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The Warming Tibetan Plateau improves winter air quality in the Sichuan Basin, China

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17 **Key points**

18

19 The Tibetan Plateau is rapidly warming, and the temperature has risen by 2 ° C from 2013 to 2017.

20

21 The 2 ° C warming of the plateau leads to an increase in PBL height and a decrease in humidity in

22 the Sichuan Basin.

23

24 The 2 ° C warming reduces $PM_{2.5}$ concentration in the basin by 25.1 μg m^{-3}, of which primary and

25 secondary aerosols are 5.4 μg m^{-3} and 19.7 μg m^{-3}, respectively.

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Abstract

Impacts of global climate change on the occurrence and development of air pollution have attracted more attentions. This study investigates impacts of the warming Tibetan Plateau on air quality in the Sichuan Basin. Meteorological observations and ERA-interim reanalysis data reveal that the Tibetan Plateau has been rapidly warming during the last 40 years (1979-2017), particularly in winter when the warming rate is approximately twice as much as the annual warming rate. Since 2013, the winter temperature over the plateau has even risen by 2 ° C. Here, we use the WRF-CHEM model to assess the impact of the 2 ° C warming on air quality in the Sichuan Basin. The model results show that the 2 ° C warming causes an increase in the Planetary Boundary Layer (PBL) height and a decrease in the relative humidity (RH) in the basin. The elevated PBL height strengthens vertical diffusion of $PM_{2.5}$, while the decreased RH significantly reduces secondary aerosol formation. Overall, $PM_{2.5}$ concentration is reduced by 17.5% (~25.1 μg m^{-3}), of which the reduction in primary and secondary aerosols is 5.4 μg m^{-3} and 19.7 μg m^{-3}, respectively. These results reveal that the recent warming plateau has improved air quality in the basin, to some certain extent, mitigating the air pollution therein. Nevertheless, climate system is particularly complicated, and more studies are needed to demonstrate the impact of climate change on air quality in the downstream regions as the plateau is likely to continue warming.

Keywords: climate change, air quality, Tibetan Plateau, WRF-CHEM model

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1 Introduction

The Tibetan Plateau is known as the third pole because of its high altitude and large area. It is also regarded as an important response region to the Northern Hemisphere, and even global climate due to its sensitivity to climate change. Previous studies on the Tibetan Plateau show that the region was experiencing warming in the second half of the 20th century, especially in the winter months (Kuang and Jiao, 2016; Liu and Chen, 2000; Rangwala et al., 2009). The warming plateau not only plays a significant role in driving the weather and climate change, as well as the ecological system, but also has an important impact on air quality in the downstream regions. Xu et al. (2016) suggest that the thermal anomaly over the Tibetan Plateau obviously increases haze frequency and surface aerosol concentration in central-eastern China.

However, the impacts of climate change on air quality in China are still unclear. Some researches hold the opinion that climate change induced by greenhouse gas emission increases severe haze occurrence and intensity in winter at Beijing, and its impact will continue in the future (Cai et al., 2017; Zou et al., 2017). Similarly, Xu et al. (2017) suggest that climate warming anomaly in the lower and middle troposphere over the continent around the Yangtze River Delta leads to more haze days in winter during recent decades. On the contrary, another opinion suggests that climate change in the past two decades is favorable for air pollution dispersion in northern China via enhancing mid-latitude cold surges in winter (Zhao et al., 2018). If cold surge is strong enough, pollutants would be transported to the downstream regions, causing a better air quality in the upstream region but a worse one in the downstream region. Thus, there may be regional differences in the impact of climate change on air quality.

Previous studies on air pollution in China are concentrated in the developed regions, such as the North China Plain, the Yangtze River Delta and the Pearl River Delta. Few studies have paid attention to the Sichuan Basin, although the region is undergoing severe air pollution, and mean $PM_{2.5}$ concentration is more than 110 μg m^{-3} in winter (Qiao et al., 2019; Tao et al., 2017; Wang et

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al., 2018; Yang et al., 2011). Thus, it is necessary to explore the underlying causes that leads to air pollution in the Sichuan Basin.

The Sichuan Basin locates in the downstream region of the Tibetan Plateau, and its weather conditions are obviously affected by the plateau (Duan et al., 2012; Hua, 2017; Zhao et al., 2019). For instance, the foggy weather, southwest vortex and low-level shear line over the basin are closely associated with the plateau (Zhu et al., 2000). These changes in weather conditions induced by the plateau undoubtedly affect the development and dispersion of air pollution in the basin, because the huge terrain can trigger a thermodynamic forcing, which is of great importance for weather conditions in the surrounding regions (Bei et al., 2016; 2017; Zhao et al., 2015).

This study therefore focuses on how climate change on the Tibetan Plateau affects air quality in the Sichuan Basin in recent years. Section 3 analyzes the climate change on the Tibetan Plateau in the past four decades, and especially emphasizes the change in recent five years. In Section 4, we design two numerical simulations to calculate the impact of climate change on air quality. One is a baseline simulation, which is constrained by observed surface meteorological parameters and pollutant concentrations. The other is a sensitivity simulation, which uses the same emission inventory and meteorological fields as the baseline simulation except for the changed air temperature. We compare the difference of $PM_{2.5}$ concentrations in these two cases, and also calculate the differences in meteorological parameters that include winds (wind speed and direction), air temperature, and relative humidity (RH), as well as the Planetary Boundary Layer (PBL) height. Based on the differences in $PM_{2.5}$ concentration and meteorological parameters above, we finally explain the cause-to-effect relationship between climate change on the Tibetan Plateau and the changes in the PBL height and RH in the Sichuan Basin. Moreover, we calculate the effect of the relationship on air quality in the Sichuan Basin.

2 Data and Methods

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2.1 Observations

To ensure a robust result, we use two datasets of surface air temperature in this study. One is the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim monthly mean reanalysis data (1979-2018), obtained from the website of http://apps.ecmwf.int/datasets/, with the finest horizontal resolution of 0.125°×0.125°. The other is hourly and monthly mean weather-station observations from the National Oceanic and Atmospheric Administration (NOAA), which is available on the website of http://gis.ncdc.noaa.gov/map/viewer/#app=clim&cfg=cdo&theme=hourly&layers=1&node=gis.

