niño event related to EAP pattern (or PJ pattern) mainly appears in boreal summer. The present study focuses on the autumn season. We think Northeast Asian anticyclonic anomaly is not part of the EAP pattern, but rather a joint result of the mid-latitude Rossby wave train emanating from Atlantic to East Asia, and an anomalous local meridional circulation forced by western North Pacific SSTA.

Two pathways of how remote SST anomalies drive the interannual variability of autumnal haze days in the Beijing–Tianjin–Hebei region, China

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Abstract. Analogous to the circumstances in wintertime, the increasing severity of autumnal haze pollution over the Beijing–Tianjin–Hebei (BTH) region may also lead to impairment of the socioeconomic development and human health in this region. Despite manmade aerosol emissions, the interannual variability of autumnal (September–October–November) haze days (AHD) in the BTH region (AHD$_{BTH}$) is apparently tied to the global and regional meteorological anomalies. The present study suggests that an above-normal AHD$_{BTH}$ is closely associated with the simultaneous sea surface temperature (SST) warming in two regions [over the North Atlantic subtropical sector (R1) and over the western North Pacific sector (R2)]. ~~When the autumnal SST warming in R1 and R2 are both remarkably significant, the joint impacts can greatly enhance the likelihood of a higher AHD$_{BTH}$. Observational and simulation evidence suggests that SST anomalies can affect the variation in AHD$_{BTH}$ via two different pathways.~~ When the autumnal SST warming in R1 and R2 are both significant, the likelihood of a higher AHD$_{BTH}$ is greatly enhanced. Observational and simulation evidence demonstrated how remote SST anomalies over R1 and R2 influence variation of AHD$_{BTH}$ via two different pathways. Firstly, SST warming in R1 can induce a downstream mid-latitudinal Rossby wave train, leading to a barotropic high-pressure and subsidence anomaly over the BTH region. Secondly, SST warming in R2 can also result in air subsidence over the BTH region through an anomalous local meridional cell. Through these two distinct pathways, localized meteorological circumstances conducive to a higher AHD$_{BTH}$ (i.e., repressed planetary boundary layer, weak southerly airflow, and warm and moist conditions) can be established.

1 Introduction

Aerosol particles (APs) are ubiquitous in the ambient air. Through aerosol-induced thermal forcing, APs can exert profound impacts on regional and large-scale circulation (e.g., Chung et al., 2002; Lau and Kim, 2006; Lau et al., 2006; Liu et al., 2009; Li et al., 2016; Wu et al., 2016), as well as global warming (e.g., Charlson et al., 1992; Tett et al., 1999; Zhang et al., 2016). Notably, due to the property of light extinction related to high concentrations of APs, especially fine particulate matter [i.e., particulate matter (PM) with an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$)] (Guo et al., 2014; Wang et al., 2014; Li et al., 2017; Seo et al., 2017; Chen et al., 2018; Luan et al., 2018), severe haze weather with low visibility ~~and high concentrations of gas pollutants~~ can readily occur (Chen et al., 2012; Li et al., 2016; Ding et al., 2017; Seo et al., 2017; Chen et al., 2018).

In recent decades, observational evidence suggests that China has become one of the most severe AP-loading regions in the world (Tao et al., 2016; Li et al., 2016), arguably because of the ~~country's~~ nationwide rapid industrialization and urbanization (Xu et al., 2015; Zhang et al., 2016). High concentrations of APs can lead to the formation of severe haze weather via complicated interactions (Wang et al., 2014). Haze weather is not only harmful to the human respiratory and cardiovascular systems (Pope III and Dockery, 2006; Tie et al., 2009; Chen et al., 2013; Xu et al., 2013), but also influences vehicular traffic and crop yields (Chameides et al., 1999; Wu et al., 2005). As a result, haze pollution has received considerable attention from ~~both~~ the government and the public. Unfortunately, on the one hand, overwhelming industrialization leads to more severe haze contamination over the Beijing–Tianjin–Hebei (BTH) region (Yin~~ et al.~~ and Wang, 2016~~5~~); whilst on the other hand, the trumpet-shaped topography (Fig. 1) of the region is unfavorable for the dissipation of air pollution, thus making the BTH region home to some of the worst haze weather in China. Since the BTH region is the most economically developed region in North China and is at the heart of Chinese politics and culture~~ (not least because it is home to the capital city, Beijing, and Xiongan New Area, for instance)~~, severe haze pollution in this region has become a critical issue (e.g., Mu and Zhang, 2014; ~~Yin et al., 2015; ~~Wang, 2018), especially since the occurrence of the unprecedented severe haze event in North China in January 2013 (Wang et al., 2014; Zhang et al., 2014; Mu and Zhang, 2014; Tao et al., 2014; Zhang et al., 2015).

To date, numerous efforts have been made to explore the causes of wintertime haze pollution over the BTH region and its surroundings, and these ~~efforts~~ previous studies roughly fall into three categories ~~of results from~~ based on the climatological perspective. The first category~~ features studies that have~~ reported that the joint effects of the emissions of various sources of APs (e.g., Cao et al., 2007; Guo et al., 2011; Zhu et al., 2016) and climate anomalies (e.g., Chen and Wang, 2015; Wang and Chen, 2016; Yin and Wang, 2016~~a~~; Cai et al., 2017~~; Yin et al., 2017; Yin and Wang, 2018~~; Wang, 2018) may have brought about the increasing severity of haze pollution over China in recent decades. The second category of studies, meanwhile, underlines the causality of the variation in winter haze days in eastern and northern China from the perspective of climate anomalies (e.g., Li et al., 2016; Yin and Wang, 2016~~b~~; ~~Yin and Wang, 2018; ~~Pei et al., 2018). For instance, it is suggested that a weakened East Asian winter monsoon (EAWM) system ~~has been suggested as being responsible for~~ could lead to the above-normal numbers of winter haze days (e.g., Niu et al., 2010; Li et al., 2016; Yin and Wang, 2016~~a; Yin and Wang, 2017; Yin et al., 2017~~)~~;~~. ~~plus~~Meanwhile, the variability of EAWM~~'s variability~~ has been shown to be significantly tied to the East Atlantic–West Russia pattern~~ (Yin et al., 2017; Yin and Wang, 2017)~~ and Eurasian pattern (Zhang et al., 2016; Yin et al., 2017). The third category ~~of studies~~ focuses on the external forcings associated with the variability of winter haze days. These forcings include the sea surface temperature (SST) (e.g., Gao and Li, 2015; Wang et al., 2015~~; Yin and Wang, 2016a; Yin et al., 2017~~), Arctic sea ice (e.g., Wang et al., 2015; Zou et al., 2017), Eurasian snowpack (e.g., Yin ~~and Wang,~~ et al., 2017~~; Yin and Wang, 2018~~), and the thermal conditions on the Tibetan Plateau (e.g., Xu et al., 2016). However, most of these previous works have focused on wintertime, with little attention having been paid to other seasons.

