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Observed Impact of Atmospheric Aerosols on the Surface Energy Budget

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ABSTRACT: Atmospheric aerosols scatter and potentially absorb incoming solar radiation, thereby reducing the total amount of radiation reaching the surface and increasing the fraction that is diffuse. The partitioning of incoming energy at the surface into sensible heat flux and latent heat flux is postulated to

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change with increasing aerosol concentrations, as an increase in diffuse light can reach greater portions of vegetated canopies. This can increase photosynthesis and transpiration rates in the lower canopy and potentially decrease the ratio of sensible to latent heat for the entire canopy. Here, half-hourly and hourly surface fluxes from six Flux Network (FLUXNET) sites in the coterminous United States are evaluated over the past decade (2000–08) in conjunction with satellite-derived aerosol optical depth (AOD) to determine if atmospheric aerosols systematically influence sensible and latent heat fluxes. Satellite-derived AOD is used to classify days as high or low AOD and establish the relationship between aerosol concentrations and the surface energy fluxes. High AOD reduces midday net radiation by 6%–65% coupled with a 9%–30% decrease in sensible and latent heat fluxes, although not all sites exhibit statistically significant changes. The partitioning between sensible and latent heat varies between ecosystems, with two sites showing a greater decrease in latent heat than sensible heat (Duke Forest and Walker Branch), two sites showing equivalent reductions (Harvard Forest and Bondville), and one site showing a greater decrease in sensible heat than latent heat (Morgan–Monroe). These results suggest that aerosols trigger an ecosystem-dependent response to surface flux partitioning, yet the environmental drivers for this response require further exploration.

1. Introduction

The surface energy budget describes the exchange of energy, mass and momentum between the land surface and the atmosphere and is strongly impacted by incoming solar radiation. Radiation absorbed at the surface (R_n) is stored in surface elements (often approximated by the ground heat flux G) or transported into the atmosphere via sensible (H) or latent (λE) heat fluxes. This relationship can be written as

$$R_n - G = H + \lambda E. \quad (1)$$

The Bowen ratio (B), or the ratio of H to λE , quantifies the partitioning of outgoing energy and impacts surface air temperatures and relative humidity. These surface fluxes apply an important thermal forcing to the lower boundary of the atmosphere and influence meteorological processes including atmospheric stability, cloud development, and precipitation (Stull 1988).

Atmospheric aerosols, or small particles suspended in the atmosphere, can reduce the amount of solar energy reaching the surface (Trenberth et al. 2009; Zhang et al. 2010) and thereby alter the surface energy budget. The reduction in solar radiation due to the scattering and absorption of aerosols is known as the “direct effect,” which decreases the total amount of radiation reaching the surface (Schwartz 1996). Because aerosols scatter radiation, this can increase the fraction of surface radiation that is diffuse (Liepert and Tegen 2002). The radiative effect of aerosols depends on size and composition of atmospheric aerosols (Forster et al. 2007), where most fine aerosols (diameters $\leq 2.5 \mu\text{m}$) scatter incoming solar radiation regardless of composition, and black or brown carbon aerosols can also absorb radiation and warm the surrounding atmosphere (Hansen et al. 1997; Péré et al. 2011; Schwartz 1996). Aerosols from a variety of sources, ranging from the 1991 eruption of Mount Pinatubo to local urban emissions, have been observed to

increase diffuse light (Gu et al. 2003; Roderick et al. 2001; Niyogi et al. 2004; Mercado et al. 2009). Additionally, modifications of these surface climate effects have been linked to changes in atmospheric boundary layer depth and diurnal evolution (Christopher et al. 2000; Cox et al. 2008; Wang and Christopher 2006; Zhang et al. 2008). Therefore, analyzing the influence of aerosols on surface energy budgets can improve our understanding of regional and local climate.

In addition to impacting climate, prior studies suggest that the increase in diffuse light can enhance the carbon uptake of vegetation by increasing the light-use efficiency (LUE) of an ecosystem (Gu et al. 2003; Matsui et al. 2008; Mercado et al. 2009; Niyogi et al. 2004). LUE is defined as the amount of carbon fixed per unit of light, and here we calculate LUE as the ratio of gross primary productivity (GPP) to photosynthetically active radiation (PAR; 400–700 nm),

$$\text{LUE} = \frac{\text{GPP}}{\text{PAR}}. \quad (2)$$

Increases in canopy photosynthetic rates have been attributed to the penetration of diffuse light into a dense forest canopy, reaching shaded leaves that would normally be light limited on a clear day (Farquhar and Roderick 2003; Matsui et al. 2008; Niyogi et al. 2004; Roderick et al. 2001). The diffuse light–photosynthesis relationship is determined by the canopy response to the combination of increased diffuse light and reduced total radiation (Knobl and Baldocchi 2008; Misson et al. 2005), where the maximum carbon uptake in vegetated ecosystems may occur at moderate aerosol concentrations (or optical depth) and diffuse fractions (Cohan et al. 2002; Knobl and Baldocchi 2008; Oliphant et al. 2011). If canopy photosynthesis is enhanced by diffuse light, the coupling between photosynthesis and transpiration could increase λE and alter the local surface energy budget (Bonan 2008; Matsui et al. 2008; Wang et al. 2008). Several modeling studies have highlighted the changes in λE under moderate aerosol loadings (Huang et al. 2007; Knobl and Baldocchi 2008; Péré et al. 2011; Steiner and Chameides 2005; Zhang et al. 2011). Prior studies have shown that vegetation type, canopy structure, and leaf area index (LAI) are important factors in the ecosystem response to diffuse light, as forests and croplands respond more strongly than grasslands (Matsui et al. 2008; Niyogi et al. 2004).

Other secondary factors may also be important in understanding the role of aerosols on the surface climate, including aerosol-driven radiation changes reducing surface and leaf temperatures, vapor pressure deficits (VPDs), and increasing ecosystem water-use efficiency (WUE; the amount of carbon fixed per unit of water). For example, a reduction in total incoming radiation or an increase in the diffuse fraction could reduce leaf temperatures (Steiner and Chameides 2005) or reduce VPD and water stress, leading to an increase in stomatal conductance and plant CO_2 uptake (Matsui et al. 2008; Urban et al. 2012; Zhang et al. 2010). While the relationship between aerosols and VPD is unclear, a reduction in VPD and temperature on cloudy days has been noted to increase canopy photosynthesis while decreasing evapotranspiration (or λE), leading to an increase in ecosystem WUE (Monson et al. 2002; Rocha et al. 2004). Zhang et al. (Zhang et al. 2011) noted variable responses in LUE and WUE to atmospheric conditions in different ecosystems in China and found the response was dependent on canopy

characteristics and water conditions. In contrast, some studies have shown aerosols to have minimal to no effect on ecosystem carbon cycling (Alton 2008; Alton et al. 2005; Krakauer and Randerson 2003), which further highlights the need to characterize how ecosystems respond to multiple environmental variables and how they vary by location, season, and external disturbances such as aerosols.

Considering the two-way interactions between surface vegetation and energy fluxes, further examination of the influence of aerosols on different land-cover types is integral to improving our understanding of the surface energy budget. Current evaluation of the aerosol–surface energy interactions is partially limited by the difficulties in measuring and obtaining regionally and seasonally representative aerosol properties in the field (Andrews et al. 2011). Few studies have investigated this effect with limited measurements (Wang et al. 2008) and most rely on models to assess the potential impacts (Matsui et al. 2008; Steiner and Chameides 2005; Zhang et al. 2008). However, continuous monitoring from the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectrometer (MODIS) provides a long-term, global-scale aerosol data product (Levy et al. 2007). In this study, we use MODIS-derived AOD in conjunction with ground-based eddy covariance measurements of surface energy budget components to investigate the impact of aerosol loadings over the continental United States. The goals of this study are to 1) broaden the observational analysis of aerosol–surface energy budget with MODIS aerosol data over the past decade, 2) examine the impact of aerosols on the surface energy budget components of net radiation and sensible and latent heat fluxes, and 3) evaluate the effect of vegetation type and structure on aerosol–energy budget interactions by comparing responses in different ecosystems.

