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# Spring biomass burning in Indochina enhances summer Yangtze River Valley rainfall through land–atmosphere interactions

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Indochina is one of the regions with the most severe biomass burning (BB) in the world, which produces enormous amounts of atmospheric aerosols, mostly in spring. Moreover, the spring soil moisture anomalies in Indochina have been found to have a significant influence on the summer rainfall in the Yangtze River Valley (YRV). It is still partially unclear how spring BB in Indochina influences the local and regional climate and land–atmosphere interactions. Here, we use regional model experiments and observational data to show that the radiative effect of BB aerosols in Indochina stabilizes the atmosphere and reduces local precipitation and soil moisture. The dry soil in Indochina persists from spring to summer, which warms the land surface and the atmosphere. As a result, the western Pacific subtropical high (WPSH) is stronger and extends westward from spring to summer. This leads to stronger moisture transport to and more precipitation in the YRV (increases of approximately 5% in July and 10% in August). Thus, the effect of BB aerosols on the YRV rainfall is similar to that of the Indochina dry soil anomaly. Additionally, the increase in the YRV summer rainfall caused by the Indochina spring dry soil anomaly is almost doubled when there are BB aerosols compared to that without BB aerosols, suggesting the importance of BB aerosols in regulating the regional land–atmosphere interactions.

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## INTRODUCTION

Biomass burning (BB) refers to the burning of living or dead vegetation through human or natural processes. It includes land clearing and land-use change by humans as well as natural wild fires. BB releases enormous amounts of particulates and gases; the former are known as atmospheric aerosols[1]. Aerosols play an important role in atmospheric physics and chemistry by affecting the diffusion and absorption of solar radiation (the radiative effect) and by changing cloud microphysics (the microphysical effect). The aerosol radiative effect usually cools the surface, reduces the planetary boundary layer (PBL) height, and stabilizes the atmosphere, which can reduce the likelihood of atmospheric convection and precipitation[2,3]. The aerosol microphysical effect is more complex and can be positive or negative, depending on the atmosphere and cloud conditions[4–6] and the aerosol composition[7].

The Indochina Peninsula (comprising Thailand, Laos, Cambodia, Myanmar, and Vietnam) is one of the regions with the most severe BB in the world[8,9]. The number of annual active fire points in the region has been >20,000 since 2004[10]. The fires in Indochina mainly occur in late winter and spring, and the peak frequency usually occurs in March. Aerosols produced from BB aerosols in Indochina have widespread impacts on the air quality and weather in the local and surrounding regions[11–13].

In addition, spring soil moisture anomalies in Indochina have been found to have a significant influence on summer rainfall in the Yangtze River Valley (YRV)[14]. This is due to the soil moisture memory in Indochina and the associated change in the western Pacific subtropical high (WPSH). As BB in Indochina mainly occurs in spring, an interesting question is how spring BB aerosols affect the local and regional climate in spring and summer. Can the effects of BB aerosols be recorded in the soil moisture and brought to summer? How do aerosols adjust the influence of the spring soil moisture in Indochina on the summer rainfall in the YRV? In this study, we use a series of regional model simulations ("Methods") to investigate these questions.

## RESULTS

### Spatiotemporal evolution of aerosols

Figure 1 shows the temporal evolution of the aerosol optical depth (AOD) in the study region. The Indochina and southern China had high AODs in March and April, an indication of the presence of BB aerosols and the transport of pollutants with the air flow[15,16]. Beginning in May, when the monsoon begins to develop, the AOD gradually decreases in Indochina and southern China. The highest summer AOD occurs in North China. Compared with the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2), the two Weather Research and Forecasting (WRF) model coupled with chemistry (WRF-Chem) experiments with BB emissions (Dry_BB and Wet_BB) simulate the spring-to-summer evolution of the AOD in Indochina quite well (Fig. 1g). However, the two experiments without BB emissions (Dry_NoBB and Wet_NoBB) produce evidently lower AODs in Indochina from March to mid-May. These differences in AOD are consistent with the differences in BB emissions (Supplementary Fig. 1).