Autumn is a transitional season from the wet and hot ~~conditions of~~ summer to the dry and cold ~~conditions of~~ winter. Climatologically, ~~T~~the weather in autumn over the BTH region is ~~climatologically~~ quite pleasant, with favorable temperatures and light winds. Outdoor activities and tourism are therefore prevailing ~~important, economically,~~ in the autumn season. However, ~~notably,~~ autumn is also a season in which haze weather frequently occurs in the BTH region (Chen and Wang, 2015~~), ~~). ~~and t~~The number of autumnal haze days (AHDs) has increased remarkably in recent years. Such an increase in the number of haze days is a potential threat to ~~the outdoor activities and~~ tourism economics in this region~~that, as mentioned, are so important to the region at this time of year~~. Therefore, research into the causes of the interannual variation in AHDs in the BTH region (AHD_{BTH}) is imperative. Such work not only provides scientific support to the year-to-year scheduling of anthropogenic emissions for dealing with autumnal haze pollution, but also helps the government with facilitating the arrangement of tourism economics~~tourism and outdoor activities~~. However, ~~as already mentioned,~~ compared to the myriad ~~publications~~ studies on wintertime haze pollution, autumn haze pollution over the BTH region has attracted far less attention, with only a few case studies on atmospheric circulation having been reported (Yang et al., 2015; Gao and Chen, 2017; Wang et al., 2018). It was this knowledge gap that motivated us to revisit the variability of AHD_{BTH}. Considering that the SST acts as a crucial driver of large–scale climate variability (e.g., Wang et al., 2009; Zhu et al., 2014; He and Zhu, 2015; Xiao et al., 2015; Zhu and Li, 2017; Zhu, 2018), we aimed to figure out the underlying air–sea interaction mechanisms for the interannual AHD_{BTH} variability in the present study.

The remainder of this paper is organized as follows. Section 2 introduces the data, model and methodology. Section 3 presents the atmospheric anomalies associated with AHD_{BTH}. Section 4 addresses the mechanisms ~~and pathways~~ of how remote SST anomalies (SSTAs) ~~in~~ drivinge the interannual variations of AHD_{BTH}. Conclusions and further discussion are provided in the final section.

2 Data, model and methodology

2.1 Data

The data used in this study are as follows: (1) monthly mean planetary boundary layer height (PBLH), with a 1° × 1° horizontal resolution, from the European Centre for Medium-Range Weather Forecasts Interim Reanalysis (ERA-Interim) (Dee et al., 2011); (2) monthly mean atmospheric data~~,~~ with a 2.5° × 2.5° horizontal resolution~~, from the National Centers for Environmental Prediction (NCEP) National Center for Atmospheric Research (NCAR) Reanalysis I (NCEP/NCAR) (Kalnay et al., 1996);~~ and total cloud cover (entire atmosphere considered as a single layer; 192 × 94 points in the horizontal direction)~~, also from NCEP/NCAR~~ from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) Reanalysis I (NCEP/NCAR) (Kalnay et al., 1996); (3) monthly mean SST, with a 2° × 2° horizontal resolution, of the Extended Reconstructed SST dataset, version 5 (ERSST.v5; Huang et al., 2017), from the National Oceanic and Atmospheric Administration (NOAA); (4) global monthly precipitation data, with a 2.5° × 2.5° horizontal resolution, from NOAA's precipitation reconstruction (Chen et al., 2002); (5) ground-timing observation datasets, at 02:00, 08:00, 14:00 and 20:00 BLT (Beijing local time), from the National Meteorological Information Center of China. The temporal coverage of the PBLH data is from 1979 to 2017, while the remaining datasets are from 1960 to 2017. Here, boreal autumn refers to the seasonal mean for September–October–November (SON).

2.2 Model

The numerical model ~~used here~~ we employed is an anomaly atmospheric general circulation model (AGCM) based on the Geophysical Fluid Dynamics Laboratory (GFDL) global spectrum dry AGCM (Held and Suarez, 1994)~~, which is employed to investigate the mechanisms for the atmospheric responses to the specified SST-induced heating~~. The horizontal resolution is T42, with five evenly spaced sigma levels (σ = p/ps; interval: 0.2; top level: σ = 0; bottom level: σ = 1). A realistic autumn mean state, obtained from the long-term mean of the NCEP/NCAR reanalysis data, is prescribed as the model basic state. This model has been used to unravel the eddy–mean interaction over East Asia and its downstream climate impacts ~~on~~ over North America ~~n climate~~ (Zhu and Li, 2016, 2018).

2.3 Methodology

The definition of a haze day in the present study is identical to ~~that used in~~ the previous studies (e.g., Chen and Wang, 2015~~; Yin et al., 2017; Pei et al., 2018~~). It is based on the ground-timing observations of relative humidity, visibility and wind speed. It is important to point out that the visibility observations switched from manual to automatic in 2014, and the visibility threshold for haze was thus also slightly modified from then on. Nevertheless~~However~~, the continuity of the data was not affected. Following Zhang et al. (2016), the mean number of haze days ($\overline{\mathrm{NHD}}$) for $\mathrm{AHD_{BTH}}$ was computed by:

$$\overline{\mathrm{NHD}}=\frac{1}{n}\sum_{i=1}^{n}N \qquad (1)$$

where n (here, n = 20) is the number of meteorological sites distributed within the BTH region (Fig. 1), and N denotes the number of haze days at a site for each autumn.

Similar to the approach proposed by Zhu and Li (2017), the 9-yr running mean of the $\mathrm{AHD_{BTH}}$ was used to represent the interdecadal component of the $\mathrm{AHD_{BTH}}$, whereas the interannual component was obtained by removing the interdecadal component from the raw $\mathrm{AHD_{BTH}}$. Since there is a tapering problem when calculating the running mean, the first four years and the last four years of the interdecadal component of the $\mathrm{AHD_{BTH}}$ could be estimated by the mean value of the available data with a shorter window. For example, the interdecadal component of the $\mathrm{AHD_{BTH}}$ for 2016 and 2017 could be obtained by the mean of 2012–17 and 2013–17, respectively. Note that the temporal correlation coefficients (TCCs) between the $\mathrm{AHD_{BTH}}$ and every single stations~~site~~ were all positive and significant (Fig. 1), indicating the coherency ~~in~~ of the interannual variability of autumnal haze days in each station over the BTH region;~~ plus~~meanwhile, the distribution of these ~~sites~~ stations was ~~also~~ fairly even. Therefore, the interannual component of the $\mathrm{AHD_{BTH}}$ could be ~~used as~~ a good representation of the year-to-year pollution state over the whole BTH region in autumn.

Linear regression, composite analysis and correlation were used to examine the ~~associated~~ circulation and SST~~As~~ anomalies that associated with the interannual $\mathrm{AHD_{BTH}}$. The two-tailed Student's t-test was employed to evaluate the statistical significance of these analyses. The wave activity flux (WAF; Takaya and Nakamura, 2001) was calculated to depict the tendency of Rossby wave energy propagation.

3 Atmospheric anomalies associated with the interannual changes of $\mathrm{AHD_{BTH}}$

Figure 2 illustrates the time series of the raw $\mathrm{AHD_{BTH}}$, along with its interdecadal and interannual components. A prominent feature is that the $\mathrm{AHD_{BTH}}$ displays both interannual and interdecadal variability. On the interdecadal timescale, the $\mathrm{AHD_{BTH}}$ was below average during 1960–1975 and the late-2000s, but above average during 1975–2003, and it increased dramatically after 2009. On the interannual timescale, the $\mathrm{AHD_{BTH}}$ presents large differences year ~~on~~ by year. For example, the $\mathrm{AHD_{BTH}}$ was at its lowest in 2012, but peaked in 2014. Since the interannual variability explains most of the total variances in the $\mathrm{AHD_{BTH}}$ variability, in this study we ~~only~~ investigate the atmospheric anomalies and unravel the underlying physical processes ~~mechanisms and pathways associated~~ that associated with the $\mathrm{AHD_{BTH}}$ on the interannual timescale.

