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Impact of Direct Radiative Forcing of Anthropogenic Aerosols on Diurnal Temperature Range in January in Eastern China

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Abstract This study investigates the changes in January diurnal temperature range (DTR) in China during 1961–2000. The observed DTR changes during 1981–2000 relative to 1961–80 are first analyzed based on the daily temperature data at 546 weather stations. These observed DTR changes are classified into six cases depending on the changes in daily maximum and minimum temperatures, and then the occurrence frequency and magnitude of DTR change in each case are presented. Three transient simulations are then performed to understand the impact of greenhouse gases (GHGs) and aerosol direct forcing on DTR change: one without anthropogenic radiative forcing, one with anthropogenic GHGs, and another one with the combined forcing of GHGs and five species of anthropogenic aerosols. The predicted daily DTR changes during the years 1981–2000 are also classified into six cases and are compared with the observations. Results show that the previously proposed reason for DTR reduction, a stronger nocturnal warming than a daytime warming, explains only 19.8% of the observed DTR reduction days. DTR reductions are found to generally occur in northeastern China, coinciding with significant regional warming. The simulation with GHG forcing alone reproduces this type of DTR reduction with an occurrence frequency of 32.9%, which is larger than the observed value. Aerosol direct forcing reduces DTR mainly by daytime cooling. Consideration of aerosol cooling improves the simulation of occurrence frequencies of different types of DTR changes as compared to the simulation with GHGs alone, but it cannot improve the prediction of the magnitude of DTR changes.

Keywords: diurnal temperature range, greenhouse gases, anthropogenic aerosols, aerosol direct effect

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1 Introduction

The surface diurnal temperature range has been decreasing over the continents since 1950 with an average trend of −1.4°C per hundred years (Karl et al., 1993). The most significant decrease has been observed at high latitudes in the Northern Hemisphere. Many studies based on either observations or model simulations have discussed possible mechanisms of the daily asymmetric temperature change. The proposed reasons included that the rate of increase in annual minimum temperature was larger than that of the increase in annual maximum temperature (Karl et al., 1993; Yan and Zhang, 1993; Easterling et al., 1997). Diurnal temperature range (DTR) reductions in a warming climate are likely associated with large changes in cloud, soil moisture, and snow cover (Cao et al., 1992; Karl et al., 1993; Stone and Weaver, 2002, 2003; Zhang et al., 2009). Zeng et al. (1993) and Dai et al. (1999) systematically studied the effects of cloud, surface humidity, soil moisture, surface wind, and precipitation on DTR based on observations. It has also been proposed that DTR can be influenced by CO_2 and water vapor that absorb radiation in infrared bands (Stenchikov and Robock, 1995) and by vegetation feedbacks (Collatz et al., 2000).

The changes in DTR may be a result of both natural climate variability and anthropogenic forcings. Karl et al. (1993) reported that aerosols increase clear-sky albedo and tend to reduce maximum temperature and thereby DTR. Stenchikov and Robock (1995) found that with fixed cloud covers, when aerosols provide diurnal average cooling, the accompanying decrease in water vapor in the atmosphere leads to less absorption of the solar radiation and increased downward solar flux. Hansen et al. (1995) compared the effects of different external forcings on DTR and found that the changes in solar radiation, stratospheric aerosols, or greenhouse gases cannot fully explain the observed DTR changes. Recently, Zhou et al. (2010) simulated the anthropogenic forcing effect on DTR and stated that the smaller predicted DTR reductions compared with observations might be partly due to the lack of some major aerosol species in their model.

In this paper, we aim to study the impacts of direct radiative forcing of anthropogenic aerosols on diurnal temperature changes in China during 1961–2000. The issues we are concerned with are the following: 1) Is aerosol's direct effect on DTR significant when all major anthropogenic aerosol species are considered? 2) Is aerosol's effect on DTR mainly though reducing the daily maximum temperature? 3) Does the relative importance of aerosol's direct effect on daily DTR change when compared to GHG forcing?

