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Aerosol-induced thermal effects increase modelled terrestrial photosynthesis and transpiration

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ABSTRACT

Previous studies suggest that the radiative effects of atmospheric aerosols (reducing total radiation while increasing the diffuse fraction) can enhance terrestrial productivity. Here, simulations using a regional climate/terrestrial biosphere model suggest that atmospheric aerosols could also enhance terrestrial photosynthesis and transpiration through an interaction between solar radiation, leaf temperature and stomatal conductance. During midday, clear-sky conditions, sunlit-leaf temperatures can exceed the optimum for photosynthesis, depressing both photosynthesis and transpiration. Aerosols decrease surface solar radiation, thereby reducing leaf temperatures and enhancing sunlit-leaf photosynthesis and transpiration. This modelling study finds that, under certain conditions, this thermal response of aerosols can have a greater impact on photosynthesis and transpiration than the radiative response. This implies that a full understanding of the impact of aerosols on climate and the global carbon cycle requires consideration of the biophysical responses of terrestrial vegetation as well as atmospheric radiative and thermodynamic effects.

1. Introduction

Photosynthesis provides a major input of energy into the terrestrial biosphere (Jones, 1992) and can control the biological and ecological processes of vegetation at the Earth's surface. It is strongly influenced by environmental parameters (e.g. temperature, light and CO_2 concentrations) and is therefore affected by regional and global climate change. However, vegetation also has the ability to exert an influence on atmospheric composition and climate via the exchange of energy, water vapour and carbon dioxide between the biosphere and atmosphere. Comprehension of these feedbacks is crucial to understanding past and future climate change.

One uncertain aspect of the climate–biosphere system is its response to increasing atmospheric aerosols from air pollution, volcanoes and dust storms (Penner et al., 2001). Atmospheric aerosols (liquid or solid particles suspended in the atmosphere) alter the solar flux reaching the Earth's surface via two mechanisms: directly, by scattering and/or absorbing solar radiation, and indirectly, by altering cloud properties (Penner et al., 2001). Both reduce the solar flux reaching the surface while increasing its diffuse fraction (Twomey, 1977; Schwartz, 1996). These modifications can alter the surface climate (e.g. temperature, specific humidity) and thus the physiological functions of terrestrial vegetation. Because the biosphere affects CO_2 uptake and evapotranspiration rates, these changes to terrestrial vegetation have the potential to feed back on climate.

It has been suggested that terrestrial photosynthetic rates can be enhanced by aerosol haze and/or cloudiness increasing diffuse light on shaded leaves (Roderick et al., 2001; Gu et al., 2003). Those studies, which investigate the effects of Mount Pinatubo aerosols on terrestrial productivity, claim that this effect is significant enough to increase net primary production (NPP) and reduce the growth rate of atmospheric CO_2, yet recent studies investigating the same event do not find an increase in NPP and discount the importance of this effect (Krakauer and Randerson, 2003; Angert et al., 2004). However, these diffuse radiation studies are limited by an almost exclusive focus on the photosynthetic response to aerosol-induced changes in the solar radiation without considering how concomitant changes in leaf temperature and transpiration rates might affect photosynthesis. Other researchers have noted that aerosol-induced changes in the surface solar radiation can influence leaf temperatures and transpiration rates (Baldocchi et al., 2002; Gu et al., 2002), but did not attempt to assess the magnitude of these interactions or their impact on photosynthesis.

In this study we use a coupled three-dimensional model driven by hourly simulated aerosols over East Asia to investigate the feedbacks between atmospheric aerosols, climate and leaf processes during 5 d in July 1995. Of particular interest are the

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relative roles of aerosol-induced radiative and thermal effects on photosynthetic and transpiration rates. While these results apply to a certain set of conditions in a specific region of the world, they imply that the temperature effects of aerosols can outweigh the radiative effects.

