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Direct radiative effects of tropospheric aerosols on changes of global surface soil moisture

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Abstract A coupled modeling framework including a terrestrial ecosystem model and an atmospheric radiative transfer model is used to evaluate the aerosols' direct radiative effects on the surface soil moisture in global terrestrial ecosystems during 2003–2010. We conduct two sets of model runs with and without aerosols in a hindcast mode. Comparison analysis indicates that the simulated soil moisture is comparable with other existing products and satellite retrievals. Simulations with aerosol loadings show an increase in the surface soil moisture by 3.8 ± 0.4 % and 4.1 ± 0.5 % during growing seasons (June to September) in temperate and boreal Northern Hemisphere (>10 °N) and the whole year in tropical regions (−10°S~10°N). This positive effect is as large as 30 % in dense-vegetated ecosystems, such as tropical forests and temperate broadleaf evergreen forests. The effect of aerosols on soil moisture varies with local leaf area index and climate, and exhibits seasonal variations. Surface soil moisture is persistently affected by high aerosols loadings in Amazonian tropical forests during drought seasons of 2005 and 2010. This study highlights the importance to consider the aerosols' effects in impacting the soil moisture dynamics of the global terrestrial ecosystems.

1 Introduction

Soil moisture, the amount of water stored in the soil vadose zone (Seneviratne et al. 2010), is an important variable in the global climate system. From the perspective of water balance, soil

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moisture has a major impact on regional hydrological processes including surface runoff, flooding, erosion, and solute transport (Western et al. 2004). In addition, soil moisture, along with the surface condition, controls the partitioning of surface available energy into sensible and latent heat fluxes, affecting water and energy balances, playing a critical role in shaping ecosystem response to the physical environment (Robock et al. 2000). Therefore, due to its large impacts on the heat fluxes, soil moisture can influence local climate, especially, air temperature (Durre et al. 2000; Diffenbaugh et al. 2007; Jaeger and Seneviratne 2011), boundary-layer structure (Findell and Eltahir 2003; Ek and Holtslag 2004; Jaeger et al. 2009) and precipitation (Cook et al. 2006; Taylor and Ellis 2006; Hohenegger et al. 2009; Taylor et al. 2012). Moreover, plant assimilation of CO_2 is closely coupled with the soil water potential and plant transpiration (Farquhar et al. 1980).

Atmospheric aerosols have great potential impacts on soil moisture. The altered atmospheric composition would affect the land surface energy regime through decreasing direct radiation and increasing diffuse radiation (Mahowald 2011; Ramanathan et al. 2001) reaching the land surface, therefore changing the microclimate, which directly affects the water cycling processes such as evapotranspiration (Roderick and Farquhar 2002; Wang et al. 2008; Steiner et al. 2013; Liu et al. 2014). Previous site-level (Murthy et al. 2014) and regional observations (Biggs et al. 2008) have attempted to study the aerosol's direct radiative effect on soil moisture or its related hydrological processes. Large-scale observation studied by Roderick (Roderick and Farquhar 2002) demonstrated that the decrease in evaporation over the past 50 years was consistent with the observed increasing cloud coverage and aerosol concentration. Also, general circulation models (GCMs) have been used to examine the aerosols' impact on the hydrological cycle (e.g., Boer et al. 2000; Liepert 2004; Huang et al. 2007; Péré et al. 2011). However, the aerosol data used in the GCMs are less accurate with coarse spatial resolution compared to continuous satellite measurements (e.g., the Moderate-Resolution Imaging Spectroradiometer, MODIS) (Chen and Zhuang 2014). Moreover, since land surface hydrological processes are coupled with other biophysical and biogeochemical processes, ecosystem models developed with necessary processes that simulate the response of surface microclimate (e.g., vegetation temperature) to aerosol-induced changes of surface radiation regime is desired to evaluate the aerosols' effects on soil moisture.