2 The model and experimental design

The model used in this study is a unified tropospheric chemistry-aerosol model in the Goddard Institute for

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Space Studies (GISS) general circulation model (GCM) II' (Liao et al., 2003, 2004, 2006; Liao and Seinfeld, 2005). The GISS GCM II' has a horizontal resolution of 4° (latitude) by 5° (longitude) and 9 σ vertical layers from the surface to 10 hPa (Rind and Lerner, 1996). The GCM is coupled with a mixed-layer ocean. The model includes 225 chemical species and 346 reactions for simulating gas-phase species and tropospheric aerosols, including sulfate, nitrate, ammonium, black carbon (BC), primary organic aerosol (POA), and secondary organic aerosol (SOA). BC is assumed to be internally mixed with other aerosol species. Our previous study showed that this model can reproduce the interdecadal change of annual mean surface air temperature in the presence of aerosol forcings (Chang et al., 2009).

We performed three ensemble transient climate simulations for the years 1951 to 2000. The control experiment (CTRL) has concentrations of GHGs and aerosols fixed at 1951 levels. The second experiment (GHG) is performed with annual changes in concentrations of CO_2, CH_4, and N_2O over 1951–2000, but aerosols are fixed at 1951 concentrations. The annual GHGs concentrations are interpolated based on the values in the IPCC (Intergovernmental Panel on Climate Change) Third Assessment Report. The third experiment, denoted as GHGAER, includes changes in concentrations of both GHGs and aerosols over 1951–2000. Aerosols considered include sulfate, nitrate, BC, POA, and SOA, the concentrations of which are simulated online every 10 years during 1951–2000 based on the IPCC Fifth Assessment Report historical emissions inventories (Lamarque et al., 2010). These concentrations are then linearly interpolated during each decade of our climate simulations.

The differences in experiments (GHG–CTRL, GHGAER–GHG, and GHGAER–CTRL) represent the effect of GHGs, the effect of aerosols, and the combined effect of GHGs and aerosols on DTR, respectively. A decrease in DTR can occur in the following cases: (1) a nocturnal warming exceeds a daytime warming, (2) a nocturnal warming occurs with a daytime cooling, and (3) a daytime cooling exceeds a nocturnal cooling. Thus, according to the changes in daily maximum (ΔT_{max}) and minimum temperature (ΔT_{min}), days with reduced DTR are classified as case D1 ($\Delta T_{min}>\Delta T_{max}>0$), case D2 ($\Delta T_{min}>0>\Delta T_{max}$), and case D3 ($0>\Delta T_{min}>\Delta T_{max}$), respectively. Similarly, days with increased DTR are divided into case I1 ($\Delta T_{max}>\Delta T_{min}>0$), case I2 ($\Delta T_{max}>0>\Delta T_{min}$), and case I3 ($0>\Delta T_{max}>\Delta T_{min}$), respectively. We focus on the prediction of DTR in January over the past decades because aerosol direct radiative forcing is the largest in winter in China (Chang and Liao, 2009).

DTR changes based on the observed temperatures are calculated. The daily maximum and minimum temperatures are taken from the historical (1961–2000) homogenized daily records at 549 stations in China (Li and Yan, 2009, 2010). These station records are firstly averaged over each grid cell of the model. The change in DTR is calculated as the difference between the periods of 1981–2000 and 1961–80. Hence, the occurrence frequency (days of occurrence of the above cases) and intensity (absolute change in DTR) of the six cases are based on data from 620 days (31 days × 20 years). The predicted occurrence frequency and intensity of DTR changes are also carried out in each model grid cell. We did not study differences between two periods in any one experiment because aerosol effects might be masked by model noise on an interdecadal time scale. Because one of our objectives is to compare the relative importance of GHGs and aerosols in predicting changes in DTR, we examine GHG–CTRL, GHGAER–GHG, and GHGAER–CTRL for the years 1981–2000.

3 Results

3.1 Observation

The observed changes in occurrence frequency and intensity of each DTR case are averaged over the whole of China as presented, respectively, in Table 1 and Table 2. The DTR in January decreased by 0.22°C during 1981–2000 relative to 1961–80. In the 620 days (31 days × 20 years) with observations, 55.8% of the days had DTR reductions with an averaged reduction of 0.7°C,

Table 1 Comparisons of the changes in occurrence frequency (%) in six DTR cases between the observations and the predictions. The predicted change in occurrence is the percentage difference between the experiments in January of 1981–2000, whereas the observational percentage change is the difference during the years of 1981–2000 relative to 1961–80. Underlined numbers denote that compared to GHG effect, aerosols reduce the predicted absolute bias of occurrence frequency exceeding 2% or reduce the bias of DTR change magnitude more than 0.1°C; the numbers in brackets denote that aerosol direct forcing does not improve prediction.

