1. Introduction

Fire is the predominant terrestrial ecosystem disturbance on the global scale and plays a key role in the Earth system (Randerson et al. 2006; Bowman et al. 2009; Bond-Lamberty et al. 2009; Li and Lawrence 2017; Arora and Melton 2018). Each year, fire burns ∼400 Mha of vegetated area globally (Giglio et al. 2013; van der Werf et al. 2017; Chuvieco et al. 2018) and emits massive amounts of tiny particles (aerosols) and trace gases into the air (Andreae and Rosenfeld 2008; van der Werf et al. 2009; Ward et al. 2012; Tian et al. 2016; Li et al. 2019). Both burned area and fire emissions are expected to increase in the future with climate change (Lasslop et al. 2020; Xie et al. 2022).

Fire aerosols mainly consist of organic carbon (OC) and black carbon (BC) (Andreae and Rosenfeld 2008; Boucher et al. 2013). They can affect climate by scattering and absorbing incoming solar radiation, by serving as cloud condensation nuclei that modulate cloud properties, and by depositing on snow and ice thereby reducing the surface albedo, termed aerosol–radiation interactions (ARI), aerosol–cloud interactions (ACI), and surface albedo changes (SAC), respectively, by IPCC AR5 and AR6 (Boucher et al. 2013; Forster et al. 2021). Such fire aerosol effects could be enhanced through climate feedbacks due to sea surface temperature (SST) change (Jiang et al. 2020) and may alter the water cycle, which relates to freshwater availability, a major environmental issue (Vörösmarty et al. 2010; Douville et al. 2021; WMO 2021).

Many studies have investigated the global and regional impacts of fire aerosols on radiation, surface climate, human health, and biogeochemical cycle. They reported that fire aerosols generated a negative radiative effect at Earth surface, cooled the surface, and decreased precipitation with global averages of −0.55 to −1.59 W m−2, −0.17 °C, and −0.01 to −0.07 mm day−1, respectively (e.g., Tosca et al. 2013; Clark et al. 2015; Jiang et al. 2016; Grandey et al. 2016; Landry et al. 2017; Thornhill et al. 2018; Hamilton et al. 2018; Jiang et al. 2020), and threatened public health through degrading air quality (Johnston et al. 2012; Chen et al. 2021). Earlier studies also pointed out that the ARI increased global gross primary production (GPP) by 1 Pg C yr−1, primarily by increasing diffuse radiation, which stimulates photosynthesis (e.g., Yue and Unger 2018). But the net effect of fire aerosols decreased global GPP by 1.6 to 2.8 Pg C yr−1, mainly by drying and/or cooling the land surface as well as weakening the solar radiation (Li 2020; Xu et al. 2021), although there is a large uncertainty in the net effect (Landry et al. 2017). In addition, Clark et al. (2015), Jeong and Wang (2010), and Grandey et al. (2016) found that submonthly, seasonal, and interannual variability in fire
emissions were important for estimating the radiative and climate effects of fire aerosols.

The influence of fire aerosols on the global water cycle has not yet been quantified and underlying mechanisms remain unclear. Previous global studies focused on fire aerosol impacts on precipitation only. It remains unknown how much and by which mechanisms fire aerosols affect other components of the global water cycle (e.g., continental evapotranspiration and runoff). Furthermore, even regarding the impacts on global precipitation, some important limitations existed in previous studies. For example, they did not consider the aerosol indirect effect (e.g., Tosca et al. 2013), used fixed or prescribed SST in their simulations (e.g., Jiang et al. 2016; Grandey et al. 2016; Zou et al. 2020; Xu et al. 2021), or adopted the earlier version of CESM aerosol model MAM3 (e.g., Clark et al. 2015). The aerosol indirect effect is the main component of ACI, and was reported to dominate the radiative effect of fire aerosols regionally and globally by Jiang et al. (2016, 2020), Lu et al. (2018), and Xu et al. (2021). The fixed- or prescribed-SST approach is suitable for diagnosing the radiative forcing and radiative effect (Hansen et al. 2002), but accounts for only the hydrological fast response (Grandey et al. 2016). The fast response contributes less to the impacts of the various forcing agents (e.g., CO₂ and fire aerosols) on precipitation than does the climate feedback (i.e., the slow response) (Bala et al. 2010; Jiang et al. 2020). Furthermore, MAM3 was found to greatly underestimate BC and OC concentration over oceans and the Arctic (Liu et al. 2012; Wang et al. 2013).

The global water cycle can be summarized schematically as follows (blue arrows in Fig. 1; Trenberth et al. 2007). Water evaporates from the ocean (E_O) to the atmosphere where it forms clouds. Water droplets in the clouds collide, grow, and partly fall to the ocean as precipitation (Pr_O). E_O exceeds Pr_O, which allows residual water vapor (E_O – Pr_O) to be transported by air currents to the land. Land precipitation (Pr_L) exceeds evapotranspiration (ET_L), which is the sum of evaporation from soil and canopy surfaces, plus transpiration from plants. The excess Pr_L – ET_L flows into streams and rivers as runoff, and then discharges into the ocean, completing the cycle.