Figure 1 shows the distribution of weather stations over the Tibetan Plateau, and these weather stations widely cover the entire plateau. Trends of annual mean and winter surface air temperature over the plateau are analyzed, and the winter is averaged over 3-month periods (December-January-February). Additionally, we use ambient air quality data to validate the model performance. Since 2013, the data are released by Ministry of Environmental Protection, China at http://www.aqistudy.cn/, including hourly $PM_{2.5}$, CO, and O_3 mass concentrations. The monitoring stations for air quality are also shown in Figure 1.

2.2 Model configuration and experiments

A state-of-the-art regional dynamical and chemical model (WRF-CHEM model) is used in the study. The simulation domain covers the Tibetan Plateau and the Sichuan Basin (Figure 1). The Tibetan Plateau covers about 2.5 million km^2, with the averaged elevation of 4500 m, and the Sichuan Basin covers about 0.16 million km^2, with the elevation in the center of the basin less than 1000 m (250 - 700 m). The model is set by a horizontal grid resolution of 9 km (451 × 221 grids), with 35 vertical sigma levels. The model description in detail is seen by Grell et al. (2005). The evaluation of the model performance has been conducted by many previous studies (Li et al., 2011a; Tie et al., 2009; 2007). In this study, we use the Goddard longwave and shortwave radiation

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parameterization (Dudhia, 1989), the WSM 6-class graupel microphysics scheme (Hong and Lim, 2006), the Mellor-Yamada-Janji (MYJ) planetary boundary layer scheme (Janjić, 2002), the unified Noah land-surface model (Chen and Dudhia, 2001) and Monin-Obukhov surface layer scheme (Janjić, 2002). For chemical schemes, we use a new flexible gas-phase chemical module and the Community Multiscale Air Quality (CMAQ, version 4.6) aerosol module developed by the US EPA (Binkowski, 2003). Gas-phase atmospheric reactions of volatile organic compounds (VOCs) and nitrogen oxide (NOx) use the SAPRC-99 (Statewide Air Pollution Research Center, version 1999) chemical mechanism. Inorganic aerosols use the ISORROPIA version 1.7, referring to Li et al. (2011a) and Feng et al. (2016). A SO_2 heterogeneous reaction mechanism on aerosol surfaces involving aerosol water is added (Li et al., 2017a), and NO_2 heterogeneous reaction to produce HONO is also considered (Li et al., 2010). The secondary organic aerosol (SOA) calculation uses a non-traditional volatility basis-set approach by Li et al. (2011b). The photolysis rates are calculated by a fast Tropospheric Ultraviolet and Visible (FTUV) radiation transfer model, in which the impacts of aerosols and clouds on the photochemistry processes are considered (Li et al., 2011a; Tie et al., 2003; 2005). The wet deposition is calculated by the method used in CMAQ and the dry deposition follows Wesely (1989).

We use the MIX anthropogenic emission inventory for the year of 2010, and it is available at Multi-resolution Emission Inventory for China (http://www.meicmodel.org/dataset-mix.html), consisting of industrial, power, transportation, and agricultural as well as residential sources (Li et al., 2017b; Zhang et al., 2009). Here, we use a 'top-down' method to constrain the emission inventory via comparing the simulations with the measurements. The biogenic emissions are online calculated by the Model of Emissions of Gases and Aerosol from Nature (MEGAN) (Guenther et al., 2006). Initial and boundary meteorological fields in the model are driven by 6-hour 1° × 1° NCEP (National Centers for Environmental Prediction) reanalysis data. Chemical lateral conditions are provided by a global chemistry transport model – MOZART (Model for OZone And Related chemical Tracer, version 4), with a 6-h output (Emmons et al., 2010; Tie et al., 2005). The spin-up time of the WRF-CHEM model is 1 day.

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159

160 Two numerical experiments are performed. One is the baseline simulation in the 2013-2014 winter
161 (January 2014), and the other is a sensitivity simulation that has an observational increase in air
162 temperature over the Tibetan Plateau. In other words, the sensitivity simulation uses the same
163 emission inventory and meteorological conditions as the baseline simulation except that the
164 temperature fields over the Tibetan Plateau are changed. We set the temperature increment to 2°C
165 in the sensitivity simulation, because observational temperature increment in winter is about 2°C
166 from 2013 to 2017 (Table S1). Comparing the difference between the sensitivity simulation and
167 the baseline simulation, we calculate the impact of the warming Tibetan Plateau on air quality in
168 the Sichuan Basin.

169

170 **3 The warming Tibetan Plateau in the last four decades**

171

172 Figure 2 shows the variability and linear trend of surface air temperature at 10 weather stations
173 over the Tibetan Plateau in winter during the last four decades (1979 - 2017). The winter mean
174 temperature recorded from all the weather stations exhibits an obvious annual fluctuation and the
175 linear regression shows a significant rising trend. Clearly, the plateau is continuously undergoing
176 a warming phase, albeit with regional differences in the warming magnitude. The warming rates
177 in different regions vary in the range of 0.5 - 1.0°C decade^{-1}. Compared with the warming rate of
178 annual mean temperature (Figure S1), the warming rate in winter is approximately twice as much,
179 suggesting that the warming in winter is more significant.

180

181 Using the ERA-interim reanalysis data, Figure 3 shows the temperature change during the same
182 period (1979 - 2017). The result is consistent with weather records, showing that air temperature
183 is significantly rising in most parts of the plateau. The maximal warming rate is around 0.6 - 0.8°C
184 decade^{-1}, appeared in the central and southern plateau. The warming in the rest areas is slighter,
185 with a rate of 0.3 - 0.6 °C decade^{-1}. Particularly, the averaged warming rate in the vast central
186 plateau reaches about 1.0°C yr^{-1} in recent five years (Figure S2), greater than the warming rate

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during the entire 40 years (Figure 3). Both the observation records and reanalysis data evidently show that the plateau has been warming in the last four decades, and also the warming trend for recent years is more significant.

From the above temperature change analysis, we notice that there is obviously a positive temperature anomaly between 2013 and 2017 winters, implying for an accelerating warming over the plateau. The observational temperature in winter increases by about 2°C between 2013 and 2017. Therefore, the impact of the 2°C warming on air quality in the Sichuan Basin is investigated. In order to isolatedly assess the effect of a rapid temperature increase and to eliminate the effect of other factors, a sensitivity study using the WRF-CHEM model is conducted for considering the 2°C temperature increase from the value in 2013 (see Figure 2 and Table S1).