2. Model description

We focus on East Asia (Fig. 1) because it is one of the most populous and rapidly developing regions of the globe with exceedingly high aerosol concentrations (Bergin et al., 2001; Xu et al., 2002). July was chosen to capture the period of peak photosynthetic activity. We use the NCAR RegCM, a mesoscale model (Giorgi et al., 1993a,b; Giorgi and Shields, 1999) with the CCM3 radiation package (Kiehl et al., 1996), coupled to the Common Land Model (CLM0) (Steiner et al., 2005). The CLM0 is a newly developed land surface parametrization with 10 unevenly spaced soil layers, a vegetation layer and up to five snow layers (Dai et al., 2003). A key feature of CLM0 is its inclusion of a coupled photosynthesis–stomatal conductance algorithm to simulate processes within the canopy (Collatz et al., 1991). This algorithm uses a semi-empirical relationship between stomatal conductance, g_c (m s^{-1}), and the rate of photosynthesis, A (μmol CO$_2$ m^{-2} s^{-1}):

$$g_c = m\frac{A}{c_s}hp_s + b \tag{1}$$

where m and b are empirical coefficients [with values of 9 (no units) and 2000 μmol m^{-2} s^{-1}, respectively, in our simulations], h is the relative humidity at the leaf surface divided by 100, p_s is the surface pressure (atm), and

$$A = \min(w_j, w_c, w_e). \tag{2}$$

In eq. (2), w_j, w_c and w_e are the electron transport (or light)-limited, carboxylation-limited and export-limited rates, respectively (Collatz et al., 1991; Farquhar et al., 1980), where

$$w_j = \frac{(c_i - \Gamma^*)\,J}{c_i + 2\Gamma^*}, \tag{3}$$

$$w_c = \frac{V_{\mathrm{cmx}}\,(c_i - \Gamma^*)}{c_i + K_c\,[1 + (o_i/K_o)]}, \tag{4}$$

$$w_e = 0.5V_{\mathrm{cmx}}, \tag{5}$$

c_i and o_i are the interior leaf CO$_2$ and O$_2$ concentrations, Γ^* is the CO$_2$ compensation point, J is the electron transport rate (a function of the absorbed solar radiation), V_{cmx} is the