This study quantifies aerosols' direct radiative effects on terrestrial ecosystem soil moisture at the global scale by using satellite aerosol data and a well-developed ecosystem model. We first apply an atmospheric radiative transfer model that uses MODIS global aerosol products to quantify the aerosols' effect on downward solar radiation. We then use the integrated Terrestrial ecosystem model (iTem, Chen 2013; Chen and Zhuang 2014; Liu et al. 2014), which was designed to include the necessary processes as described above to quantify the aerosol direct radiative effects on the soil moisture of global terrestrial ecosystems from 2003 to 2010. In addition, there may be severe and widespread droughts over vast land areas in the future (Dai 2011) and it is worthwhile to evaluate aerosols' direct effects on soil moisture during droughts given their potential influences on hydrological cycling (Rosenfeld et al. 2008; Liepert 2004). Therefore, we use the Amazon drought as an example to investigate the aerosol direct radiative effects on soil moisture under the extreme drought condition.

2 Method

Our modeling framework consists of a two-broadband atmospheric radiative transfer model (ARTM) and an ecosystem model (Chen and Zhuang 2014). The two-broadband (visible and near-infrared bands) ARTM (Chen et al. 2014) incorporates a high-performance clear-sky solar radiation model (Gueymard 2012) and a cloud transmittance model (Stephens et al. 1984) to calculate downward solar radiation under all-sky conditions. It uses MODIS-derived atmospheric parameters (Platnick et al. 2003; King et al. 2003) and land surface albedo (Schaaf et al. 2002) as inputs (Table .S1), and estimates direct and diffuse radiation in both visible and near-infrared bands over the land surface. Major atmospheric radiative transfer processes such as Rayleigh scattering, well-mixed gas absorption, ozone and water vapor absorption, and aerosol scattering and extiction are included in the ARTM. Ångström turbidity coefficients and band-averaged aerosol optical depth have been parameterized with a spectral radiation model to calculate the broadband aerosol transmittances (Chen et al. 2014). In a previous study (Chen et al. 2014), we have demonstrated that the estimated direct and diffuse radiation components by ARTM showed good agreement with observations at 48 Baseline Surface Radiation Network (BSRN) sites (Ohmura et al. 1998) and the Clouds and Earth's Radiant Energy System (CERES) data (Trenberth et al. 2009) and they showed substantially better performance than the widely-used National Centers for Environmental Prediction (NCEP) dataset (Kalnay et al. 1996).

The integrated Terrestrial ecosystem model (iTem) was designed for assessing the atmospheric aerosol's direct radiative effects on land surface energy budget in the global terrestrial ecosystems (Chen and Zhuang 2014; Liu et al. 2014). In iTem, the canopy is modeled in a one-layer, two-big-leaf approach (Dai et al. 2004), which diagnoses energy budget, leaf temperature, evapotranspiration and photosynthesis separately for sunlit and shaded leaves. The boundary layer turbulent processes are modeled based on the Monin-Obukhov Similarity Theory. The hydrological processes include the interception, through fall of precipitation, snow accumulation, sublimation and melt, surface runoff, surface evapotranspiration, water infiltration and redistribution in soil and subsurface drainage. The thickness of six soil layers defined in iTem are 0.1, 0.2, 0.4, 0.8, 1.6 and 3.2 m, respectively. These algorithms allow the model to simulate the response of land surface processes to changing direct and diffuse radiation regimes, such as surface energy balance, thermal dynamics, leaf and canopy conductance, and surface evapotranspiration, which could substantially influence the soil moisture. The iTem has been calibrated and validated using various sources of observation data. Technical details of the iTem are documented in Chen (2013).

We use iTem to assess the aerosol direct effects on global soil moisture with two sets of simulations. The first simulation (S0) uses transient solar radiation estimated with the ARTM considering the aerosol loadings. The second one (S1) uses the ARTM-estimated solar radiation without considering the aerosol loadings (i.e., removing the aerosol-related terms in ARTM). Therefore, the aerosol direct radiative effect on soil moisture can be evaluated by comparing the results from the two simulations. In addition, given the aerosols' potential influences on hydrological cycling (Rosenfeld et al. 2008; Liepert 2004), we use the Amazon 2005 and 2010 droughts (Marengo et al. 2008, 2011; Zeng et al. 2008; Lewis et al. 2011) as an example to investigate the aerosol effects on soil moisture under the extreme drought condition.