In this study, we provide the first quantitative assessment of fire aerosols on the global water cycle, and investigate related mechanisms. The impacts of fire aerosols are quantified by comparing present-day simulations with and without fire aerosols using a coupled atmosphere–land–ocean configuration of the Community Earth System Model (CESM), with a slab ocean model. The simulations use prescribed 2003–11 daily fire aerosol emissions from the satellite-based Global Fire Emissions Database inventory as forcing data that have submonthly, seasonal, and interannual variabilities. The state-of-the-art aerosol model MAM4 is adopted, which models both aerosol direct and indirect effects, and in which the primary particulate organic matter (POM) and BC concentrations are increased by up to 40% over oceans and the Arctic to reduce the bias in MAM3 (Liu et al. 2016). Also, the slab ocean model is active to account for both the hydrological fast and slow responses of fire aerosols, in contrast to the prescribed-SST method that accounts for the fast response only.

2. Methods and data

a. Model platform

The CESM is a widely used Earth system model that can simulate the global atmosphere, land, ocean, and sea ice, and
Table 1. Comparison between the CESM FIRE simulation and benchmarks for global precipitation (Pr), Pr over land (Pr_L) and ocean (Pr_O), land evapotranspiration (ET_L), runoff, ocean evaporation (E_O), and E_O minus Pr_O. Superscript letter “a” means that Antarctica is excluded. Global totals (units: 10^3 km^3 yr^-1) and spatial correlations between the benchmarks and the CESM simulation (Cor) are listed. All the correlations are statistically significant according to a Student’s t test at the 0.05 level. Spatial patterns of the benchmarks and CESM simulations are shown in Figs. S1–S5.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Period</th>
<th>CESM</th>
<th>Benchmark</th>
<th>Cor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr</td>
<td>2003–11</td>
<td>558</td>
<td>GPCP v2.3: 504</td>
<td>0.88</td>
</tr>
<tr>
<td>Pr_L^a</td>
<td>2003–11</td>
<td>116</td>
<td>GPCPv2.3: 115</td>
<td>0.82</td>
</tr>
<tr>
<td>Pr_O</td>
<td>2003–11</td>
<td>436</td>
<td>GPCP v2.3: 385</td>
<td>0.88</td>
</tr>
<tr>
<td>ET_L^a</td>
<td>2003–05</td>
<td>74</td>
<td>LandFlux-EVAL (ET-Diag): 66 ± 20</td>
<td>0.71</td>
</tr>
<tr>
<td>Runoff^a</td>
<td>2003–05</td>
<td>43</td>
<td>Pr_L(GPCP/CRU)-ET-Diag: 42 ± 20</td>
<td>0.59</td>
</tr>
<tr>
<td>E_O</td>
<td>2003–11</td>
<td>481</td>
<td>ERAS: 469</td>
<td>0.97</td>
</tr>
<tr>
<td>E_O – Pr_O</td>
<td>2003–11</td>
<td>45</td>
<td>ERAS: 40</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The two simulations were run for 99 years with the fire emissions data cycling 11 times. The last 27 years of each simulation were analyzed. The uncertainties were computed using the standard deviation of annual values for the 27 years. Both simulations used 0.9° (latitude) × 1.25° (longitude) horizontal resolution for the land and atmosphere (30 atmospheric levels), while the ocean and sea ice components used a gx1v6 displaced pole grid. The model time step was 30 minutes. Input data except for fire aerosol emissions were the default (without any change) inputs provided with the CESM (values for a year were used throughout the simulations, e.g., anthropogenic aerosols for the year 2000).

c. Evaluation

The CESM simulates the global amounts and spatial patterns of the present-day water cycle reasonably well (Table 1). The simulated global total precipitation is 11% higher than satellite-based GPCPv2.3 for 2003–11 (Adler et al. 2018), mainly due to an overestimation of ocean precipitation (Table 1). The CESM generally captures the spatial pattern of precipitation well, but overestimates precipitation over equatorial central and eastern Pacific and southern Atlantic in the Southern Hemisphere (SH) (see Fig. S1 in the online supplemental material), which is described as the double intertropical convergence zone (ITCZ) bias, the most prominent and common bias among climate/Earth system models (Tian and Dong 2020). Biases in land precipitation are mainly a dry bias in South America and northwest Eurasia, and a wet bias in Australia and southern Africa.

CESM-simulated global land evapotranspiration (ET), with Antarctic excluded, was 74 × 10^3 km^3 yr^-1 for 2003–05, which was within the range (66 ± 20 × 10^3 km^3 yr^-1) of the LandFlux-EVAL ET merged synthesis product based on satellite and in situ observations (ET-Diag) (Mueller et al. 2013). Antarctic was excluded from the simulation results for a fair comparison with the LandFluxEVAL dataset, which excluded the region. The simulated global runoff (43 × 10^3 km^3 yr^-1) was close to the benchmark of 42 ± 20 × 10^3 km^3 yr^-1 estimated by GPCP and CRU land precipitation minus LandFluxEVAL ET-Diag and the global continental discharge of 37 × 10^3 km^3 yr^-1 mainly...
Based on streamflow data from the world’s largest 921 rivers (Dai and Trenberth 2002). The global spatial correlation between CESM simulations and benchmarks is 0.71 for land ET and 0.59 for runoff, significant at a 0.05 level using the Student’s *t* test, indicating that the CESM can skillfully simulate the global spatial pattern of land ET and runoff. Biases in CESM simulations appear mainly as overestimated ET in Australia and southern Africa, underestimated ET in South America and northwest Eurasia (Fig. S2), and underestimated runoff in South America (Fig. S3).

