Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-99
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 11 February 2019

Atmospheric Chemistry and Physics
Open Access
Discussions

Quantifying the contribution of anthropogenic influence to the East Asian winter monsoon in 1960–2012

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Abstract

The East Asian winter monsoon (EAWM) can be greatly influenced by many factors that can be classified as anthropogenic forcing and natural forcing. Here we explore the contribution of anthropogenic influence to the change in the EAWM over the past decades. Under all forcings observed during 1960–2013 (All-Hist run), the atmospheric general circulation model is able to reproduce the climatology and variability of the EAWM-related surface air temperature and 500 hPa geopotential height, and shows a statistically significant decreasing EAWM intensity with a trend coefficient of ~ −0.04 yr^{-1} which is close to the observed trend. By contrast, the simulation, which is driven by the same forcing as All-Hist run but with the anthropogenic contribution to them removed, shows no decreasing trend in the EAWM intensity. By comparing the simulations under two different forcing scenarios, we further reveal that the responses of the EAWM to the anthropogenic forcing include a rise of 0.6℃ in surface air temperature over the East Asia as well as weakening of the East Asia trough, which may result from the poleward expansion and intensification of the East Asian jet forced by the change of temperature gradient in the troposphere. Additionally, compared with the simulation without anthropogenic forcing, the frequency of strong (weak) EAWM occurrence is reduced (increased) by 45% (from 0 to 10/7). These results indicate that the weakening of the EAWM during 1960–2013 may be mainly attributed to the anthropogenic influence.

Key words: anthropogenic influence, East Asian winter monsoon, contribution

1. Introduction

The East Asian winter monsoon (EAWM) is one of the most dominant climate systems in East Asia. It greatly affects the disastrous winter weather such as cold waves, snowstorms, air pollutions, and spring duststorms (Li et al., 2016; Li and Wang, 2013; Wang et al., 2009; Zhou et al., 2009; Chang et al., 2006). Prominent circulation components from surface to the upper troposphere associated with temperature condition during the boreal winter are dynamically linked to the EAWM. At surface, the EAWM contains the cold Siberian high dominated over the East Asian continent and the warm Aleutian low located in the high-latitude North Pacific, which accompanies with prevailing northwesterly winds in the low-level troposphere (He and Wang, 2013; Wang and Jiang, 2004; Gong et al., 2001; Guo 1994; Lau and Li, 1984). At 500 hPa locates the East Asian trough which determines the outbreak and intensity of the EAWM (He et al., 2013; Cui and Sun, 1999; Sun and Li, 1997). In the upper troposphere, a key component of the EAWM is the East Asian jet with its maximum core being located to the southeast of Japan (Jhun and Lee, 2004; Boyle and Chen, 1987). Concurrent with the change of these atmospheric circulation, the change of winter surface air temperature (SAT) over East Asia is closely related to the variation in the EAWM (Hao and He, 2017; Lee et al., 2013; Wang et al., 2010).

Above primary components of the EAWM system are subject to obvious changes under the influence of global warming (e.g., Li et al., 2018; Li et al., 2015; IPCC, 2013; Hori and Ueda, 2006; Kimoto, 2005; Zhang et al., 1997). Under different global warming scenarios, thermodynamic contrast between the East Asian continent and the Pacific Ocean is reduced uniformly characterized with weakening of the East Asian trough (EAT) as well as the East Asian jet, indicating a weakening of the EAWM (e.g., Xu et al., 2016; Kimoto, 2005). Previous studies based on Coupled models generally agree on the effect of global warming on the EAWM (Hong et al., 2017; Xu et al., 2016; Kimoto, 2005; Hu et al., 2000). However, previous studies mainly conduct qualitative research on the potential influence of the global warming, it's still unclear to what extent can the anthropogenic activities impact the EAWM. This study aims to quantitatively estimate the contribution of increasing anthropogenic emissions over the past decades to the change of the EAWM, which is essential for the projection of the EAWM in the future.