Model runs are carried using a 3 hourly time step for the period 2003–2010, and at a spatial resolution of $1° \times 1°$ for the global land area except the Antarctic. Forcing data including the MODIS atmospheric (MOD08) and land surface albedo products (MCD43C3) for driving the ARTM, other meteorological data (air temperature, wind speed, radiation, CO_2, precipitation, water vapor concentration and surface air pressure), the initial conditions, soil properties, and the vegetation distribution are from Chen and Zhuang (2014).

We compare our simulated soil moisture with the global ERA-Land soil moisture data (Balsamo et al. 2013) and satellite retrievals of soil moisture. In ERA-Land, the European Centre for Medium-Range Weather Forecasts Interim reanalysis (ERA-Interim) near-surface meteorology explores the most recent version of the Land Surface Scheme of the operational Integrated Forecasting System used at European Centre for Medium Range Weather Forecasts (ECMWF), incorporating some major advancements with respect to soil moisture (Albergel et al. 2012). In addition, satellite remote sensing has offered surface moisture estimates at the global scale with good daily repetitivity (Al-Yaari et al. 2014). Several quasi-global satellite-based soil moisture datasets have been generated from scatterometer observations. The Essential Climate Variables for surface soil moisture (ESV_SM) products, which was initially developed under European Space Agency (ESA) Water Cycle Multi-Mission Observation Strategy (WACMOS) project, is now being extended and improved within ESA's Climate Change Initiative (http://www.esa-soilmoisture-cci.org/). This product is generated by ensembling multiple active and passive microwave sensors (AMSR_E, SMMR, SSM/I, TMI, Windsat) and has demonstrated the potential for evaluating model performance (Loew et al. 2013; Schrier et al. 2013; Szczypta et al. 2014), and for studying the link between soil moisture and vegetation dynamics (Barichivich et al. 2014; Muñoz et al. 2014). However, we should note that ESV_SM has large variations of observation densities at the global scale, due to the dense vegetation canopy and snow cover (Dorigo et al. 2015). Thus, the fraction of days with valid observations is generally low in tropical forest and high latitudes (Figure.S1). Therefore we only use the regions where the observation fraction is greater than 0.6 when comparing the first layer soil moisture by iTem estimation and ESV_SM data.

3 Results and discussion

3.1 Key results

The global annual mean ratio of diffuse radiation to direct radiation (Df/Di, for the whole shortwave band including both visible and near infrared bands) increased by 0.32 ± 0.07 under aerosol condition (Fig. 1a, b and c) during the study period. The radiation component exhibits large differences in Central Africa, part of East and Central Asia and northern high latitude (Fig. 1c). Generally, the Df/Di difference is larger in regions which have higher diffuse radiation ratios, except the Amazonia area and parts of northern high latitudes (Fig. 1c). The aerosol-induced changes of soil moisture have been observed in model simulations. Over the period of 2003–2010, S0 estimates of the annual mean soil moisture of the global terrestrial ecosystems are 0.232 ± 0.007 m^3m^{-3}. The highest soil water content is found in forest ecosystems, ranging from 0.200 to 0.400 m^3m^{-3} (Table 1, Fig. 1d and e). Without considering aerosol loadings, the S1 estimates lower soil moisture of 0.224 ± 0.006 m^3m^{-3}. In all six layers, the direct aerosol effects increase soil moisture by 10~30 % (0.03~0.05 m^3 m^{-3}) in vast areas of Central Africa, South and East Asia (Fig. 1f) and increase the annual mean soil moisture by 4.1 ± 0.5 % in tropical areas (−10°S~10°N). The annual averaged changes in soil moisture are significantly correlated ($p < 0.01$) with the annual averaged changes in Df/Di across the globe except the high latitudes (60°N~90°N) in the North Hemisphere. In 30°S ~ 0°, the changes in soil moisture can be mostly explained ($R^2 = 0.45$) by the changes in Df/Di, and they are more sensitive (larger slope) to the radiation components (Figure.S2d). Previous studies (Yu et al. 2006; Liu et al. 2014) showed that aerosol direct radiative effects have a great negative impact on latent heat