The CESM simulates a similar spatial pattern of $E_O$ and $E_O - Pr_O$ to the ERA5 (Hersbach et al. 2020), with high and significant spatial correlation between them (0.97 and 0.91). The CESM simulates the global total of $E_O$ slightly higher than ERA5 (Table 1) mainly due to an overestimation in the Atlantic (Fig. S4). The simulated $E_O - Pr_O$, whose global total represents atmospheric water vapor transport from ocean to land, was 12.5% higher than ERA5 mainly due to overestimation in the tropical North Atlantic and the extratropical oceans (Fig. S5).

In addition, we evaluated the simulated aerosol optical depth (AOD) with observations from the Aerosol Robotic Network (AERONET; http://aeronet.gsfc.nasa.gov) at sites in SH tropical Africa and South America and boreal North America where AOD was largely affected by fire aerosols (Fig. 2). The AERONET AOD data were averaged over 2003–11 to match the period of fire emission input data used here.

As shown in Fig. 2, CESM captures the distinct seasonal cycle of the observations at all sites, that is, high AOD during the fire season (the dry season in the tropics and the warm season in the extratropics). It also successfully reproduced the observed AOD at the tropical sites (Figs. 2a–f) for the periods outside the fire season. However, it underestimates year-round AOD at the boreal North America site (Fig. 2g) and fire-season AOD at the tropical sites (Figs. 2a–f). The potential reasons for the underestimation include not only a bias in surface fire emissions (e.g., lacking emissions from small fires in GFED3.1; Randerson et al. 2012; van der Werf et al. 2017), but also limitations in the CESM modeling of aerosol–cloud interactions (e.g., excessive scavenging of primary carbonaceous aerosols by liquid-phase clouds; Liu et al. 2016). Similar to Jiang et al. (2016, 2020), Grandey et al. (2016), and Zou et al. (2020), the present study does not attribute the underestimation of AOD to only the surface fire emissions and thus does not scale the surface fire emissions.

![Fig. 2. Comparison of 2003–11 monthly aerosol optical depth (AOD) from CESM FIRE and NOFIRE simulations with AERONET observations at sites in (a)–(c) tropical southern Africa, (d)–(f) tropical South America, and (g) boreal North America, where AOD is largely affected by fire aerosols. The error bars show the standard deviation of multiyear AOD values in that month.](image-url)
emissions to inflate modeled AOD magnitudes as done by Ward et al. (2012), Tosca et al. (2013), and Xu et al. (2021).

3. Results

a. Fire aerosols and induced change in AOD

Fire aerosol column burdens (the difference of the aerosol column burden between the FIRE and NOFIRE cases) peak in the tropics, with a secondary peak in the Arctic-boreal region (Figs. 3a–c). Southern Africa and tropical South America have the maximum fire aerosol column burdens (i.e., vertically integrated concentration) as the regions with highest surface fire emissions (Li et al. 2019). Remote open oceans also exhibit large fire aerosol concentration, suggesting that fire aerosols can be long-range transported from their source regions. Globally, fire contributed 46 ± 4% (0.10 ± 0.01 mg m$^{-2}$) to the total BC burdens (0.21 ± 0.02 mg m$^{-2}$) and 74 ± 3% (1.15 ± 0.19 mg m$^{-2}$) to the total POM (1.55 ± 0.19 mg m$^{-2}$) burdens for 2003–11, similar to estimates in Bond et al. (2013) and Andreae (2019). Fire is the largest source of BC and POM globally and in most regions of the world except for East Asia and South Asia, compared to contributions from biofuel burning and fossil fuel combustion (Jiang et al. 2016). The fire contribution to atmospheric sulfate aerosols is relatively small (2% ± 1%).

Fire aerosols increase AOD, with spatial patterns similar to those of the fire impacts on atmospheric POM burdens (Fig. 3). Fire aerosols produce a global area-weighted AOD increase of 7 ± 2 × 10$^{-3}$ (5.7% ± 2.0%). Our estimate is lower than the values of 10% of Tosca et al. (2013) and 14% ± 7% of Xu et al. (2021), which scaled the fire emissions by about a factor of 2 to inflate the modeled AOD.

b. Impacts of fire aerosols on the global water cycle

Globally, fire aerosols decrease land precipitation by 4.1 ± 1.8 × 10$^3$ km$^3$ yr$^{-1}$ (0.07 ± 0.03 mm day$^{-1}$) (3.3% ± 0.8%), land ET by 2.5 ± 0.5 × 10$^3$ km$^3$ yr$^{-1}$ (3.3% ± 1.4%), runoff by 1.5 ± 1.4 × 10$^3$ km$^3$ yr$^{-1}$ (3.3% ± 2.9%), ocean evaporation by 8.1 ± 1.9 × 10$^3$ km$^3$ yr$^{-1}$ (1.7% ± 0.4%), ocean precipitation by 6.6 ± 2.3 × 10$^3$ km$^3$ yr$^{-1}$ (0.05 ± 0.02 mm day$^{-1}$) (1.5% ± 0.5%), and water vapor transport from ocean to land by 1.5 ± 1.4 × 10$^3$ km$^3$ yr$^{-1}$ (3.3% ± 2.9%) (Fig. 1). All of these changes are statistically significant at the 0.05 level according to Student’s t test, indicating that fire aerosols weaken the global water cycle significantly.