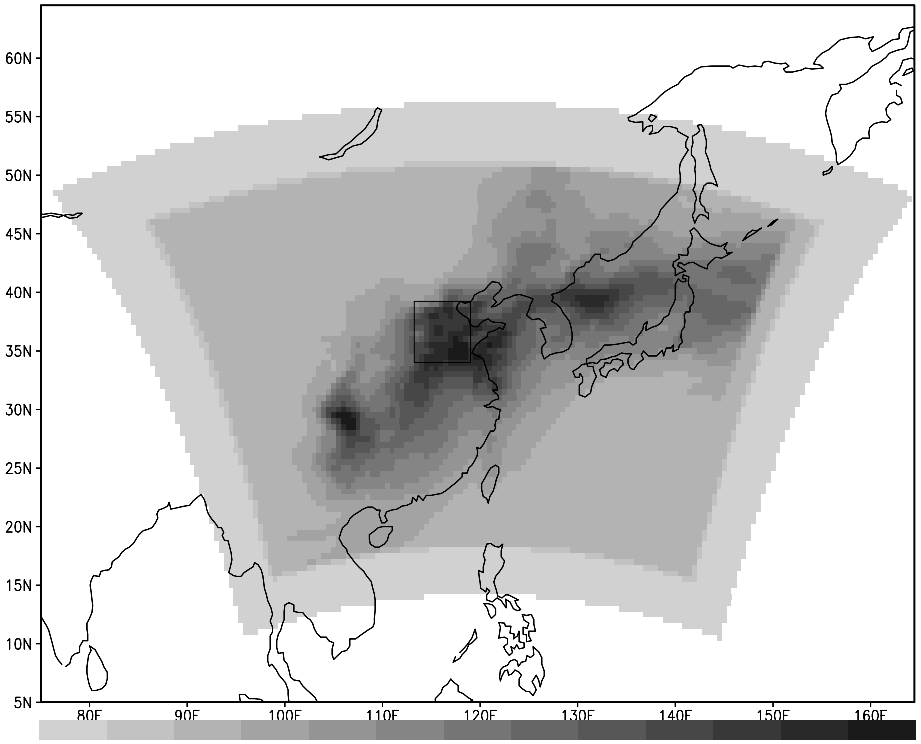

Fig 1. Average midday anthropogenic aerosol optical depth at 550 nm assumed in the model simulation. The box outlines the Yellow River region (YRR).

temperature-dependent maximum rate of carboxylation and K_c and K_o are the Michaelis–Menten constants for the carboxylation and oxygenation reactions, respectively. A and g_c in eqs (1) and (2) are solved simultaneously in an iterative fashion. The model divides the canopy into sunlit and shaded leaves and calculates g_c and A for each fraction. Leaf temperature (T_{leaf}) and transpiration are calculated for the total canopy based on the canopy water and energy balances. Water stress is included by limiting the maximum transpiration rate derived from root zone soil characteristics and soil water. Because A, g_c and transpiration are calculated by the algorithm at each model time step at each gridpoint, its inclusion makes it possible to investigate the effects of aerosols on the terrestrial biosphere in a self-consistent manner.

Aerosol concentrations over the model domain are specified hourly and include a background aerosol (with an optical depth of ~0.1) and anthropogenic sulfate (SO_4^{2-}), nitrate (NO_3^-), black carbon and organic carbon species calculated off-line using a chemical transport model (Chameides et al., 1999a,b, 2002; Luo et al., 2000). We consider only the direct radiative effect of aerosols on climate and radiation, as this is the best characterized (Penner et al., 2001). The scattering and absorption properties of each aerosol species are specified in 19 spectral intervals spanning 200 to 5000 nm. All aerosol species scatter solar radiation; black carbon also absorbs radiation. The overall aerosol single-scattering albedo ranged from 0.88 to 0.92 (Chameides et al., 2002). At 550 nm the asymmetry parameter is set at ~0.7 for SO_4^{2-}, NO_3^- and organic carbon (Kiehl and Briegleb, 1993; Giorgi et al., 2002) and 0.35 for black carbon (Adarsh and Hermann, 1983).

Figure 1 shows the average midday aerosol optical depth (τ) at 550 nm during the 5-d simulation period. There is a localized maximum with $\tau > 0.5$ over Sichuan (~28°N and 105°E) and a broader area with τ ranging from 0.4 to 0.55 over the Yellow River region (YRR), outlined in Fig. 1. During the 5-d period, the greatest impact of aerosols on model-calculated surface climate occurred over the YRR as opposed to the Sichuan. This is because the YRR had low cloud cover (on average <0.4), while the Sichuan was heavily clouded.

Because of the large response over the YRR, we focus on the impact of aerosols in this region. The land cover in this area is dominated by a mix of croplands and natural vegetation based on 1 km satellite land cover data EDC DAAC (1997) for the International Biosphere–Geosphere Programme (IGBP) land cover categories. The region on which we focus is composed of 70% cropland (IGBP category 12) and 20% cropland/natural vegetation (IGBP category 14), with the remaining 10% a mix of shrubs and deciduous broadleaf forest. The land cover type determines the vegetation parameters used in the CLM canopy model. Leaf area index (LAI) ranges from 2–4 m^2 leaf area per m^2 ground area over the focus area, consistent with LAI values measured from crops (Asner et al., 2003). The type of land cover also determines the maximum rate of carboxylation at 25 °C (V_{cmx25}). In our simulation, all categories were specified with a V_{cmx25} of 33 μmol m^{-2} s^{-1}.