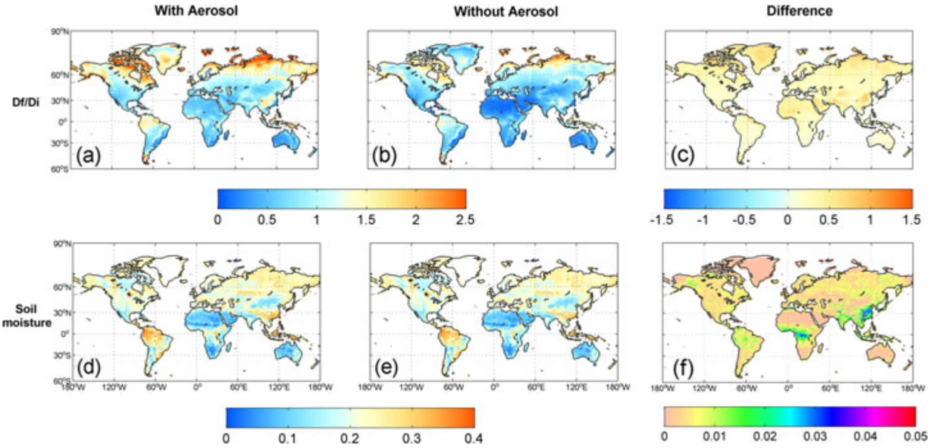

Fig. 1 The ratio of diffuse solar radiation (Df) to direct radiation (Di) in S0 (**a**), S1 (**b**) and the ratio difference (**c**) between S0 and S1; global annual mean soil moisture (Units: m^3/m^3) in S0 (**d**) and S1 (**e**) and the difference (**f**) between S0 and S1. All differences were calculated by subtracting S1 results from S0 results (S0-S1). S0, S1 are the simulation with and without considering the aerosols direct radiative effects, respectively

flux (LE) across the tropical region in the South Hemisphere, resulting in an increase in soil moisture. The statistically significant difference (Figure. S2) of soil moisture estimations may impact local climate variables given the strong coupling between soil moisture and evapotranspiration (Seneviratne and Stöckli 2008), temperature (e.g. Diffenbaugh et al. 2007; Zhang et al. 2009) and precipitation (e.g. Koster et al. 2004; Hohenegger et al. 2009).

From the perspective of seasonal variations (Fig. 2a), soil moisture is generally low during summer in 30 °N~60 °N and 20 °S~30 °S regions, whereas tropical region across the equator has low SM1 variation. The aerosols' effects on soil moisture also show strong seasonal variations (Fig. 2b). The soil moisture difference between two simulations is larger at

Table 1 Comparison of annual mean soil moisture (SM) during 2003–2010 for each ecosystem type (The difference is calculated as S0 minus S1)

ecosystem type	SM1*100 (m^3/m^3)		
	S0	S1	Difference
Ice	–	–	–
Alpine tundra and polar deserts	24.21	23.90	0.31
Wet tundra	23.37	22.90	0.47
Boreal forest	22.58	22.03	0.55
Temperate coniferous forest	21.56	20.93	0.63
Temperate deciduous forest	20.50	19.93	0.57
Grasslands	19.01	18.53	0.48
Xeric shrublands	12.57	12.31	0.26
Tropical forests	22.03	21.18	0.85
Xeric woodland	17.25	16.74	0.51
Temperate broadleaved Evergreen forest	25.56	24.44	1.08
Mediterranean shrublands	19.86	19.27	0.59

S0, S1 are the simulations with and without considering the aerosol direct radiative effects, respectively