4 Results and Discussion

4.1 Model validation

To systemically evaluate the model performance on simulation O_3, CO and $PM_{2.5}$ mass concentrations, three statistical indices are used. They are the mean bias (MB), root mean square error (RMSE), and index of agreement (IOA). The calculation formulas are given in Text S1. The IOAs of air temperature and RH are 0.85 and 0.79, respectively (Figure S3), suggesting that the model well captures the diurnal cycle of temperature and the variability of RH. However, the calculated wind speed is overestimated, especially in the region between the Tibetan Plateau and the Sichuan Basin. This is because there is a dramatic elevation drop in the region, which makes it difficult for the model to replicate the observed wind speed and direction.

Figure 4 shows comparisons of hourly O_3, CO and $PM_{2.5}$ concentrations between the model simulations and measurements. The result shows that the simulated CO mean level is close to the measurement, with a MB of 0.11 mg m^{-3}, indicating that the model reasonably reproduces the

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meteorological fields and long-range transport. Because the chemical lifetime of CO is relatively long (~months), the variability of CO is dominantly determined by the meteorological fields and atmospheric transport process. For the simulation of O_3, in addition to the effects of meteorological fields and atmospheric transport process, its variability is strongly controlled by the photochemical process. The model result shows that the simulated diurnal cycle of O_3 is reasonably agreed with the measurement, with an IOA of 0.79. There is only a small bias between the simulated and measured O_3 mean concentration. The simulated O_3 concentration is 1.7 μg m^{-3} higher than the measurement, suggesting that both the photochemistry and long-range transport well capture the O_3 variability in the region. Finally, the IOA between the simulated and measured $PM_{2.5}$ concentrations is 0.80, indicating that the aerosol module in the model generally captures the measured $PM_{2.5}$ variation.

However, there are some noticeable discrepancies between the simulations and the measurements. For instance, the simulated magnitude of $PM_{2.5}$ concentration is larger than the measurement, and its mean level is underestimated by 13.1 μg m^{-3}, less than 10% of the measurement (~153.5 μg m^{-3}). These discrepancies are likely due to the biases in the uncertainties in emission inventory and small-scale dynamical fields. During the period of Jan 17th to Jan 20th, the overestimated $PM_{2.5}$ concentration is mainly caused by the overestimated wind speed and the departure of wind direction (Figure S3). This is also shown by the overestimation of CO concentration because the observed northwest wind is not well simulated due to the complicated topography.

4.2 Change in winter $PM_{2.5}$ concentration over the basin

To examine impacts of the warming plateau on $PM_{2.5}$ concentration in winter in the Sichuan Basin, the time series of $PM_{2.5}$ concentrations in the two case simulations (i.e., with and without the 2°C warming over the plateau) are respectively calculated (Figure 5). The results show that $PM_{2.5}$ concentration in the basin is significantly reduced by an average of 25.1 μg m^{-3} in the case of 2°C warming. The maximum hourly reduction reaches to 84.6 μg m^{-3} (Figure S4a) and the maximum

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243 percentage reduction is about 64.5% (Figure S4b). Interestingly, the maximum reduction always
244 occurs while $PM_{2.5}$ concentration reaches a peak value, which suggests that the impact of the
245 warming plateau is extremely significant during the period of high $PM_{2.5}$ concentration. This result
246 is similar to previous studies which also point out that extreme weather plays important roles in
247 affecting air quality (De Sario et al., 2013; Hong et al., 2019; Tsangari et al., 2016; Zhang et al.,
248 2016). That is to say, the impact of the warming plateau on air quality is apt to be amplified in
249 extremely high $PM_{2.5}$ concentrations.
250
251 To better understand the impact of the warming plateau on $PM_{2.5}$ concentration in the Sichuan
252 Basin, we also calculate the changes in $PM_{2.5}$ chemical composition in the basin (Figure 6). As a
253 result, secondary aerosol reduces by 19.7 μg m^{-3}, accounting for 78.5% of the total reduction. For
254 example, the largest reduction is SOA, reducing from 23.2 μg m^{-3} in the base case to 10.8 μg m^{-3}
255 in the warming case. The second reduction is sulfate (31.8 μg m^{-3} in the base case and 28.6 μg m^{-3}
256 in the warming case). The next are nitrate and ammonium (22.3 μg m^{-3} and 19.1 μg m^{-3} in the base
257 case, and 20.2 μg m^{-3} and 17.5 μg m^{-3} in the warming case).
258
259 There are also significant changes in the spatial distribution of $PM_{2.5}$ concentration. Figure 7 shows
260 the spatial distribution of changes in surface $PM_{2.5}$ concentration and winds after 2°C warming over
261 the plateau. Apparently, there is a larger decrease in $PM_{2.5}$ concentration in the whole basin, and the
262 maximum reduction is more than 30 μg m^{-3}. By contrast, $PM_{2.5}$ concentration increases by 5 - 15 μg
263 m^{-3} at the eastern edge of the plateau. Wind patterns show that easterly winds over the basin enhance
264 while westerly wind over the plateau weaken (Figure S5 and Figure 7). Enhanced easterly winds
265 cause an increased transport of $PM_{2.5}$ from the basin to the plateau. Moreover, weakened westerly
266 winds convergent with enhanced easterly winds on the border between the plateau and the basin,
267 jointly leading to an increase in $PM_{2.5}$ concentration at the eastern edge of the plateau. Additionally,
268 northerly winds over the basin slightly enhance, conducive to diluting the air and reducing $PM_{2.5}$
269 concentration. Thus, easterly winds transport and northerly winds dilution are both favorable for a
270 reduction of $PM_{2.5}$ concentration in the basin. In addition to the wind effect, there are also other

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important factors to produce the $PM_{2.5}$ reduction in the basin, such as the PBL height and RH, which will be analyzed as follows.

4.3 Impact of PBL height on $PM_{2.5}$ concentration

Previous studies show that the PBL development plays an important role in diffusing pollutants (Miao et al., 2017; Su et al., 2018; Tie et al., 2015). Here we calculate the change in the PBL height due to the 2°C warming over the plateau, and then analyze the effect of the change in PBL height on $PM_{2.5}$ concentration in the basin.