2. Methods

2.1. FLUXNET data

We utilize observations of surface energy budget components from Flux Network (FLUXNET) eddy covariance measurement towers in the coterminous United States (Baldocchi et al. 2001). We select a subset of FLUXNET sites that 1) have at least 5 years of data, 2) represent different ecosystems to account for vegetation type effects, and 3) have sufficient days with high aerosol optical depth (AOD). General details of individual FLUXNET tower measurements and instrumentation are described by Baldocchi et al. (Baldocchi et al. 2001), with specific site information provided online (<http://fluxnet.ornl.gov/>) and in published manuscripts. Because these are long-term monitoring sites, it is difficult to separate the effects of confounding variables such as temperature, soil moisture, vapor pressure deficit, and radiation. However, by analyzing data over a 9-yr period, we attempt to discern broad trends regarding the role of aerosols on complex ecosystems.

To increase our data representativeness, we exclude sites where the number of high AOD days during the summer months [June–August (JJA)] is less than approximately 10% of the available data. This results in six sites with a sufficient number of high AOD days (Figure 1), including two mixed forests (Harvard Forest and Duke Loblolly), two deciduous broadleaf forests (Morgan–Monroe and Walker Branch), one grassland (Fort Peck), and one crop site (Bondville). Land-cover

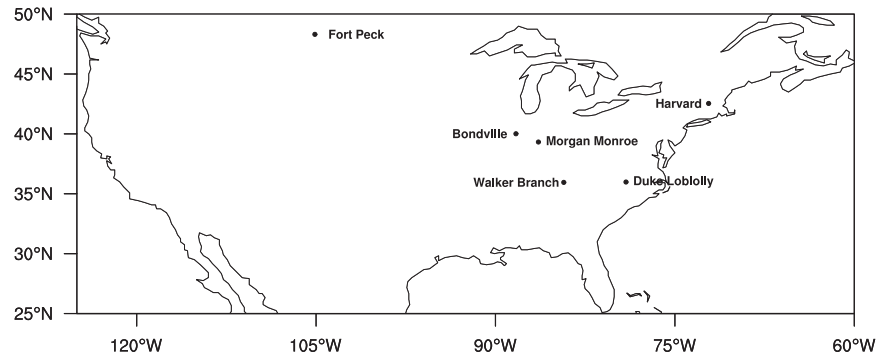


Figure 1. Six selected FLUXNET site locations.

classifications are based on FLUXNET site descriptions. Surface energy fluxes, CO₂ fluxes, and air temperatures are derived from fast-response sonic anemometer measurements to provide half-hourly or hourly fluxes (Table 1). We use half-hourly or hourly non-gap-filled data for surface energy budget variables, including net radiation R_n (W m^{-2}), sensible heat flux H (W m^{-2}), latent heat flux λE (W m^{-2}), and air temperature T (K as measured at the sonic anemometer height). Of these six sites, non-gap-filled net ecosystem exchange (NEE; $\mu\text{mol C m}^{-2} \text{s}^{-1}$) and GPP ($\mu\text{mol C m}^{-2} \text{s}^{-1}$) data are available at Duke Loblolly, Harvard Forest, and Morgan–Monroe.

It is likely that the flux data used in our analysis (H , λE , and CO₂ fluxes) underestimate actual flux values because of the so-called closure problem in the

Table 1. FLUXNET site information (land-cover type from Ameriflux website: <http://ameriflux.lbl.gov/AmeriFluxSites/SitePages/Home.aspx>).

Variable	Duke Loblolly	Harvard Forest	Morgan–Monroe	Walker Branch	Bondville	Fort Peck
Land-cover type	Mixed forest	Mixed forest	Deciduous broadleaf	Deciduous broadleaf	Cropland	Grassland
Latitude	35.98°N	42.54°N	39.32°N	35.95°N	40.01°N	48.31°N
Longitude	79.09°W	72.18°W	86.41°W	84.29°W	88.29°W	105.10°W
Years	2001–08	2000–08	2000–08	2000–01, 2003–07	2000–07	2000–07
Data availability	Half-hourly	Hourly	Hourly	Half-hourly	Half-hourly	Half-hourly
Low AOD days	98	126	142	80	144	244
High AOD days	51	16	26	64	24	21
LAI ($\text{m}^2 \text{m}^{-2}$)	5.5 ^a	3.4 ^b	4.9 ^b	4.9–6.0 ^c	5–5.5 ^d	2.5 ^b
Canopy height (m)	18 ^a	23 ^b	27 ^b	15–26 ^c	0.3–0.9	0.2–0.4 ^b
Precipitation (mm yr^{-1})	1150 ^e	992 ^b	1094 ^b	1333 ^f	1043 ^g	386 ^b

^a Stoy et al. 2006.

^b Thompson et al. 2011.

^c Hui et al. 2004.

^d Hollinger et al. 2010.

^e Ellsworth et al. 2012.

^f Miller et al. 2007.

^g El Maayar and Sonnentag 2009.

eddy covariance technique (Foken 2008; Franssen et al. 2010; Leuning et al. 2012; Oliphant et al. 2004; Oncley et al. 2007; Twine et al. 2000; Wilson et al. 2002). To close the energy budget, R_n must be balanced by the sum of H , λE , and all storage terms (including G). While near closure can be attained on time scales of a month or even a day, the FLUXNET latent and sensible heat flux data at the half-hourly to hourly time scale can be underestimated by 10%–30% on average (Oncley et al. 2007; Twine et al. 2000; Wilson et al. 2002) because of a number of possible errors in measurement technique or from failure to capture all of the component fluxes with eddy covariance theory (Finnigan et al. 2003). There is evidence that suggests CO_2 flux (used to calculate NEE and GPP) is also underestimated (Kondo and Tsukamoto 2008; Leuning and King 1992; Twine et al. 2000), although to what extent remains uncertain (Baldocchi 2008). While measured values of R_n may vary among net radiometers, several studies have concluded that errors are generally within 5% during daytime and cannot account for the relatively large lack of closure (Leuning et al. 2012; Twine et al. 2000). While we did not manipulate the data to assume energy budget closure, we minimize bias by analyzing data at midday [1000–1400 local time (LT)] when R_n values are greatest. Additionally, if we assume closure error does not vary with the Bowen ratio, potentially because the energy balance errors affect H and λE equally (Barr et al. 1994; Jaeger et al. 2009; Oliphant et al. 2004; Twine et al. 2000), then our Bowen ratio analysis (section 3.3) is likely unaffected by energy balance closure error.

2.2. MODIS aerosol optical depth data

AOD (or τ ; unitless) describes the attenuation of radiation through the atmosphere due to the presence of atmospheric aerosols. AOD represents the integral of radiation extinction from the surface to the top of the atmosphere (TOA) through an extinction coefficient (σ_e , a sum of scattering and absorption by aerosols dependent on the aerosol composition and concentration) at a specified wavelength λ ,

$$\text{AOD} = \int_0^{\text{TOA}} [\sigma_e(\lambda)] dz. \quad (3)$$

AOD can be measured at the surface [e.g., the Aerosol Robotic Network (AERONET) network; Holben et al. 1998] or derived from satellites (Kaufman et al. 2002). Because surface observations are sparse, we use satellite-derived AOD from MODIS. The MODIS instrument observes 36 spectral bands with a 2330-km swath at $10 \text{ km} \times 10 \text{ km}$ spatial resolution, with a retrieval algorithm defined by Levy et al. (Levy et al. 2007). We implement MODIS data from the *Terra* and *Aqua* satellites and select AOD at the 550-nm wavelength to represent the middle of the PAR (400–700 nm) band, the range of radiation that vegetation utilizes for photosynthesis and the band typically used to investigate the role of aerosols on vegetation (e.g., Niyogi et al. 2004). MODIS *Terra* and *Aqua* retrieve approximately 2–4 AOD values per location per day between 1030 and 1300 LT depending on the site. Level-2 collection-5 MODIS AOD pixels containing FLUXNET site locations within a 0.1° distance criteria are selected and collocated with flux data over three summer months (JJA) from 2000 to 2008 (Figure 2). Data gaps represent time periods when clouds obscured MODIS retrievals and prevented AOD detection.