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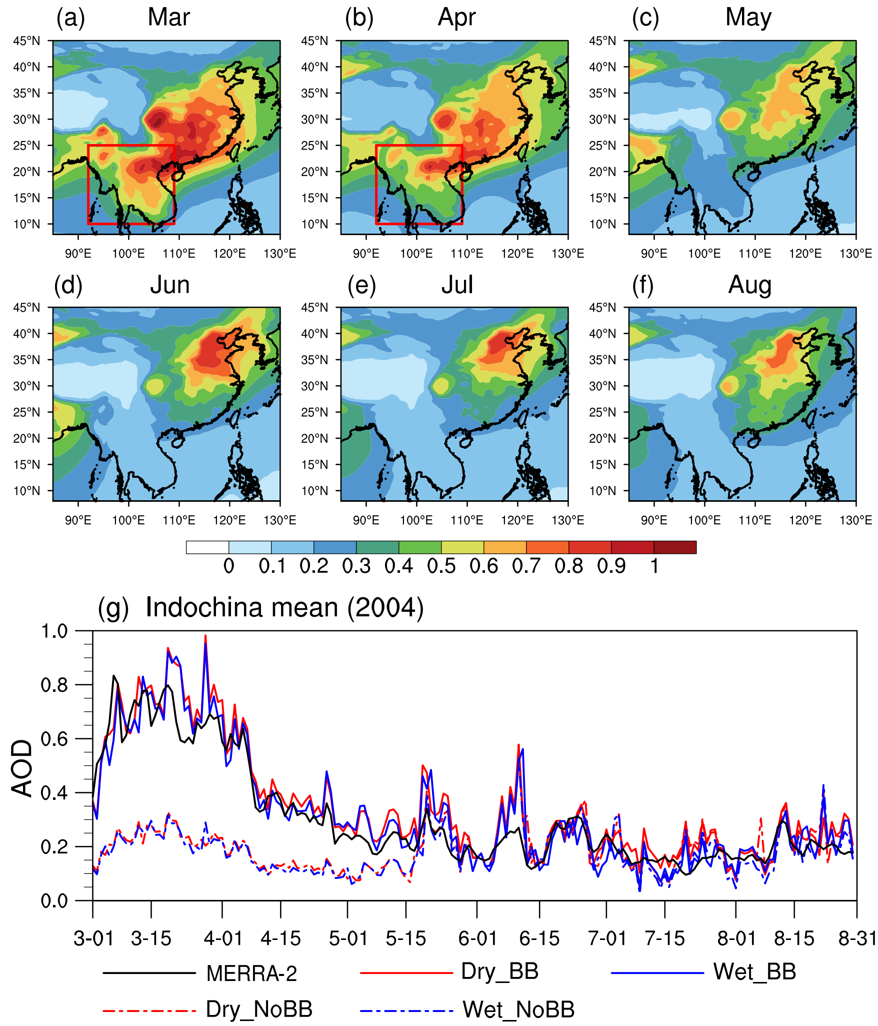


**Fig. 1 Temporal evolution of AOD. a–f** Climatological mean AOD in March–August 1980–2021 from MERRA-2. **g** Time series of Indochina daily mean AOD from 1 March to 31 August 2004 from MERRA-2 and experiments. The red box encloses the Indochina region defined in this study.

**Influence of BB aerosols on local and regional climate**

Next, we examine the climate differences in spring and summer caused by the BB emissions. Figure 2 shows the simulated spring-to-summer precipitation, geopotential height (GPH), and soil moisture differences due to differences in BB emissions (BB −NoBB). The BB aerosols reduce the spring (March–May) precipitation and soil moisture over Indochina and parts of eastern China. This is related to the radiative effect of aerosols, which cools the surface and warms the upper atmosphere (Supplementary Fig. 2). The more stable atmosphere makes it more difficult for convection and rainfall to occur. As a result, Indochina becomes drier.

Moreover, the spring soil moisture and precipitation anomalies in Indochina extend to summer (Fig. 2), although the BB aerosols have diminished during this period (Fig. 1). This is due to the memory of the soil moisture and the associated land–atmosphere interactions, including the response of the WPSH to drier Indochina[14,17]. The Indochina upper-level heating is much weaker in summer than in spring because of the reduction of BB, and eastern China shows strong summer heating in response to the westward extension of the WPSH (Supplementary Fig. 2). In July and August, the WPSH moves northward and is located further westward when there are BB emissions, leading to stronger moisture transport to the YRV and enhanced precipitation (Fig. 2e, g). The increases in precipitation in the YRV are 4.65% in July and 10.3% in August. The soil moisture exhibits changing patterns similar to those of the precipitation but with greater statistical significance (Fig. 2f, h). For the area-average precipitation in YRV, the changes are insignificant in June ($p > 0.1$) but significant in July and August ($p < 0.05$). The June-July-August mean of the area also exhibits a significant increase ($p < 0.1$).

Are the simulation results consistent with observations? We selected 9 years with the highest BB aerosols and 9 years with the lowest BB aerosols according to the regional mean spring AOD in Indochina during 1980–2021, corresponding to AOD anomalies greater than 0.8 times the standard deviation. The high BB aerosol years are 1982, 1983, 1992, 1998, 2004, 2010, 2012, 2014, and 2016, and the low BB aerosol years are 1988, 1989, 1994, 1996, 1997, 2001, 2002, 2017, and 2018. The composite differences between the high and low BB aerosol years exhibit patterns very similar to those from the simulations, including the drying of Indochina in spring and summer and the wetting of the YRV and part of the North China Plain in July and August (Fig. 3). Another set of observation-based datasets produced similar results (Supplementary Fig. 3). Thus, the results of the simulations are supported by the observations.