Our results suggest that the 2°C warming plays different roles in the PBL development over the plateau and the basin. Due to the 2°C warming, the PBL height decreases in most areas of the plateau, but rises by 50 - 200 m over the basin (Figure 8). As known, a shallow PBL constrains $PM_{2.5}$ near the surface via suppressing vertical dispersion (Fan et al., 2011; Iversen, 1984). Conversely, a deep PBL is favorable for $PM_{2.5}$ diffusion. Thus, we explore the underlying cause that leads to the difference in the PBL height over the plateau and the basin. Figure 9 shows that vertical profiles of changes in temperature and winds in the plateau and the basin, because the PBL height is strongly related to the changes in vertical temperature and wind. The results show that the 2°C warming causes a maximum warm layer around 1 km above the ground of the plateau. Interestingly, the warm layer acts as a dome covering 4.5 km above the Sichuan Basin (Figure 9a). Xu et al. (2017) also finds out a significant warm plume extending from the plateau to the downstream Sichuan Basin and Yangtze River Delta by use of NCEP/NCAR reanalysis data. This is closely associated with a sharp topography decrease (from ~ 5 km in the plateau to < 1 km in the basin). In the basin, there is a decrease in the temperature from the surface to ~ 4 km, with a maximal temperature reduction (1 - 2°C) located at 1.5 km to 3 km above the ground (Figure 9a). As a result, the vertical temperature gradient increases and the instability also increases in the lower troposphere of the basin, thereby causing a higher PBL height than that in the non-warming case (Figure 9b). On the contrary, the change in vertical temperature profile leads to a decreased vertical temperature gradient and

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299 increased thermal stability in the lower troposphere of the plateau, so the PBL height decreases in
300 the region.
301
302 Moreover, the 2°C warming reduces the zonal temperature gradient from the plateau to the basin,
303 which causes a weakened westerly wind over the plateau. Meanwhile, the east wind strengthens in
304 the basin. The weakened westerly wind and the strengthened east wind converge on the east side of
305 the plateau, triggering an ascending motion. The mechanism of the ascending motion is similar to
306 the plateau "heat pump" effect that implies for a warm updraft forced by a heating plateau (Lau et
307 al., 2006). Thus, both the ascending motion at the eastern edge of the plateau and the east wind in
308 the basin strengthen, which is favorable for the development of the PBL. The elevated PBL
309 facilitates vertical diffusion, leading to a reduction in $PM_{2.5}$ concentration over the basin.
310 Additionally, the updraft enhances the $PM_{2.5}$ transport from the basin to the plateau, which also
311 leads to a decrease in $PM_{2.5}$ concentration over the basin.
312
313 **4.4 Effect of RH on $PM_{2.5}$ concentration**
314
315 In addition to the PBL height, ambient RH is a key factor for secondary aerosol formation (Tie et
316 al., 2017; Wang et al., 2016). Previous studies indicate that aerosol hygroscopic growth cannot
317 occurs until the humidity exceeds 50% (Liu et al., 2008). When the humidity is greater than 60%,
318 hygroscopic growth factor of urban aerosol increases significantly with humidity (Liu et al., 2008).
319
320 Figure 10 shows that there is remarkable change in RH in the basin due to the 2°C warming of the
321 plateau. In the baseline simulation, the RH varies in the range of 40% - 80% over the basin (Figure
322 10a). However, the RH varies from 40% to 70% in the 2 °C warming simulation (Figure 10b),
323 suggesting that the basin becomes drier when the plateau is warmer.
324
325 The RH comparison between these two numerical simulations reveals that the 2 °C warming causes
326 a 2.5% - 10% decrease in the RH over the basin (Figure 11). This change in RH has a critical effect
327 on the secondary aerosol formation. As explained by Tie et al. (2017), the reduction of RH

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(especially during the stage of RH from 80% to 70%) causes a significant decrease of hygroscopic growth on the aerosol surface, resulting in less water surface for producing secondary aerosol, such as sulfate and nitrate. As a result, the $PM_{2.5}$ concentration decreases in the basin. There are also some fingerprints of the RH's effect on $PM_{2.5}$ concentration. Firstly, the spatial distributions of RH reduction and $PM_{2.5}$ concentration reduction have similar patterns (Figure 11 and Figure 7), and the region with more humidity decrease overlaps the region with more $PM_{2.5}$ decreases. Secondly, as shown in Figure 6, the changes in $PM_{2.5}$ compositions indicate that the reduced $PM_{2.5}$ concentration is mainly caused by the decrease in secondary aerosol concentration. Therefore, the RH change plays an important role for $PM_{2.5}$ concentration in the basin.

5 Conclusions

ERA-interim reanalysis data and observation records at 10 weather stations show that the Tibetan Plateau is significantly warming during the past four decades (1979-2017), particularly in winter. The temperature increase rate is 0.5°C decade^{-1} to 1.0°C decade^{-1} in winter, approximately twice as much as the increase rate of annual mean temperature. In recent 5 years (2013-2017), the central plateau is significantly warming with an increase rate of 1.0°C yr^{-1}, encompassing the warming rate during the entire 40 years. Rapid warming has caused the winter temperature to increase by an average of 2°C over the entire plateau from 2013 to 2017.

The WRF-Chem model is used to assess the impact of 2°C warming of the plateau on air quality over the downstream Sichuan Basin. The most significant impact of the 2°C warming on $PM_{2.5}$ concentration in the basin is via reducing relative humidity and increasing PBL height. A lower ambient humidity decreases aerosol hygroscopic growth, which weakens secondary aerosol formation and leads to a significant reduction in secondary aerosol concentration. Moreover, the 2°C warming induces an increase in vertical temperature gradient over the basin, strengthening turbulence mixing and elevating PBL height. The elevated PBL height is favorable for vertical diffusion that causes a reduction of $PM_{2.5}$ in the basin. Additionally, the uplift effect by an enhanced