2. Data and Method

Monthly mean dataset including SAT, 500 hPa geopotential height and 250 hPa zonal wind is obtained from National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 dataset at a horizontal resolution of 2.5° × 2.5° (Kalnay et al., 1996). Hereafter it is referred to as "observations". To explore the contribution of the anthropogenic emissions to climate change, two different simulations from the C20C+ Detection and Attribution Project (http://portal.nersc.gov/c20c/data.html) are compared in the context of two different forcing scenarios. One is the ***All-Hist*** which was forced with time-vary boundary conditions (e.g., greenhouse gas concentrations, anthropogenic and natural aerosols, ozone, solar luminosity, land cover, sea surface temperatures and sea ice) observed during the past few decades. The other is the ***Nat-Hist*** which was forced with observed sea surface temperature and sea ice concentrations from which the anthropogenic contribution has been removed (please refer to http://portal.nersc.gov/c20c/data.html for more details). Meanwhile, the natural external forcing such as greenhouse gas concentrations and aerosols was set to preindustrial levels. We analyses the simulations by an atmospheric general circulation model HadGEM3-A-N216 (Christidis et al., 2013; approximately 0.56° × 0.83° horizontally) available from the C20C+ Detection and Attribution, which has been used to conduct the above two sets of experiments from 1960 to 2013. Both

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-99
Manuscript under review for journal Atmos. Chem. Phys.
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All-Hist and Nat-Hist runs include 15 ensemble members. Each realization in the two scenarios differs from the other only in its initial state. The ensemble-mean of the runs number 1, 2, 5, 13, 14, and 15 (which show a better performance in simulating interannual, decadal and linear trend change of EAWM) under the All-Hist scenarios agrees best with the reanalysis dataset (such as climatology, interannual and decadal change of EAWM; evaluation of other runs of model shown in supplementary). Therefore, the simulations of these 6-members ensemble are used in this study.

In this study, we focus on the winter mean which is the average of December, January and February (e.g., the winter 2008 refers to the boreal winter of 2008/2009). Two intensity indices are used to describe the variability of the EAWM: one is defined as the area-averaged height geopotential at 500 hPa in 35°–45°N, 125°–145°E (EAWMI_HGT; Sun and Li, 1997); the other is defined as the area-averaged SAT in 25°–45°N, 105°–145°E (EAWMI_SAT; Lee et al., 2013). Both area-averaged values are multiplied by -1 so that positive values correspond to strong EAWM; 9-year running mean of the index represents the interdecadal variability of the EAWM.

3. Results and Discussions

3.1 Assessment of the atmospheric circulation pattern simulated by model in All-Hist runs

The EAWM is characterized by northerly winds over East Asia, the Siberian high, the Aleutian low, the deep East Asian trough, the upper tropospheric East Asian jet stream, as well as the cold and dry conditions over East Asia (e.g., Hao et al., 2016; Lee et al., 2013; He and Wang, 2013; Wang and Jiang, 2004; Sun and Li, 1997). In this study, the performance of the HadGEM3-A-N216 model in simulating the above characteristics of the EAWM is firstly evaluated by comparing the corresponding results in the All-Hist runs with reanalysis dataset in the period of 1960–2012.

Figures 1a-d show the climatology of the SAT and 500 hPa geopotential height in winter from the observations and simulations in the All-Hist run. The winter SAT climatology over East Asia in simulations (Fig. 1a) is generally consistent with the

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observed counterpart (Fig. 1b). The model has successfully reproduced the dominant features of East Asian winter SAT such as the northwest-to-southeast temperature gradient, the 0°C isotherm of SAT stretching from western China (around 27.5°N) northeastward to north Japan (around 42.5°N), the cold center located over the Tibetan Plateau (Figs. 1a and 1b). Compared with the observations, the simulated SAT shows apparent cold bias over the north of 40°N but less bias over the south of 40°N. In the middle troposphere, the main features (position of axis and intensity) of the EAT are also generally reproduced by the model. The simulated SAT in 25°–45°N, 105°–145°E (Lee et al., 2013) and 500 hPa geopotential height in 35°–45°N, 125°–145°E (Sun and Li, 1997) used for the EAWM indices show high spatial correlations with the observations (Fig. 1e), which are exceed 0.99. Additionally, high spatial correlations of the simulated SAT and 500 hPa geopotential height with the observation are accompanied by small root mean square errors (Fig. 1e). It means that the All-Hist runs have well simulated the EAWM climatology.

The variability of the EAWM is also compared between the simulations and the observations. It is found that the correlations between the simulated EAWM indices and the observed EAWM indices are 0.3 for EAWMI_SAT and 0.31 for EAWMI_HGT, respectively (Fig. 2), which are statistically significant. Additionally, the interdecadal variability of the EAWM indices are closely correlated between the simulations and the observation with correlation coefficients of 0.7 for EAWMI_SAT and 0.76 for EAWMI_HGT (Fig. 2). The result suggests that the All-Hist runs have well simulated the interannual and interdecadal variability of the EAWM and can be further used to investigate the anthropogenic impact on the EAWM.