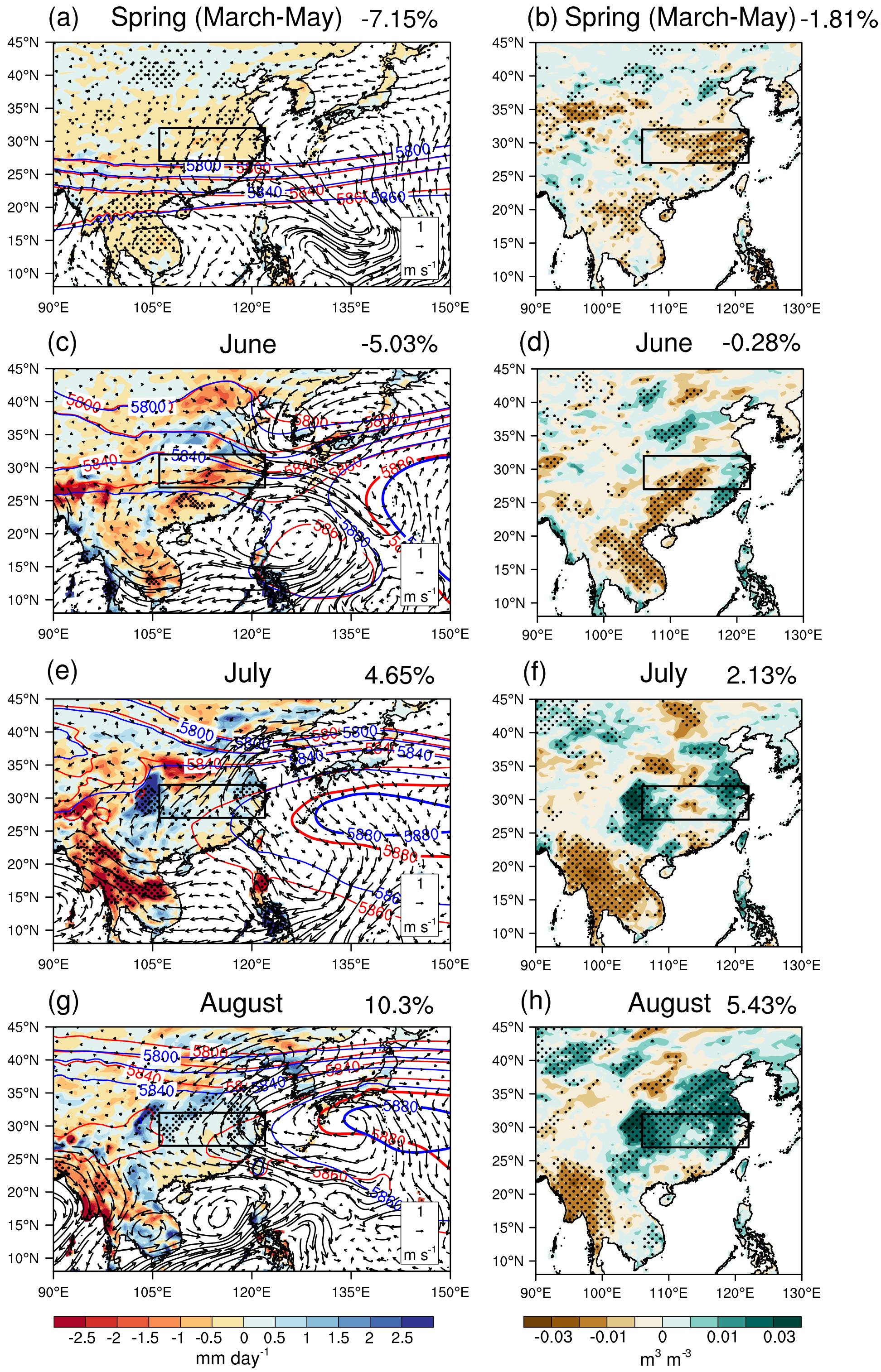


**Fig. 2 Model simulated climate responses to BB emissions.** **a**, **b** Spring (March–May); **c**, **d** June; **e**, **f** July; **g**, **h** August. Simulated spring-to-summer (left panels) precipitation (shading) and (right panels) soil moisture differences due to differences in BB emissions (BB−NoBB). The red (blue) contours are the 500 hPa GPH (units: m) from BB (NoBB). The arrows are the 850 hPa wind differences. The contour of 5880 m is thicker than other contours (same in subsequent figures). The mean percentage difference in the YRV ((BB−NoBB)/NoBB) is shown in each plot. Stippling highlights differences confident at 95% level based on a bootstrap test of resampling the ensemble members 10,000 times. The box encloses the YRV region (same in subsequent figures).