Close scrutiny of the large-scale and localized dynamic and thermodynamic fields associated with the $\mathrm{AHD_{BTH}}$ ~~should help in~~ could advanc~~eing~~ our understanding of the ~~possible~~ underlying mechanisms. In this regard, we firstly examine the climatological mean autumnal 500-hPa geopotential height (Z500), 850-hPa winds (UV850) and total cloud, along with the surface relative humidity and surface air temperature that potentially impact the climate over the BTH region (Fig. 3). There is a shallow mid-tropospheric trough over coastal East Asia (Fig. 3a), which resembles the trough in winter (Zhao et al., 2018; Pei et al., 2018) but with a smaller magnitude. Behind the trough, a clear anticyclonic circulation appears over the central-eastern China, with remarkable westerly/northwesterly winds dominating the BTH region (Fig. 3a). ~~Cold~~ Cool and dry air from higher latitudes is advected by the winds, and the BTH region is thus much cooler and drier and has less cloud than other regions at the same latitudes (e.g., the central ~~portion of~~ Japan). As such, the autumnal BTH region features breezy and windy conditions ~~climatologically~~, with low surface relative humidity (Fig. 3b), reducing the likelihood of haze there via the effect of cold advection~~/~~ and ventilation effect. Note, however, that if the breezy conditions are interrupted, haze pollution ~~may be enhanced~~ is likely to occur. One may ask whether a higher AHD_{BTH} is related to the interference of such breezy conditions. Figures 4 and 5 were therefore plotted to examine the associated atmospheric parameters/circulations. For simplicity, the regression and composite analyses in this study reported hereafter are interpreted with respect to positive phase of AHD_{BTH} anomalies only.

Previous studies have revealed that haze pollution is closely correlated with local meteorological parameters in the planetary boundary layer (e.g., You et al., 2017; Chen et al., 2018). Figure 4 suggests that an above-normal AHD_{BTH} is tied to a localized increase ~~enhancement~~ of surface relative humidity (Fig. 4a) and surface air temperature (Fig. 4b), along with suppressed surface wind speed (Fig. 4c), sea-level pressure (SLP) (Fig. 4d) and PBLH (Fig. 4e). ~~Specifically, it seems that autumnal haze pollution is more significantly correlated with temperature and PBLH~~. The question is~~So~~, what causes the above anomalous parameters that are favorable for a higher AHD_{BTH}?

Figure 5 shows the associated large-scale atmospheric circulation anomalies at different levels of troposphere. ~~From~~ In Figs. 5a–5d, the most noticeable feature is that there is a planetary-scale, quasi-barotropic Rossby wave train emanating from the North Atlantic subtropical sector. In addition to an anticyclonic anomaly centered over the North Atlantic subtropics, this teleconnection pattern has another two pairs of anomalous cyclones (low pressure) and anticyclones (high pressure) stretching across Eurasia to the ~~North Pacific~~ Northeast Asia, i.e., a cyclonic anomaly centered over the ocean south of Greenland, an anticyclonic anomaly centered over Scandinavia, a cyclonic anomaly centered over the adjacent central Siberia, and an ~~Northeast Asian~~ anticyclonic anomaly centered over the Sea of Japan (SJ). In general, based on the regressed atmospheric fields, the teleconnection has a much larger amplitude in the upper troposphere (Fig. 5a)~~, rather~~ than that in the mid-troposphere (Fig. 5b) and lower troposphere (Fig. 5c). Intriguingly, from the surface projection of the above quasi-barotropic teleconnection pattern, we can discern a positive phase of North Atlantic Oscillation -like mode in connection with this pattern (Hurrell and Deser, 2009).

Among all the height anomalies within the teleconnection, the anomalous quasi-barotropic Northeast Asian anticyclonic anomaly centered over the SJ (A_{SJ}) plays a direct role in driving a higher AHD_{BTH}. The related physical~~physico~~-meteorological causes are as follows: There are southerly/southeasterly anomalies along the western flank of the A_{SJ} in the lower troposphere (Figs. 5c and 5d), manifesting the capability of suppressed atmospheric horizontal diffusion and thus favoring a buildup of substantial local and nonlocal APs and warmer moisture over the BTH region (Yang et al., 2015; Yang et al., 2016) under the specific topographical forcing of the Taihang Mountains and Yan Mountains (Fig. 1). On the other hand, the significant positive pressure anomaly in the mid-to-upper parts of the A_{SJ} (Figs. 5a and 5b) not only impedes the intrusion of cold air into the BTH region, but also facilitates consistent air subsidence over the BTH region and its surrounding areas (Fig. 4f), resulting in the decrease of the PBLH and increaseamplification of static stability (i.e., the dampened vertical dispersion of the atmosphere). Consequently, the meteorological conditions connected to a higher AHD_{BTH} are adverse toquite different from the autumn climate mean stateclimatological characteristics (Fig. 3).

To summarize, the A_{SJ} and the associated subsidence can induce the capacity for suppressed local horizontal and vertical dispersion over the BTH region and its surrounding areas, as shown in the above-mentioned anomalous parameters in the boundary layer (Fig. 4); and these parameters are further responsible for the accumulation and secondary formation/hygroscopic growth of APs (Jacob and Winner, 2009; Ding and Liu, 2014; Mu and Liao, 2014; Jia et al., 2015). As such, the haze pollution over the BTH region is readily established within a narrow space. Therefore, The the question of how the above-normal AHD_{BTH} is stimulated could plausibly be transferred into questioning the pathways of how the A_{SJ} is developed and sustained. In fact, the A_{SJ} and the associated air subsidence are modulated by remote SSTAs. We tackle the underlying mechanismsthis issue in the next section.