3. Results

We compare results from two simulations after a 1-yr atmospheric spin-up without aerosols: one includes only background aerosols ("no-aerosol case") and the other includes background aerosols plus anthropogenic SO_4^{2-}, NO_3^-, black carbon and organic carbon ("aerosol case"). In order to focus on the immediate effects of aerosols, as opposed to the effects of longer-term climatic changes caused by aerosols, both simulations begin with the same initial conditions.

Figure 2 displays the diurnal variations (averaged temporally over the 5-d simulation period and spatially over all grid cells in the YRR) calculated for leaf temperature (T_{leaf}), sunlit and shaded absorbed photosynthetically active radiation (APAR) and sunlit and shaded leaf photosynthesis for the two cases. The photosynthetic rates obtained here tend to be lower than the maximum rates often cited for crops. For example, Bonan (2002) reports a range in maximum A for crops of 20–40 μmol m^{-2} s^{-1} while the sum of sunlit and shaded A in Fig. 2 peaks at slightly less than 15 μmol m^{-2} s^{-1}. The lower photosynthetic rates obtained with our model are partly due to the presence of a striking depression in the photosynthesis rates of the sunlit leaves at midday (Fig. 2D). The cause of this midday photosynthetic depression and its role in determining how the crops in our model respond to aerosols are discussed below.

As expected, the addition of aerosols causes a decrease of ~30–50 W m^{-2} in sunlit-leaf APAR due to the reduction in direct radiation (Fig. 2A), a slight increase of ~5 W m^{-2} in shaded-leaf APAR due to the increase in diffuse radiation (Fig. 2B) and a decrease in T_{leaf} (Fig. 2C). In the YRR, diurnally averaged T_{leaf} decreases by ~3 °C at midday with the addition of aerosols. In general, T_{leaf} is about 4–10 °C higher than surface air temperatures in the no-aerosol case and 4–6 °C higher in the aerosol case. Air–leaf temperature differences of this magnitude have been observed in previous field studies (e.g. Campbell, 1977; Leakey et al., 2003) and leaf temperatures of this magnitude have been noted previously (Mulkey and Pearcy, 1992; Koeniger et al., 1998; Leakey et al., 2003).

Unexpectedly, the sunlit photosynthetic rate increases with the addition of aerosols (Fig. 2D) in spite of the decrease in sunlit APAR (Fig. 2A). The decrease in APAR would depress sunlit-leaf photosynthesis if these leaves were light limited or have no effect if these leaves were light saturated. However, a decrease in APAR cannot directly lead to an increase in photosynthesis. A closer investigation of sunlit leaves shows that during most daylight hours the canopy has sufficient light and sunlit-leaf A is generally limited by w_c (eq. 4). Note in Fig. 2D that the aforementioned midday depression in sunlit-leaf A (as w_c) is less pronounced in the aerosol case. This midday depression in A is often observed in the field under conditions of high heat and light,