3.2 Contribution of anthropogenic influence to the East Asian winter monsoon

To investigate the anthropogenic contribution to the change of the EAWM, we compare the EAWM in the All-Hist runs with those in the Nat-Hist runs. Both of the EAWM indices in the All-Hist runs show statistically significant decreases over the past decades, with trend coefficients of −0.044 (yr^{-1}) and −0.038 (yr^{-1}), respectively, which are similar to the observed trends (-0.023 and -0.02, respectively; Fig. 2). By contrast, the EAWM indices in Nat-Hist run show an increasing trend, instead (Fig. 2). It suggests that the increasing anthropogenic emissions in the past decades may contribute to the weakening of the EAWM.

Figure 3 displays the composited differences of the simulated winter SAT and 500 hPa geopotential height between the All-Hist runs and in the Nat-Hist runs, which approximately reflect the response of the EAWM to anthropogenic forcing. The composited differences show clearly that winters with anthropogenic forcing see apparent warmer anomalies over most parts of East Asia except for southeast China as well as warmer conditions over the western North Pacific (Fig. 3a). Such a response is similar to the one revealed by previous CMIP5 studies (Hong et al., 2017; Xu et al. 2016). Xu et al. (2016) suggested that the large positive anomalies over high-latitude western North Pacific are due to a north ward shift of the significantly intensified Aleutian low induced by the melting sea ice in the Bering Sea and Okhotsk Sea (Gan et al., 2017). Quantitatively, compared with the situation without anthropogenic influence, the wintertime SAT averaged over (20°–60°N, 100°–140°E) increases by 0.6°C over the last half-century due to anthropogenic influence (Fig. 3a). At middle troposphere, responses of the 500 hPa geopotential height to anthropogenic forcing shows obviously positive anomalies over East Asia with a value of 15.7 m, implying a shallower EAT which results in less powerful cold air to East Asia (Fig. 3b). The model simulations indicate clearly that the anthropogenic influence may induce a weaker EAWM.

It should be noted that, in the low-level troposphere, the high-latitude warming induced by the anthropogenic forcing is apparently stronger than the warming at lower-latitudes (Fig. 4a), which is the so-called "polar amplification" (Meehl et al., 2007; Collins et al., 2013). Meanwhile, in the high-level troposphere, obviously warming occurs over the tropical regions and the Arctic, but cooling occurs over the high-latitude regions under the anthropogenic influence (Fig. 4a). As a result, a broadening and intensifying Hadley circulation appears, which is consistent with the observed phenomena revealed by previous studies that a poleward expansion and intensification of the winter Hadley circulation in the past few decades (Hu and Fu, 2007; Mitas and Clement, 2005; Hu et al., 2005). Such a change in the Hadley circulation implies a poleward shift of the East Asian jet (Fig. 4b), together with a reinforcement and expansion of Western Pacific subtropical high and an increase of SLP in the high-latitude East Asia (Fig. 4c). The change of SLP also indicates a weak decrease of the Siberian high and an intensified Aleutian low. Thus, under the anthropogenic influence, significant easterly anomalies occur in the mid- and high-latitude of East Asia and significant southerly anomalies occur in the low-latitude of East Asia (Fig. 4c), leading to a subdued EAWM. We further explore the contribution of anthropogenic influence to the occurrence of strong/weak EAWM. The case with the normalized index larger than 1.0 (smaller than −1.0) is defined as a strong (weak) EAWM event. The number of the strong/weak EAWM events is shown in Fig. 5. The two observed EAWM indices display 10 (8) and 9 (9) strong (weak) EAWM events during 1960–2012, respectively. Interestingly, the two simulated EAWM indices in the All-Hist run display 11 (10) and 11 (7) strong (weak) EAWM events, respectively. The number of strong or weak EAWM events forced by the observed time-varying boundary conditions during the past few decades (All-Hist run) is very close to the number in observations. However, during 1960–2012, the simulated two EAWM indices in the Nat-Hist runs display 21 (0) and 19 (0) strong (weak) EAWM events, which is remarkably different from the number in the All-Hist runs as well as the observations. It implies that, in the past decades, the frequency of occurrence of strong EAWM may have reduced by 45% due to the anthropogenic forcing and the anthropogenic forcing is a dominant contributor to the occurrence of weak EAWM.

