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Key Points:
- Aerosols direct radiative forcing has negative impacts on heat fluxes
- Global mean soil moisture as well as the evaporative fraction has increased
- The direct radiative effects are more stronger in dense vegetation ecosystems

Supporting Information:
- Readme
- Figure S1
- Figure S2
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- Table S1
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Aerosol effects on global land surface energy fluxes during 2003–2010

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Abstract Aerosols affect downward solar radiation, impacting the terrestrial ecosystem carbon dynamics and energy budget. Here we apply a coupled modeling framework of a terrestrial ecosystem model and an atmospheric radiative transfer model to evaluate aerosol direct radiative effects on the surface heat fluxes of global terrestrial ecosystems during 2003–2010. We find that aerosol loadings decrease the mean latent heat flux by 2.4 $\mathrm{W\,m^{-2}}$ (or evapotranspiration by 28 mm) and sensible heat flux by 16 $\mathrm{W\,m^{-2}}$. As a result, global mean soil moisture and water evaporative fraction have increased by 0.5% and 4%, respectively. Spatially, aerosol effects are significant in tropical forests and temperate broadleaf evergreen forests. This study is among the first quantifications of aerosols' effects on the heat fluxes of the global terrestrial ecosystems. The study further suggests that both direct and indirect aerosol radiative effects through aerosol-cloud interactions should be considered to quantify the energy budget of the global terrestrial ecosystems.

1. Introduction

The energy budget at the earth surface (with negligible storage by the canopy) is balanced by net radiation (R_n), latent heat flux (LE), sensible heat flux (SH), and ground heat flux (G) [*Wang and Dickinson*, 2012]. Atmospheric aerosols have various levels of effects on the surface radiation and energy budget depending on their characteristics [*Wang et al.*, 2009] and vertical distributions [*Knapp et al.*, 2002; *Sakaeda et al.*, 2011]. The microclimate in the terrestrial biosphere can be greatly influenced by the aerosol-induced changes in the solar radiation [*Gu et al.*, 2003; *Mercado et al.*, 2009]. Further, large aerosols' direct radiative effects on plant productivity have been suggested in numerous studies [*Roderick et al.*, 2001; *Gu et al.*, 2003; *Niyogi et al.*, 2004; *Oliveira et al.*, 2007; *Chen and Zhuang*, 2014]. On the one hand, aerosols can reduce the total downward solar radiation, negatively impacting plant productivity. On the other hand, aerosols can increase the diffuse radiation that reaches the land surface, enhancing the plant carbon uptake [e.g., *Gu et al.*, 2003].

Plant carbon uptake and heat flux of ecosystems are closely related through photosynthesis [*Law et al.*, 2002; *Niyogi et al.*, 2009; *Beer et al.*, 2010]. Some observational experiments have been attempted to study the aerosols' direct effects on the land surface energy flux at site levels [*Wang et al.*, 2008; *Steiner et al.*, 2013; *Murthy et al.*, 2014], regional scales [*Biggs et al.*, 2008], and even global scales [*Roderick and Farquhar*, 2002]. To date, modeling studies have focused their analyses on the aerosol effects on energy fluxes at local and regional scales [e.g., *Quaas et al.*, 2004; *Miller et al.*, 2004; *Hohenegger and Vidale,* 2005; *Steiner and Chameides,* 2005; *Huang et al.,* 2007; *Mallet et al.*, 2009; *Pere et al.,* 2011]. These studies have shown that aerosols generally reduce the SH and LE, and the different responses to aerosol loadings depend on the canopy structure and leaf amount. However, there are few studies focusing on the aerosols' direct effects on the energy flux at the global scale. Although some global circulation models (GCMs) have been used to examine the aerosols' impact on current and future climate [*Douville et al.*, 2002; *Feichter et al.*, 2004; *Hohenegger and Vidale*., 2005], the aerosol data used are less accurate with coarse spatial resolution compared to continuous satellite measurements (e.g., the Moderate-Resolution Imaging Spectroradiometer, MODIS) [*Chen and Zhuang*, 2014]. In addition, since land surface energy balance involves both biophysical and biogeochemical processes, process-based models are needed to adequately analyze the aerosols' effects on the energy fluxes.