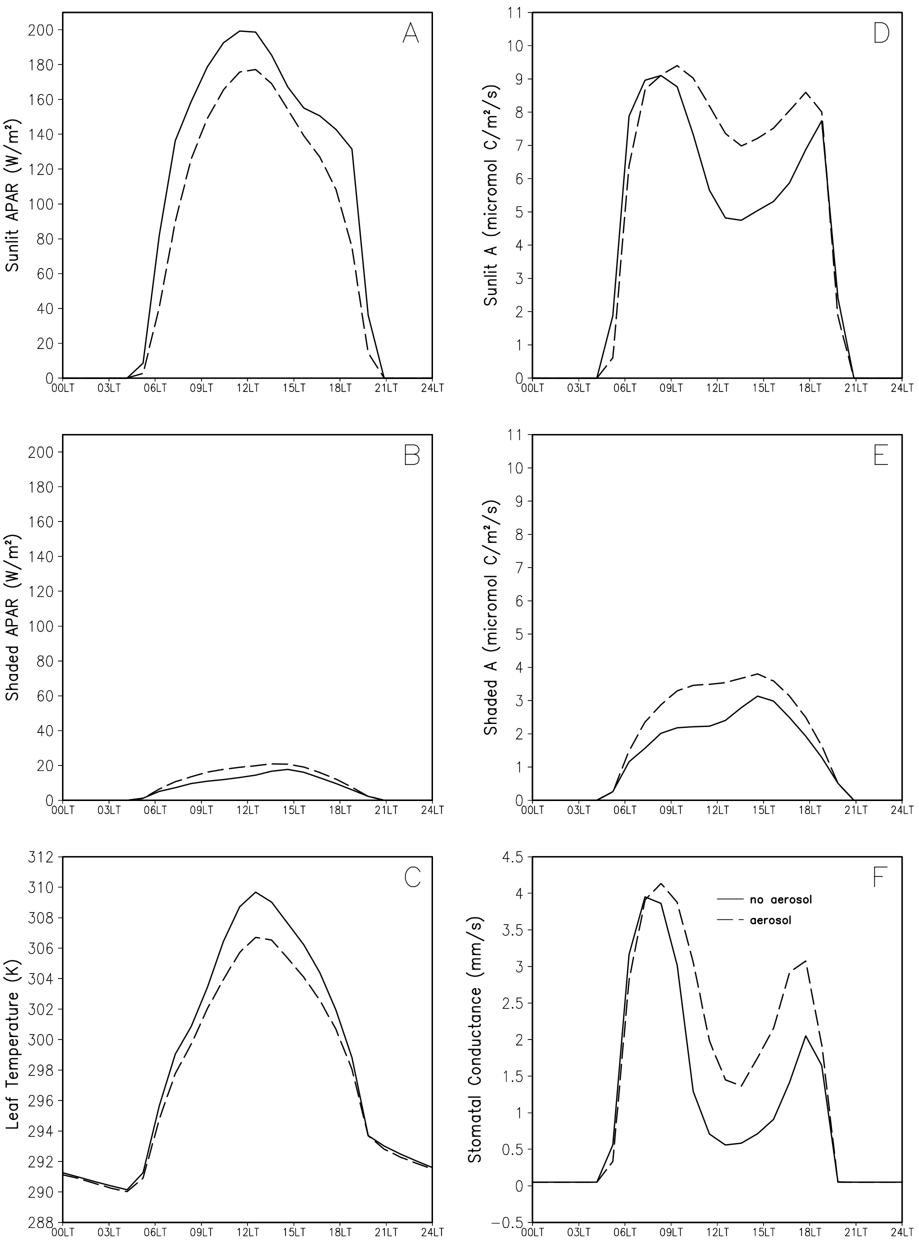

Fig 2. Average diurnal cycle over the 5-d simulation period for the YRR of (A) sunlit APAR per unit leaf area, (B) shaded leaf APAR per unit leaf area, (C) leaf temperature (in K), (D) sunlit leaf photosynthetic rate, (E) shaded leaf photosynthetic rate and (F) sunlit-leaf stomatal conductance.

although its full mechanism is not well understood (Lambers et al., 1998). In the model, the depression is triggered by (1) the dependence of w_c on V_{cmx}, which decreases with increasing T_{leaf} when T_{leaf} exceeds an optimum of ∼308 K, and (2) a suppression in the rate of the carboxylation reaction relative to that of the oxygenation reaction at higher T_{leaf} (Farquhar et al., 1980). This initial reduction in *A* is then further amplified by a decrease in g_c (eq. 1), which acts to decrease c_i and increase T_{leaf}, further decreasing *A*. In our simulation, the addition of aerosols reduces T_{leaf} and this substantially increases midday sunlit-leaf *A* and, in turn, the overall rate of photosynthesis for the region.