		OBS	GHG	AER	GHG –OBS	GHGAER –OBS	GHGCOOL –OBS	GHGBC –OBS
Case D1	$\Delta T_{min}>\Delta T_{max}>0$	19.8	32.9	12.0	13.1	<u>6.1</u>	<u>6.0</u>	12.7
Case D2	$\Delta T_{min}>0>\Delta T_{max}$	17.6	12.0	12.3	−5.6	−4.0	<u>−3.7</u>	(−5.9)
Case D3	$0>\Delta T_{min}>\Delta T_{max}$	18.4	8.9	26.0	−9.5	<u>−3.9</u>	<u>−3.6</u>	(−9.7)
Sum of decrease DTR		55.8	53.8	50.3	−2.0	−1.8	−1.3	(−2.9)
Case I1	$\Delta T_{max}>\Delta T_{min}>0$	20.7	28.8	12.2	8.1	<u>1.7</u>	<u>1.2</u>	(9.0)
Case I2	$\Delta T_{max}>0>\Delta T_{min}$	12.0	9.4	12.2	−2.6	−1.6	−1.5	−2.4
Case I3	$0>\Delta T_{max}>\Delta T_{min}$	11.5	8.0	25.3	−3.5	<u>1.7</u>	<u>1.6</u>	(−3.7)
Sum of increase DTR		44.2	46.2	49.7	2.0	1.8	1.3	(2.9)
Total		100.0	100.0	100.0	0.0	0.0	0.0	0.0

Table 2 Same to table 1 but for the change of intensity (°C).

		OBS	GHG	AER	GHG –OBS	GHGAER –OBS	GHGCOOL –OBS	GHGBC –OBS
Case D1	$\Delta T_{min}>\Delta T_{max}>0$	–0.54	–0.56	–0.16	–0.02	(0.12)	(0.12)	0.01
Case D2	$\Delta T_{min}>0>\Delta T_{max}$	–1.00	–0.43	–0.39	0.56	0.52	0.50	(0.59)
Case D3	$0>\Delta T_{min}>\Delta T_{max}$	–0.56	–0.13	–0.42	0.44	0.32	0.34	0.44
Average of decrease DTR		–0.70	–0.37	–0.32	0.33	0.32	0.32	(0.35)
Case I1	$\Delta T_{max}>\Delta T_{min}>0$	0.56	0.44	0.17	–0.12	(–0.24)	(–0.25)	–0.10
Case I2	$\Delta T_{max}>0>\Delta T_{min}$	0.61	0.30	0.40	–0.31	–0.27	–0.28	–0.30
Case I3	$0>\Delta T_{max}>\Delta T_{min}$	0.27	0.11	0.39	–0.16	–0.07	–0.08	–0.16
Average of increase DTR		0.48	0.28	0.32	–0.20	–0.19	–0.20	–0.19
Total		–0.22	–0.09	0.00	0.13	0.13	0.12	0.16

and 44.2% of the days had DTR increases with an average increase of 0.48°C. Among the cases with DTR reductions, case D1 represents stronger warming at night than in the daytime and is the commonly suggested reason for DTR reduction. However, the days of case D1 accounted for only 19.8% of the total 620 days (Table 1). The rest of the days with DTR reductions experienced daytime cooling, which were further classified into case D2 and case D3, accounting for 17.6% and 18.4% of the 620 days, respectively. Case D2 experienced a daytime cooling and a nocturnal warming, and the regional mean DTR decrease in case D2 was found to be 1.00°C, which is approximately twice the averaged reduction in cases D1 and D3. Of the cases with DTR increases, case I1 has a stronger daytime warming than nocturnal warming, accounting for approximately half of the days with DTR increases. The regional mean change in DTR in case I1 was 0.56°C, which is comparable in magnitude to that in case D1, leading to a small monthly mean DTR change. On the other hand, cases I2 and I3 experienced a nocturnal cooling, both of which had a low occurrence frequency of approximately 12% because the number of cold nights decreased significantly over the continents in the warming climate (Alexander et al., 2006). Meanwhile, these two cases increased DTR by 0.61°C and 0.27°C, which are smaller than the reductions of 1.00°C in case D2 and of 0.56°C in case D3. As a result, the monthly mean DTR decreased by 0.22°C as shown in Table 2.