4 Possible mMechanisms of the $A_{SJ}$and pathways

4.1 Observational diagnoses

Figure 5c shows that an above-normal AHD_{BTH} is closely correlated with SST warming in two key regions: One is the North Atlantic subtropical sector (R1: 22°–32°N, 90°–40°W), and the other is the western North Pacific sector (R2: 10°–30°N, 108°–140°E), with its southern portion belonging to the Western Pacific Warm Pool (You et al., 2018). One may ask why we chose these two key SSTA regions. Firstly, the subtropical North Atlantic SSTA is the only region over North Atlantic that highly correlated with the AHD_{BTH} on interannual timescale. Although the regression SSTA pattern over North Atlantic looks like a tri-pole SST pattern which has profound impacts on Eurasian climate, the relationship between AHD_{BTH} and simultaneous NAT SST pattern is insignificant. The correlation coefficient between AHD_{BTH} and NAT SST triple-pole index (Deser and Michael, 1997) is only 0.17. Therefore, we chose the middle oceanic region of North Atlantic as the key region for AHD_{BTH}. Secondly, the positive correlated SSTA over R1 and R2 region can both induce positive rainfall anomaly (diabatic heating), the SSTA should play an active role in local air-sea interaction and in turn influence the large-scale circulation. Therefore, we chose the R1 and R2 as the key SSTA regions from both statistical diagnosis and physical basis. Meanwhile, from Fig. 5e we can discern that enhanced and significant precipitation appears to the north of R1, indicating an active atmospheric response to the SST warming over R1; whereas, there is an insignificant positive precipitation signal over R2 and its surrounding areas. Figure 6 further depicts that the SON SSTs over both R1 and R2 are positively correlated with AHD_{BTH}, and the TCC between the AHD_{BTH} and SON SST over R1 (R2) is 0.45 (0.28), exceeding the 99% (95%) confidence level. By virtue of the above analyses, we speculate that the SST over R1 may play a more important role than that over R2 in driving a higher AHD_{BTH}. Note, however, that when the SON SSTs over R1 and R2 are both obviously elevated, the AHD_{BTH} is more likely to be higher than normal, such as in 1980, 1987 and 2015. Furthermore, aAs indicated above, the AHD_{BTH} is closely correlated with the A_{SJ} and the associated air subsidence, which allows us to speculate that the positive SSTAs over R1 and R2 might drive the interannual variability of AHD_{BTH} by modulating the intensity of the A_{SJ} and associated subsidence. To validate this hypothesis, we firstly examine the pathway of SSTAs over R1 in driving AHD_{BTH}.

Figure 5c suggests that the SST warming in R1 may induce larger-area concomitant low-level easterly anomalies to its east, leading to anticyclonic wind shear over this region, which mainly form over the southeastern portion of R1 and the area to its south. In such a scenario, an anticyclonic anomaly is induced (Fig. 5c), with its center to the northeast of R1. Along the western flank of this anticyclonic anomaly, warm and moist airflows move northwards. When these warm and moist airflows meet cold air mass in the areas to the north of R1, enhanced precipitation is thus generated (Fig. 5e). Meanwhile, the resultant enhanced rainfall condensation heating induces a cyclonic anomaly to its north, thereby exciting the other two pairs of the aforementioned teleconnection pattern along the westerly jet, as demonstrated by the Rossby wave train induced by SST warming in R1 (Figs. 7 and 8). Specifically, from the regressed SON UV850 (Fig. 7), we can see that the SST warming in R1 can indeed induce a significant low-level teleconnection pattern arising from the North Atlantic subtropics, bearing a close resemblance to that in Fig. 5c; and to the north of R1, where the rainfall condensation heating is triggered, the corresponding WAF exhibits a distinctive arc-shaped trajectory, perturbing the other two pairs of cyclones and anticyclones of the teleconnection (Fig. 8). This teleconnection extends from the North Atlantic towards Scandinavia, goes through the Eurasia and arrives at the Northeast Asiawestern North Pacific. Therefore, by means of this trajectory, Rossby wave energy in the middle (Fig. 8b) and upper (Fig. 8a) troposphere may propagate southeastwards into the A_{SJ} and its surrounding region, favoring the formation/sustainability of the A_{SJ} and the associated air subsidence. In this context, the associated meteorological parameters (Fig. S1), which resemble those tied to a higher AHD_{BTH} (Fig. 4), might increase the likelihood of SON haze pollution over the BTH region. Again, this induced teleconnection is quasi-barotropic in structure, with its magnitude larger in the upper troposphere (Fig. 8a), which is consistent with that in Fig. 5a.

As for the role ofWhen focusing on region R2 SSTA warming (Fig. 9a), we find that, corresponding to the SSTAs over R2, there exists a cyclonic anomaly to the west of R2. Besides, substantial SSTA-induced low-level easterly anomalies are appeared to mainly located to the southeast of R2; meanwhileplus, a large-scalehuge anticyclonic anomaly to the northeast is excited, with its center situated over the northern Pacific. In such a scenario, R2 is thoroughly controlledpenetrated by significant warm and humid airflows transported from the eastern flank of the cyclonic and the western flank of anticyclonic anomaly respectively (Fig. 9a), warming the SST over R2. Furthermore, the airflow convergence primarily occurs over the southwestern portion of R2, where the strongly significant and positive rainfall anomaly is triggered (Fig. 9b). Thus, the enhanced significant rainfall heating perturbation may greatly intensify the ascending motion over R2 and the adjacent region, resulting in subsidence over the BTH region and Northeast Asia via an anomalous local meridional cell (Fig. 10a). As such, the BTH region and its adjacent areas areis dominated by significant warm temperatures in the middle and upper troposphere (Fig. 10b),); leading to the maintenance and reinforcement ofand the A_{SJ} and , the downward motions over the BTH region, as well as the regional low-level stability over BTH, are maintained and reinforced. Under such circumstances, the vertical transport of APs is restricted (Zhang et al., 2014; Pei et al., 2018), and the near-surface winds are weakened (Li et al., 2016). Meanwhile, tThe parameters associated with SST warming in R2 (Fig. S2) also support the formation of haze weather over the BTH region.

4.2 Numerical model simulations

Two experiments were conducted to further validate the above-mentioned two pathways in of how SSTAs drive the variation of AHD_{BTH}. The first experiment (H_NAS) simulated the responses to the heating induced by SSTAs over R1 (Fig. 11). H_NAS was imposed with a specified heating centered over the region to the north of R1 (center: 37.67°N, 64.69°W) that largely matched with the SON positive rainfall anomaly as shown in Fig. 5e. The second experiment (H_WNP) mimicked the responses to the prescribed heating over the neighboring areas of R2 (center: 15.35°N, 109.69°E; Fig. 12), where the corresponding regressed precipitation rate was the most significant~~ and amplified~~, as exhibited in Fig. 9b. The heating had a cosine-squared profile in an elliptical region in the horizontal direction. The maximum heating, with 1 K day^{-1} amplitude, was set to be at 300 hPa.

Figure 11 presents the 200- and 500-hPa geopotential height and wind responses to the specified heating over the North Atlantic subtropical region. As anticipated, the equilibrium state (mean output from day 40 to day 60) of the Z200 (Fig. 11a) and Z500 (Fig. 11b) responses to the heating resembles the aforementioned teleconnection (Figs. 5a and 5b), and the simulated response of the Z200 anomalies is generally larger than its counterpart at 500 hPa (Fig. 11b), which concurs with the observational evidence. Besides, a similar low-level portion of the A_{SJ} could also be simulated (figure not shown). As a result, a strengthened A_{SJ} is induced.

Figure 12 delineates the 850-hPa geopotential height (Z850) and UV850 responses to the specified heating centered at (15.35°N, 109.69°E). Although there are some differences in spatial distribution compared with the observations, the well-organized cyclonic anomaly to the west of the heating center and the anticyclonic anomaly over Northeast Asia~~to the north~~ can be ~~properly~~ well simulated (Fig. 12). Meanwhile, the A_{SJ} and the coherent tropospheric subsidence over the BTH region and the Northeast Asian anticyclonic anomaly were also simulated well (figure not shown~~omitted~~)~~, leading to the amplified A_{SJ} as well~~.