Here we conduct a global-scale study to understand the aerosols' radiative effects on terrestrial ecosystem heat fluxes using a process-based modeling approach. We first apply an atmospheric radiative transfer model [*Chen et al.*, 2014] that uses MODIS-based global aerosol properties. We then integrate the model with a

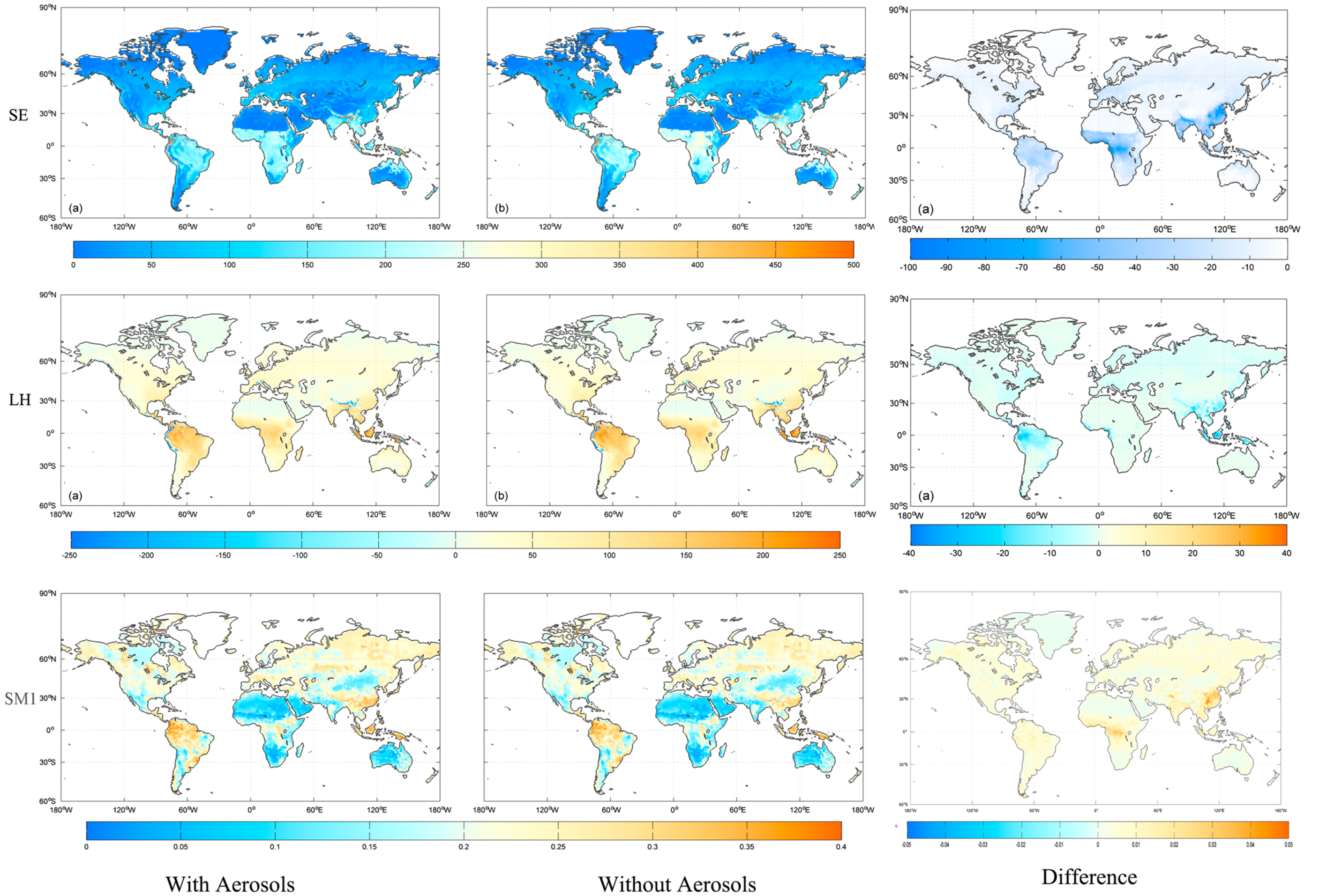

Figure 1. Comparison of global annual mean SH (first row), LE (second row) (Units: W m^{-2}), and SM1 (third row) (Units: m^3/m^3) in S0 (first column) and S1 (second column) from 2003 to 2010. The difference (third column) is calculated as S0 minus S1.