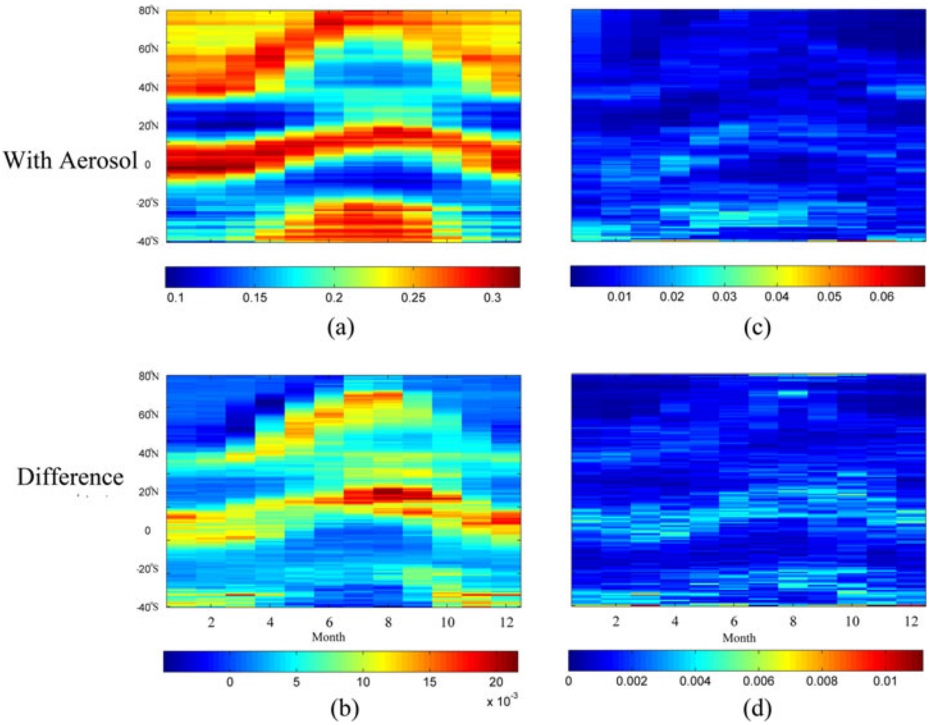

Fig. 2 Seasonal zonal mean (**a**) and standard deviation (**c**) of soil moisture in S0, and the difference between two simulations (**b**; S0-S1) and its standard deviation (**d**) over the study period. Units are m^3/m^3. S0, S1 are the simulation with and without considering the aerosols direct radiative effects, respectively

0.030~0.050 $m^3 m^{-3}$ in summer season in each hemisphere, while for the tropical region (10 °S ~ 10 °N), the difference is associated with the monsoon season. In addition, the strongest aerosol direct radiative effect on soil moisture in north high latitude (>60°N) only occurs in plant growing season (June to September), resulting in an increase of soil moisture by 3.8 ± 0.4 %. The derived latitudinal annual mean soil moisture in two simulations (Figure.S4) demonstrates that aerosol direct radiative effects generally have relatively larger positive impact on soil moisture across the tropical region (10 °S ~ 10 °N) and in mid-latitude (30 °N ~ 50 °N) in the North hemisphere.

3.2 Comparison between iTem and satellite products

The ERA-Land product estimates the global annual mean surface soil moisture to be 0.260 ± 0.009 m^3m^{-3} during 2003–2010 (Fig. 3a), which is 0.026 m^3m^{-3} higher than that in S0. The spatial patterns of global surface soil moisture in Fig. 3 are comparable with the ERA-Land soil moisture product. Over the study period, both S0 estimated soil moisture and ERA-land soil moisture product show that most forest areas exhibit high surface soil moisture, ranging from 0.25to 0.40 m^3m^{-3}, and tropical desert as well as grassland generally holds the lowest surface soil moisture. There are relatively large discrepancies between our simulations and the ERA-Land soil moisture product in arid regions (e.g. inland of Australia) but not when comparing with ESV_SM. The ERA-Land product generally has higher soil moisture when compared with the ESV_SM (Fig. 3b), which has good observation fraction in the arid regions. For example, our simulations estimate the surface soil moisture around 0.15 ± 0.003 m^3m^{-3} in