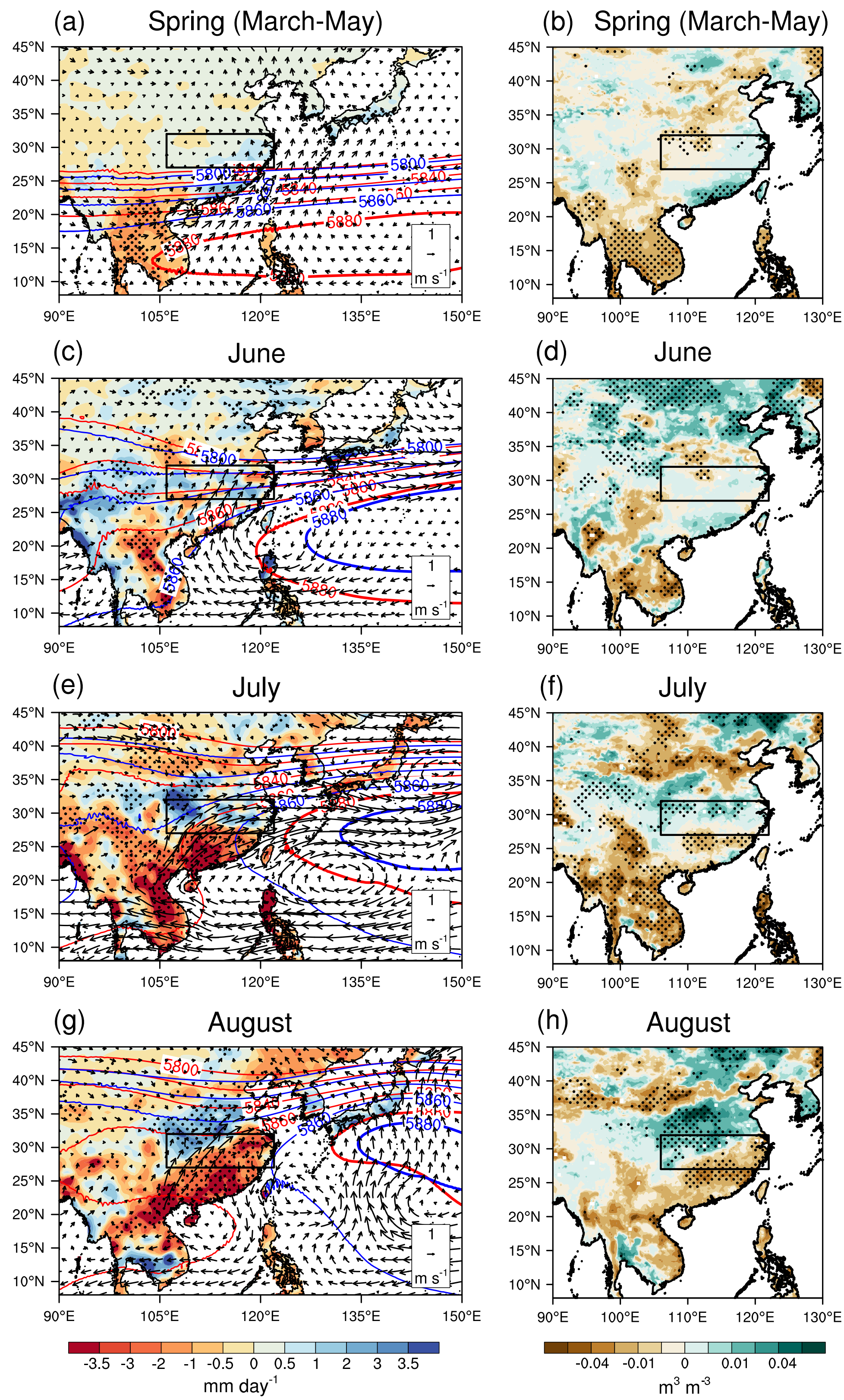


**Fig. 3 Response of climate to BB emissions based on observational data. a, b** Spring (March–May); **c, b** June; **e, f** July; **g, h** August. Same as in Fig. 2, but based on the composite differences between the 9 years with the highest BB aerosols and the 9 years with the lowest BB aerosols. See text for details. The AOD is from MERRA-2, the precipitation is from the Climate Prediction Center (CPC) Unified dataset, the soil moisture is from GLEAM, and the GPH, and 850 hPa winds are from ERA5.