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356 ascending motion at the eastern edge of the plateau also contributes to $PM_{2.5}$ reduction within the
357 basin.
358
359 In summary, the 2°C warming over the plateau in recent five years comprehensively induces a rising
360 PBL height and a drying ambient air over the basin, which greatly reduces $PM_{2.5}$ secondary
361 compositions. On average, $PM_{2.5}$ concentration reduces by 25.1 μg m^{-3}, of which the primary and
362 secondary aerosols decrease by 5.4 μg m^{-3} and 19.7 μg m^{-3}, respectively. Since the plateau is likely
363 to continue warming, in-depth understanding to climate change on the Tibetan Plateau is required.
364 Long-term $PM_{2.5}$ monitoring is also needed to validate the impact of the warming plateau on air
365 quality.
366
367 *Data availability*. The data used in this study are available from the corresponding author upon
368 request (tiexx@ieecas.cn).
369 *Supplement.* Supplemental materials to this article can be found online at http://xxxxxx
370 *Author contributions.* XX designed research, and revised the final paper. SY performed research,
371 and wrote the paper. XX and SY provided financial support. TF validated the model, modified the
372 chart code and reviewed the paper. ZB collected and analyzed the weather-stations data.
373 *Competing interests.* The authors declare that they have no conflict of interest.
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377 Medium-Range Weather Forecasts (ERA-interim) for reanalysis data which are freely obtained by
378 a following registration on the website http://apps.ecmwf.int/datasets/. Ambient weather-station
379 observations are obtained from the National Oceanic and Atmospheric Administration (NOAA),
380 http://gis.ncdc.noaa.gov/map/viewer/#app=clim&cfg=cdo&theme=hourly&layers=1&node=gis.
381 The hourly ambient surface O_3, CO and $PM_{2.5}$ mass concentrations are real-timely released by
382 Ministry of Environmental Protection, China on the website http://www.aqistudy.cn/, freely
383 downloaded from http://106.37.208.233:20035/. The MEIC-2012 (Multi-resolution Emission
384 Inventory for China) anthropogenic emission inventory is available on the website,
385 http://www.meicmodel.org. The authors also thank anonymous reviewers for their helpful
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Figure captions

Figure 1 (a) Location map of the Tibetan Plateau (the region surrounded by the dark line) and the Sichuan Basin (the region surrounded by the gray line). (b) The model domain and the distribution of weather stations marked in the triangles over the Tibetan Plateau and air quality stations marked in the circles over the Sichuan Basin.

Figure 2 Trends of observational winter (Dec-Jan-Feb) mean temperature anomaly recorded by 10 weather stations over the Tibetan Plateau during the last four decades (1979-2017).

Figure 3 Trends of ERA-interim reanalysis winter mean temperature over the Tibetan Plateau from 1979 to 2017. The dotted regions show statistical significance with 95% confidence level (p-value < 0.05) from the Student's t test.

Figure 4 Comparison between the observed (black dots) and simulated (blue line) hourly O_3 (μg m^{-3}), CO (mg m^{-3}) and $PM_{2.5}$ mass concentrations (μg m^{-3}) over the Sichuan Basin in January 2014.

Figure 5 Time series of $PM_{2.5}$ concentrations over the Sichuan Basin, the baseline simulation is selected in January 2014 and the sensitivity simulation in which 2°C warming occurs over the Tibetan Plateau relative to the baseline simulation.

Figure 6 Comparison of chemical composition of $PM_{2.5}$ mass concentrations between the (a) baseline simulation and (b) sensitivity simulation over the Sichuan Basin. The yellow fan-shaped area presents the component of secondary aerosol, and the rest presents primary aerosol.

Figure 7 Difference in spatial distributions of surface $PM_{2.5}$ concentrations and winds between the sensitivity simulation and baseline simulation. The negative shows $PM_{2.5}$ concentrations decrease when the Tibet is 2°C warming, and the positive shows $PM_{2.5}$ concentrations increase when the Tibet is 2°C warming.

Figure 8 Spatial change in the PBL height induced by 2°C warming over the Tibet. The positive shows the PBL height increases while the negative shows the PBL height decreases.

Figure 9 Vertical profiles of changes in temperature (color shading and gray contour) and winds (arrows) along 30°N in January 2014. The gray shaded area presents topography. The green box for the Sichuan Basin, and the red solid (baseline simulation) and dash (sensitivity simulation) lines for the PBL height. (a) The Tibet and Sichuan Basin, and (b) The Sichuan Basin.

Figure 10 Comparison of spatial distributions of relative humidity (RH) between the (a) baseline simulation and (b) sensitivity simulation over the Tibet and Sichuan Basin.

Figure 11 Spatial change in the relative humidity after the Tibet becomes 2°C warming. The positive shows the RH increases while the negative shows the RH decreases.

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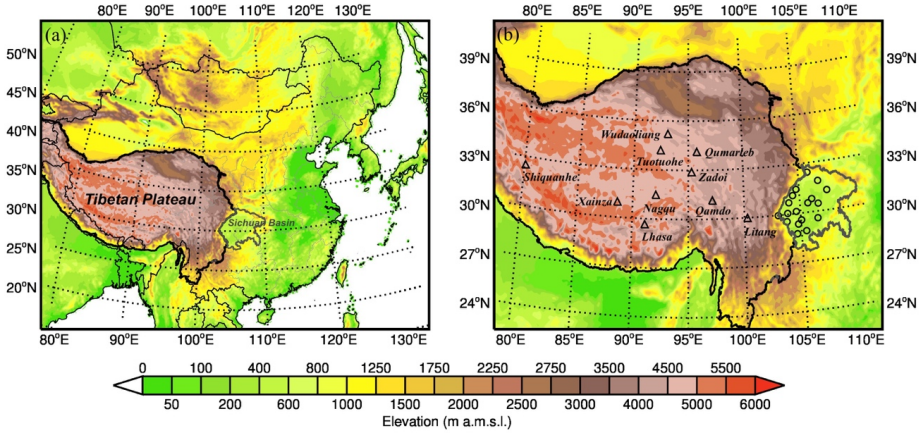