In contrast, shaded-leaf photosynthesis is typically limited by w_j all day. In agreement with several previous investigations (e.g. Roderick et al., 2001; Gu et al., 2003), we find that the addition of aerosols increases the diffuse fraction of light which increases shaded-leaf APAR and thus also shaded-leaf *A* (Fig. 2E). However, the increase in shaded-leaf *A* is only about half of the increase in sunlit-leaf *A*. Therefore the reduction in T_{leaf} from aerosols constitutes the major driver increasing total canopy photosynthetic rates in our model simulations.

In addition to altering photosynthesis, aerosols increase midday sunlit-leaf g_c (Fig. 2F). The absolute increase in midday

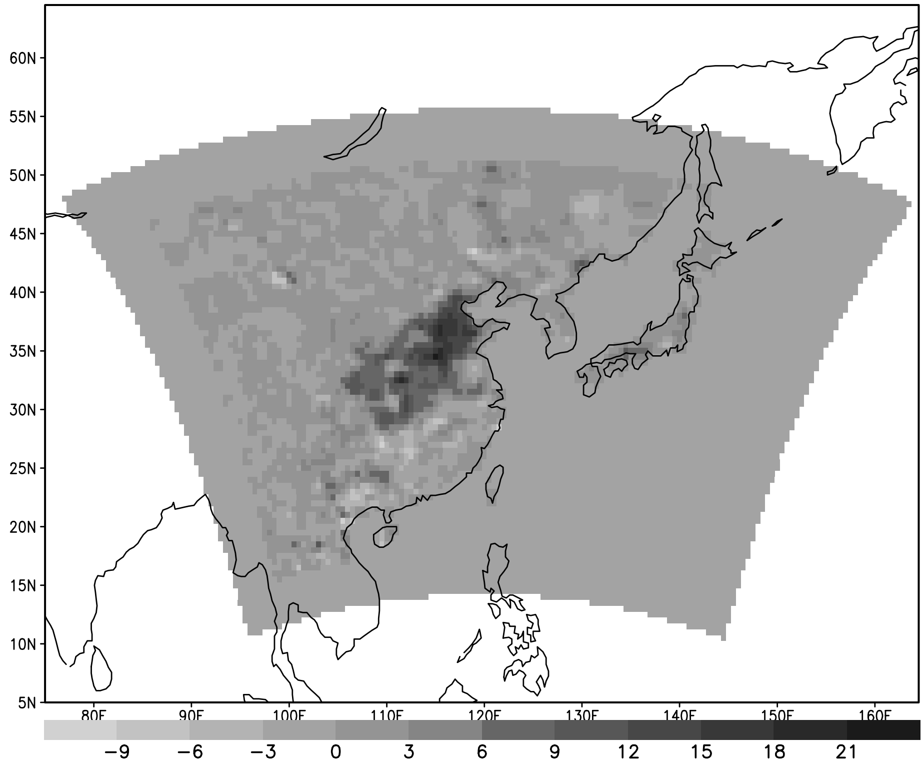

Fig 3. Difference in transpiration ($T_{\mathrm{aerosol}} - T_{\mathrm{noaerosol}}$) in $\mathrm{mmH_2O\ s^{-1}} \times 10^{-6}$. Positive values indicate that rates are higher in the aerosol case than the no aerosol case.

g_{c} is as much as 1 mm $\mathrm{s^{-1}}$ (i.e. an increase of a factor of 2–3). One factor contributing to the aerosol-induced g_{c} increase is the increase in A (eq. 1). Another important factor is the change in the water vapour pressure deficit (VPD) across the leaf surface. The humidity term, h, in eq. (1) is related to VPD by:

$$h = \frac{e_{\mathrm{surf}}}{e_{\mathrm{i,sat}}\,(T_{\mathrm{leaf}})} = 1 - \frac{VPD}{e_{\mathrm{i,sat}}\,(T_{\mathrm{leaf}})} \tag{6}$$

where

$$VPD = e_{\mathrm{i,sat}}\,(T_{\mathrm{leaf}}) - e_{\mathrm{surf}} \tag{7}$$

$e_{\mathrm{i,sat}}$ is the internal leaf vapour pressure (or the saturated vapour pressure at T_{leaf}) and $\mathrm{e_{surf}}$ is the water vapour pressure at the surface of the leaf. The addition of aerosols lowers the calculated VPD by as much as 1000–2000 Pa (or a factor of 2), largely because a lower T_{leaf} reduces $\mathrm{e_{i,sat}}$.