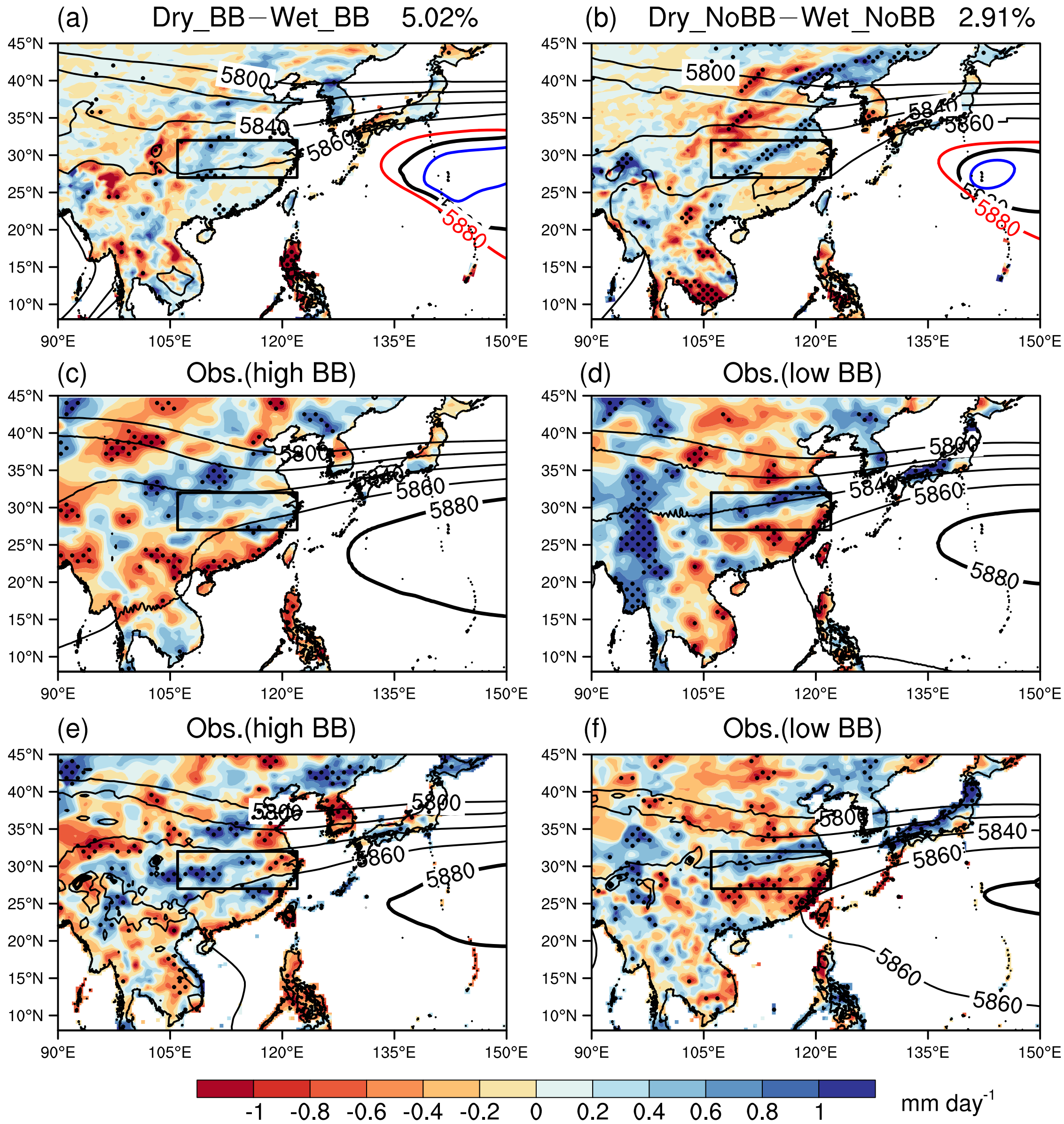


**Fig. 4 Response of summer YRV rainfall to spring soil moisture anomalies in Indochina under different BB emissions.** Summer mean precipitation difference caused by the initial soil moisture difference in March from experiments **a** with and **b** without BB emissions (shading). The contours denote the summer mean 500 hPa GPH from the two experiments, and the red and blue contours are 5880 m contour of the 500 hPa GPH from **a** Dry_BB and Wet_BB (or **b** Dry_NoBB and Wet_NoBB) experiments, respectively. The interannual regression of the summer precipitation in each grid cell on the Indochina spring mean soil moisture in **c**, **e** 9 years with high BB aerosols and in **d**, **f** 9 years with low BB aerosols. To be consistent with the precipitation anomalies in **a**, **b**, the regressed precipitation in **c**–**f** are multiplied by −1 to denote the influence of negative soil moisture anomalies. The contours are summer mean 500 hPa GPH from the respective years. **c**, **d** Use precipitation from the CPC Unified dataset, 500 hPa GPH from ERA5, and soil moisture from GLEAM. **e**, **f** Use precipitation from GPCC, 500 hPa GPH from MERRA-2, and soil moisture from ERA5. Stippling highlights differences confident at 95% level based on a bootstrap test of resampling the data 10,000 times.

### Influence of spring soil moisture on summer rainfall adjusted by BB aerosols

The above analyses show that the soil moisture anomalies caused by BB aerosols in Indochina can persist into summer and influence the local and regional climate. Specifically, the drier soil in Indochina combined with the westward extended WPSH not only reduces the summer precipitation in Indochina but also increases the summer precipitation in the YRV. An interesting question is how the BB aerosols adjust the influence of the spring soil moisture anomalies in Indochina on the summer climate. Figure 4a, b show the simulated summer precipitation response to the initial soil moisture difference in March. Regardless of whether there are BB emissions, the YRV shows increased precipitation in response to drier initial soil. However, the WPSH extends westward when there are BB emissions, which leads to stronger moisture transport to the YRV and more widespread precipitation increases. When there are no BB emissions, the WPSH is located further eastward and the precipitation increase is limited to a narrow band. The percentage of the precipitation increase in the YRV is 5.02% when there are BB emissions and 2.91% when there are no BB emissions. Thus, the effect of spring soil moisture anomalies on the summer YRV is almost doubled when there are BB emissions compared to when there are no BB