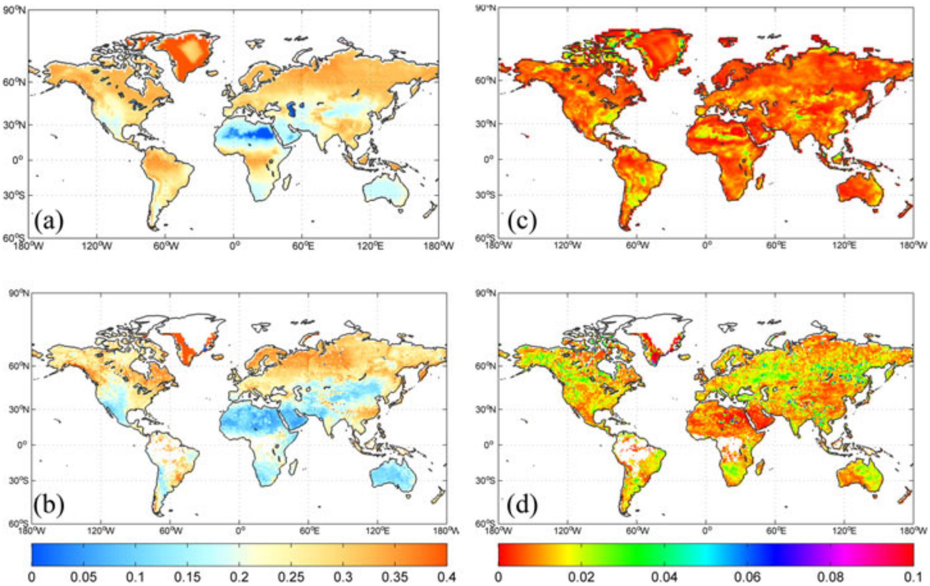

Fig. 3 Spatial pattern of the annual mean column soil moisture (SM) in ERA_land (**a**) and ESV_SM products (**b**);(**c**) and (**d**) stand for the standard deviation of ERA_land and ESV_SM over the study period, respectively.(Units: m^3m^{-3})

Rocky Mountain of US, which is similar to the ESV_SM products, while the ERA-Land shows about 0.05 m^3m^{-3} higher estimates.

Aerosol-induced direct radiation greatly influences the surface soil moisture in forest ecosystems (Fig. 1f). Here we choose five regions that are dominated with forests to compare iTem simulations with the ERA reanalysis, including Central Africa, East China, East Russia, and India (Figure.S3) as well as the Amazonia region (Figure.S8b). The criteria for choosing the regions are based on the large difference (>0.015 m^3 m^{-3}) of soil moisture between simulation with aerosol and simulation without aerosol (Fig. 1f). In addition, we also compare model simulations with the ESV observations for China and India because good-quality observed ESV products are available in these regions (Figure.S1). Generally, the seasonal cycle of soil moisture estimations in iTem are comparable with ERA-land/ESV_SM products except in East Russia (Figure.S5). The magnitude of monthly and annual mean soil moisture in S0 is closer with the ERA-land/ESV_SM products (Table 2), indicating that incorporating

Table 2 Comparison of the regional annual mean soil moisture (SM) in iTEM, ERA_land and ESV_SM products during 2003–2010

Region	S0	S1	ERA_land	ESV_SM
Amazon	0.283 ± 0.022	0.280 ± 0.022	0.313 ± 0.019	–
Central Africa	0.213 ± 0.024	0.209 ± 0.022	0.239 ± 0.029	–
East China	0.312 ± 0.052	0.302 ± 0.042	0.308 ± 0.044	0.310 ± 0.043
East Russia	0.221 ± 0.021	0.218 ± 0.025	0.282 ± 0.018	–
India	0.191 ± 0.018	0.189 ± 0.015	0.243 ± 0.025	0.221 ± 0.020

(Units: m^3 m^{-3}). S0, S1 are the simulations with and without considering the aerosol direct radiative effects, respectively. (ESV_SM has no valid observation at Amazon, Central Africa and East Russia) aerosols' direct effects into land surface models improves the soil moisture simulations. Besides the inherent model uncertainty, one possible reason of the large discrepancy between our estimations and the reanalysis/satellite products may be the usage different driving forcing data in developing these estimates. iTem is driven by the Land Surface Hydrology datasets from Princeton University (Sheffield et al. 2006), while ERA-land soil moisture products are based on point-wise extended Kalman filter by incorporating the model forecast and proxy observation (Albergel et al. 2012).

