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Enhanced water use efficiency in global terrestrial ecosystems under increasing aerosol loadings

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ABSTRACT

Aerosols play a crucial role in the climate system, affecting incoming radiation and cloud formation. Based on a modelling framework that couples ecosystem processes with the atmospheric transfer of radiation, we analyze the effect of aerosols on surface incoming radiation, gross primary productivity (GPP), water losses from ecosystems through evapotranspiration (ET) and ecosystem water use efficiency (WUE, defined as GPP/ET) for 2003–2010 and validate them at global FLUXNET sites. The total diffuse radiation increases under relatively low or intermediate aerosol loadings, but decreases under more polluted conditions. We find that aerosol-induced changes in GPP depend on leaf area index, aerosol loading and cloudiness. Specifically, low and moderate aerosol loadings cause increases in GPP for all plant types, while heavy aerosol loadings result in enhancement (decrease) in GPP for dense (sparse) vegetation. On the other hand, ET is mainly negatively affected by aerosol loadings due to the reduction in total incoming radiation. Finally, WUE shows a consistent rise in all plant types under increasing aerosol loadings. Overall, the simulated daily WUE compares well with observations at 43 eddy-covariance tower sites ($R^2 = 0.84$ and RMSE = 0.01 g C (kg H_2O)$^{-1}$) with better performance at forest sites. In addition to the increasing portions of diffuse light, the rise in WUE is also favored by the reduction in radiation- and heat-stress caused by the aerosols, especially for wet and hot climates.

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1. Introduction

Ecosystem water use efficiency (WUE), defined as the ratio of ecosystem gross primary production (GPP) to evapotranspiration (ET), represents the tradeoff between carbon uptake from photosynthesis and water loss from transpiration, soil evaporation and interception (Lu and Zhuang, 2010; Bruemmer, 2012; Xiao, 2013; Saurer, 2014). Understanding the sensitivity of WUE to environmental factors is essential to predict future trends in carbon and water cycles over land. Global differences in ecosystem WUE largely reflect the general patterns of water availability and the adaptability of different vegetation types to water stress (Niu, 2011; Zhu, 2011). Meanwhile, temporal dynamics in ecosystem WUE reflect a variety of environmental factors. CO_2 enrichment may enhance WUE due to reducing stomatal conductance (Keenan et al., 2013). Changes in temperature and precipitation can have complex effects on WUE (Huang et al., 2015): increasing temperature results in higher WUE in high latitudes, while it causes a decline in WUE in humid regions. Precipitation is negatively correlated to WUE in arctic regions, but more precipitation can enhance WUE in most other regions (Xue et al., 2015). Moreover, changes in incoming radiation may significantly affect plant growth, ET and WUE (Strada et al., 2015; Wang and Yang, 2014; Rocha et al., 2004; Liu et al., 2013, 2014a,b, 2015). Previous studies based on flux measurements have shown that, apart from the total incoming radiation, the ratio of diffuse to total irradiance (F_D) is a key factor determining trends in GPP (Choudhury, 2001; Roderick et al., 2001) while its effect on ET is less clear (Wang et al., 2008; Davin and Seneviratne, 2012). For example, moderate cloudy conditions have been found to increase both ecosystem productivity (Gu et al., 1999, 2002; Knohl and Baldocchi, 2008) and WUE (Knohl and Baldocchi 2008; Zhang, 2011; Yang et al., 2013). The magnitude of increase in WUE under optically thick clouds has been shown to be larger than for patchy/thin clouds (Min

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2005). In addition to an increase in diffuse radiation, variations in other factors—such as leaf temperature, soil moisture and vapor pressure deficit – should also be considered in analyzing trends in WUE (Kanniah et al., 2012, Min 2005).

The impacts of aerosols on GPP may be complex. The photosynthesis rate of a deciduous forest was found to increase due to aerosol-induced increase in diffuse radiation by more than 20% after the Mount Pinatubo eruption (Gu et al., 2003). Also, variations in diffuse radiation were shown to enhance the land carbon sink by approximately 25% during 1960 and 1999 (Mercado, 2009). In principle, this occurs because the increased diffuse radiation leads to both less light saturation and more leaf surface exposed to incoming radiation (Knohl and Baldocchi, 2008). A more recent study also corroborated that close canopies with clumped leaves respond positively to enhanced diffuse radiation (Cheng et al., 2015). Conversely, other studies have found that vegetation productivity could be either positively or negatively affected by aerosols depending on the loading (Cox et al., 2008; Niyogi, 2004), with high aerosol concentrations leading to low carbon sequestration due to the reduction in incoming solar radiation (Oliveira, 2007). These findings suggest that both aerosol loading and canopy structure should be considered when analyzing the impact of aerosols on GPP. Conversely, the response of ET to aerosols is comparatively less studied, but potentially more straightforward: higher loadings lead to less solar energy received by land surface, which should decrease water loss through ET. In other words, ET may be, in principle, less sensitive to the partitioning of radiation into direct and diffuse light than GPP (Wang et al., 2008), especially because of the contribution of evaporation from bare soils being rather insensitive (Davin and Seneviratne, 2012). The responses of GPP and ET to changes in aerosols may be different in direction and magnitude. Other associated changes such as leaf temperature may also affect GPP and ET differently. Therefore, in addition to examining the behaviors of GPP and ET, it is also important to analyze impacts of aerosol loading on WUE.