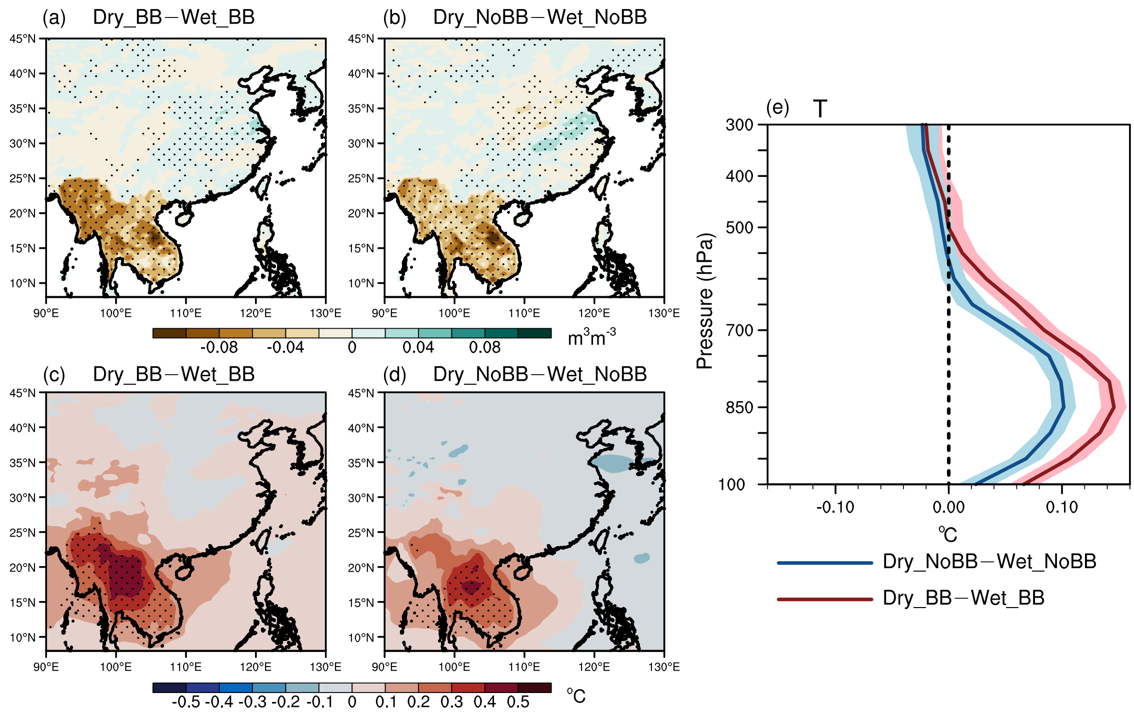


**Fig. 5 Simulated response of summer soil moisture and air temperature to spring soil moisture anomalies in Indochina.** Simulated summer mean differences in **a**, **b** surface soil moisture, **c**, **d** surface air temperature at 2 m, and **e** vertical profile of air temperature between the experiments with dry and wet initial soil moisture conditions. Stippling highlights differences confidence at 95% level based on the Student's *t* test. The shading in **e** shows the range of one standard deviation among the ensemble members.

emissions. Regression of the summer precipitation to the spring Indochina soil moisture in the years with high and low BB aerosols based on observational data produces patterns similar to those of the model experiments (Fig. 4c–f). It is also found that when there are BB emissions, the same initial spring soil moisture difference can cause larger differences in the summer soil moisture and air temperature in Indochina (Fig. 5). These larger differences lead to stronger WPSH responses and finally leads to stronger influences of the spring soil moisture anomaly in Indochina on the summer YRV rainfall (Fig. 4).

## DISCUSSION

In this study, we perform a series of WRF-Chem experiments to study the influence of BB aerosols in Indochina on the local and regional climate and investigate the role of BB aerosols in adjusting the influence of the Indochina spring soil moisture on the summer rainfall in the YRV. The major findings are summarized schematically in Fig. 6. The spring BB in Indochina increases the aerosol concentration, which cools the land surface and warms the upper atmosphere. This stable atmospheric structure reduces the precipitation and dries the soil. Due to the memory of the soil moisture, the dry soil conditions persist from spring to summer, which warms the land surface and the atmosphere. As a result, the WPSH is stronger and extends further westward. This leads to stronger moisture transport and more precipitation in the YRV (~5% more in July and 10% more in August). Previous studies have found that Indochina spring soil moisture dry (wet) anomalies may enhance (reduce) the summer rainfall in the YRV. We further show that the effect of BB aerosols on the rainfall in the YRV is similar to that of the Indochina dry soil anomalies. Additionally, the summer rainfall increase in the YRV due to the Indochina spring dry soil anomalies is almost doubled when there are BB emissions compared to when there are no BB emissions.

This study's regional model simulations are limited to the year 2004. Further investigation is warranted to explore how interannual variations in background climate may impact the role of BB in regional land–atmosphere interactions. In this study, we mainly investigate the responses of the monthly and seasonal mean precipitation; however, the extremes and seasonal evolution of precipitation have also changed. Generally, the BB emissions increase (reduce) the high-intensity (low-intensity) precipitation in the YRV, but the reverse is true for Indochina (Supplementary Fig. 4). BB emissions also slightly prolong the rainy season in the YRV (Supplementary Fig. 5). As these characteristics of precipitation have stronger socioeconomic impacts than the mean precipitation[18], the potential impacts of BB aerosols deserve further investigation.