We might expect that a decrease in VPD would suppress the rate of transpiration. However, plants have a feed-forward response that closes the stomata under high VPDs to prevent excessive water loss (Farquhar, 1978; Lambers et al., 1998). This effect has been observed under experimental conditions and is built into the model through eqs (1) and (6). While the value of VPD is dependent on $e_{\mathrm{i,sat}}$ and therefore T_{leaf}, the general response in the model tends to decrease g_{c} when the VPD gets large. In our simulations, the addition of aerosols causes VPD to decrease and this, along with the increase in A, leads to an increase in g_{c}. (Offline tests that separately fixed A and VPD indicate that both contribute significantly to the overall increase of g_{c}.) As a result of the increase in g_{c} with aerosols, transpiration rates increase (Fig. 3). Previous investigators had speculated that aerosols would lower evapotranspiration by reducing solar radiation (Stanhill and Cohen, 2001). However, our calculations suggest that the interaction between photosynthesis and stomatal activity may actually lead to the opposite response. The effect of this enhancement of transpiration on the climate system and its response to increasing atmospheric aerosols has yet to be assessed.

In addition to controlling transpiration, $\mathrm{g_c}$ also influences T_{leaf} via latent energy release. When midday T_{leaf} rises above the optimum and/or VPD becomes, plants close their stomata causing a shutdown and wilting of the leaf. However, this causes T_{leaf} to rise even further and may encourage a positive feedback that further restricts photosynthesis and transpiration. Previous studies (Raupach, 1998; Wilson et al., 2003) have examined these types of high-temperature feedbacks with respect to photosynthesis and stomatal conductance; however, the influence of atmospheric aerosols on these relationships has not yet been considered. Our results suggest that aerosols could mitigate this process by reducing T_{leaf}, thereby making it possible for plants to increase photosynthetic activity throughout the middle of the day.

4. Discussion

The key environmental condition for this interaction between aerosol, leaf temperature and photosynthesis is high midday temperatures in the absence of water stress. This condition is fulfilled over central China, a mid-latitude location experiencing hot summertime temperatures and wet soils following the Asian monsoon. Regions that are not affected by a midday depression in photosynthesis would not experience this phenomenon. However, the high temperatures causing the midday depression are typical in the tropics and this temperature-driven effect could be significant in any location subject to temperature-induced midday photosynthetic depressions. Further investigation will be required to determine the spatial scale of this phenomenon.

As mentioned previously, A values are slightly lower than what would be expected for crop ecosystems. This is due in part to the midday photosynthetic depression, which prevents the vegetation from reaching its midday maximum. It is also likely due in part to our parametrization of V_{cmx}, which uses a V_{cmx25} value of 33 μmol m^{-2} s^{-1}, while crops can reach a value of up to 50 μmol m^{-2} s^{-1} (Bonan, 1996). We conducted separate offline tests to determine if an increase in V_{cmx25} would affect our conclusions, and found that only sunlit leaves were significantly affected by this change. Shaded A values were within 5% of those obtained with the lower V_{cmx25} value, indicating that the radiative response is not significantly affected by an increase in V_{cmx25}. In the $V_{\mathrm{cmx25}} = 50$ case, sunlit A increased up to $\sim$33% at the beginning and end of the day, but still experienced a midday depression as in the $V_{\mathrm{cmx25}} = 33$ case. Moreover, we found that the relative magnitude in the midday depression in sunlit A for the $V_{\mathrm{cmx25}} = 50$ case was similar to that of the $V_{\mathrm{cmx25}} = 33$ case, indicating a similar thermal effect. Because the relative importance of the thermal and radiative responses did not change under different V_{cmx25} values, it appears that our conclusions are not affected by the specific choice of V_{cmx25} used in our model.