To sum up, from observational diagnoses and numerical simulations, we can conclude that there are two pathways regarding how remote SSTAs impact the formation and maintenance of the A_{SJ} and the associated air subsidence. One pathway operates via a heating-induced large-scale teleconnection pattern arising from SST warming in R1, and the other is connected to an anomalous local meridional cell triggered by heating-reinforced ascending motion via local SST warming over R2.

5 Conclusions and discussion

Motivated by a lack of in-depth understanding with respect to the interannual variations of the AHD_{BTH}, in the present study we explored the related climate anomalies (localized meteorological parameters, and large-scale atmospheric and oceanic anomalies) tied to the AHD_{BTH}. We have substantiated that an above-normal AHD_{BTH} is closely correlated with the simultaneous SST warming in two key regions (R1 over the North Atlantic subtropical sector, and R2 over the western North Pacific sector), and once the SON SST warming in R1 and R2 are both remarkably significant, their joint climate impacts can greatly enhance the likelihood of an above-normal AHD_{BTH}.

Potential mechanisms associated with an above-normal AHD_{BTH} have been proposed through further investigations. Since the A_{SJ} and the associated subsidence over the A_{SJ} and the surrounding region can yield meteorological circumstances conducive to enhancing the likelihood of haze pollution in the BTH region, the issue of an above-normal AHD_{BTH} can be reasonably transferred into uncovering how the SON A_{SJ} and associated air subsidence are developed and sustained. We found that there are two possible pathways. First, SST warming in R1 can induce a downstream Rossby wave teleconnection, and the associated Rossby wave energy can propagate into Northeast Asia~~the A_{SJ} and its surrounding region~~ through an arc-shaped trajectory, developing and strengthening the A_{SJ} and the associated subsidence over BTH. The other pathway, however, operates through localized heating-reinforced ascending motion over R2, also resulting in subsidence over the BTH region~~ and Northeast Asia~~ via an anomalous local meridional cell.

AGCM simulations supported ~~reinforced~~ our hypothesis. With prescribed heating over the region to the north of R1, a quite similar teleconnection—starting from the North Atlantic subtropics—was excited. If we imposed an idealized heating over the adjacent R2, where the corresponding precipitation rate was the most significant~~ and amplified~~, the ~~concomitant~~ significant low-level convergence around the heated areas was simulated, ~~enhancing the SST warming in R2 and~~ inducing the A_{SJ}-resembled circulation to the north and the subsidence over the BTH region~~ and Northeast Asia~~. However, because the model we used is an intermediate anomaly AGCM, and the heating prescribed in the model is idealized, the simulated patterns were slightly spatially different to those observed. Although the model cannot reproduce the geopotential height and wind anomalies perfectly, it can ~~nonetheless~~ still support ~~the~~ our proposed mechanisms. As a summary, a schematic illustration (Fig. 13) of the occurrence of a higher AHD_{BTH} is provided, which encapsulates the major characteristics of the two pathways of how remote SSTAs over R1 and R2 drive the AHD_{BTH} respectively.

From the perspective of seasonal prediction, among all the previous individual months of boreal summer (June–July–August), the SON SST in R1 (R2) was most significantly correlated with the August SST in R1 (R2) on the interannual timescale, with a TCC of 0.35 (0.61) that exceeded the 95% (99%) confidence level. This suggests that, when the August SST over R1 (R2) is higher, the subsequent SON SST over R1 (R2) is more likely to become warmer. As such, the previous August SSTA over R1 (R2) could serve as a possible precursor for the seasonal prediction of the AHD_{BTH}.

In this study, we solely emphasize the potential impacts of SSTAs on the interannual variations of the AHD_{BTH}. It should be noted that other external forcings, such as the Arctic sea ice (e.g., Wang et al., 2015), Eurasian snowpack~~ (e.g., Yin and Wang, 2018)~~, thermal conditions on the Tibetan Plateau (e.g., Xu et al., 2016) and soil moisture~~ (e.g., Yin and Wang, 2016b)~~, may also exert profound impacts on haze pollution over China. Studying the mechanisms tied to these forcings may enhance the seasonal predicting skill for the AHD_{BTH}. Meanwhile, in this study, we only focus on the variability of AHD_{BTH} on interannual timescale. Whether the proposed mechanism of AHD_{BTH} is still at play on intraseasonal timescale? Is it possible for making an extended-range forecast of the occurrence of haze days? ~~This~~ These ~~is an important~~ topics are of both scientific and practical importance, and merit~~deserving of~~ further explorations.

Data availability. The atmospheric data and land-surface data are available from the NCEP/NCAR data archive: http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html (NCEP/NCAR, 2018). The SST data were downloaded from https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html (NOAA, 2018). The precipitation data were downloaded from https://www.esrl.noaa.gov/psd/data/gridded/data.prec.html (NOAA, 2018). The monthly PBLH data are available on the ERA-Interim website: http://www.ecmwf.int/en/research/climate-reanalysis/era-interim (ERA-Interim, 2018). The ground observations are from the National Meteorological Information Center of China (http: //data.cma.cn/) (CMA, 2018).

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

Author contributions. JW analyzed the observational data, ZZ and JW designed the numerical experiments. JW and ZZ wrote the manuscript. LQ, QZ, JH and JXW were involved in the scientific interpretation and discussion.

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Figures Captions

Figure 1. Topographic map (shaded; m) for the BTH region and the locations of 20 meteorological sites (colored dots). The dots colored red (light red; magenta) represent significant positive temporal correlation coefficients at the 99% (95%; 90%) confidence level between the AHD_{BTH} and AHD for every individual site on the interannual timescale.

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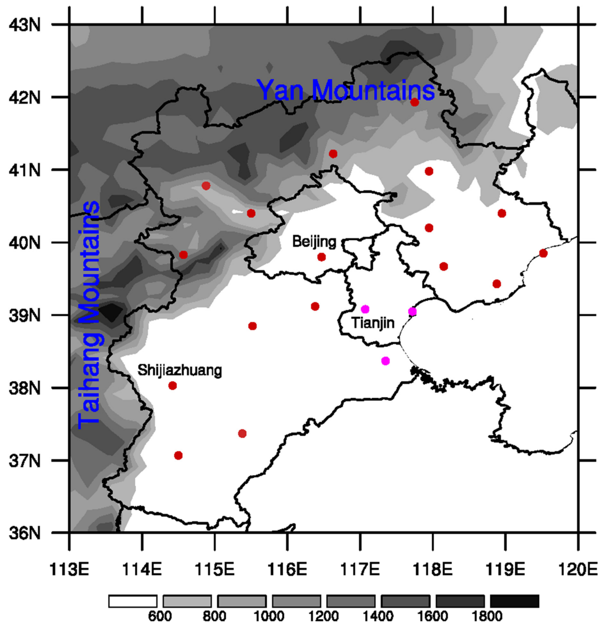