4 Conclusion

The contribution of the anthropogenic influence to the climatology, trends, and the frequency of occurrence of strong/weak EAWM is explored in this study based on numerical simulations. Firstly, we evaluate the performance of the climate model (HadGEM3-A-N216) in simulating the climatology of wintertime circulation over

East Asia and variation of EAWM indices during 1960–2012. The winter-mean states of SAT and 500 hPa geopotential height related to the EAWM in the All-Hist runs resemble well those in observation with spatial correlation coefficients of greater than 0.99. Also, the interannual and interdecadal variation of the EAWMI_HGT and EAWMI_SAT can be well reproduced by the model under All-Hist scenario. Because of the well performance of the All-His runs in simulating the EAWM indices and winter-mean atmospheric circulation over the East Asia, the exploration about changes of the EAWM induced by anthropogenic influence is considered reliable.

Under All-Hist scenario, the EAWM indices have significantly decline trends over the past decades, which are consistent with those in observations, indicating that the weakening of the EAWM could be simulated by the climate model with all forcing. However, the EAWM indices do not have such trends in the Nat-Hist runs. Compared the area-averaged SAT and 500 hPa geopotential height related to the EAWM for the period of 1960–2012 between two families of experiments, it is found that anthropogenic emissions induce obviously positive SAT anomalies in the most region of East Asia and a weakened EAT, as shown in previous results (Hu et al., 2000; Hori and Ueda, 2006; Xu et al. 2016; Hong et al., 2017; Hong et al., 2017). Additionally, 11 (11) strong EAWM events and 10 (7) weak EAWM events are forced by All-Hist scenario during 1960–2012, which are close to the frequency of occurrence of strong and weak EAWM in observations, while 21 (19) strong EAWM events and 0 (0) weak EAWM event are forced by Nat-Hist scenario. Overall, under anthropogenic influence, during 1960–2012, the EAWM continued to be weakened, and the frequency of occurrence of strong (weak) EAWM had decreased (increased) by 45% (from 0 to 10/7). The poleward expansion and intensification of East Asian jet induced by anthropogenic influence may be the reason for the weakening of the EAWM. A decrease trend is found both in observation and in the All-Hist runs, therefore more attention should be given to the EAWM variability under anthropogenic influence.

Author contributions. Xin Hao conceived the idea for the study and wrote the paper. All authors contributed to the development of the method and to the data analysis.

Acknowledgements

This work was supported by the National Science Foundation of China (Grant 41421004, 41875118, 41605059 and 41505073). All datasets can be accessed publicly. The NCEP analysis dataset can be downloaded from https://www.esrl.noaa.gov/psd/data, and the simulations can be downloaded from http://portal.nersc.gov/c20c/data.html.

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Figure caption:

Figure 1 Climatology of winter-mean (DJF) (a) surface air temperature (shading, °C) (c) 500 hPa geopotential height (shading, m) during 1960–2012, based on NCEP reanalysis data. (b), (d) As in (a), (b), but for the model's All-Hist runs. (e) Taylor diagram of winter-mean climatology for surface air temperature (TAS; 25°–45°N, 105°–145°E) and 500 hPa geopotential height (H500; 25°–45°N, 105°–145°E). The rectangle marks the areas used to calculate the climatology in taylor diagram.

Figure 2 (a) The time series of the normalized EAWMI_SAT (curve) and their linear trend (line) during 1960–2012, based on NCEP reanalysis dataset (top), outputs of model in All-Hist run (middle), and outputs of models in Nat-Hist run (bottom). (b) As in (a), but for the EAWMI_HGT. "tr" is an abbreviation for "linear trend coefficient". "*"means the tr is significant at 95% confidence level based on the Mann-Kendall test, and "’ " means the tr is significant at 90% confidence level. "cor" is an abbreviation for "correlation coefficient between simulated EAWM index under All-Hist scenario and observed EAWM index", "cor_dec" is an abbreviation for "correlation coefficient in decadal time-scale". Note that the time series of the EAWM indices base on outputs of model in the Nat-Hist runs are standardized by the climatology simulated by the All-Hist runs.

Figure 3 Composite differences of winter-mean (a) surface air temperature (shading, ℃) and (b) 500 hPa geopotential height (shading, m) between the All-Hist runs and Nat-Hist runs, during 1960–2012. The plus signs denotes where the composite differences are significant at the 95% confidence level based on two-sided Student *t* test.