The next important consideration is the longer-term response of these interactions and if they occur on a scale that would alter NPP. The simulated changes in photosynthesis have the ability to affect the carbon cycle and potential carbon sequestration, although the ultimate impact on the carbon balance has yet to be determined. Despite the uncertainty and scale of the impacts on the carbon cycle, the results indicate that there may be important impacts on the water cycle. Because changes in the amount of water vapour can have a more local and immediate effect, the increased transpiration may affect the amount and structure of cloud, precipitation and surface hydrology, creating a complex system of feedbacks between the biosphere and the atmosphere. Another interesting feedback could be the stomatal uptake of ozone by vegetation. Because our model domain is a region that is often subject to ozone pollution episodes, the increase in transpiration and stomatal conductance could lead to an increase in ozone uptake and affect the growth and function of the vegetation.

In the context of the significance of these results, there are several caveats associated with the model approach used in this study. First, it adopts a modified "big leaf" approach, calculating sunlit and shaded photosynthesis and g_{c} separately, but a single T_{leaf} for the entire canopy. Single-layer canopy variables are derived from the vertical profile through the canopy, and this approach is widely utilized in global models (e.g. NCAR CCSM) for its skill in approximating the environmental parameters within the canopy without a large computational expense. In a multilayer, complex canopy model, leaf temperatures are calculated separately for different portions of the canopy, a process likely to make sunlit leaves warmer than the average canopy temperature and more susceptible to a midday photosynthetic depression. Therefore, a simple one-layer model may underestimate this effect depending on the proximity to the optimum temperature and if the aerosol-induced reduction in leaf temperature is sufficient to lower leaf temperatures to near or below the optimum temperatures. Another possibility is that the complex model may allow more diffuse light to reach shaded leaves, potentially causing the simple model to underestimate the radiative effect. Varying levels of complexity in the canopy model may alter the relative weight of the thermal effect versus the radiative effect; however, this possibility does not invalidate our overall conclusion that leaf temperatures effects need to be assessed in order to fully understand aerosol–photosynthesis interactions.

Another important limitation arises from the temperature parametrizations used for V_{cmx} and the kinetic parameters, $\mathrm{K_c}$ and $\mathrm{K_o}$. All three are key to determining w_{c} as a function of T_{leaf}; however, their values are uncertain and are assumed in the model to be invariant across species and ecosystems. The parametrization of the temperature response is driving the response to aerosols in our simulation, and this should receive more attention in future studies. Also, it has been observed that plant canopies can adapt to optimize functioning under different light and temperature conditions (e.g. Kull, 2002), and this dynamic nature of the temperature function has not been included in our simulation.

Despite these limitations, our results present an interesting feedback that occurs between terrestrial photosynthesis and anthropogenic aerosols. As atmospheric scientists move towards coupled chemistry–climate studies, this may be an important feature in understanding interactions between anthropogenic pollution and the land surface. Because most models use a similar parametrization of photosynthesis, transpiration and the vegetation canopy, this feedback should be noted as a possible outcome of future simulations.

5. Conclusions

To date, most studies of the impact of aerosols have investigated the radiative effects of aerosols on vegetation. Our study uses a climate–biosphere model to consider thermal as well as radiative effects on photosynthesis, and we find that under certain conditions aerosols can reduce leaf temperatures and alleviate a midday depression in photosynthesis. This indicates that effects on leaf temperature, while not considered in many past studies using ground-based measurements, may be an important if not dominant interaction driving aerosol–biosphere feedbacks. While further work will be required to characterize and quantify these effects and feedbacks, our results point out the need to include the full gamut of biophysical responses when assessing the impact of environmental change on primary productivity, the terrestrial carbon balance and the climate.

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