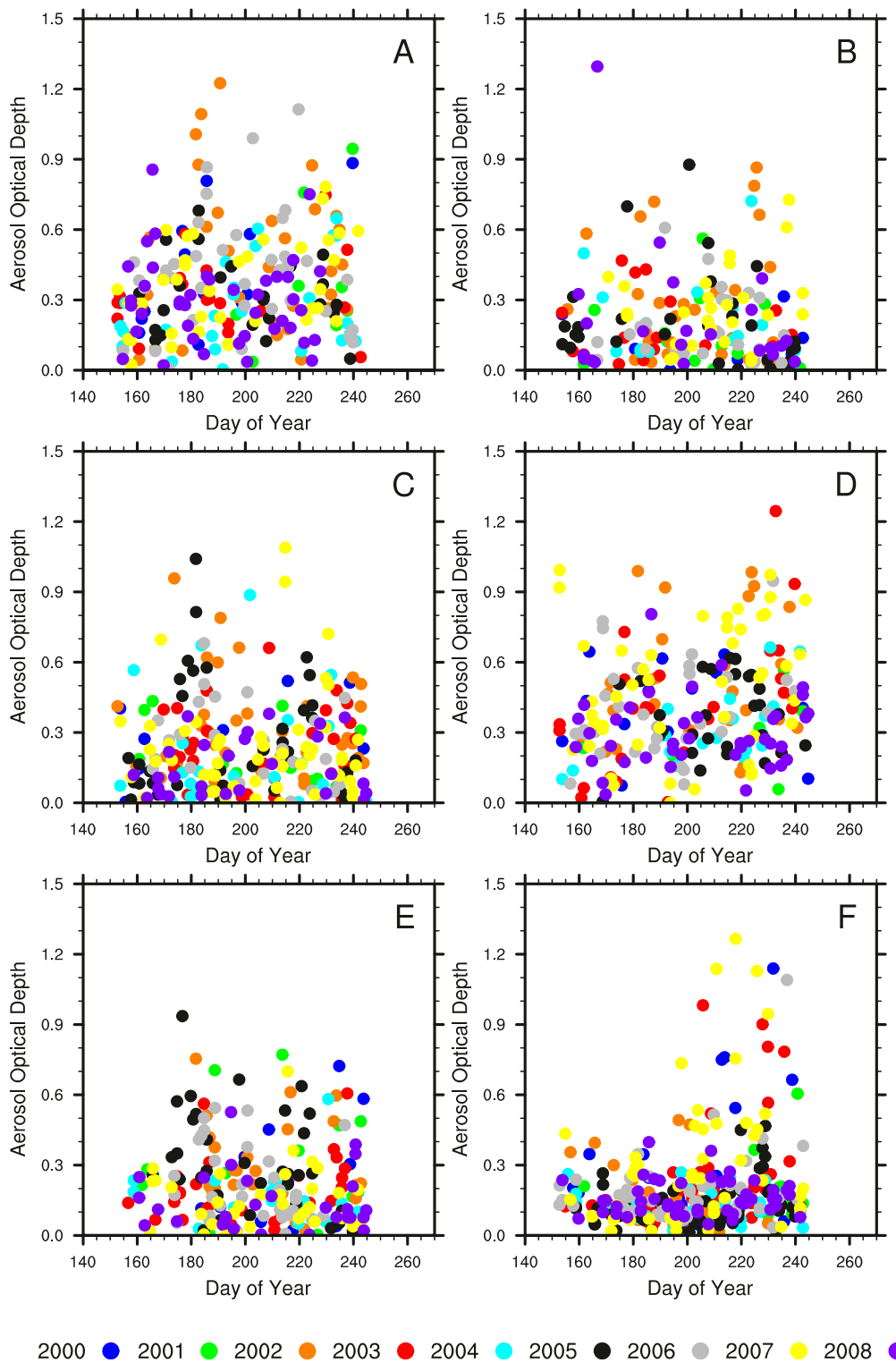


Figure 2. MODIS AOD time series for the six selected FLUXNET sites: (a) Duke Loblolly, (b) Harvard Forest, (c) Morgan–Monroe, (d) Walker Branch, (e) Bondville, and (f) Fort Peck. Data points represent instantaneous *Terra* and *Aqua* platform AOD retrievals that correspond with available FLUXNET surface energy budget data.

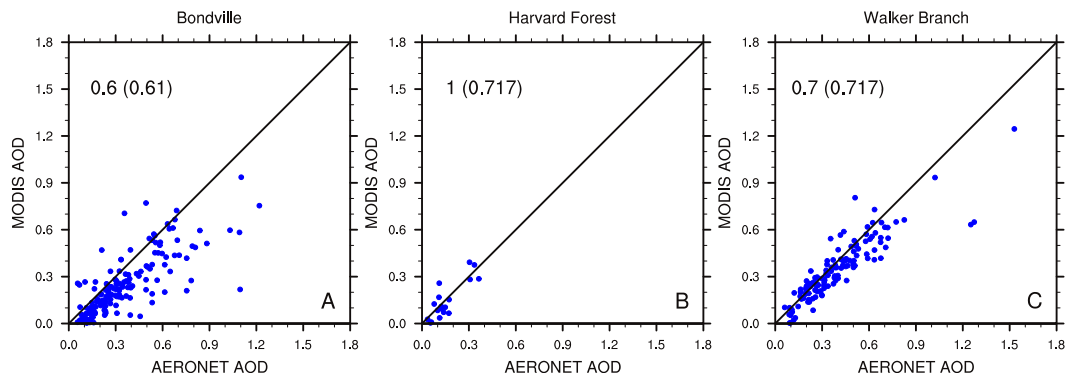


Figure 3. Instantaneous MODIS AOD (550 nm) compared to ground-based AERONET (500 nm) measurements at three available FLUXNET sites in JJA: (a) Bondville, 2000–07; (b) Harvard Forest, 2001–08; and (c) Walker Branch, 2001–07. The regression slope (correlation coefficient) is shown for each site.

This conveniently selects for clear-sky days and potentially removes the confounding effects of cloud cover, although there are some cloud-cover artifacts evident in our analysis, as discussed in section 4.

Past aerosol–ecosystem studies have used ground-based measurements to investigate the science questions presented here (e.g., Wang et al. 2008); therefore, we cross validate the MODIS AOD with ground-based AERONET observations where available. AERONET observations of AOD at 500 nm are available for portions of 2000–08 at three of the selected sites (Bondville, Harvard Forest, and Walker Branch). MODIS AOD correlates well with AERONET AOD (R between 0.6 and 0.7) with slopes ranging from 0.6 to 1 (Figure 3), indicating that our results based on MODIS AOD will be comparable with AERONET-based studies. Figure 3 shows that AERONET estimates higher AOD values than MODIS, with increasing discrepancies at higher AOD ($AOD > 0.5$). This is consistent with other studies that have found that MODIS tends to overestimate low AOD and underestimate high AOD (Levy et al. 2007; Li et al. 2009; Remer et al. 2005), suggesting that our sampling of high AOD days based on MODIS data may be underrepresented. However, because we use the MODIS AOD data to classify days as high AOD or low AOD and do not rely on exact values, this bias will be unlikely to affect our conclusions.

MODIS AOD can be used as a proxy for diffuse light when ground-based measurements are not available. One of our selected sites, Morgan–Monroe, had ground-based measurements of total and diffuse PAR in 2007 and 2008 from a BF3 sensor (Delta-T, Cambridge, United Kingdom) (Oliphant et al. 2011). The amount of diffuse radiation increases linearly with increasing AOD (Figure 4; $R = 0.68$), indicating that the use of MODIS AOD can provide a useful metric for estimating diffuse light when ground-based diffuse radiation measurements are not available.