terrestrial ecosystem model (the integrated Terrestrial ecosystem model, iTem; *Chen*, 2013; *Chen and Zhuang*, 2014) to estimate aerosol direct radiative effects on the energy fluxes of the global terrestrial ecosystems. The affected sensible heat and latent heat fluxes are finally analyzed.

2. Method

2.1. The Modeling Framework

The modeling framework includes a two-broadband atmospheric radiative transfer model, which provides the estimation of the direct-beam and diffusive radiation in both visible and near-infrared light using the MODIS-based atmospheric profile parameters. The model is a combination of a clear-sky solar radiation model and a cloud transmittance model. It considers the major atmospheric radiative transfer processes such as Rayleigh scattering, well-mixed gas absorption, ozone and water vapor scattering, and aerosol extinction. The model does not simulate aerosol effects of each wavelength and directional scattering. Instead, it uses two Ångström turbidity coefficients and band-averaged aerosol optical depth, and it is carefully parameterized with a spectral radiation model to calculate the broadband aerosol transmittances. The use of MODIS-measured atmospheric parameters allows the model to provide accurate quantification of the downward solar radiation considering aerosols' effects. The modeling framework also includes the integrated Terrestrial ecosystem model (iTem) to quantify the changes of land surface energy fluxes of the global terrestrial ecosystems due to the aerosol direct radiative effects. The algorithms of key biophysical and biogeochemical processes in iTem are mainly developed based on the process-based Land Surface Model 1.0 (LSM 1.0) [*Bonan*, 1996] and the Terrestrial Ecosystem Model (TEM) [*McGuire et al.*, 1992; *Raich et al.*, 1991; *Zhuang et al.*, 2003]. In iTem, the

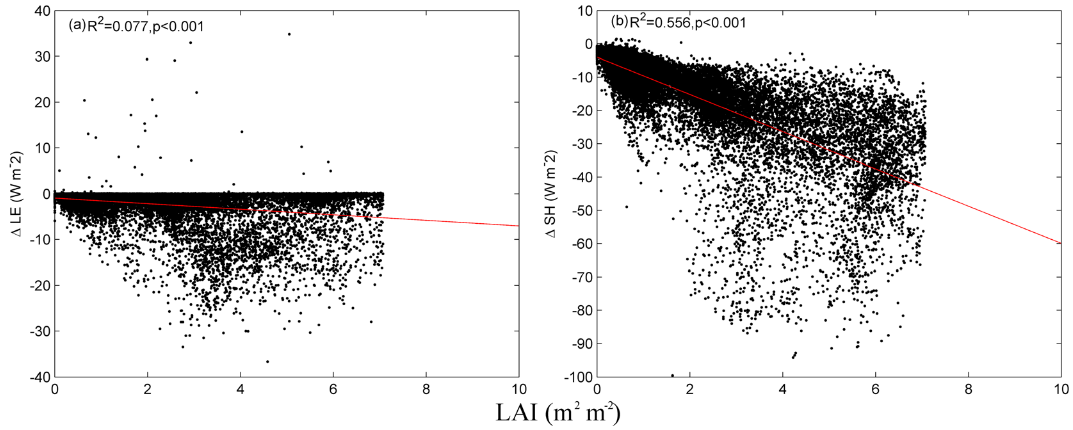

Figure 2. Aerosol-induced changes of heat fluxes ((a) LE and (b) SH) at different leaf area index levels. The change is the difference between annual mean values of these variables of the S0 and S1 estimates.