The distribution of occurrence frequency of each DTR case is shown in Figs. 2 and 3. Case D1 generally occurred in northeastern China because snow melting reduces surface albedo and increases both daily maximum and minimum temperatures in the high latitudes (Alexander et al., 2006). Meanwhile, a large portion of the DTR decrease in case D1 was offset by case I1, which often occurred in northern and southern China. Case D2 had a relatively high occurrence frequency in central China and led to a large monthly mean DTR reduction there. Case D3 had a high occurrence frequency in northeastern and southern China. Cases D2 and D3 led to a monthly DTR reduction that extended to central China and the south coast of China. The maximum DTR reduction exceeds 1.0°C (Fig. 1), which is consistent with the findings of Qian and Lin (2004).

3.2 Predicted decreases in DTR

The warming associated with GHG forcing led to DTR reductions in global continents, a result which agrees qualitatively with the observations. The magnitude of DTR reductions is underestimated (Fig. 1). In China, 53.8% of the 620 simulated days (31 days × 20 years) with GHG forcing showed decreases in DTR, which is comparable to the observed value of 55.8%. The days with reduced DTR are primarily from case D1 throughout the country and from case D2 in central China (Fig. 2). Both of these two cases have nocturnal warming,

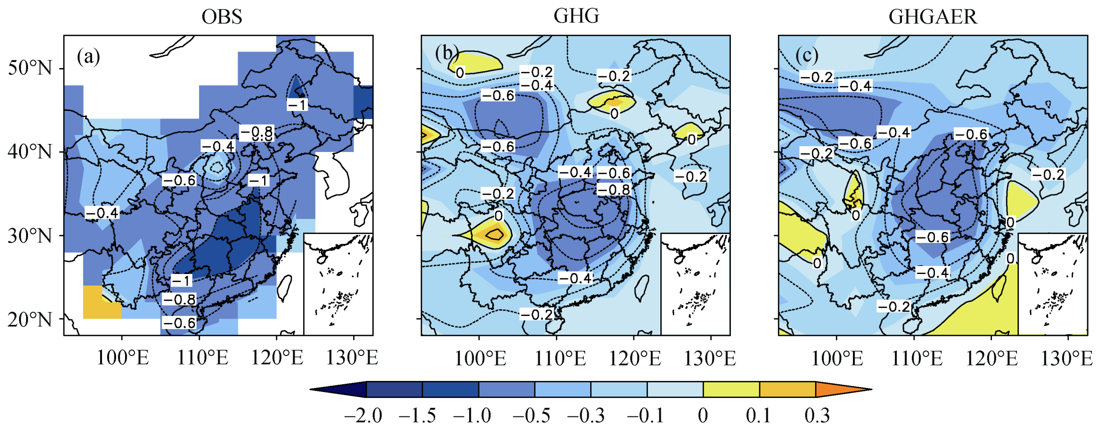

Figure 1 Diurnal temperature change in Eastern China. (a) the observed DTR changes in January during 1981–2000 relative to 1961–80 and the predicted DTR changes (Units: °C) during 1981–2000 in simulations (b) GHG and (c) GHGAER, respectively, relative to the CTRL run.