The clear-sky requirement for MODIS AOD retrievals reduces the number of collocated flux tower measurements and AOD measurements (Table 1). Thus, for collocated flux and AOD data, we bin data into high AOD days ($AOD > 0.5$) and

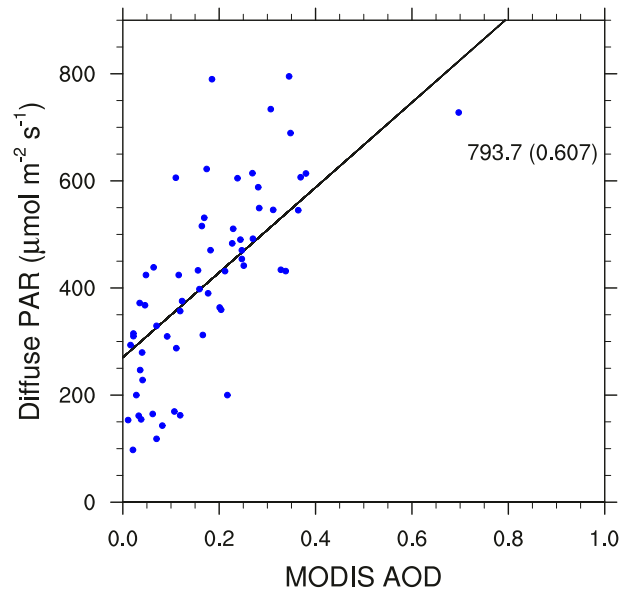


Figure 4. MODIS AOD compared to observed ground-based hourly diffuse PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$) at Morgan–Monroe in 2007 and 2008. The black line and text represent the regression line and slope (R value).

low AOD days ($\text{AOD} < 0.3$) based on the highest daily AOD value. AOD in the range of 0.3–0.5 are excluded to provide a clear separation between high and low AOD effects. This may introduce artifacts into our analysis, as clouds may be present at other time periods during the diurnal cycle of a high AOD day. To determine the statistical significance between midday surface fluxes for high and low AOD days, we use a Student's t test with a 95% confidence interval ($p < 0.05$). We note that, while this method determines that the high and low AOD samples may be significantly different, it cannot account for the multiple physical processes that occur or instrument error, as we discuss in the analysis and discussion sections below.

3. Results

3.1. Diurnal cycle

Figure 5 shows the average diurnal cycle for surface energy budget components (R_n , H , and λE), temperature (T), and carbon flux data (where available; NEE and GPP) from six FLUXNET sites during JJA for 2000–08. Midday (1000–1400 LT) percentage changes between high and low aerosol days in the surface energy budget components, T , VPD, PAR, LUE, and WUE are listed in Table 2.

At the Duke Loblolly site (Figure 5 and Table 2), high AOD days have higher T throughout the diurnal cycle (2-K difference at the midday maximum and 3 K at night) and reduced VPD. While this may be due to absorbing aerosols warming the

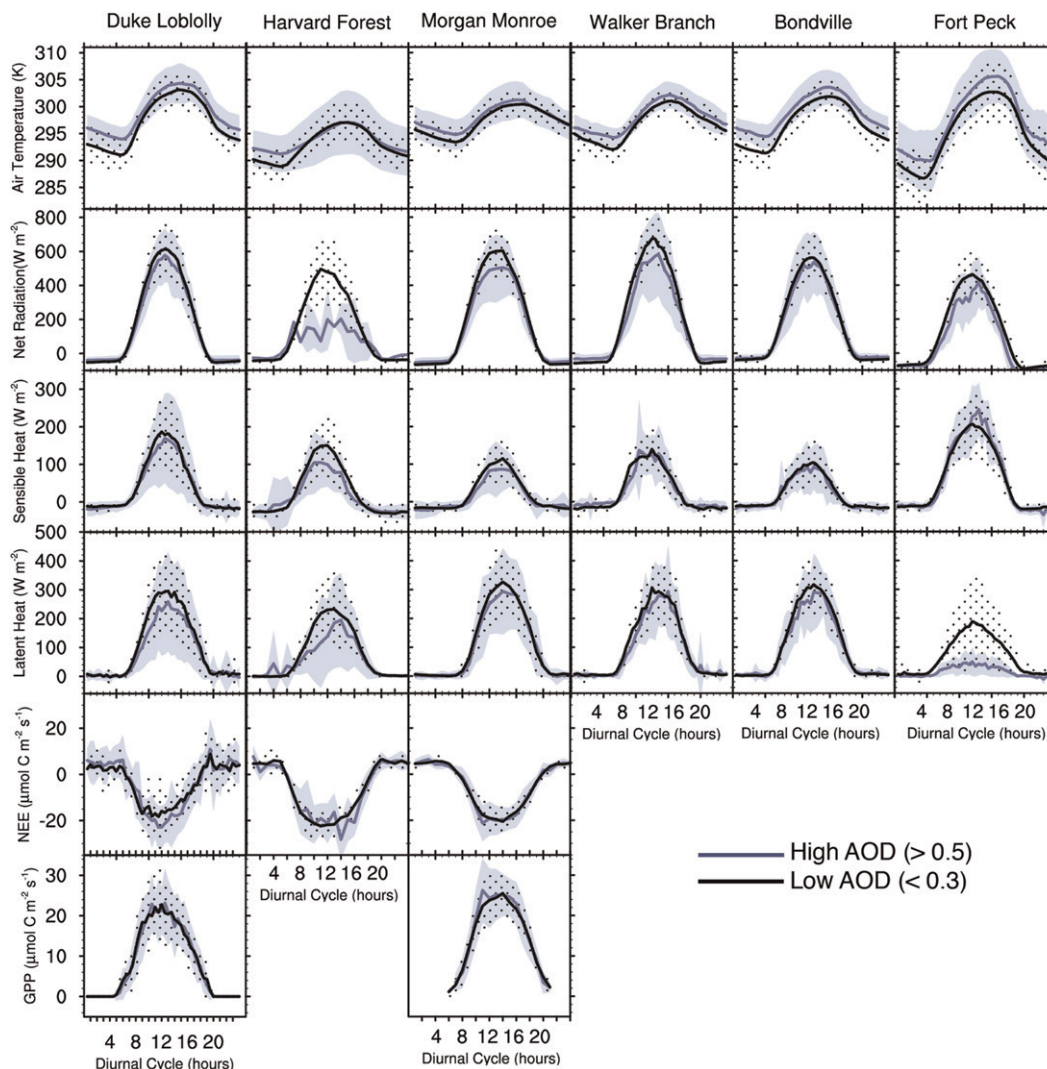


Figure 5. Diurnal cycle at six FLUXNET sites of hourly or half-hourly averaged air temperature (K), net radiation (W m^{-2}), sensible heat flux (W m^{-2}), and latent heat flux (W m^{-2}) binned by high AOD (AOD > 0.5; blue) and low AOD (AOD < 0.3; black). NEE ($\mu\text{mol C m}^{-2} \text{s}^{-1}$) and GPP ($\mu\text{mol C m}^{-2} \text{s}^{-1}$) are presented based on data availability. One standard deviation is displayed with blue shading for high AOD, and black stippling is displayed for low AOD.

atmosphere, it is more likely a result of summer stagnation events that are correlated with high AOD days, as they tend to accumulate aerosols, heat, and water vapor. This suggests overall warmer conditions during high AOD days and more heat stress on vegetation, but the overall percentage change in temperature is small (<1%). In accordance with midday R_n and PAR decreases of 9% on high AOD days relative to low days, H and λE are reduced by 12% and 20%, respectively, suggesting a slightly greater partitioning of R_n toward H . Generally, a decrease in

Table 2. Midday (1000–1400 LT) percentage change in surface energy budget and carbon flux variables between high AOD and low AOD days (e.g., positive values indicate that fluxes increase under high AOD while negative values indicate that fluxes decrease under high AOD). Statistically significant changes are in bold, based on a Student's *t* test at a 95% confidence level.