The decrease in global land ET caused by fire aerosols is comparable to the decrease of 0.76 to 3.5 ± 10$^3$ km$^3$ yr$^{-1}$ associated with land use and land cover change (LULCC; present-day land cover compared to potential natural vegetation cover or 1850 land cover) (Sterling et al. 2013; Boisier et al. 2014; Bosmans et al. 2017). It is larger than the decrease of 1.5 to 1.7 ± 10$^3$ km$^3$ yr$^{-1}$ due to present-day ozone pollution effects on land ecosystems estimated by Lombardozzi et al. (2015). The impact of fire aerosols is larger than that caused by LULCC for continental precipitation (−0.27 to +0.38 × 10$^3$ km$^3$ yr$^{-1}$) (Lawrence et al. 2012) and for global precipitation (−1.5 × 10$^3$ km$^3$ yr$^{-1}$) (Findell et al. 2007).

Spatially, fire aerosols decrease ET and evaporation over most regions of the world (Fig. 4a). The largest changes occur in central Africa and the ocean to its west (<−100 mm yr$^{-1}$). Overall,

FIG. 3. Impacts of fire aerosols (FIRE − NOFIRE) on annual (a) BC, (b) POM, and (c) sulfate aerosol column burdens (mg m$^{-2}$; i.e., vertically integrated concentration) as well as (d) AOD.
correlation between them (0.87), except in boreal forests over Asia and North America. Fire aerosols significantly decrease runoff in tropical forests over central Africa, Indonesia, and the northern Amazon basin, as well as in Greenland. A total of 7.8% of global land area shows significant changes in runoff, much smaller than the impacts of fire aerosols on land precipitation (17.6%) and ET (46.9%) and the impacts of fire on runoff through changing terrestrial ecosystems (20%; Li and Lawrence 2017), but comparable to estimates of LULCC impacts (7.3%; Findell et al. 2007).

**c. Mechanisms for the effect of fire aerosols on the water cycle**

1) **LAND ET AND OCEAN EVAPORATION**

Fire-aerosol-induced cooling (Fig. 5a) due to the decrease in shortwave radiation flux reaching the surface (Jiang et al. 2020; Fig. 6a) explains the decline in ocean evaporation (Fig. 4a), because of no limitation in water availability there. Cooling can also decrease land ET (Figs. 5g–i) through decreasing atmospheric water demand and decreasing stomatal conductance in the extratropics where temperature is generally lower than the optimal value (Bonan 2008). The surface cooling is most evident in the NH middle and high latitudes (Fig. 5a). Jiang et al. (2020) reported that the surface cooling could be attributed primarily to aerosol–cloud interactions (\(-0.70 \pm 0.20\) W m\(^{-2}\)), dominating the global fire aerosol radiative effect of \(-0.78 \pm 0.29\) W m\(^{-2}\) and climate feedbacks (enhanced cooling from 0.03° to 0.64°; e.g., air–sea feedbacks). Besides, the positive ice/snow albedo feedback can enhance the fire-aerosol-induced cooling. As shown in Fig. 5b, fire aerosols generally lead to sea ice/snow expansion, especially in the NH middle and high latitudes. They produce area-weighted increases of 8.0 \(\pm\) 3.5, 9.9 \(\pm\) 6.4, and 10.6 \(\pm\) 7.4 \(\times\) 10\(^6\) km\(^2\) in Arctic sea ice, global sea ice, and global snow cover, respectively, all statistically significant at a 0.05 level.

Fire aerosols also attenuate the visible band of solar radiation reaching the canopy (Fig. 5c), which tends to decrease leaf stomatal conductance due to a stomatal light response and thus decreases transpiration (i.e., the moisture carried from plant roots to the atmosphere) (Fig. 5h). The visible solar radiation consists of the diffuse and direct radiation. The diffuse radiation could redistribute the visible solar radiation load from light saturated sunlit leaves to nonsaturated shaded leaves (Mahowald 2011; Kanniah et al. 2012), and thus has 1.5–2.5-times-higher light-use efficiency than the direct radiation (Mercado et al. 2009; Zhou et al. 2021). However, fire aerosols decrease the direct radiation (1.29–2.67 W m\(^{-2}\)) much more than increasing the diffuse radiation (0.05–0.45 W m\(^{-2}\)) (Li 2020; Xu et al. 2021), so this decrease dominates the effect of fire aerosols on transpiration through changing surface visible solar radiation.

In addition, decreased precipitation due to fire aerosols (Fig. 4b) can reduce the intercepted precipitation by canopy in most regions (Fig. 5d), and therefore also decrease the evaporation of canopy-intercepted water (Fig. 5g). The link can be supported by the global change totals shown in Fig. 6 and also by the similar spatial patterns of them (the global

---

40.6% of global area shows a statistically significant change in land ET and ocean evaporation at the 0.05 level, higher than the 6.5% due to LULCC estimated by Findell et al. (2007).

Precipitation is generally reduced by fire aerosols, but significantly increased in most SH tropical oceans, especially the tropical southeast Pacific (Fig. 4b). The reduction is most evident in central Africa, NH deep tropical oceans, Indonesia, the northern Amazon basin, and the Arctic-boreal region. A total of 17.7% of global area shows significant changes in precipitation, which is also higher than estimates of LULCC impacts (3.9%; Findell et al. 2007).