Figure 4 Composite differences of winter-mean (a) air temperature (shading, ℃) over 90 °E–150 °E, (b) 250 hPa zonal wind (shading, m/s) and (c) sea level pressure (shading, hPa) and 850 wind (vector, m/s) between the All-Hist runs and Nat-Hist runs, during 1960–2012. Red contours denote the climatology of All-Hist runs. The plus signs denotes where the composite differences are significant at the 95% confidence level based on two-sided Student *t* test.

Figure 5 (a) The number of strong EAWM events during 1960–2012, based on NCEP reanalysis dataset (left), outputs of model in the All-Hist runs (middle), and outputs of model in the Nat-Hist runs (right). (b) As in (a), but for weak EAWM events.

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Figures

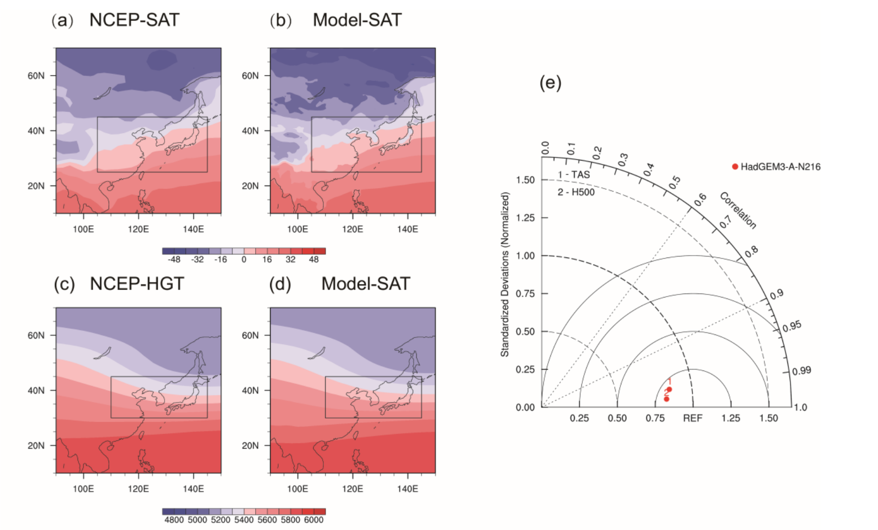

Figure 1 Climatology of winter-mean (DJF) (a) surface air temperature (shading, °C) (c) 500 hPa geopotential height (shading, m) during 1960–2012, based on NCEP reanalysis data. (b), (d) As in (a), (b), but for the model's All-Hist runs. (e) Taylor diagram of winter-mean climatology for surface air temperature (TAS; 25°–45°N, 105°–145°E) and 500 hPa geopotential height (H500; 25°–45°N, 105°–145°E). The rectangle marks the areas used to calculate the climatology in taylor diagram.

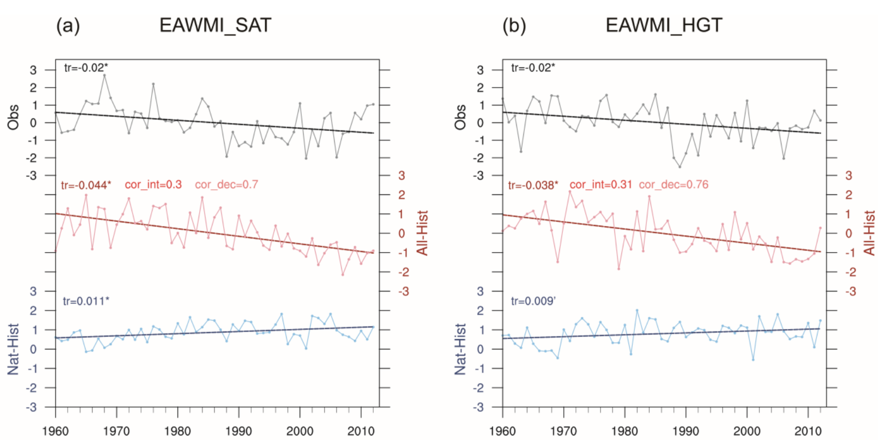

Figure 2 (a) The time series of the normalized EAWMI_SAT (curve) and their linear trend (line) during 1960–2012, based on NCEP reanalysis dataset (top), outputs of model in All-Hist run (middle), and outputs of models in Nat-Hist run (bottom). (b) As in (a), but for the EAWMI_HGT. “tr” is an abbreviation for “linear trend coefficient”. “*”means the tr is significant at 95% confidence level based on the Mann-Kendall test, and “’ ” means the tr is significant at 90% confidence level. “cor” is an abbreviation for “correlation coefficient between simulated EAWM index under All-Hist scenario and observed EAWM index”, “cor_dec” is an abbreviation for “correlation coefficient in decadal time-scale”. Note that the time series of the EAWM indices base on outputs of model in the Nat-Hist runs are standardized by the climatology simulated by the All-Hist runs.