Variable	Duke Loblolly	Harvard Forest	Morgan–Monroe	Walker Branch	Bondville	Fort Peck ^a
% ΔT	0.4	–0.1	0.3	0.4	0.5	0.1
% ΔVPD	–0.9	–35.5	–13.2	–7.0	–0.02	7.0
% ΔR_n	–8.9	–65.5	–16.7	–13.4	–5.6	–16.0
% ΔPAR	–8.8	–14.1	–30.3	–6.3	–10.4	–6.2
% ΔH	–12.1	–31.6	–22.2	3.0	–9.0	9.9
% $\Delta \lambda E$	–20.0	–29.0	–10.7	–10.1	–9.0	–67.5
<i>B</i> , low AOD	0.61	0.59	0.35	0.47	0.31	1.21
<i>B</i> , high AOD	0.67	0.61	0.30	0.55	0.31	4.32
% ΔNEE	23.5	–0.5	4.5			
% ΔGPP	0.7	—	4.8			
% ΔLUE^b	10.4	—	50.3			
% ΔWUE^c	54.5	41.0	17.0			

^a Fort Peck values based on late summer (days of year 198–244) only.

^b LUE calculated as GPP/PAR.

^c WUE calculated as NEE/ λE .

VPD could reduce λE by weakening the water vapor gradient; however, the change in VPD is not large enough (<1%) to support this change nor is it statistically significant. While the overlap between standard deviations of both *H* and λE during high and low AOD conditions suggests that differences are small, the Student's *t* test does indicate that midday changes are statistically significant ($p < 0.05$). Average midday NEE and GPP increase 24% and <1%, respectively, under high AOD days, but only the NEE change is statistically significant. LUE [Equation (2)] increases 10% but the change is not statistically significant. The enhanced decrease in λE as compared to *H* suggests a lack of transpiration enhancement by increased diffuse light, despite an increase in NEE.

At Harvard Forest, a different surface flux signal is observed (Figure 5 and Table 2). Under high AOD, *T* is slightly lower during the day (less than 1-K change) and 2 K higher at night. Net radiation is reduced significantly at the site under the high AOD case by 66% and a 14% decrease in PAR; however, we note that the R_n has a large number of missing data during high AOD days (only 33% of the hourly data were available under high AOD conditions, as compared with 90% availability of *H* data and 60% availability of the λE data) and this likely drives the large percentage change in R_n . Average midday energy fluxes (*H* and λE) decrease approximately 30% on high AOD days as compared to low AOD days. A 36% decrease in VPD suggests a sufficiently large and statistically significant change that is likely a complementary factor in the reduction of λE . In contrast to Duke Loblolly, NEE decreases less than 1% under high AOD accompanied by a modest increase in WUE (41%), but these results are not statistically significant. Prior studies at Harvard Forest found enhanced LUE under high diffuse fractions based on single-year events (Gu et al. 2003), yet these occurred under enhanced GPP, which is unavailable for analysis here.

The Morgan–Monroe forest site experiences a different aerosol–energy budget relationship than the two forest sites presented above (Figure 5). Under high AOD,

T is higher than the low AOD case by 1–2 K and VPD decreases 13%. At midday, R_n decreases approximately 100 W m^{-2} (17%) with a greater decrease in PAR (30%). This corresponds with a statistically significant decrease in H (22%) and λE (11%). In contrast to other forest sites, H reductions are approximately 2 times greater than λE reductions.

Similar to Morgan–Monroe and Duke Loblolly, T at Walker Branch is higher (1–2 K) throughout the entire diurnal cycle on high aerosol days (Figure 5). Midday R_n decreases about 150 W m^{-2} (13%), H increases 3%, and λE decreases 10%. This is the only forest site that shows an increase in one of the surface fluxes, but this H increase is not statistically significant. Generally, the Walker Branch site shows some similarities to the Duke Forest site, including a modest decrease in R_n , similar T and VPD decreases, and smaller H reductions than λE .

At the Bondville cropland site, T increases by 1–3 K throughout the day under high AOD, R_n decreases by about 50 W m^{-2} (6%), and H and λE decrease during midday hours. Because of the high B typical of crop sites, λE has a larger absolute decrease ($\sim 100 \text{ W m}^{-2}$) than H ($\sim 50 \text{ W m}^{-2}$) with similar proportional decreases of 9%. As noted at Harvard Forest and Walker Branch, this suggests that there is no λE enhancement because of diffuse light. This could be attributed to the fact that croplands have a high fraction of sunlit canopy and a relatively lower LAI compared to forests. Thus, the overall reduction in R_n may outweigh the diffuse light effect on photosynthesis and transpiration, as noted in other modeling studies (Matsui et al. 2008).

At Fort Peck, a grassland site, aerosol loadings reduce T and increase VPD (Figure 5 and Table 2). Under high AOD, R_n decreases 16%, with a corresponding 50 W m^{-2} increase in H (9%; lasting over 2 h in the afternoon) and a 150 W m^{-2} decrease in λE (76%) during the day. The response of H and λE is markedly different from the other five sites, and the exceptionally large λE response and the site location suggest a seasonal response in the surface fluxes. The Fort Peck location in the western plains makes it susceptible to seasonal drought; therefore, the JJA analysis time period was grouped by early (days of year 152–197) and late (days of year 198–244) days of the season (Figure 6). All of the high AOD events occur in late summer (after day of year 198; Figure 2) and are likely due to biomass burning events in the western United States. The differences between early and late season low AOD days show an increase in daily maximum H from 180 to 220 W m^{-2} (20%) and a λE decrease from 250 to 125 W m^{-2} (–100%), clearly indicating seasonal changes in the surface energy fluxes. The large reduction in λE with time suggests that the midseason change is driven by soil moisture effects on energy partitioning rather than AOD loading, as this response is much larger than observed R_n reduction under high AOD. When analyzing the AOD driven changes in the late summer, R_n and PAR decrease about 6%, with a slight increase in H (6%) and a large decrease in λE (68%) (Table 2).

3.2. Surface heat fluxes versus AOD

The diurnal cycle analysis presented in section 3.1 provides one method of analyzing the role of aerosols on surface heat flux partitioning. However, the high standard deviations of the diurnal cycles and potential cloud-cover contamination