canopy is modeled with a one-layer, two-big-leaf approach [*Dai et al.*, 2004], which diagnoses energy budget, leaf temperature, and photosynthesis separately for sunlit and shaded leaves. Canopy light penetration depends on the position of the sun and the area of sunlit and shaded leaves, which is based on leaf angle and the vegetation-specific canopy leaf distribution. The shaded leaves are assumed to only receive diffuse radiation including both sky diffuse radiation and the diffuse radiation produced by scattering of the direct-beam radiation. In contrast, the sunlit leaves receive both direct and diffuse radiation. Heat transfer, evapotranspiration, and photosynthesis are then simulated separately in sunlit and shaded leaves responding to the different radiation regimes to estimate energy and mass (e.g., carbon and water) budget. More technical details of iTem are documented in *Chen* [2013].

2.2. Modeling Experiments and Forcing Data

We use iTem to assess the aerosol direct effects on global surface energy fluxes with two sets of simulations. The first simulation (S0) uses transient solar radiation data estimated with the atmospheric radiative transfer model considering the aerosol loadings (The aerosols level is shown in Figure S1 in the supporting information).The second one (S1) uses the atmospheric radiative model estimated solar radiation data without considering the aerosol loadings. We focus our analysis on the simulated heat fluxes including latent heat flux (LE) and sensible heat flux (SH) as well as the first-layer soil moisture (SM1), which play an important role in water cycle and energy budget of terrestrial ecosystems.

iTem is applied at a spatial resolution of a 1° by 1° (longitude × latitude) for the global land area except the Antarctic. The model is run at a 3-hourly time step for the period 2003–2010. Forcing data including the MODIS atmospheric products for driving the atmospheric radiative transfer model, the initial conditions, soil properties, and the plant distribution as well as the meteorological data are from *Chen and Zhuang* [2014].

3. Results and Discussion

Over the period of 2003–2010, the S0 estimates LE and SH of the global terrestrial ecosystems are 43.60 and 79.57 W m^{-2} (approximately 18×10^{22} and 34×10^{22} J yr^{-1}), respectively. The LE simulation results agree with estimates of 65.00 W m^{-2} [*Jung et al.*, 2011], 37.34 W m^{-2} [*Yao et al.*, 2014], 38.50 W m^{-2} [*Trenberth et al.*, 2009], and 37–59 W m^{-2} [*Jiménez et al.*, 2011]. The estimated SH is larger than 27.00 W m^{-2} reported by *Trenberth et al.* [2009], 41.00 W m^{-2} by *Jung et al.* [2011], and 18–57 W m^{-2} by *Jiménez et al.* [2011]. Without considering aerosol loadings, the S1 estimates higher LE and SH, which is 46.00 and 95.26 Wm^{-2}, respectively. Due to the aerosol-induced change of LE, the global annual mean SM1 is 0.5% higher than that of S0. The above comparison suggests that the aerosols' direct radiative effects have a negative impact on the global heat fluxes and slightly increase soil moisture.

Over the period 2003–2010, the negative aerosol effects on terrestrial ecosystem LE and SH take place in vast areas of Central Africa, South, East Asia, and Amazon basin (Figure 1), reaching −40 and −100 W m^{-2}, respectively. The high aerosol loadings in these regions [*Chen et al.*, 2014] reduce the incoming solar

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Table 1. Comparison of Annual Mean Heat Fluxes (LE and SH) and Surface Soil Moisture (SM1) During 2003–2010 for Each Vegetation Type[a]