The influence of fire aerosols on runoff (Fig. 4c) is spatially similar to that of precipitation over land, with high spatial

---

Fig. 4. Impacts of fire aerosols (FIRE – NOFIRE) on global annual (a) ocean evaporation (E) and land evapotranspiration (ET), (b) precipitation, and (c) runoff (mm yr\(^{-1}\)). Regions are striped where the difference between FIRE and NOFIRE passed Student’s t test at the 0.05 significance level.
spatial correlation is 0.89 between changes in precipitation and canopy interception and 0.84 between changes in canopy interception and evaporation). Conversely, fire aerosols have limited impact on the root-zone and surface soil moisture, and even slightly increase them in some regions (Figs. 5e,f and 6). Because transpiration and soil evaporation are actually decreased due to fire aerosols (Figs. 5h,i), decreased precipitation has limited impact on transpiration and soil evaporation. The change in global canopy evaporation ($-0.4 \pm 0.2 \times 10^3$ km$^3$ yr$^{-1}$) contributes only 16% of the change in land ET ($-2.5 \pm 0.5 \times 10^3$ km$^3$ yr$^{-1}$), so the influence of fire aerosols on precipitation is not the main pathway of fire aerosols’ effect on land ET.

In summary, surface cooling is the main pathway by which fire aerosols affect the global ocean evaporation and land ET. The decrease in land ET is enhanced by attenuated visible solar radiation, which decreases transpiration, and by decreasing precipitation, which decreases canopy evaporation.

2) PRECIPITATION

Fire aerosols increase cloud droplet number concentration (Fig. 7a) to produce smaller droplets in clouds and slow droplet growth through collision and coalescence, which ultimately leads to more water stored in clouds (Fig. 7b) and less falling out as precipitation (i.e., lower precipitation efficiency) (Fig. 8a). At the same time, the decrease in ocean evaporation and land ET due to fire aerosols (Fig. 4a) reduces atmospheric water vapor (Figs. 7c and 8a) and, therefore, precipitable water. As the result, precipitation decreases over most regions (Figs. 4b and 8a). Jiang et al. (2020) found that the slow response (due to change in global annual surface air temperature) dominated the fire-aerosol-induced change in precipitation, suggesting that the decreased ocean evaporation and land ET [primarily caused by fire-aerosol-induced surface cooling as analyzed in section 3c(1)] is the primary pathway for precipitation decrease.

An exception is the increased precipitation over SH oceans (Fig. 4b), which can be explained with the global energetic framework (e.g., Hwang and Frierson 2013; Schneider et al. 2014). There are more fire aerosols in the NH middle and high latitudes than in equivalent latitudes in the SH (Fig. 3), which results in interhemispheric energy flux asymmetry (lower in NH; hemispheric asymmetry: 0.05 PW). The interhemispheric energy asymmetry induces an anomalous Hadley circulation to transport energy from the SH to the NH in the upper troposphere (Fig. 9).
Since most of the water vapor is in the lower troposphere, this anomalous Hadley circulation creates an anomalous southward moisture flow (Fig. 9b). Correspondingly, the ITCZ shifts southward and tropical precipitation is significantly increased in tropical southern oceans and decreased in northern oceans (Figs. 4b and 9a).

In addition, the surface cooling also increases atmospheric static stability (more stable) in the lower troposphere over the Arctic and boreal regions, and thus suppresses convection and decreases precipitation (Fig. S6). However, over tropical oceans, especially SH oceans, fire aerosols decrease atmospheric static stability (more unstable) (Fig. S6), possibly because (i) much greater heat capacity of the oceans than that of atmosphere leads to slower cooling over ocean surface and (ii) the change of ITCZ increases convection over southern oceans. Globally, fire aerosols mainly decrease atmospheric stability, which, all else being equal, might increase precipitation; however, precipitation generally decreases, suggesting that changing atmospheric stability does not play a dominant role.

3) RUNOFF

Fire-aerosol-induced changes in runoff mainly correspond to the changes in land precipitation. Their spatial patterns are similar (Figs. 4b,c) with a global spatial pattern correlation of 0.87. Globally, fire aerosols decrease precipitation over land by $-4.1 \pm 1.8 \times 10^3$ km$^3$ yr$^{-1}$, causing a decrease in precipitation reaching the ground ($-3.7 \pm 1.6 \times 10^3$ km$^3$ yr$^{-1}$), which further decrease surface runoff ($-0.5 \pm 0.4 \times 10^3$ km$^3$ yr$^{-1}$) and infiltration ($-2.2 \pm 1.1 \times 10^3$ km$^3$ yr$^{-1}$) (Fig. 8b). The decrease in infiltration results in a decrease in drainage (i.e., subsurface runoff; $-0.9 \pm 1.0 \times 10^3$ km$^3$ yr$^{-1}$). Spatially, the fire-aerosol-induced changes in these land hydrological fluxes are similar, with a global spatial correlation of 0.73 between...
4. Conclusions and discussion

This study provides the first quantitative assessment of the impacts of fire aerosols on the whole picture of the global water cycle. We performed simulations with and without fire aerosols using the Earth system model CESM, which generates a reasonable simulation of the global water cycle. We find that fire aerosols significantly weaken the global water cycle, with the largest regional reductions in the tropics and the Arctic-boreal zone. Our results can be supported by the earlier analyses of satellite and flight observations showing that fire aerosols suppressed precipitation over central Africa (Tosca et al. 2015) and from Rondonia to the western Amazon (Andreae et al. 2004).