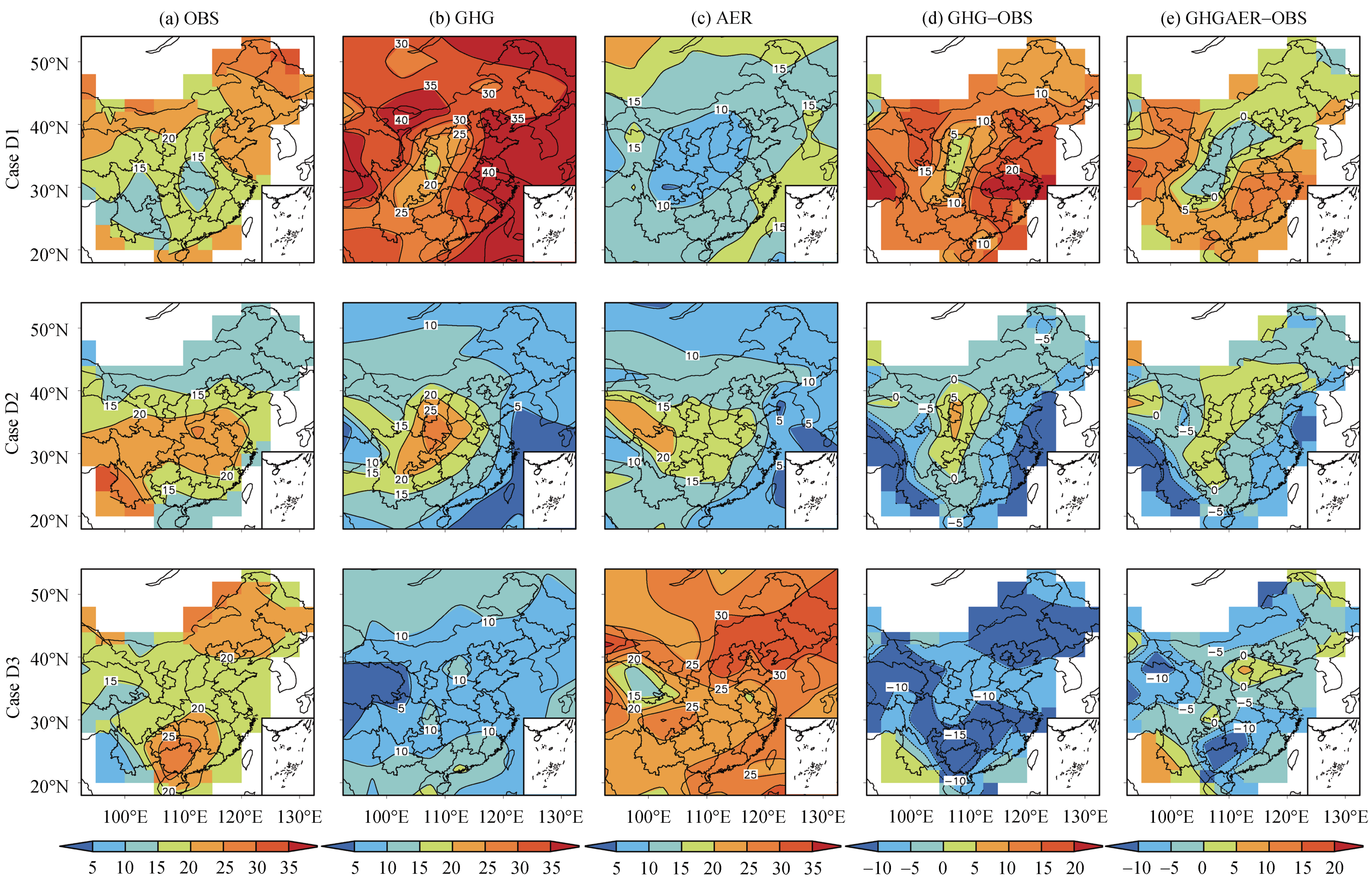

Figure 2 Occurrence frequencies (Units: %) of the three DTR reduction cases in column (a) observations during 1981–2000 relative to 1961–80, the occurrence frequencies of the three DTR reduction cases during 1981–2000 in simulations with column (b) GHGs (compared with the control experiment) and column (c) aerosols (compared with GHG experiment), and the differences in occurrence frequencies of model predictions with the presence of column (d) GHG and column (e) GHGAER forcing, respectively, minus observations.