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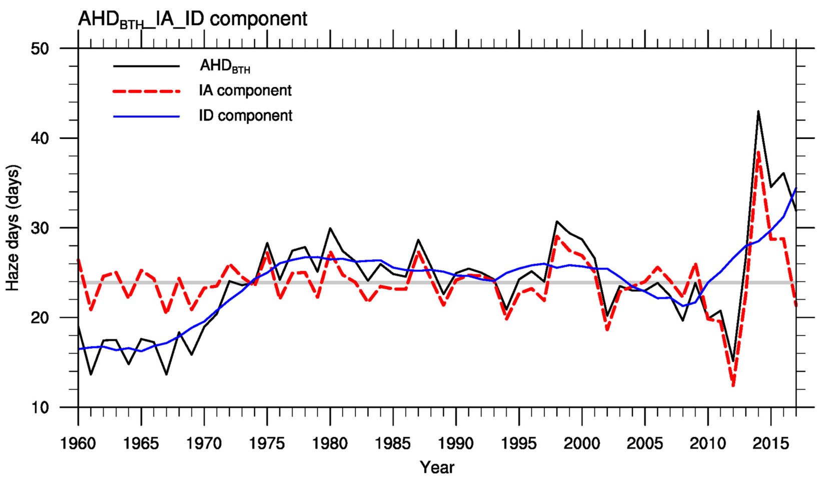

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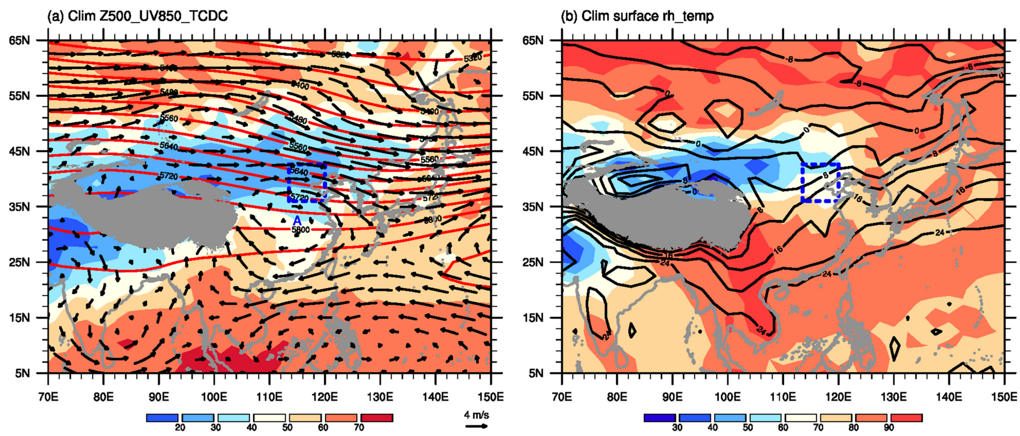

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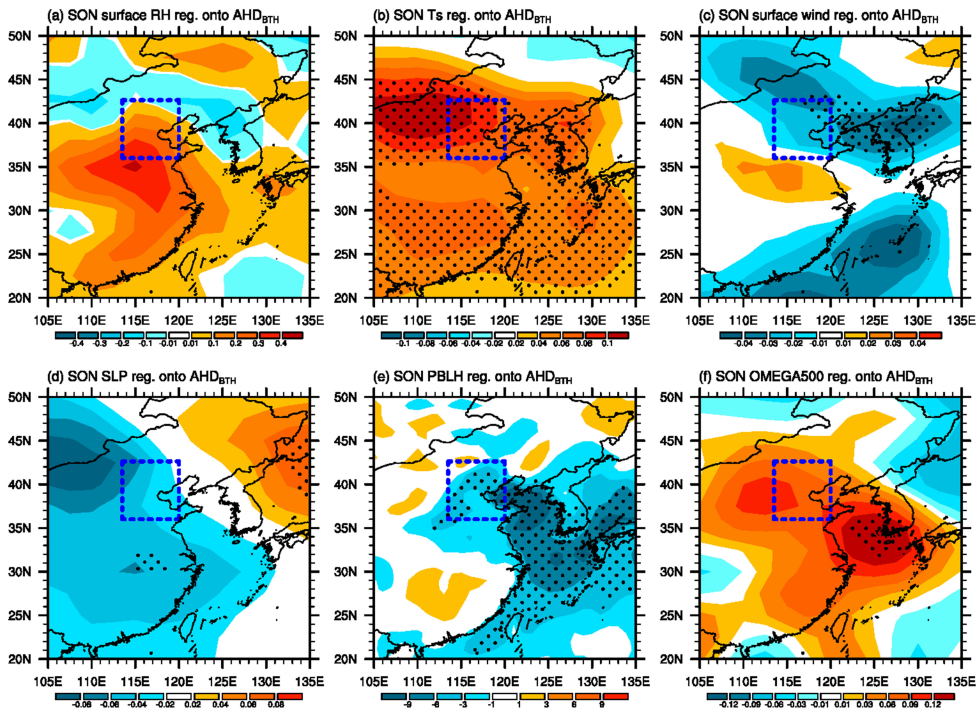

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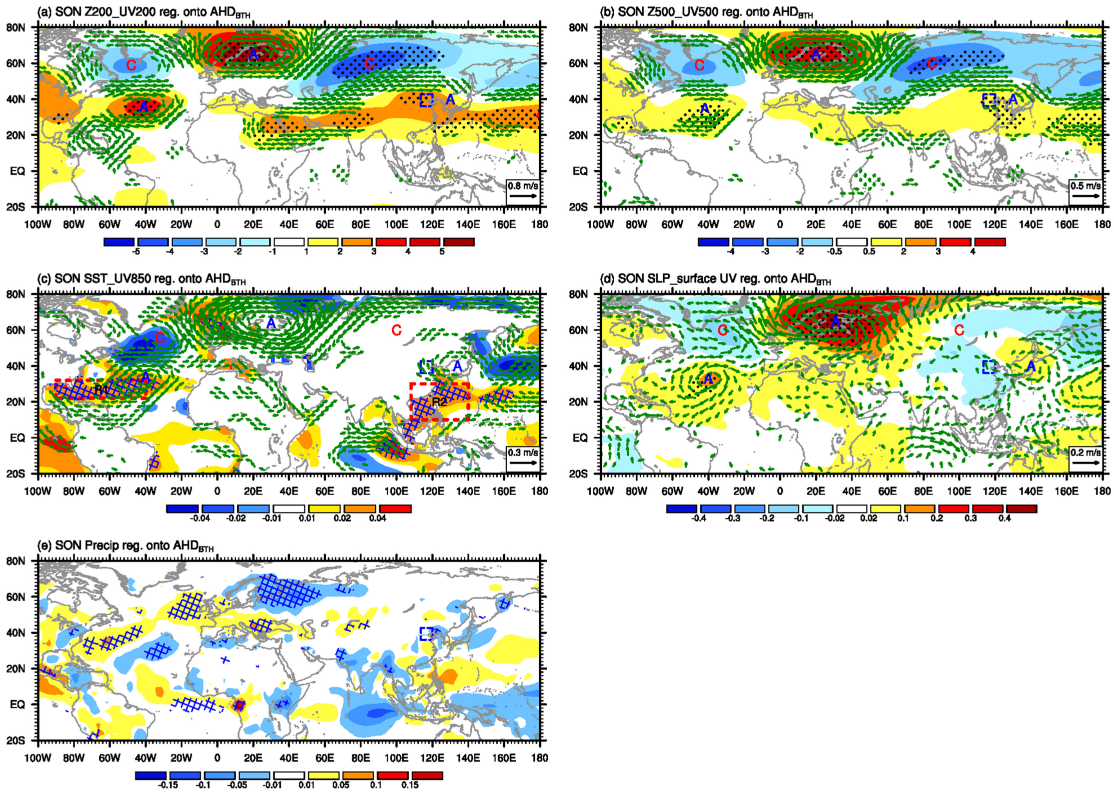