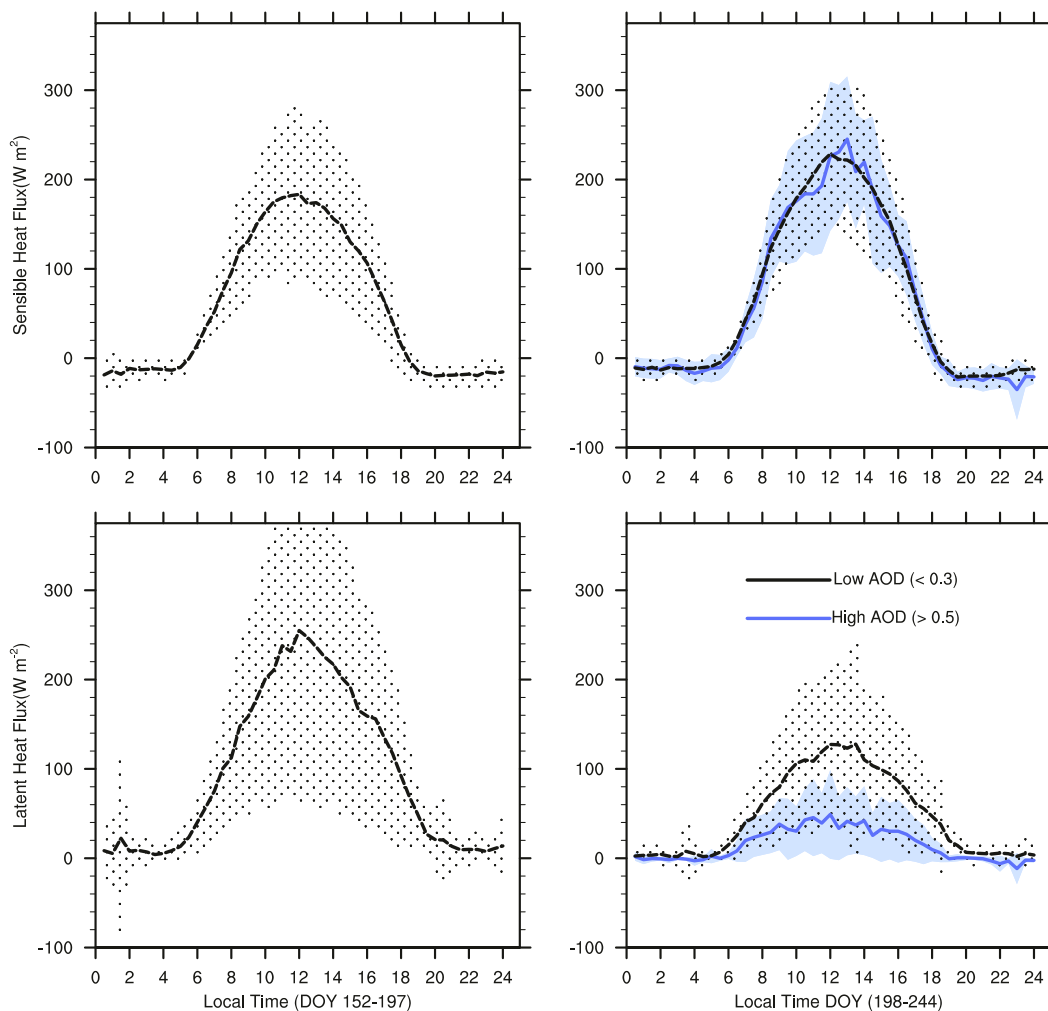


Figure 6. Average diurnal cycle of half-hourly averaged (top) sensible heat (W m^{-2}) and (bottom) latent heat (W m^{-2}) at Fort Peck, averaged for all days in (left) the first half of the summer (days of year 152–197) and (right) the second half of the summer (days of year 198–244).

can complicate interpretation of these figures. Therefore, correlations between H and λE fluxes in a half-hourly or hourly interval are matched directly with satellite AOD retrievals (Figure 7).

The four forest sites (Duke Loblolly, Harvard Forest, Morgan–Monroe, and Walker Branch) show a decrease in H with increasing AOD, with very low correlation coefficients (0.007–0.125). The cropland (Bondville) and grassland (Fort Peck) sites show a slight increase in H with increasing AOD, with near-zero correlation coefficients (0.001), suggesting that the positive relationship is negligible. Correlations in Figure 7 are generally consistent with the diurnal cycle analysis in Figure 5 and Table 2, which showed midday decreases in H at most but not all sites.

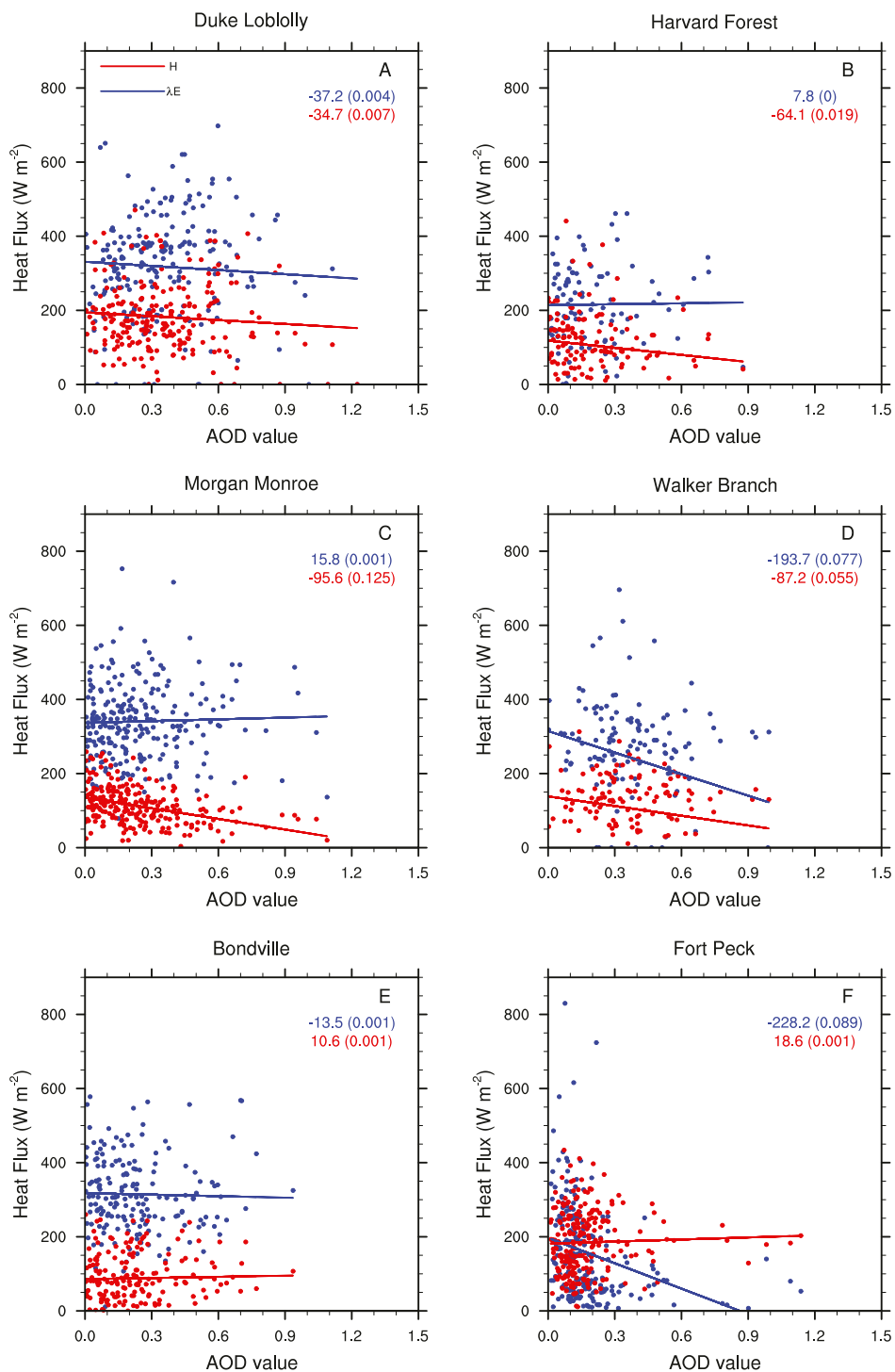


Figure 7. Relationship between sensible heat H ($W m^{-2}$; FLUXNET observation; red), latent heat λE ($W m^{-2}$; FLUXNET observation; blue), and MODIS AOD for all available years at the six sites. Points are selected based on available instantaneous MODIS AOD (typically 1000–1400 LT) and the corresponding half-hourly or hourly averaged FLUXNET data point. The linear regression slope (and R values) is included for each site.

The λE –AOD relationship is negative for four of the six sites, with the exception of Morgan–Monroe and Harvard Forest (Figure 7). However, at these two sites with positive relationships, the correlation coefficient is near zero (0.001 and 0, respectively), suggesting that any positive relationship between AOD and surface heat fluxes is weak and likely not robust. Fort Peck shows the strongest λE –AOD relationship, corresponding to the large difference in λE diurnal cycle between high and low AOD days (Figure 6). This is consistent with late season AOD events and a large shift in surface flux partitioning to H .

3.3. Bowen ratio versus AOD

We use a similar methodology to evaluate the relationship between AOD and B at the six sites (Figure 8). The Bowen ratio synthesizes the changes in energy partitioning at the surface of different ecosystems. Using average midday B values (Table 2), we group the sites into three categories: 1) low B sites (less than 0.35), Morgan–Monroe and Bondville; 2) moderate B sites (0.45–0.7), Walker Branch, Duke Loblolly, and Harvard Forest; and 3) high B sites (>1), Fort Peck. At the forested low B site of Morgan–Monroe, a decrease in B with increasing AOD is driven predominantly by a greater decrease in H than λE (Table 2). Morgan–Monroe is the only site of the six that shows a decrease in B based on midday averages (Table 2), indicating that this forested ecosystem may be responding differently to diffuse light created by the presence of aerosols. The Bondville site also indicates a slight decrease in B (Figure 8), although the individual signals from H and λE are mixed. For example, despite similar reductions in midday H and λE (Table 2), the correlations in Figure 7 show a mixed response in sign with increasing H fluxes and decreasing λE fluxes with increasing AOD. Additionally, Figure 8e shows an outlier data point where B has a value of approximately 10. If this point is removed, then the slope of the line becomes slightly positive (0.006) and the correlation goes to zero. This is further evidence of a lack of a robust response at the Bondville site.