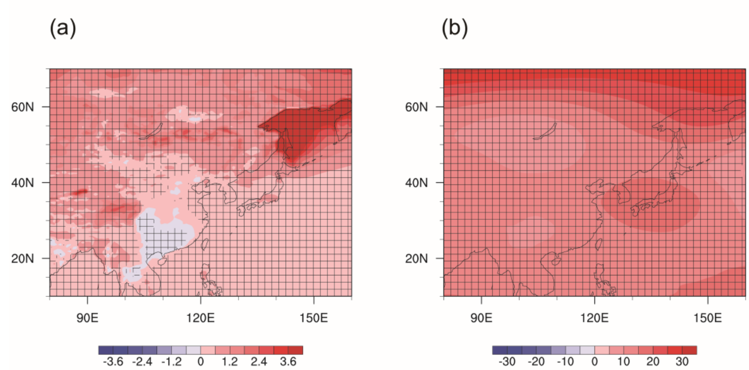

Figure 3 Composite differences of winter-mean (a) surface air temperature (shading, ℃) and (b) 500 hPa geopotential height (shading, m) between the All-Hist runs and Nat-Hist runs, during 1960–2012. The plus signs denotes where the composite differences are significant at the 95% confidence level based on two-sided Student *t* test.

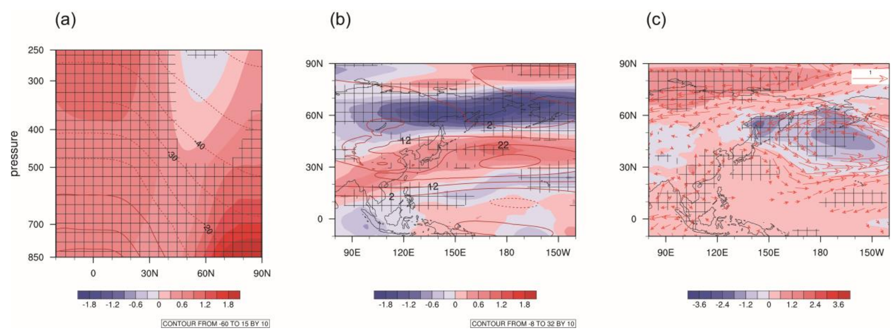

Figure 4 Composite differences of winter-mean (a) air temperature (shading, ℃) over

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-99
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 11 February 2019

Atmospheric Chemistry and Physics
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90 °E–150 °E, (b) 250 hPa zonal wind (shading, m/s) and (c) sea level pressure (shading, hPa) and 850 wind (vector, m/s) between the All-Hist runs and Nat-Hist runs, during 1960–2012. Red contours denote the climatology of All-Hist runs. The plus signs denotes where the composite differences are significant at the 95% confidence level based on two-sided Student *t* test.

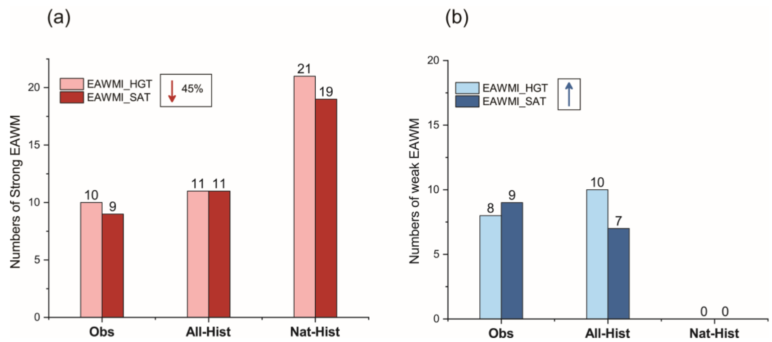

Figure 5 (a) The number of strong EAWM events during 1960–2012, based on NCEP reanalysis dataset (left), outputs of model in the All-Hist runs (middle), and outputs of model in the Nat-Hist runs (right). (b) As in (a), but for weak EAWM events.