	LE ($W m^{-2}$)		SH ($W m^{-2}$)		SM1 (m^3/m^3)	
Vegetation Type	S0	S1	S0	S1	S0	S1
Alpine tundra and polar deserts	−0.07	−0.01	−1.04	−0.66	5.91	5.91
Wet tundra	−0.76	0.09	0.56	2.41	18.76	18.58
Boreal forest	2.95	3.21	2.69	4.33	5.41	5.32
Temperate coniferous forest	0.07	1.19	8.92	11.37	10.29	10.13
Temperate deciduous forest	13.57	13.88	16.73	21.49	9.50	9.36
Grasslands	10.32	10.81	7.12	9.36	10.19	9.89
Xeric shrublands	8.19	9.37	3.38	4.78	11.46	10.96
Tropical forests	38.58	38.75	53.35	87.84	6.93	6.03
Xeric woodland	18.24	18.30	7.56	12.37	15.96	14.92
Temperate broadleaved Evergreen forest	−51.33	−47.53	131.40	135.33	9.73	9.55
Mediterranean shrublands	16.40	16.98	9.64	12.89	24.94	24.58

[a]Negative LE values mean that the water transforms from gas to liquid phase, and negative SH represents the heat conduction from the atmosphere to land surface.

radiation, cool land surface (Figure S2 in the supporting information) and soils, therefore inhibiting surface water transpiration and increasing SM1 by 2 ~ 5% in these areas. The temporal and spatial patterns of LE and SH differences in two simulations are associated with leaf area index (LAI). The aerosol-induced changes of LE and SH are positively correlated with LAI, which is consistent with previous studies (Figure 2; *Niyogi et al.*, 2004; *Matsui et al.*, 2008).The surface energy fluxes coupled with plant photosynthesis are highly influenced

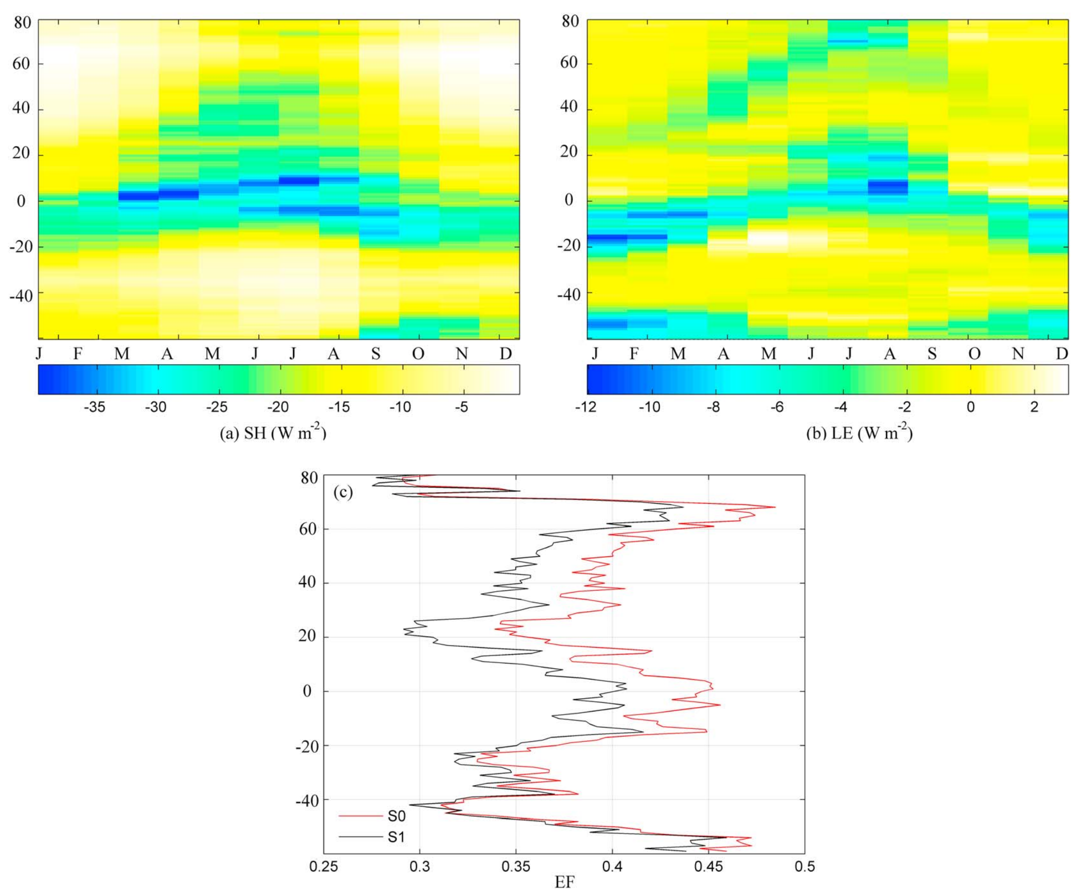

Figure 3. Comparison of zonal mean seasonal (a) SH, (b) LE, and (c) EF averaged over the study period in S0 and S1. The difference is calculated as S0 minus S1.