In this study, we use a modelling framework, which combines an atmospheric radiative transfer model and a process-based biogeochemical model, to analyze responses of ecosystem WUE to aerosol conditions. After describing the response of GPP, ET and WUE to aerosols, we characterize the role played by leaf area index (LAI, $m^2\ m^{-2}$) aerosol loading, cloud fraction and cloud optical depth in this response.

2. Methods

2.1. Models

Our modelling framework is composed by two coupled models: (1) a two-broadband (visible and near-infrared bands) atmospheric radiative transfer model (ARTM), and (2) a process-based biogeochemistry model. The ARTM uses atmosphere and land parameters retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS), and considers major scattering or absorbing processes due to ozone, water vapor, air molecules, aerosols and clouds, as well as multiple reflections between land surface and atmosphere (Chen et al., 2014a). The ARTM estimates the incident solar radiation including total, direct, and diffuse downward solar radiation under all-sky conditions in both visible and near-infrared bands. Our previous study (Chen et al., 2014a) showed that the ARTM compares well with observations from the 48 Baseline Surface Radiation Network (BSRN) sites distributed across the globe (Ohmura, 1998).

Building upon its precursor, the Terrestrial Ecosystem Model (TEM, Mcguire et al., 1993; Raich et al., 1991; Zhuang, 2003), the integrated Terrestrial ecosystem model (iTem) simulates the carbon, water, and energy cycling processes in terrestrial ecosystems. The iTem has been applied in evaluating effects of aerosols on terrestrial ecosystem carbon cycle (Chen et al., 2014b), land surface energy balance (Liu et al., 2014a,b) and soil moisture (Liu et al., 2016). The previous validation works showed that the model can reasonably estimate incoming direct-beam and diffuse solar radiation (Chen, 2013) and the partitioning of this radiation between sensible and latent heat fluxes (Liu et al., 2014a,b). Compared to TEM, iTem has several important upgrades which make it suitable for assessing aerosol effects: (1) canopy is described as a one-layer, two-big leaves (Dai et al., 2004); the photosynthesis and energy balance are estimated separately for sunlit and shaded leaves; (2) solar energy is partitioned into direct and diffuse parts when it transfers through canopy and (3) hourly time step is implemented, which makes it capture high-frequency variations in radiation regime. iTEM uses a Farquhar-based photosynthesis model (Farquhar et al., 1980) and a Ball-Berry stomatal conductance model (Ball et al., 1987). Leaf-level photosynthesis is coupled with leaf stomatal resistance, and both of them are a function of leaf temperature, absorbed photosynthetic active radiation on sunlit and shaded leaves, CO2 concentration, atmospheric pressure, soil moisture and vapor pressure. The canopy-level photosynthesis is the weighted sum of that in sunlit and shaded leaves. ET, the other variable involved in calculating WUE, is the sum of evaporation from intercepted water and bare ground, sublimation from snowpack and transpiration from sunlit and shaded leaves. Quantitatively, the energy balance equations for ground surface, leaves and snow pack are solved iteratively to retrieve temperatures, sensible heat and latent heat fluxes. More details about iTem can be found in Chen (2013).

2.2. Experiments and datasets

In this study, land ecosystem WUE is estimated globally with a spatial resolution of $1 \times 1^\circ$ during 2003–2010. Both ARTM and iTem were applied at a 3-hourly temporal resolution. The downward shortwave radiation data (direct and diffuse radiation in the near infrared and visible bands) are provided by the ARTM, and we assume that the radiation in the visible band is equal to the photosynthetically active radiation (the visible band has a broader wavelength by 10 nm). To isolate the contribution of aerosols on WUE, we performed one simulation with aerosol direct radiative effects (termed S0 hereafter) and one without radiative effects (termed S1 hereafter). In S0, iTem used solar radiation which incorporated the effects of aerosol loading as estimated by the ARTM; in S1, iTem was forced by the solar radiation estimated without considering the radiative impacts of aerosols. It is important to note that the difference in WUE calculated from S0 and S1 represents the direct radiative effect of aerosols, which only involves changes in scattering and absorption. Other indirect radiative effects of aerosols, such as those on cloud albedo and cloud lifetime (Rap et al., 2013), are not accounted for in this study.

The atmospheric variables for the ARTM – which include ozone, cloud top pressure and cloud optical thickness, Ångström exponent, aerosol optical thickness (AOD, 550 nm), water vapor column, cloud fraction and cloud optical depth (COD) – are derived from the MODIS Level 3 Atmosphere Products (Platnick, 2015), which are provided at three different temporal scales: daily, 8-day, and monthly. To capture short-time variations in aerosol and atmospheric conditions, we use the 1° daily products generated by MODIS onboard Terra (MOD08) and Aqua (MYD08), which provide observed atmospheric profiles in the morning and afternoon every day. The other two variables required by the ARTM, i.e. solar zenith and solar declination angle, are updated at a 3-hourly time steps according to time and location of each grid-cell. The albedo of land surface from the MODIS 16-day average albedo product (MCD43C3) is used to calculate multiple scattering between the sky and land surface, and it is assumed to be constant during each 16-day period.

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