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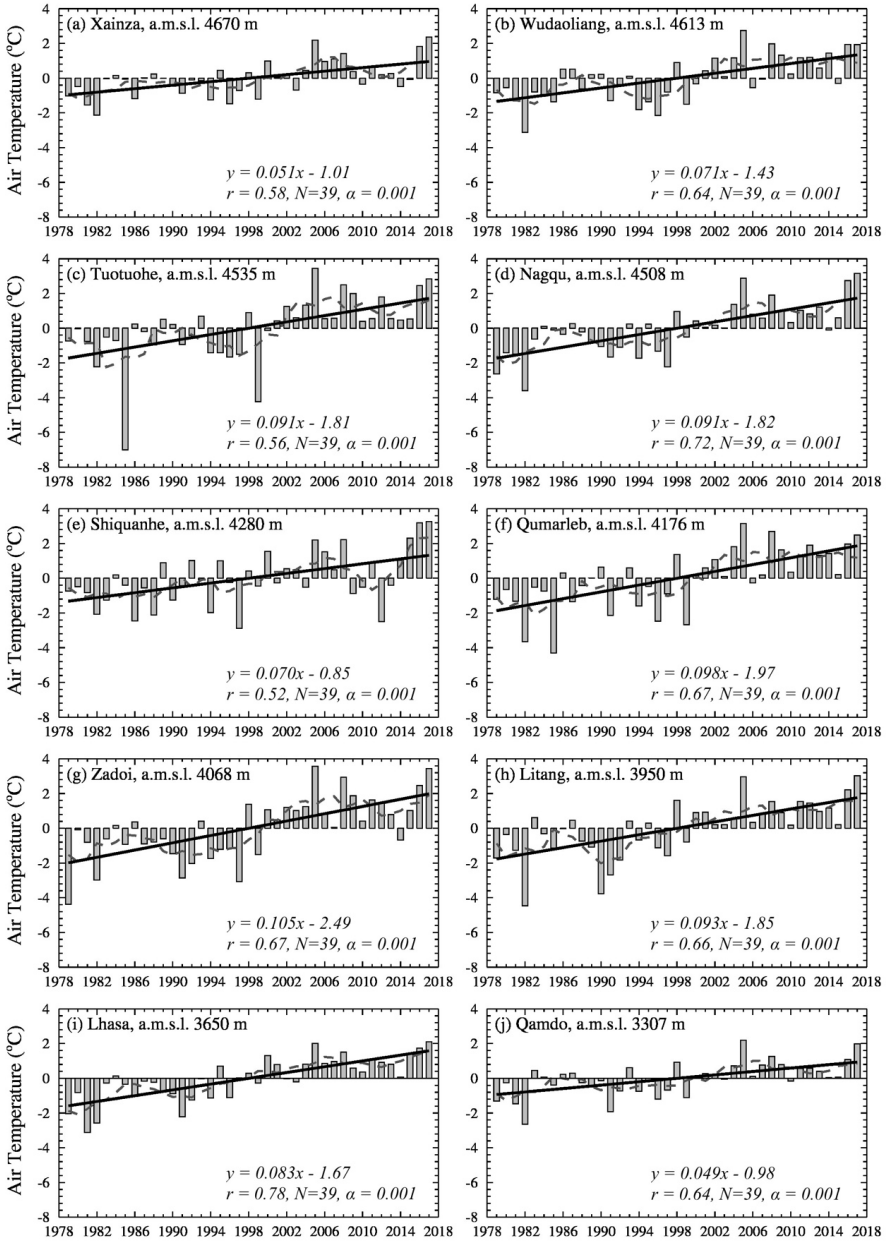

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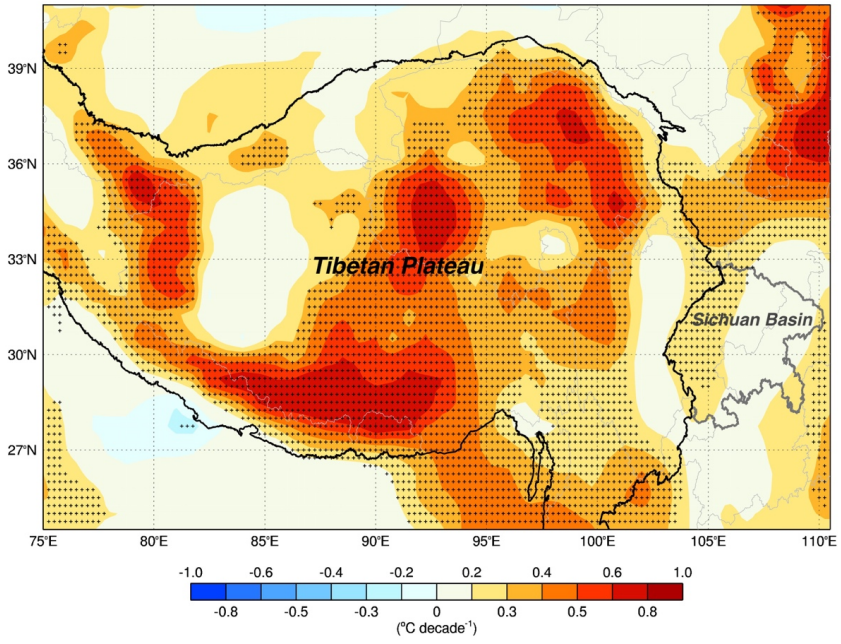

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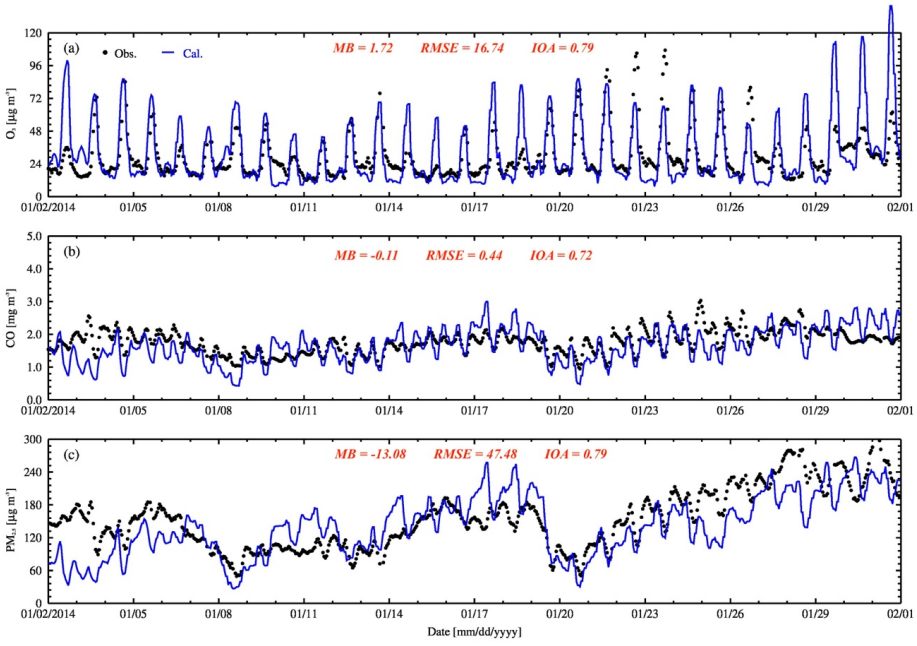