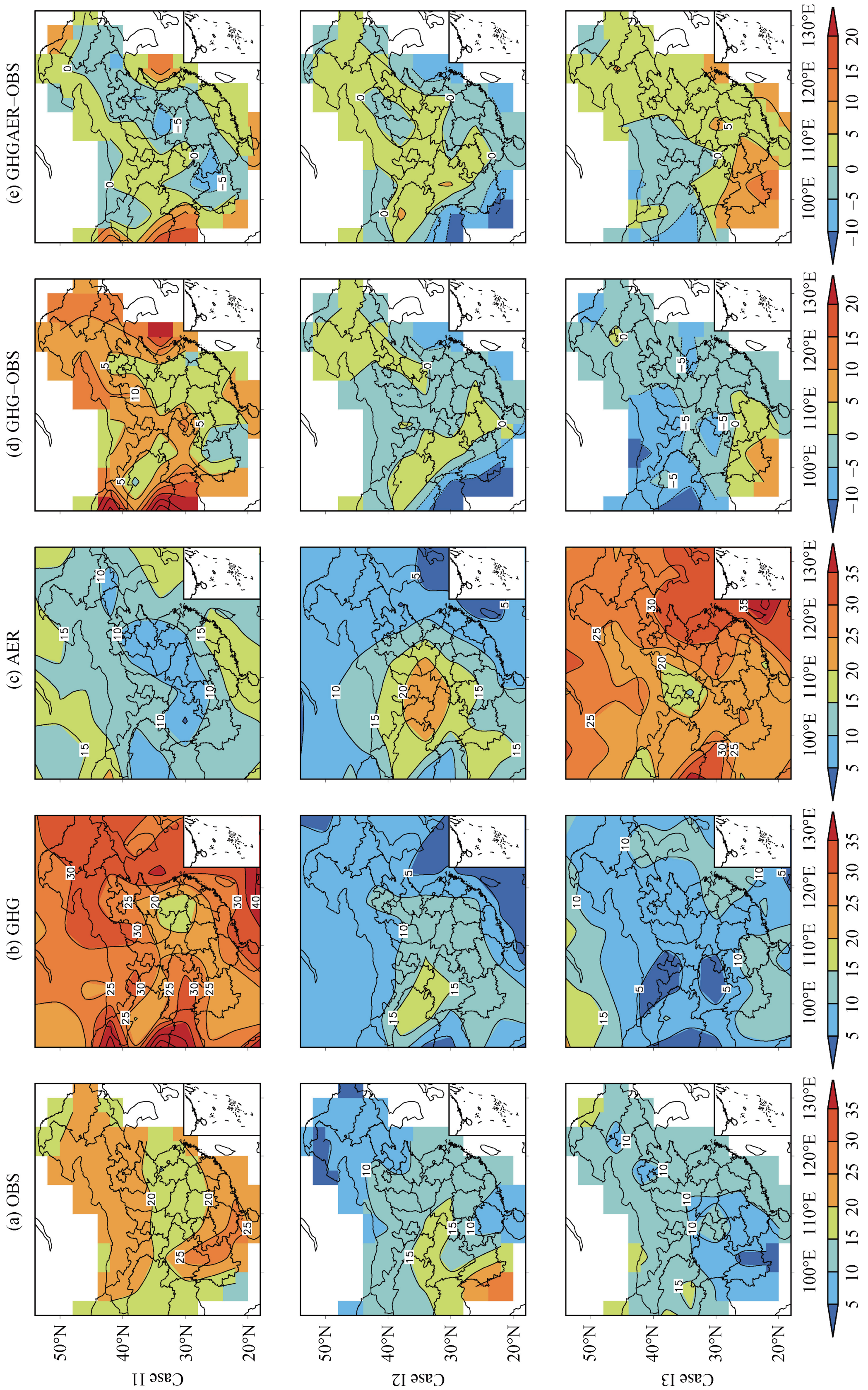

Figure 3 Same as Fig. 2 but for DTR increase cases.

which supports the previous suggestion that a stronger warming at night than in the daytime is an effective way to reduce DTRs. Further comparisons with observations show that the simulation with GHG forcing overestimates daily temperatures. Case D1 (with a daytime warming) had an occurrence frequency of 32.9% in the GHG experiment, which is higher than the observed frequency of 19.8%. The occurrence frequencies of cases D2 and D3 (with a daytime cooling) were simulated to be 12.0% and 8.9%, respectively, both of which are lower than the observations. Cases D2 and D3 have averaged DTR reductions of 0.43°C and 0.13°C, respectively, which are all smaller than the observed values given in Table 2. Averaging over China and over cases D1, D2, and D3, the resulting DTR reduction was 0.37°C, which is approximately 50% of the observed reduction.

Aerosols have negative forcings in daytime and reduce DTRs mainly through daytime cooling. In the simulation with aerosols, most DTR reductions are from cases D2 or D3, with averaged DTR reductions of 0.39°C and 0.42°C, respectively. These reductions exceed 70% of the 0.56°C DTR reduction in case D1 of the GHG experiment. Moreover, aerosols can extend much of the daytime cooling into night (Yu et al., 2002). Case D3 showed a cooling during both the day and night and had an occurrence frequency of 26.0% over all 620 days, almost twice the frequency of 12.0% in case D2. Aerosol forcing was found not to influence the geographical distribution of DTR changes. Case D3 still had a high occurrence frequency in northeastern China because of the snow-albedo response to aerosol cooling. Case D2 occurred mostly in central China, similar to the prediction for case D2 in the simulation with GHG forcing (Fig. 2).