Although the BB aerosols mainly occur in early spring, and we only prescribe the anomalous Indochina initial soil moisture in early spring, the resulting soil moisture anomalies persist through spring and summer. This demonstrates the strong soil moisture memory in the region, which is related to the land–atmosphere interactions, including the interactions between the Indochina soil moisture and the WPSH. The strengthening and westward extension of the WPSH persist from spring to summer, contributing to the long persistence of the soil moisture anomalies. The study provides an illustration of the land–atmosphere interactions beyond local processes.

## METHODS

### Observational datasets

Monthly data for 1980–2021 from several observation-based global datasets are used. We used the AOD from the MERRA-2[19] with a 0.5° × 0.625° resolution, a product that assimilates the AOD data from various ground- and space-based remote sensing platforms[20]. We used the precipitation data from Climate Prediction Center (CPC) Unified Gauge-Based Analysis[21] at 0.5° × 0.5° resolution and the Global Precipitation Climate Center (GPCC[22]) at 1° × 1° resolution. For soil moisture, we used the first layer (0–7 cm) of soil moisture from the fifth-generation

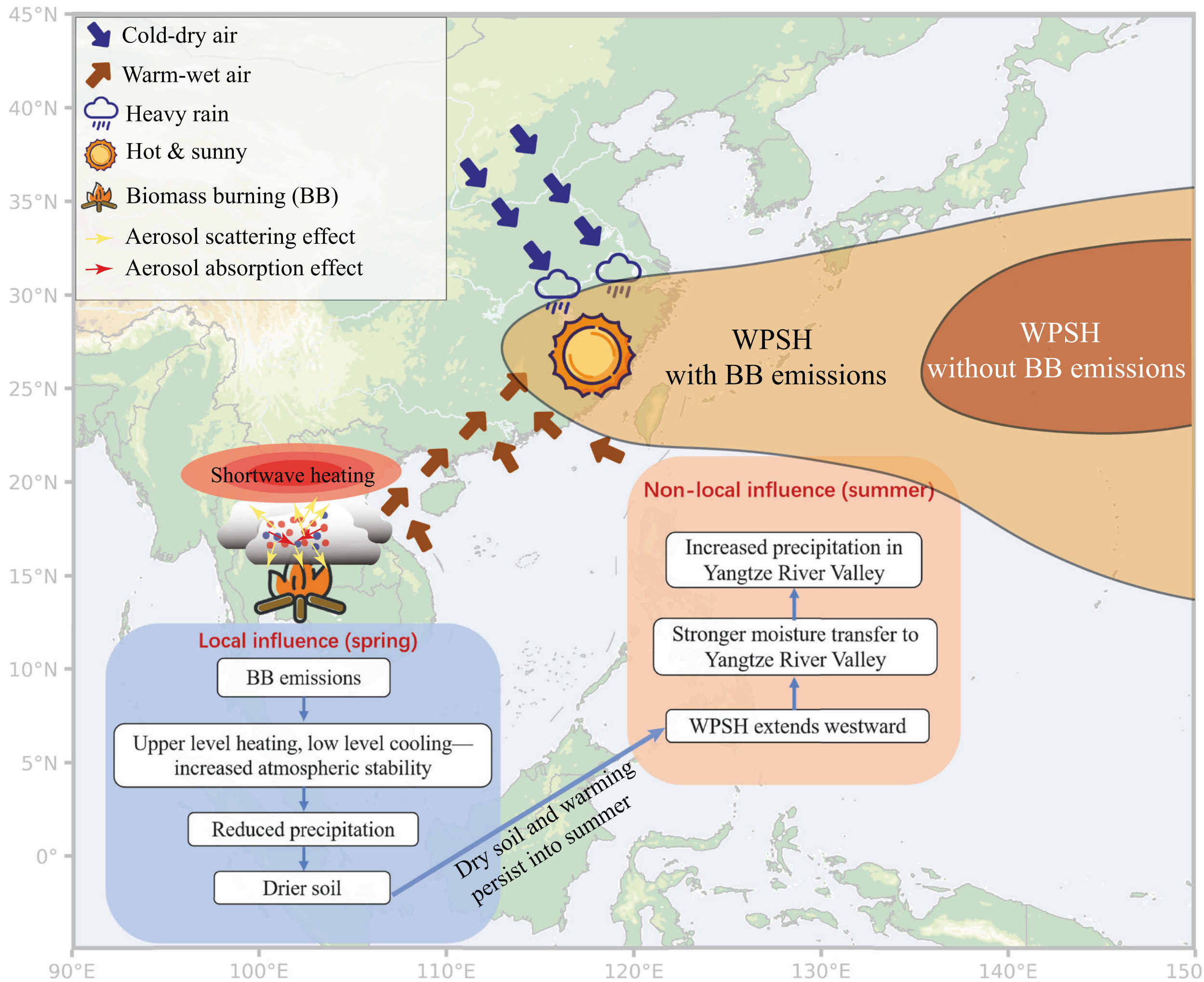


**Fig. 6 Schematic diagram of the major processes by which BB aerosols in Indochina influence local and nonlocal climate.** WPSH western pacific subtropical high, BB biomass burning.