Moderate B sites show weak and variable relationships between B and AOD (slopes of -0.08 , -0.28 , and 0.02 for Walker Branch, Harvard Forest, and Duke Loblolly, respectively). At Duke and Walker Branch, the decreases in λE are about twice that of H (Table 2 and Figure 7), which leads to an increase in B under high AOD. At Harvard Forest, decreases in λE are approximately equal to decreases in H , leading to only a slight decrease in B . At the high B site, Fort Peck, there is a strong signal of B increasing with AOD. We attribute this increase to seasonal moisture availability, late season biomass burning events, and the increasing role of H over λE in the surface energy budget. Overall, correlations for all six sites are extremely weak or nonexistent, with only four sites having R values greater than 0.1.

4. Discussion and conclusions

Past research has observed an increase in carbon storage and LUE as a result of atmospheric aerosols (Gu et al. 2003; Niyogi et al. 2004), yet other studies have found that moderate aerosol loadings do not translate to an increase in LUE (Wang

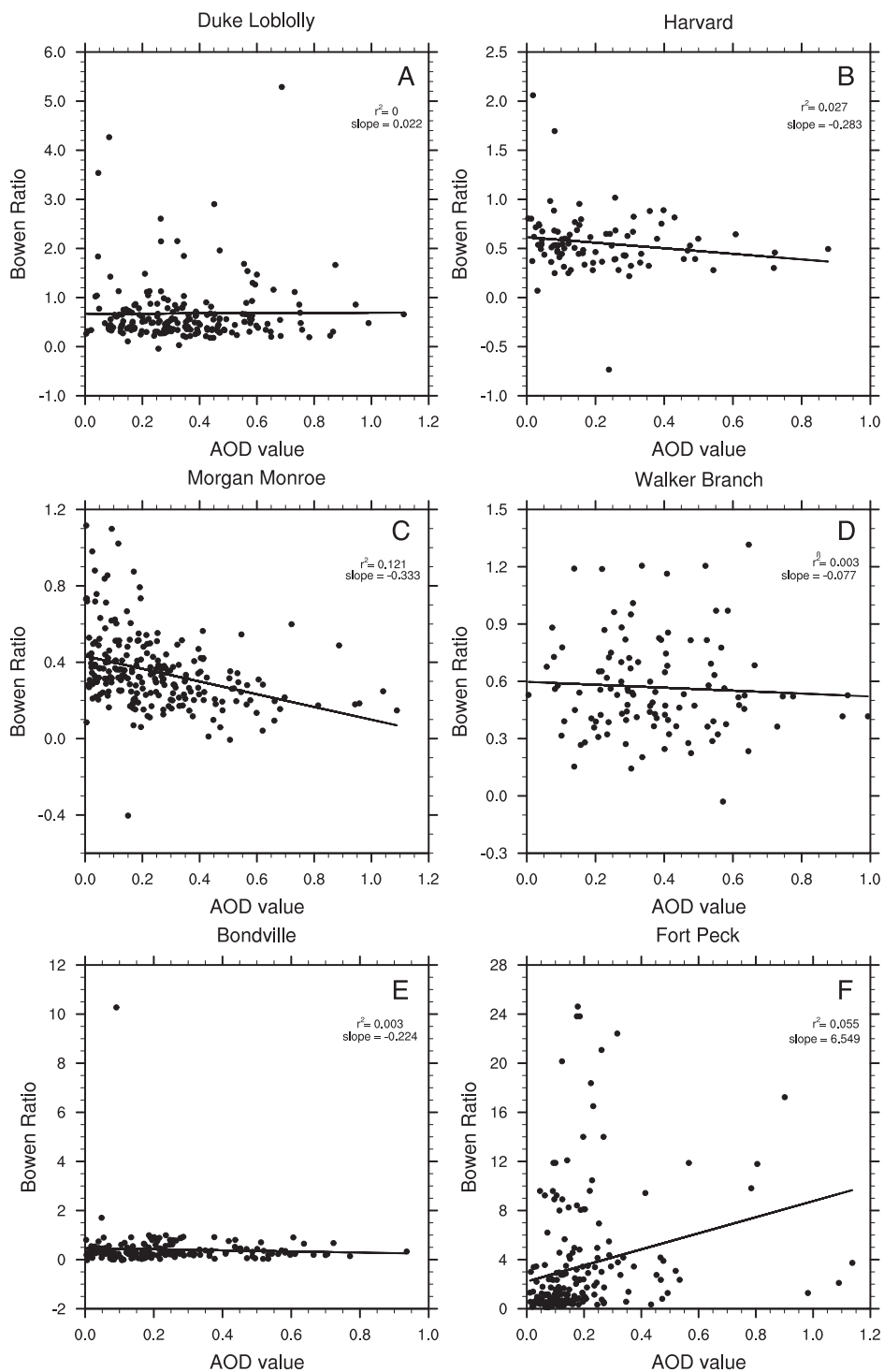


Figure 8. Relationship between Bowen ratio (B) and MODIS AOD for all available years at each site. Points are selected based on available instantaneous MODIS AOD (typically 1000–1400 LT) and the corresponding half-hourly or hourly averaged FLUXNET data point. The linear regression slope (and R values) is included for each site.

et al. 2008). Additionally, WUE has been noted to increase at some locations under diffuse sky conditions, yet the response has been observed to be ecosystem dependent (Rocha et al. 2004; Zhang et al. 2011). In this study, we use satellite-derived observations of AOD from MODIS and surface energy fluxes from six FLUXNET sites in the continental United States to examine the relationships between aerosol-driven light extinction and the surface energy budget. Our results indicate that aerosols decrease R_n by 6%–65%, and T is typically higher with aerosols likely due to stagnation associated with regional-scale high AOD events. Net radiation reductions translate to an overall decrease in midday H and λE at five of the six sites, including all forest sites and the cropland site. Excluding the grassland site that exhibits strong seasonal changes in aerosol loading and the surface energy budget, H and λE decrease by 10%–30% between low and high AOD days. None of these changes is outside of the range of high and low AOD standard deviation for averaged diurnal cycles, yet midday reductions in H at three of the forest sites (Duke, Harvard Forest, and Morgan–Monroe) are statistically significant and the λE reductions are statistically significant at all six sites. Overall, the results presented here are consistent with the hypothesis that aerosols reduce R_n , H , and λE by reducing R_n radiation and consequently reducing incoming surface energy, and we quantify these reductions in surface energy fluxes to be 10%–30% with variations likely driven by ecosystem-dependent factors.

A major finding of this study is that the partitioning of H and λE under moderate aerosol loadings varies between forest ecosystems. At Duke Forest and Walker Branch, λE reductions are about twice that of H , suggesting the absence of a coupled photosynthesis–transpiration response. At Harvard Forest, the H and λE reductions are similar in magnitude, and this is likely driven by relatively cooler temperature conditions and reduced VPD at the site under high AOD. Additionally, our results show that NEE at Harvard Forest shows only a small change (0.5%) on high AOD days, indicating that the enhanced diffuse light effect from aerosols does not systematically support increased carbon sequestration.

At the Morgan–Monroe forest site, H decreases about twice as much as λE under high AOD, leading to a decrease in B . However, analysis of individual points for Morgan–Monroe shows a weakly positive λE –AOD correlation (Figure 7c), which suggests a more nuanced response and potential increase in λE with higher AOD. Morgan–Monroe is consistent with modeling results that suggest a greater reduction in H in forested ecosystems because of an increase in shaded canopy photosynthesis, a decrease in stomatal resistance, and an increase in modeled transpiration rates (Matsui et al. 2008). This difference of partitioning at Morgan–Monroe compared to the other two forest sites suggests that there may be a transpiration and λE enhancement due to the increase in diffuse radiation under high aerosol loadings. We also note a 4%–5% increase in NEE and GPP during midday hours that cause a 50% increase of LUE. The carbon flux and λE response suggest that canopy height and crown distribution may play a role, which could affect shaded canopy photosynthesis. The subsequent coupled stomatal response may cause the different response in H and λE .