The pathway by which fire aerosols affected the global water cycle can be summarized as follows. Fire aerosols cool the surface and thus decrease ocean evaporation as well as land soil evaporation and plant transpiration. The decrease in land ET is enhanced by attenuated visible solar radiation (which decreases transpiration) and decreased precipitation (which decreases canopy evaporation). The decreased ocean evaporation and land ET further decrease the water vapor in the atmosphere and thus contribute to decreases in precipitation. The decrease in precipitation is enhanced by aerosol-cloud interaction (which decreases precipitation efficiency) and the more stable extratropical low-troposphere atmosphere. It drives a reduction in surface runoff and drainage by reducing precipitation reaching the surface and infiltration, respectively. The presence of more fire aerosols in the middle and high latitudes of the NH than the SH generates an interhemispheric energy asymmetry, leading to a southward shift of the planetary ITCZ and significantly changing tropical precipitation, increasing it on average south of the equator and decreasing it north of the equator.

**Fig. 8.** As in Fig. 6, but for (a) precipitation and (b) runoff.
Earlier studies have quantified the impact of various factors on global runoff over the historical period, including fire’s effects on terrestrial ecosystems, the effects of twentieth-century changes in atmospheric CO₂ concentration on terrestrial ecosystems, twentieth-century climate change, irrigation, and land use and land cover change (LULCC). Li and Lawrence (2017) estimated their impacts based on a meta-analysis of these earlier studies. Here, we compare these impacts against the impact of fire aerosols quantified in this study. Note that the impact of fire effects through changing land ecosystems is updated in Seo and Kim (2019; two cases) and 1991–2000 data of Li and Lawrence (2017) and Li et al. (2017). Except for climate and CO₂ changes, others are for present-day scenarios versus scenarios with no fire aerosols, no fire effects on land ecosystems, no irrigation, and potential natural/1850 land cover, respectively. As shown in Fig. 11, irrigation and fire aerosols reduce runoff, whereas fire and rising CO₂ concentrations on terrestrial ecosystems, twentieth-century climate change, and LULCC tend to increase runoff. The impact of fire aerosols $\left(1.5 \pm 1.4 \times 10^3 \text{ km}^2 \text{ yr}^{-1}\right)$ is larger than that of fire $\left(1.1 \pm 0.5 \times 10^3 \text{ km}^2 \text{ yr}^{-1}\right)$ and rising CO₂ concentrations effects on terrestrial ecosystems $\left(0.5 \pm 0.1 \times 10^3 \text{ km}^2 \text{ yr}^{-1}\right)$ and irrigation $\left(-1.0 \pm 0.3 \times 10^3 \text{ km}^2 \text{ yr}^{-1}\right)$, and is smaller than the impact of LULCC $\left(1.8 \pm 1.3 \times 10^3 \text{ km}^2 \text{ yr}^{-1}\right)$, irrigation excluded) and climate change $\left(1.8 \pm 0.4 \times 10^3 \text{ km}^2 \text{ yr}^{-1}\right)$. This highlights the relative importance of fire aerosols in affecting the land water budget and implies that changes in fire aerosols should be considered in the freshwater management.

Global fire emissions are projected to increase during the twenty-first century by the Coupled Model Intercomparison Project phase 6 (CMIP6) models (Lasslop et al. 2020). Based on our results, changes in fire aerosols will contribute to a slowing of the global water cycle and a decrease in freshwater resources in the twenty-first century. The slowing of global water cycle could compensate the impact of global warming in the twenty-first century (Dowville et al. 2021). In addition, the increase in fire emissions is mainly in NH middle and high latitudes (Lasslop et al. 2020). Based on our analyses in section 3c(2), this could drive a southward shift in the ITCZ in the future with increased precipitation over tropical southern oceans and decreased precipitation in northern tropical areas, and further modulate the freshwater resources in these regions.

Some earlier studies investigated the influence of anthropogenic aerosols on the hydrologic cycle. Ramanathan et al. (2001) pointed out that anthropogenic aerosols decrease precipitation, and further qualitatively derived that anthropogenic aerosols spin down the global water cycle by reducing the amount of shortwave radiation reaching the surface, cooling the surface, and thereby leading to decreases in evaporation. Ming and Ramaswamy (2009) quantified the climate and hydrological response to anthropogenic aerosols based on an atmospheric model AM2.1 coupled to a mixed layer ocean model. They found anthropogenic aerosols decrease global annual precipitation by 0.17 mm day$^{-1}$, with the same value for evaporation owing to global-scale balance between precipitation and evaporation, quantitatively supporting the speculation of Ramanathan et al. (2001). Results of our study show that fire aerosols also slow down the global water cycle. Fire aerosols affect the precipitation and
evaporation through mechanisms similar to the anthropogenic aerosols, but with the magnitude around one-third of the annual mean influence of anthropogenic aerosols when compared to the results of Ming and Ramaswamy (2009).

Four main sources of uncertainty in our estimates are worth noting:

- The first is the surface fire emission inventory. We used GFED3.1, which underestimates surface fire emissions (van der Werf et al. 2017) due to lack of accounting for small fires (Randerson et al. 2012) (GFED3.1’s global emissions are about 10% lower than GFED4’s), which may lead to underestimation in our simulated deceleration of the global water cycle. Whether and how to scale surface fire aerosol emissions according to AOD also contributes to the big discrepancy among surface fire emission products. Even though GFED4 includes small fires, its global fire aerosol emissions are less than half that of other satellite-based products FEER1 and QFED2.5, which are scaled by AOD (Li et al. 2019).
- The second source of uncertainty is model uncertainty. It is known that the CESM simulates a higher radiative effect due to aerosol–cloud interactions (REaci) than many other climate/Earth system models (ESMs) and the observational estimates (Malavelle et al. 2017). This may lead to an overestimation of fire aerosol influence on the water cycle. Nevertheless, CESM does not take into account brown carbon effects (Brown et al. 2018, 2021) as well as a potential warming REaci due to aerosol effects on other types of clouds (e.g., deep convective clouds) (Rosenfeld et al. 2019). Besides, CESM’s double ITCZ bias (section 2c) may lead to overestimation in the precipitation increase over SH tropical oceans caused by fire aerosols, and may thus underestimate the impact of fire aerosols on global total precipitation.
- Third, responses and feedbacks of terrestrial ecosystems to fire aerosols are not included here, except for responses through stomatal conductance and photosynthesis. For example, changes in surface climate (e.g., temperature, precipitation, and humidity) induced by fire aerosols would likely affect vegetation functioning, structure (e.g., LAI, root mass, and distribution), and composition, and even the fire regime itself, which may further modulate the water cycle (Bonan 2008; Mahowald 2011; Yue and Unger 2018).

![Diagram](https://example.com/diagram.png)

**Fig. 10.** As in Fig. 4, but for (a) precipitation reaching the ground, (b) infiltration, (c) surface runoff, (d) drainage (i.e., subsurface runoff), (e) runoff from glaciers, wetlands, and lakes, and runoff due to snow capping, (f) snowfall, (g) surface forcing of BC in snow, and (h) snowmelt.
Fourth, a slab ocean model (SOM) instead of a fully dynamic ocean model is used in this study. SOM includes an interactive treatment of surface exchange processes, but does not consider the feedback processes associated with horizontal ocean heat transport and deep water exchange (Kang et al. 2018). Therefore, this study may not capture the full slow response to fire aerosols. According to Zhao and Suzuki (2019), due to the application of SOM, this study may overestimate the precipitation response (especially in the tropics) and ITCZ shift induced by fire aerosols.

Including fire aerosol emissions can help increase the simulated skill of annual precipitation, land ET, ocean evaporation, and water vapor transpiration to the land, including their global totals (Table 1; Fig. 1) and values over most regions (Fig. 4; see also Figs. S1–S4). However, it also increases the double-ITCZ bias in simulated precipitation because fire aerosols tend to increase precipitation over SH equatorial central and eastern Pacific and Atlantic.

Jiang et al. (2020) found that the fire aerosol indirect effect dominated the total fire aerosol radiative effect regionally and globally by using the same CESM model but with prescribed SSTs. The fire aerosol direct and indirect effects were calculated by diagnostic calls to a radiation package in the model, using the method of Ghan (2013) to single out the fire aerosol direct and indirect radiative effects. Globally, the direct and indirect radiative effects of fire aerosols were +0.16 and −0.70 W m⁻², respectively, and the latter dominated the total radiative effect of fire aerosols of −0.57 W m⁻² (the change in net solar radiative flux at the top of the atmosphere between with and without fire aerosol simulations) [see Table 3 in Jiang et al. (2020)]. Spatially, the indirect effect of fire aerosols was also larger than the direct effect over most areas in the world (Figs. 3b,c in Jiang et al. 2020). Although we cannot directly diagnose the relative influence of the fire aerosol indirect versus the direct effect on the global water cycle, the results of Jiang et al. (2020) suggest that the fire aerosol indirect effect would dominate. Although it would be interesting to separately quantify the relative contributions of the indirect and direct effects on the global water cycle, due to the technical challenges with respect to turning off the indirect effect in this version of CESM we leave this to a future study.

Acknowledgments. This study is co-supported by the National Key Research and Development Program of China (2022YFE0106500, 2017YFA0604302, and 2017YFA0604804), National Natural Science Foundation of China (41875137), and the National Key Scientific and Technological Infrastructure project “Earth System Science Numerical Simulator Facility” (EarthLab). We are grateful to S. J. Ghan, S. Levis, G.-X. Lin, X.-J. Liu, J. T. Randerson, S. C. Swenson, and D. S. Ward for their helpful suggestions and discussions, three anonymous reviewers for their valuable comments and suggestions, and editor Dr. Xin-Zhong Liang for handling this paper. We would also acknowledge the CESM project supported primarily by the National Science Foundation (NSF) for providing Earth system model CESM1.2 code and input data, and the National Center for Atmospheric Research (NCAR)–Wyoming Supercomputing Center for providing computational resources on

![Diagram showing estimated impacts on global annual runoff over the historical period due to different factors: fire aerosols, fire effects on land ecosystems, twentieth-century change in atmospheric CO₂ concentration on land ecosystems, twentieth-century climate change, irrigation, and land-use and land-cover change (LULCC). Here n refers to the number of estimates; bars and error bars represent the average and one standard deviation of the estimates, respectively. The impact of fire aerosols is quantified in the present study; the impact of fire through changing terrestrial ecosystems is based on Li and Lawrence (2017), Li et al. (2017), and Seo and Kim (2019; two cases); the impacts of other factors were estimated in Li and Lawrence (2017) based on the meta-analysis of earlier literature.](https://example.com/diagram.png)
Cheyenne (ark:/85065/d7wdx3hc). This material is based upon work supported by the NCAR, which is a major facility sponsored by the NSF under Cooperative Agreement 1852977.


REFERENCES


Tosca, M. G., J. T. Randerson, and C. S. Zender, 2013: Global im-
Tian, H., and Coauthors, 2016: The terrestrial biosphere as a net

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld,
2001: Aerosols, climate, and the hydrological cycle. Science,

Randerson, J. T., and Coauthors, 2006: The impact of boreal for-
doi.org/10.1026/science.1132075.