**Table 1.** Experimental design.

| Experiment name | Experimental setup |
|---|---|
| Dry_BB | Initial soil moisture is prescribed as a dry condition in Indochina; prescribed BB emission |
| Wet_BB | Initial soil moisture is prescribed as a wet condition in Indochina; prescribed BB emission |
| Dry_NoBB | Initial soil moisture is prescribed as a dry condition in Indochina; no BB emission |
| Wet_NoBB | Initial soil moisture is prescribed as a wet condition in Indochina; no BB emission |

atmospheric reanalysis from the European Center for Medium-Range Weather Forecasts (ERA5[23]) and the root zone soil moisture (varying depths) from the Global Land Evaporation Amsterdam Model (GLEAM) v3.7a[24], both at 0.25° × 0.25° resolution. The choice of soil moisture in other soil layers has little influence on the results. In addition, the 500 hPa geopotential heights (GPHs) and 850 hPa winds from the ERA5 and MERRA-2 are used.

## Model and experiments

We use version 3.6.1 of the WRF-Chem[25,26], which is a fully coupled online air quality and transport model. The model simulation domain is set to South and East Asia (Supplementary Fig. 6), and it is forced by the 3-hourly ERA-Interim global reanalysis data. The horizontal resolution of the model is 50 km, and there are 30 vertical atmosphere layers. Four experiments are performed by considering the influence of the initial soil wetness (Dry or Wet) and aerosol emissions from BB aerosols (BB or NoBB), both over Indochina. As such, there are four combinations (Table 1).

The experiments started on February 25 and ended on September 1 2004. This year is selected because it is a non-El Nino Southern Oscillation (ENSO) year and the climate in Indochina is near the average. The data in March–August are used for analysis. These simulations are prescribed with dry or wet initial soil moisture conditions on March 1 for all four model layers across only Indochina (10°N–25°N, 92°E–109°E). The dry (wet) initial soil is defined as the 5th (95th) percentile values of the 31-day daily soil wetness centered around March 1 during 1979 to 2014 (1116 days in total). The initial soil moisture is from Global Land Data Assimilation System version 2.0 (GLDAS-2.0[27]), which was produced using the same land model (Noah) as our experiments.

To estimate the uncertainties associated with the various model physical parameterization schemes, each experiment has 12 ensemble members. They are produced by perturbation of the parameterization schemes, including two different PBL schemes, three different microphysics schemes, and two different short-wave radiation schemes (Supplementary Table 1). All of the experiments have prescribed standard emissions from the monthly mosaic Asian anthropogenic emission inventory (MIX) for the year 2010[28], which provides the emission intensity of main gaseous and particulate pollutants as well as carbonaceous and inorganic aerosols. MIX does not include emissions from BB, fugitive dust, aviation, and international shipping. In the two BB experiments, the BB emissions during the simulation period from the fourth-generation global fire emission database (GFED4)[29] are added. The major emission categories and their monthly variations can be found in Supplementary Fig. 1. We turn on the aerosol radiative (direct) effect in the model, including its semi-direct effect on the cloud cover and liquid water path, but the aerosol microphysical (indirect) effects are turned off to reduce the uncertainties in simulations.

To check the influence of BB aerosols on the regional climate, we compare the simulation results from WRF-Chem experiments with (Wet_BB and Dry_BB) and without (Wet_NoBB and Dry_NoBB) BB emissions. For simplification, we use BB and NoBB to represent the average results of the two experiments with different initial soil moisture conditions, that is,

$$\begin{aligned} \mathrm{BB} &= (\mathrm{Wet\_BB} + \mathrm{Dry\_BB})/2; \\ \mathrm{NoBB} &= (\mathrm{Wet\_NoBB} + \mathrm{Dry\_NoBB})/2. \end{aligned} \tag{1}$$

The differences between BB and NoBB are thus the influence of BB aerosols.

## DATA AVAILABILITY

The ERA5 data can be downloaded from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The MERRA-2 data can be downloaded from https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/. The MIX emission data can be downloaded from http://meicmodel.org/. The GFED4 data can be downloaded from http://www.globalfiredata.org/. The GLEAM soil moisture can be downloaded from https://www.gleam.eu/. The CPC Unified precipitation can be downloaded from https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html. The GPCC precipitation data can be downloaded from https://www.psl.noaa.gov/data/gridded/data.gpcc.html.

## CODE AVAILABILITY

The computer code used in the present study is available from the corresponding author on reasonable request.

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## AUTHOR CONTRIBUTIONS

J.W. and Q.M. designed and conceived the research. Q.M. performed the model simulations and most data analysis. Y.S. contributed to the graphics. J.W. and Q.M. wrote the initial draft. All authors discussed the results and contributed to the writing of the article.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1038/s41612-023-00514-z.

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