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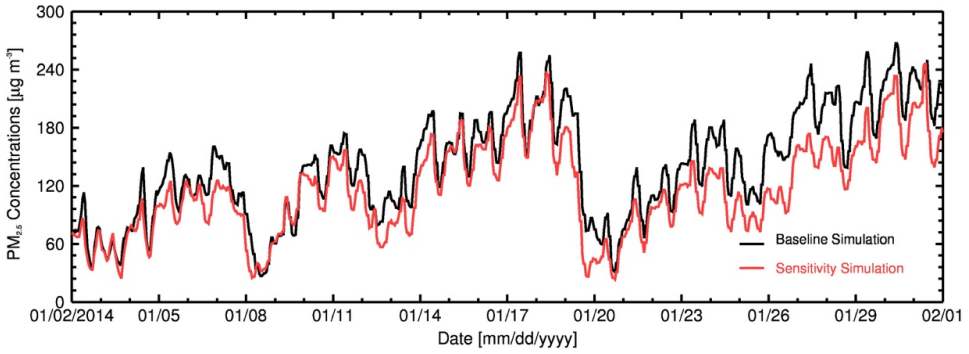

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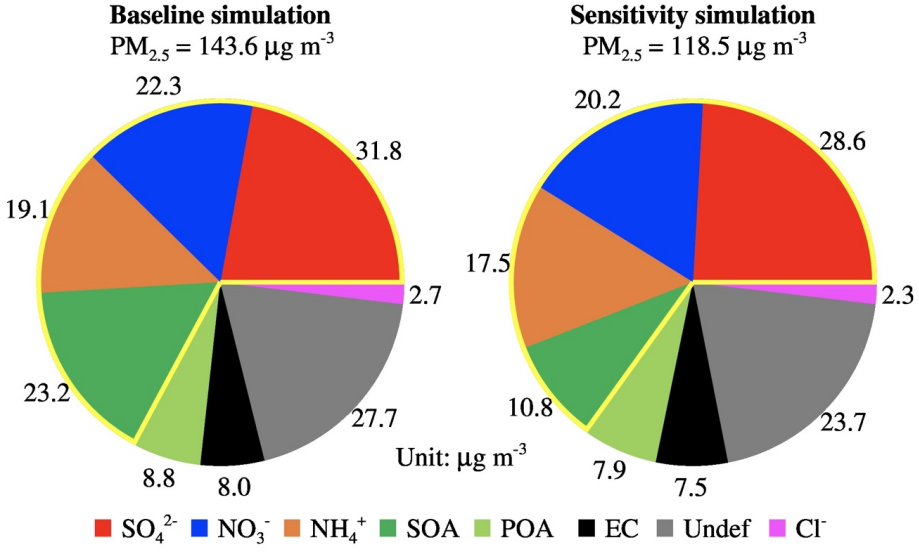

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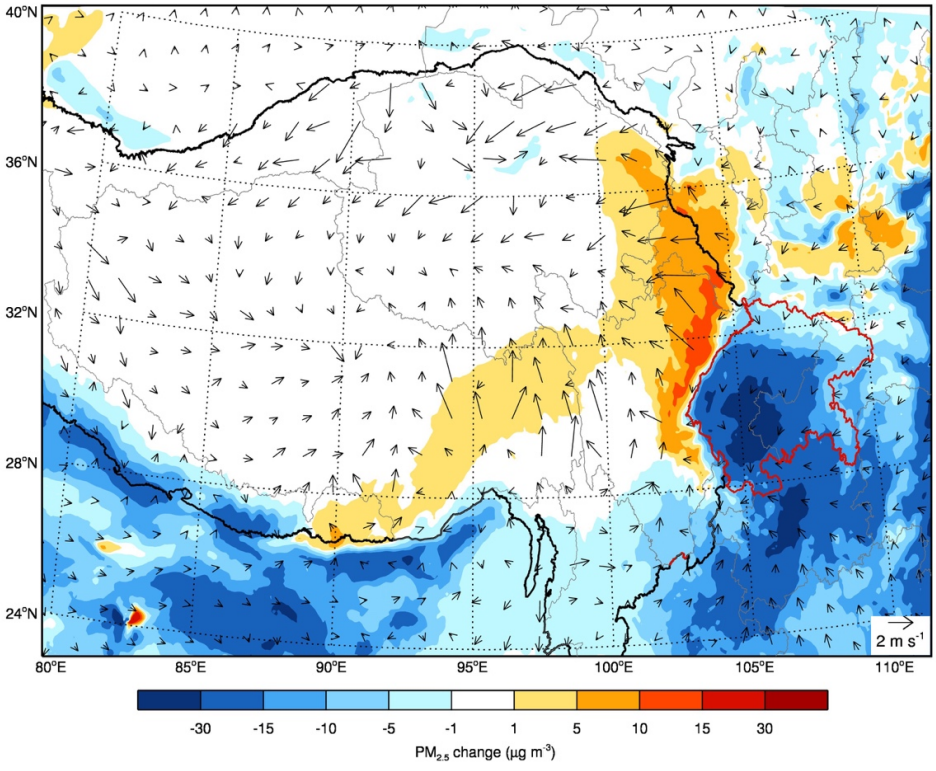

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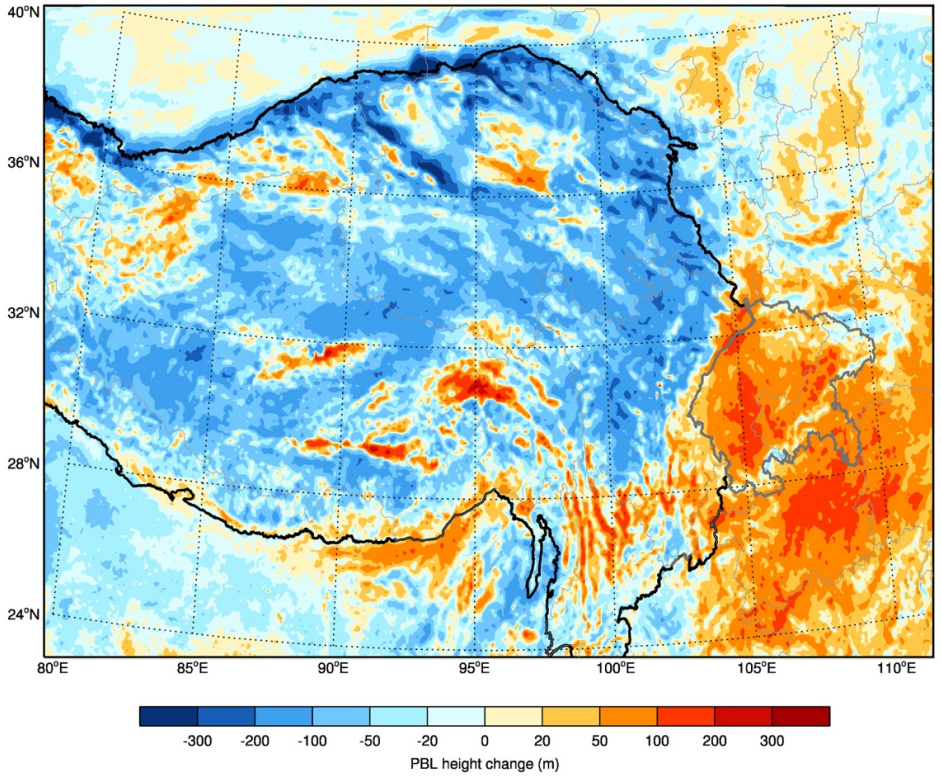