The model results also show that the total number of days with DTR reductions is not sensitive to aerosol direct radiative forcing. Compared with the observations, the GHGAER experiment underestimates the occurrence frequency of DTR reductions by an absolute value of 1.8%, which is close to the low bias of 2.0% in the GHG experiment. However, aerosol direct forcing improves the prediction of days with DTR reductions in different cases. In the GHGAER experiment, the presence of aerosols reduces the biases of occurrence frequencies to 6.1% in case D1, −4.0% in case D2, and −3.9% in case D3, all of which are closer to the observed values than the predicted frequencies in the GHG simulation.

To distinguish the impacts of BC and scattering aerosols (sulfate, nitrate, POA, and SOA) on DTR, we also performed two additional experiments with fixed scattering aerosols and BC and denoted as GHGBC and GHGCOOL, respectively. The biases in these two simulations relative to the observation are also shown in Tables. BC induces additional surface warming and does not lead to improvements in cases D2 and D3 where daytime cooling occurs; the GHGBC experiment underestimates the frequency of DTR reduction days by 2.9%, which is larger than the underestimation of 2.0% in the GHG experiment. On the other hand, the GHGCOOL experiment shows improvements in the occurrence frequencies of each DTR reduction case. This finding indicates that the asymmetric radiative forcing by aerosols does not always lead to improvements in DTR frequency prediction. Furthermore, aerosol direct radiative forcing does not have a large impact on the magnitude of DTR reductions, although aerosols change surface mean temperature significantly (Chang et al., 2009).

3.3 Predicted increases in DTR

The cases with DTR increases have some similarity to the cases with DTR decreases. For instance, both cases D1 and I1 have warming during the daytime and at night; these two cases also have comparable occurrence frequencies of 32.9% and 28.8%, respectively, in the GHG simulation. Cases D3 and I3 experienced cooling throughout the day and have comparable frequencies of 26.0% and 25.3%, respectively, in the presence of aerosol forcing. This result implies that GHGs and aerosols have approximately the same probability to either increase or decrease daily DTR in the model. In the GHGAER experiment, biases in occurrence frequency for all DTR cases are generally smaller than those in the GHG experiment. Changes in cloud cover may account for the improvement in prediction because the improvements are mainly located along the damp eastern coastal region (e.g. case I3 in Fig. 3e) and clouds have strong correlations with surface temperatures in the model (not shown). Furthermore, the improvement is contributed from scattering aerosols rather than BC. This improvement is probably due to the regional negative aerosol forcing greatly offsetting the GHG effect and inducing an opposite change in cloud cover.

4 Conclusion

This study investigates the diurnal temperature changes in January during the end of the 20th century in China. The daily DTR changes are classified into six cases depending on the changes in daily maximum and minimum temperatures. Each case has a different occurrence frequency, geographical distribution, and magnitude of DTR change. The previously proposed explanation of DTR reductions, a stronger nocturnal warming than daytime warming, explains only 19.8% of January days based on the observations from 1981–2000. This behavior occurs mainly in northeastern China, coinciding with significant regional warming. Other DTR reductions are associated with daytime cooling and mainly occur in central and southern China.

The simulation with GHG forcing alone generally reproduces the occurrence frequency of each DTR case but overestimates the days with nocturnal warming. Although aerosols have small effects on the total number of days with DTR decreases or increases, the presence of aerosols helps to better predict the occurrence frequencies of the different cases. Compared to the observations, aerosol direct forcing did not improve the prediction of the magnitude of DTR changes. Because aerosol indirect effects can induce an additional nocturnal warming in East Asia

(Huang et al., 2006), the absence of aerosol indirect effects in our study may have led to an underestimation of the aerosol impacts on DTR changes. Other uncertainties associated with the model results include cloud parameterization, land processes that control evaporative cooling, and natural climate variation associated with atmosphere-ocean interactions. All of these processes are model dependent and require multi-model experiments in future work.

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