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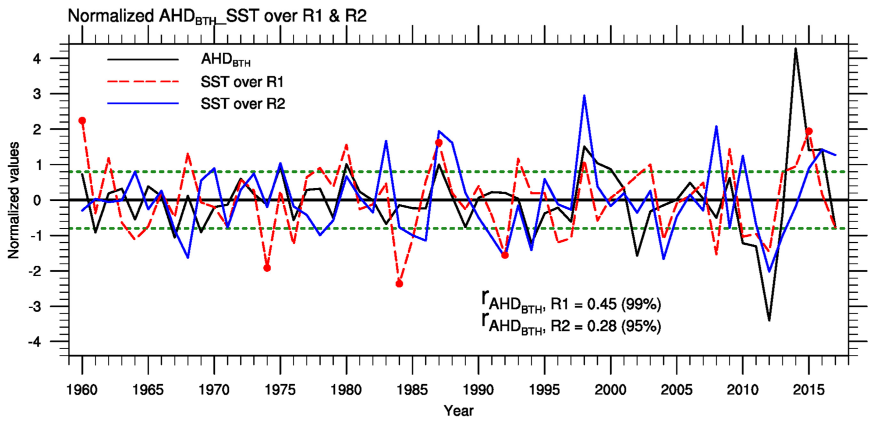

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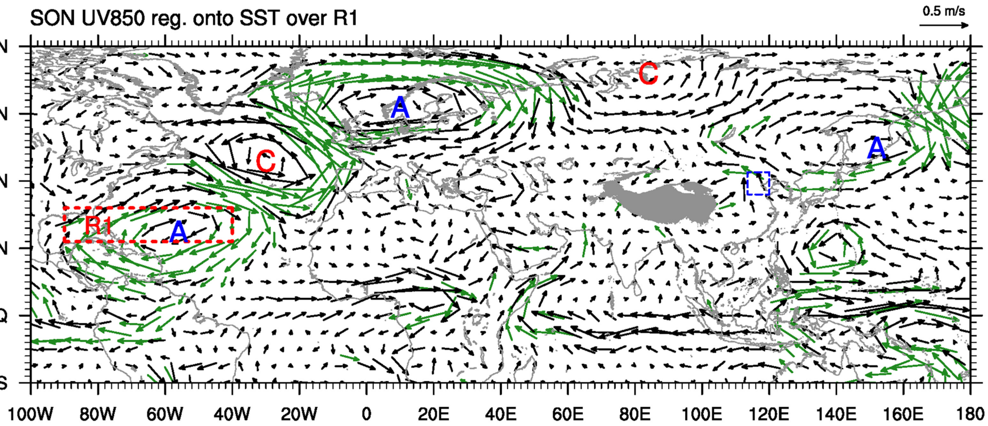

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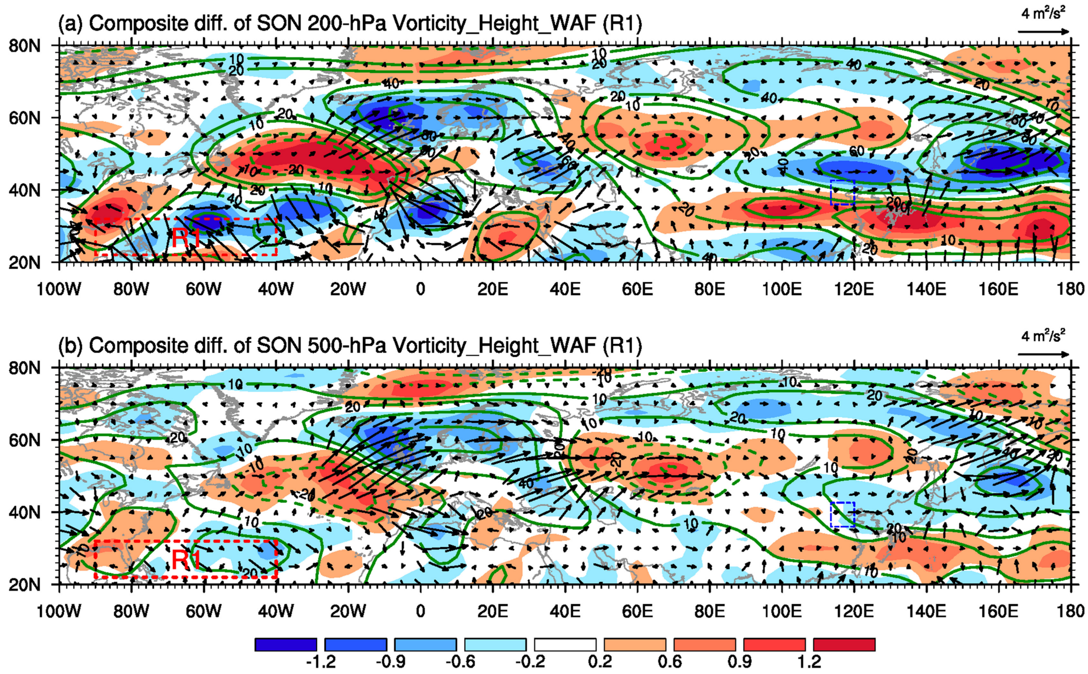

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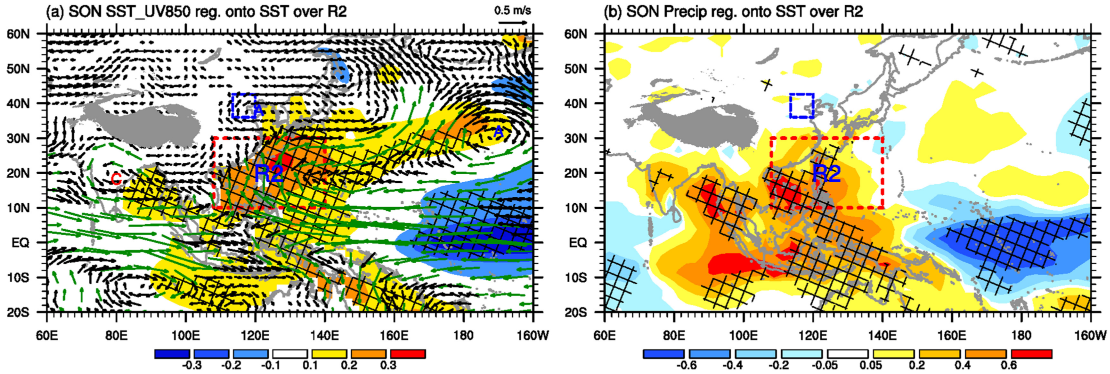