3.3 Aerosol effects related with LAI and climate variables

Previous studies (Niyogi et al. 2004; Matsui et al. 2008) demonstrated that surface energy balance is more influenced in high-LAI ecosystems under aerosol conditions, implicating the similar impact on soil moisture. Our simulations here also show that the aerosol loadings increase the ratio of diffuse radiation to direct radiation and increase soil moisture by 0.02 ~ 0.05 m^3m^{-3} in highly dense vegetated regions during growing season (Fig. 1b), indicating a positive relationship between aerosols effect on soil moisture and LAI (Fig. 4). Moreover, the annual averaged changes in soil moisture are significantly correlated ($p < 0.01$) with the leaf area index across the globe except the South latitude (30°S ~ 0°). In addition, the changes in Df/Di mostly explain ($R^2 = 0.45$) the changes in soil moisture at northern high latitudes (60°N ~ 90°N). This is also consistent with the observed differences in growing season (Fig. 2b), indicating that the direct aerosols' effects are closely related with LAI seasonal variation in these areas.

Aerosol-induced changes of soil moisture are also significantly correlated ($p < 0.01$) with the annual mean air temperature and relative humidity (Figure S7a, S7b). Figure. S3 shows how the aerosol effects on soil moisture vary with the annual mean air temperature, and relative humidity (RH). The difference of soil moisture between two simulations is generally obvious (>0.02 m^3 m^{-3}) when the air temperature is greater than 10 °Cacross the range of RH, indicating the aerosol affects soil moisture more at temperate regions. The relationships also explain the seasonal pattern of soil moisture differences between two simulations (Fig. 4b). The obviously different soil moisture estimation generally occurs in summer at each

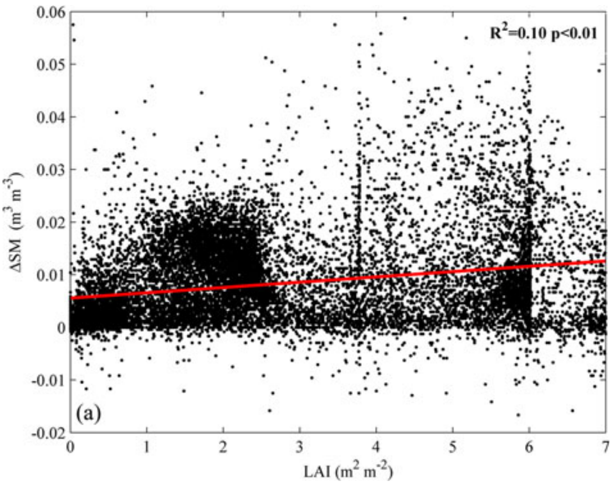

Fig. 4 Aerosol-induced changes of soil moisture at different leaf area index levels during growing season. The change is the difference between annual mean values of these variables of the S0 and S1 estimates

hemisphere, indicating air temperature plays a significant role in controlling the aerosols' direct effects on soil moisture. Moreover, this positive impact on soil moisture of aerosol loadings across the globe is more significant in high RH (>70 %) climate regions.

3.4 Aerosols effects on soil moisture during drought

In 2005 and 2010, vast areas of western Amazonian forest suffered severe drought from July to September due to the El Niño events and unusually warm North Atlantic sea surface temperatures (Marengo et al. 2008, 2011; Zeng et al. 2008; Lewis et al. 2011). Both simulations and ERA datasets are able to detect the drought-induced soil moisture drawdown during drought periods (Figure S8b), with negative anomalies (-0.100 m^3 m^{-3}~ -0.050 m^3 m^{-3}) in the western Amazonia region (Fig. 5). However, higher soil moisture (Figure S8 and Fig. 5e and f) is observed under aerosol loadings conditions. The different responses indicate that the aerosol-induced changes may result in higher soil moisture during drought season. We also derived the seasonal cycle of Df/Di (FigureS8a) and the spatial distribution of Df/Di anomalies (Fig. 5g and h) from the ARTM in the Amazon area. Overall, the Df/Di is 0.2 larger, while Df/Di anomalies are 0.3~0.5 larger in drought periods when compared with the same periods in other non-drought years (Fig. 5g and h). The increasing Df/Di anomalies are accompanied with high aerosols loadings in drought seasons of 2005 and 2010. Therefore, the regional difference between two simulations is larger than the annual mean difference (around 0.001 m^3m^{-3}) (Fig. 3), suggesting that increased aerosol loadings caused by local dry-season biomass burning and fire (Bevan et al. 2009) may further help keep soil moist during drought periods. Previous studies also demonstrated that biomass burning and fire showed the greatest impact on radiation ratio during the Amazon basin dry season, with little impact during the wet season (Holben et al. 2001; van der Werf et al. 2010). This significant direct radiative effect leads to large negative effect in latent heat flux, therefore maintaining the soil moisture level.