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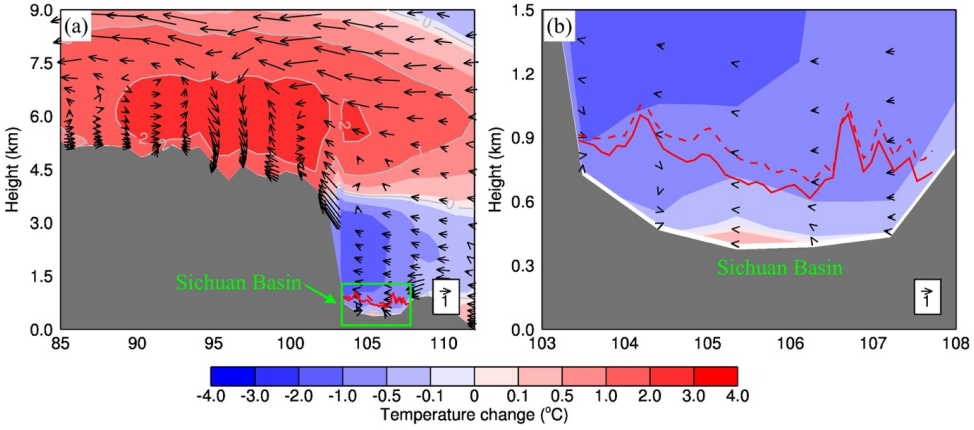

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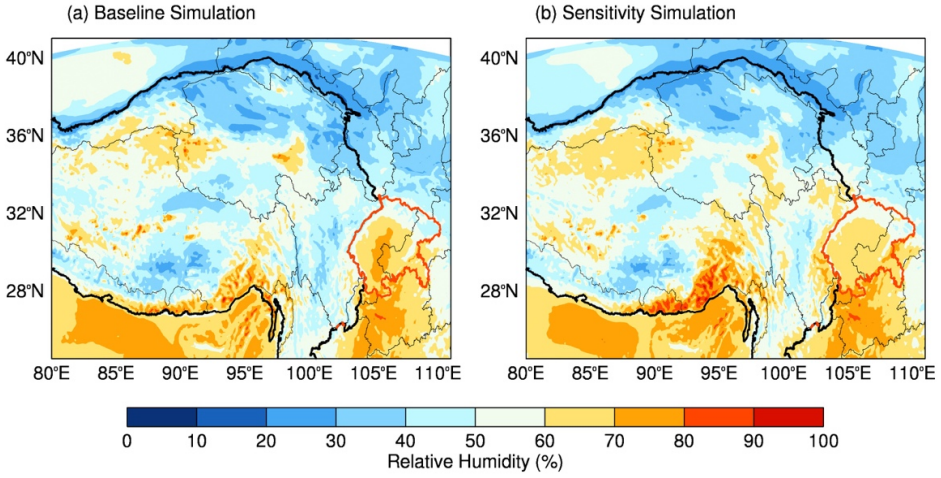

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Atmospheric Chemistry and Physics Discussions

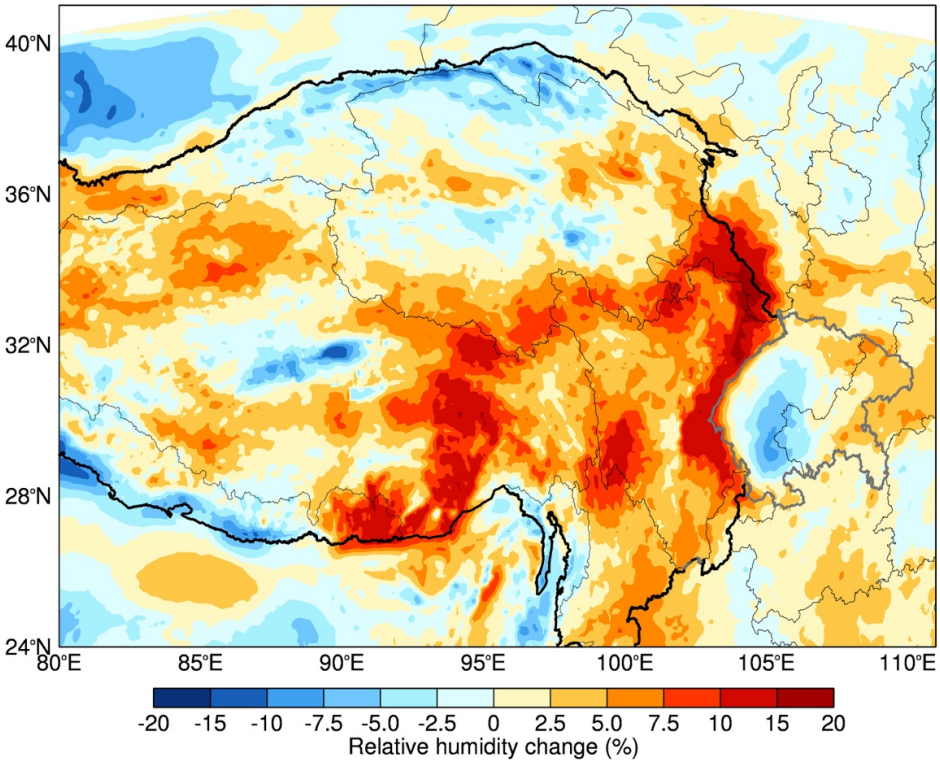

Figure 11 Spatial change in the relative humidity after the Tibet becomes 2°C warming. The positive shows the RH increases while the negative shows the RH decreases.