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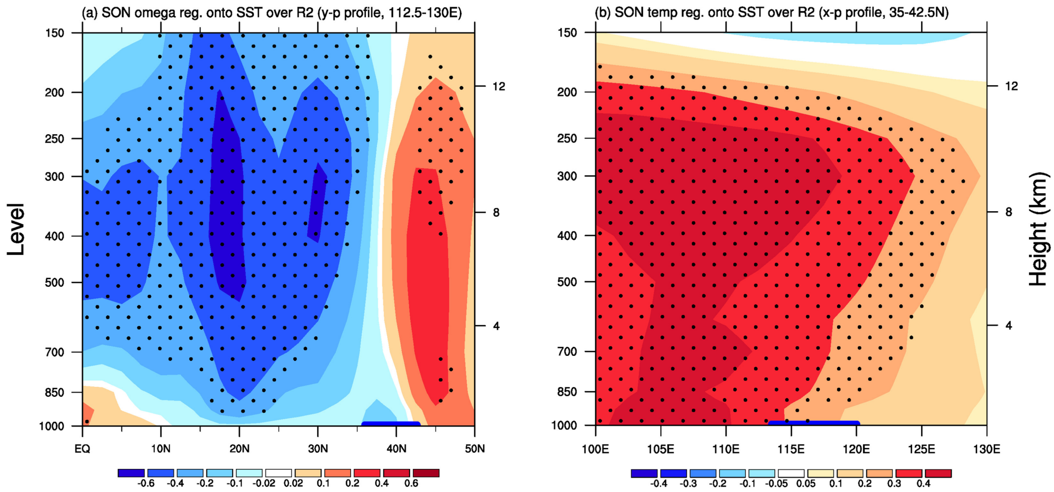

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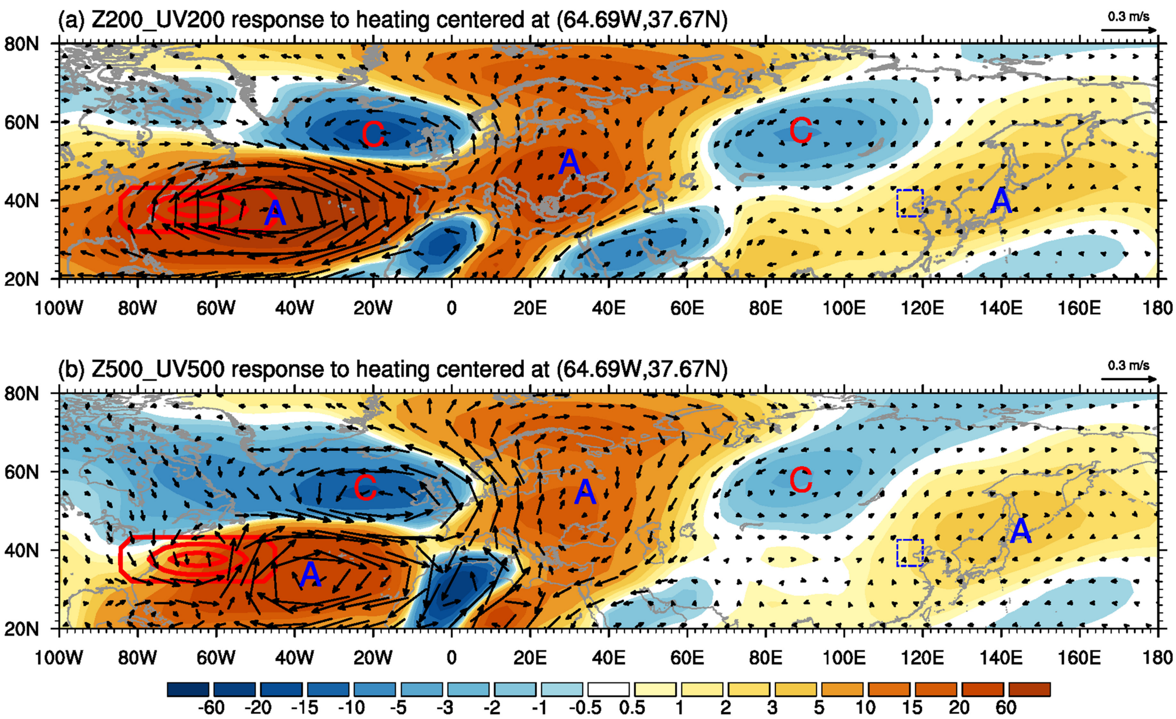

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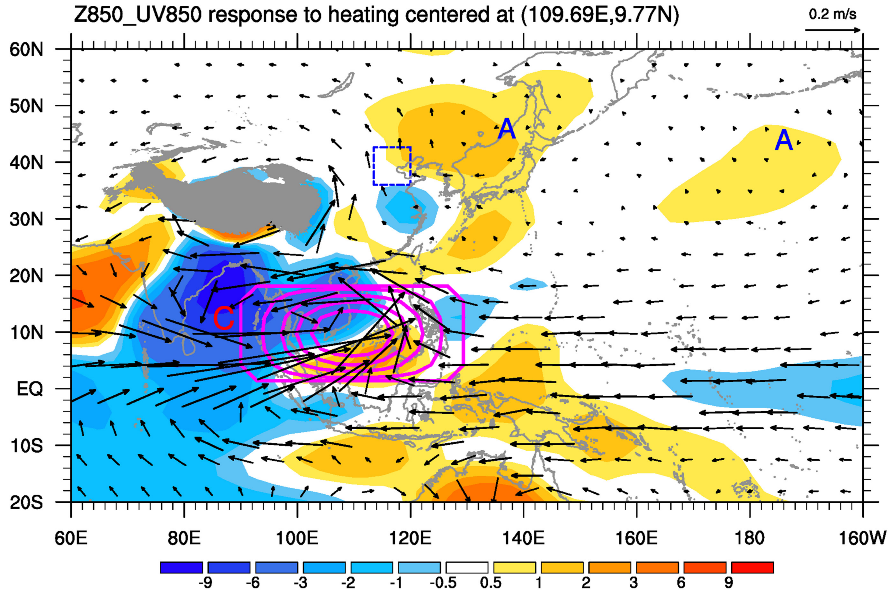

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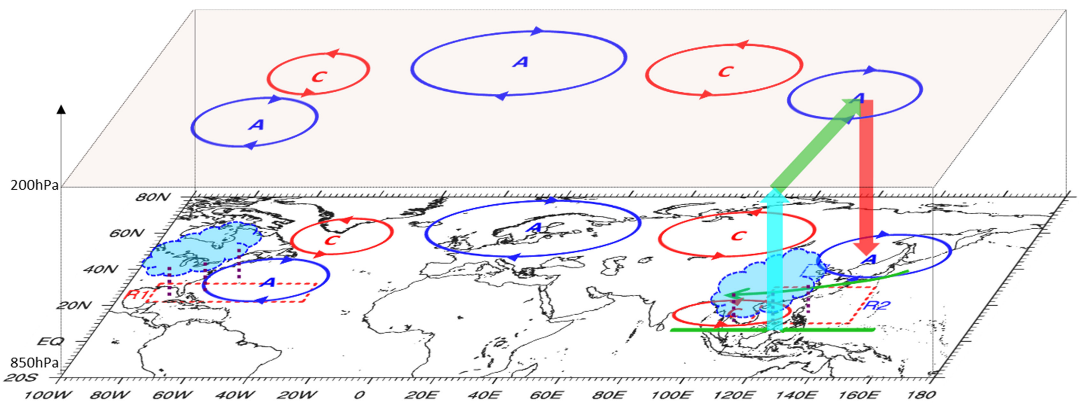

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