——, Y. Chen, G. R. van der Werf, B. M. Rogers, and D. C. Mor-
ton, 2012: Global burned area and biomass burning emissions
from small fires. J. Geophys. Res. Biogeosci., 117, G04012, 
https://doi.org/10.1029/2012JG002128.

Rosenfeld, D., Y. Zhu, M. Wang, Y. Zheng, T. Goren, and S. Yu,
2019: Aerosol-driven droplet concentrations dominate cover-
age and water of oceanic low-level clouds. Science, 363,
eaav0566, https://doi.org/10.1126/science.aav0566.

Schneider, T., T. Bischoff, and G. H. Haug, 2014: Migrations and
dynamics of the intertropical convergence zone. Nature, 513,
45–53, https://doi.org/10.1038/nature13636.

Seo, H., and Y. Kim, 2019: Interactive impacts of fire and vegeta-
tion dynamics on global carbon and water budget using Com-

munity Land Model version 4.5. Geosci. Model Dev., 12, 457–

Sterling, S. M., A. Ducharme, and J. Polcher, 2013: The impact of
global land-cover change on the terrestrial water cycle. Nat.
Climate Change, 3, 385–390, https://doi.org/10.1038/nclimate1690.

Thornchill, G. D., C. L. Ryder, E. J. Highwood, L. C. Shaffrey,
and B. T. Johnson, 2018: The effect of South American bio-

mass burning aerosol emissions on the regional climate. At-
mos. Chem. Phys., 18, 5321–5342, https://doi.org/10.5194/acp-
18-5321-2018.

Tian, B., and X. Dong, 2020: The double-ITCZ bias in CMIP3,
CMIP5, and CMIP6 models based on annual mean precipita-
org/10.1029/2020GL087232.

Tian, H., and Coauthors, 2016: The terrestrial biosphere as a net
source of greenhouse gases to the atmosphere. Nature, 531,
225–228, https://doi.org/10.1038/nature16946.

Tosca, M. G., J. T. Randerson, and C. S. Zender, 2013: Global im-
pact of smoke aerosols from landscape fires on climate and
the Hadley circulation. Atmos. Chem. Phys., 13, 5227–5241,
https://doi.org/10.5194/acp-13-5227-2013.

——, D. J. Diner, M. J. Garay, and O. V. Kalashnikova, 2015:
Human-caused fires limit convection in tropical Africa: First

Trenberth, K. E., L. Smith, T. Qian, A. Dai, and J. Fasullo, 2007:
Estimates of the global water budget and its annual cycle us-
ing observational and model data. J. Hydrometeor., 8, 758–
769, https://doi.org/10.1175/JHM600.1.

van der Werf, G. R., and Coauthors, 2010: Global fire emissions
and the contribution of deforestation, savanna, forest, agricul-
11707–11735, https://doi.org/10.5194/acp-10-11707-2010.

——, and Coauthors, 2017: Global fire emissions estimates during

Vorosmarty, C. J., and Coauthors, 2010: Global threats to human
water security and river biodiversity. Nature, 467, 555–561,
https://doi.org/10.1038/nature09440.

Wang, H., and Coauthors, 2013: Sensitivity of remote aerosol dis-
tributions to representation of cloud-aerosol interactions in a

global climate model. Geosci. Model Dev., 6, 765–782, https,

doi.org/10.5194/gmd-6-765-2013.

Ward, D. S., S. Kloster, N. M. Mahowald, B. M. Rogers, J. T.
Randerson, and P. G. Hess, 2012: The changing radiative

forcing of fires: Global model estimates for past, present and
org/10.5194/acp-12-10857-2012.

WMO, 2021: State of climate services: Water. WMO-1278, 146

Xie, Y., M. Lin, B. Decharme, C. Delire, L. W. Horowitz, D. M.
Lawrence, F. Li, and R. Seferian, 2022: Tripling of western US

particle pollution from wildfires in a warming climate.
org/10.1073/pnas.2111372119.

Xu, L., Q. Zhu, W. J. Riley, Y. Chen, H. Wang, P.-L. Ma, and J. T.
Randerson, 2021: The influence of fire aerosols on surface cli-
tate and gross primary production in the Energy Exascale
Earth System Model (E3SM). J. Climate, 34, 7219–7238,
https://doi.org/10.1175/JCLI-D-21-0193.1.

Yue, X., and N. Unger, 2018: Fire air pollution reduces global ter-

org/10.1038/s41467-018-07921-4.

Zhao, S., and K. Suzuki, 2019: Differing impacts of black carbon
and sulfate aerosols on global precipitation and the ITCZ loca-
tion via atmosphere and ocean energy perturbations. J. Cli-

Zhou, H., X. Yue, Y. Lei, T. Zhang, C. Tian, Y. Ma, and Y. Cao,
2021: Responses of gross primary productivity to diffuse radia-
tion at global FLUXNET sites. Atmos. Environ., 244,

Zou, Y.-F., Y.-H. Wang, Y. Qian, H.-Q. Tian, J. Yang, and E.
Alvarado, 2020: Using CESM-RESFire to understand climate–fire–ecosystem interactions and the implications for
decadal climate variability. Atmos. Chem. Phys., 20, 995–
1020, https://doi.org/10.5194/acp-20-995-2020.