by aerosol loadings in high-LAI ecosystems. The main differences between the two simulations occurred in tropical and subtropical ecosystems (Table 1), in which aerosols show the greatest impact on SH in tropical forests (with the relative difference ((S0 − S1) / S1) of 39.3%) and LE in temperate broadleaved evergreen forests (with the relative difference ((S0 − S1) / S1) of 7.9%).

The aerosols' effects on SH and LE show strong seasonal variations (Figures 3a and 3b). As for LE, the difference between the two simulations mainly occurs in lower latitudes (20 °S ~ 20 °N), with the strongest effect in summer season at each hemisphere. The seasonal patterns of aerosols' effects on LE are generally consistent with ones of LAI or plant productivity in these regions. By contrast, the aerosols' effects on SH are mostly negative in fall at Southern Hemisphere and in spring and summer at Northern Hemisphere, which cannot be explained by the seasonal variation of LAI. We use the evaporative fraction (EF) (LE / [LE + SH]) to examine the influence of aerosols on partitioning of the latitudinal energy fluxes (Figure 3c). EF is considered to be a constant during daytime hours [*Wang et al.*, 2008; *Gentine et al.*, 2011]. The EF in S0 is generally 4% higher than that in S1, and their differences are more obvious in Northern Hemisphere (0 °N ~ 60 °N). This positive impact of aerosols' direct effects on EF agrees with the results based on site-level continuous ground measurements across the southern Great Plains from *Wang et al.* [2008], indicating that the relative contributions of the turbulent energy fluxes to surface energy budget were larger under aerosol loadings.

Our study is among the first to quantify the aerosols' effects on terrestrial surface energy fluxes at the global scale. The simulations agree with previous studies, indicating that aerosols decrease land surface heat fluxes and increase soil moisture. Regions with dense vegetation are more likely influenced by aerosol loadings. However, this study only considers the aerosols' direct radiative effects, but not the indirect effects caused by cloud-aerosol interactions [*Twomey*, 1977; *Costantino and Bréon*, 2010]. In addition, some aerosols may act as a source of nutrient for plants through atmospheric deposition of particulates to the Earth's surface [*Mahowald et al.*, 2005; *Magnani et al.*, 2007; *Carslaw et al.*, 2010], affecting plant growth, in turn, affecting energy fluxes of ecosystems. These effects have not been considered in this study either. Finally, this study has not differentiated aerosol types in quantifying their radiative effects. However, aerosol species varying across the globe could have different effects on earth surface energy fluxes and climate [*Menon et al.*, 2002; *Martin et al.,* 2010; *Zhang et al.*, 2009].

4. Conclusion

A modeling framework of a terrestrial ecosystem model and an atmospheric radiative transfer model is used to evaluate aerosols' direct radiative effects on the heat fluxes of the global terrestrial ecosystems during 2003–2010. Model simulations indicate that aerosol loadings decrease the mean latent heat flux by 2.4 $\mathrm{W m^{-2}}$ (or evapotranspiration by 28 mm) and sensible heat flux by 16.0 $\mathrm{W m^{-2}}$. As a result, global mean soil moisture and the evaporative fraction increased by 0.5% and 4.0%, respectively. Aerosol effects are significant in tropical and temperate broadleaf evergreen forests. This study is among the first to quantify aerosols' effects on the heat fluxes of the global terrestrial ecosystems. Our study further suggests that both direct and indirect aerosol radiative effects shall be considered in future energy budget quantifications for the global terrestrial ecosystems.

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