3.5 Limitation and future needs

Aerosol direct radiative effects on terrestrial soil moisture exist in various complicated biophysical and biogeochemical processes. Our modeling study has various uncertainties. First, the MODIS measurements of the key atmospheric components have significant retrieval biases (Levy et al. 2005, 2010; Remer et al. 2005). The systematic biases were closely related

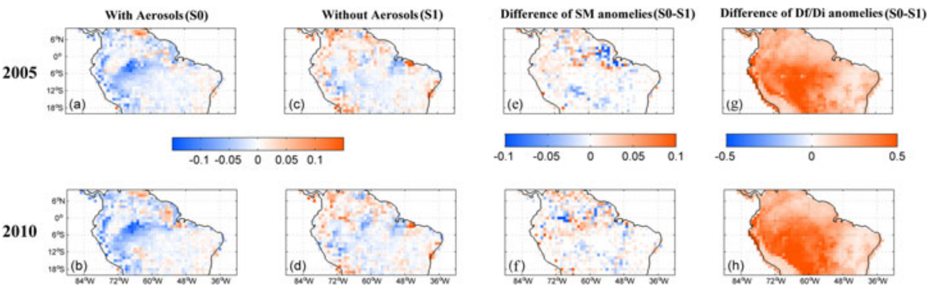

Fig. 5 SM anomalies (**a** to **d**), the aerosols' effects on SM (**e** and **f**) (Units: m^3m^{-3}) and the Df/Di anomalies difference (**g** and **h**) during the 2005 and 2010 Amazonia drought periods. The difference is calculated as S0 minus S1. S0, S1 are the simulation with and without considering the aerosols direct radiative effects, respectively

to a variety of observed and assumed conditions, such as the cloud fraction, scattering angle, surface reflectance properties, etc. (Levy et al. 2010). For example, the comparison between MODIS and ground measurement suggested that MODIS underestimates AOD (by 0.02 or more) where the surface is unusually green or dark (2.1 um reflectance < 0.05) (Levy et al. 2010). In these regions, direct solar radiation and latent heat flux may be overestimated, while diffuse radiation may be underestimated with consequent underestimated ecosystem productivity and soil moisture.

In addition, we noted that this study only considers the aerosols' direct radiative effects, although indirect effects caused by cloud-aerosol interactions are widely existing. Aerosols could act as cloud condensation nuclei, change the cloud droplet size distribution, the cloud albedo, and consequent atmospheric circulation (Twomey 1977; Costantino and Bréon 2010). For example, Auffhammer et al. (2006) showed that the aerosols composed by black carbon reduced the historical rice harvest in India through reducing the rainfall in this region. In addition, MODIS retrievals cannot differentiate the species of aerosols. The natural dust may deposit nutrient to soils to aid plant growth (Mahowald et al. 2005; Magnani et al. 2007; Carslaw et al. 2010), while most of the anthropogenic aerosols containing the sulfuric or nitric pollutants may be deposited as acid rain (e.g. Desboeufs et al. 2005), which will adversely affect plant growth. These effects have not been considered in this study either. Further work by using a coupled earth system model with more comprehensive simulation of the land-atmosphere interaction processes is necessary to investigate aerosols' indirect effects on global soil moisture.

4 Conclusion

A coupled model with the atmospheric radiative transfer and land surface biophysical module is used to quantify the aerosol effects on global surface soil moisture. Our simulations show that although aerosol direct radiative effects slightly increase the annual mean soil moisture by 0.006 m^3m^{-3}, the regional relative difference can be as large as 30 % and this positive effect is highly associated with leaf area index and climate drivers. In addition, we find that there is a large difference in estimated soil moisture between two simulations during the Amazonia extreme drought period. Our study suggests that aerosols' direct effects on hydrological cycling should be considered in order to adequately estimate soil moisture of the global terrestrial ecosystems.

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