The lack of consistent response between the four forests suggests that there are likely multiple ecosystem characteristics that are influencing the surface energy budgets. Possible site-specific controls on λE , GPP, WUE, and LUE that are not included in this study include 1) soil characteristics such as soil texture, soil

moisture, and soil structure, which could affect the total λE fluxes; 2) precipitation differences (noted in Table 2), which would in turn affect soil moisture and λE ; 3) nutrient concentrations, such as leaf nitrogen concentration and soil nitrogen availability, which affect GPP and NEE; 4) forest structure, including canopy height, architecture, and layering complexity; and 5) species composition of the individual forests such as broadleaf versus conifer and species-specific traits such as drought-tolerant species. Because of the uncontrolled nature of FLUXNET observations, it is difficult to parse out other potential drivers in the energy budget partitioning in this study.

Questions remain about why the four forest sites presented here display variable responses to the changes in surface energy flux partitioning under high AOD conditions. Canopy architecture is frequently cited as one driver of differing responses to diffuse light (Niyogi et al. 2004). However, other studies have compared forest sites analyzed here (Curtis et al. 2002) and noted many similarities in stand characteristics (e.g., canopy height, basal area, maximum and mean diameter breast height) between Morgan–Monroe and Walker Branch. We note that Walker Branch has a higher average LAI compared to Morgan–Monroe (6.2 versus 4.9; Curtis et al. 2002), yet λE is about 10%–30% greater in Morgan–Monroe than other forest sites (Figure 5). Another possible explanation may be the ecosystem's surface flux partitioning. As noted in section 3.3, Morgan–Monroe has a lower B (0.3–0.4) than the two other forest sites (ranging from 0.48 to 0.6), and therefore smaller changes in H may elicit a more noticeable effect in the partitioning between H and λE .

Another confounding factor of our analysis is that the high AOD days are slightly warmer than low AOD days by up to 3 K at midday (<1% increase) in surface air temperature. This is likely reflective of the accumulation of particulate matter during stagnant conditions, which also leads to higher temperatures and reduced circulation. The surface flux response is dependent primarily on the response of vegetation to these higher temperatures. For example, if vegetation is not under stress, higher temperatures can enhance photosynthesis and transpiration and enhance latent heat fluxes. However, if the ecosystem is under moisture or temperature stress, photosynthesis and transpiration may be restricted, inducing a midday photosynthetic depression and the reduction of latent heat fluxes and increase in sensible heat fluxes. Therefore, the overall temperature response is closely tied to the ecosystem factors and surface flux partitioning as noted above, and untangling these effects warrants further investigation.

Many of the AOD–flux relationships described in this manuscript are subject to a number of uncertainties, including 1) the presence of clouds, 2) energy balance closure errors, and 3) the confounding factors of multiple variables that influence surface fluxes and the lack of control in the FLUXNET environment. For the impacts of other atmospheric phenomena such as clouds on diffuse light, the use of MODIS data provides a convenient screen for cloud-free conditions. However, the screening reduces the number of available MODIS retrievals over the past decade and likely drives the lack of statistical significance at some locations. Additionally, because of the nature of cloud cover, FLUXNET sites may have localized cloud cover that may not be observed at the broader MODIS pixel scale. This scale discrepancy can lead to large standard deviations in the surface energy budget components (e.g., Figure 5) and may contribute to the differences in the diurnal

cycle analysis (Figure 5 and Table 2) and the correlation analysis (Figures 7, 8). Because a high or low AOD day is determined by the single highest satellite AOD value during a specific day, portions of the diurnal cycle may be contaminated by clouds, contributing to relatively large standard deviations in radiation and flux measurements (Figure 5). Under lower light levels when clouds may influence the site, some locations show positive H –AOD (Bondville and Fort Peck) and λE –AOD (Morgan–Monroe and Bondville) relationships. It is unclear if this effect can be attributed to aerosols, and we note similar studies that have found increasing λE under cloudy conditions (Matsui et al. 2008; Zhang et al. 2011).

Finally, we note that uncertainty in H and λE from closure errors is within the range of reductions in energy budget terms under high AOD (Table 2). The impact of closure error on the correlations presented in Figures 7 and 8 is unclear but may not be relevant if errors are consistent at all values. Eddy covariance techniques are typically assumed to underestimate H and λE but should affect B equally; therefore, relationships of AOD with B (Figure 8) provide a normalized response to the energy balance error.

Despite these limitations, the results presented here show that moderate aerosol loadings (AOD = 0.5–1) cause a 10%–30% decrease in H and λE that varies by ecosystem. This suggests that treating the response of all mixed and broadleaf forests equally in models may lead to inaccurate estimates of energy fluxes under various aerosol loadings. Further modeling and observational studies of this effect and comparison with diffuse radiation measurements are required to confirm this result, particularly across multiple ecosystem types to improve our understanding of the role of vegetation type and structure on these biosphere–atmosphere feedbacks.

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References

- Alton, P. B., 2008: Reduced carbon sequestration in terrestrial ecosystems under overcast skies compared to clear skies. *Agric. For. Meteorol.*, **148**, 1641–1653.
- , P. North, J. Kaduk, and S. Los, 2005: Radiative transfer modeling of direct and diffuse sunlight in a Siberian pine forest. *J. Geophys. Res.*, **110**, D23209, doi:10.1029/2005JD006060.
- Andrews, E., and Coauthors, 2011: Climatology of aerosol radiative properties in the free troposphere. *Atmos. Res.*, **102**, 365–393.
- Baldocchi, D. D., 2008: ‘Breathing’ of the terrestrial biosphere: Lessons learned from a global network of carbon dioxide flux measurement systems. *Aust. J. Bot.*, **56**, 1–26.
- , and Coauthors, 2001: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bull. Amer. Meteor. Soc.*, **82**, 2415–2435.
- Barr, A. G., K. M. King, T. J. Gillespie, G. Denhartog, and H. H. Neumann, 1994: A comparison of Bowen ratio and eddy correlation sensible and latent heat flux measurements above deciduous forest. *Bound.-Layer Meteorol.*, **71**, 21–41.

- Bonan, G. B., 2008: Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, **320**, 1444–1449.
- Christopher, S., J. Chou, J. Zhang, X. Li, T. Berendes, and R. Welch, 2000: Shortwave direct radiative forcing of biomass burning aerosols estimated from VIRS and CERES. *Geophys. Res. Lett.*, **27**, 2197–2200.
- Cohan, D. S., J. Xu, R. Greenwald, M. H. Bergin, and W. L. Chameides, 2002: Impact of atmospheric aerosol light scattering and absorption on terrestrial net primary productivity. *Global Biogeochem. Cycles*, **16**, 1090, doi:10.1029/2001GB001441.
- Cox, P. M., and Coauthors, 2008: Increasing risk of Amazonian drought due to decreasing aerosol pollution. *Nature*, **453**, 212–217.
- Curtis, P. S., P. J. Hanson, P. Bolstad, C. Barford, J. C. Randolph, H. P. Schmid, and K. B. Wilson, 2002: Biometric and eddy-covariance based estimates of ecosystem carbon storage in five eastern North American deciduous forests. *Agric. For. Meteorol.*, **113**, 3–19.
- Ellsworth, D. S., R. Thomas, K. Y. Crous, S. Palmroth, E. Ward, C. Maier, E. DeLucia, and R. Oren, 2012: Elevated CO₂ affects photosynthetic responses in canopy pine and subcanopy deciduous trees over 10 years: A synthesis from Duke FACE. *Global Change Biol.*, **18**, 223–242.
- El Maayar, M. E., and O. Sonnentag, 2009: Crop model validation and sensitivity to climate change scenarios. *Climate Res.*, **39**, 47–59.
- Farquhar, G. D., and M. L. Roderick, 2003: Atmospheric science: Pinatubo, diffuse light, and the carbon cycle. *Science*, **299**, 1997–1998.
- Finnigan, J. J., R. Clement, Y. Malhi, R. Leuning, and H. A. Cleugh, 2003: A re-evaluation of long-term flux measurement techniques—Part I: Averaging and coordinate rotation. *Bound.-Layer Meteorol.*, **107**, 1–48.
- Foken, T., 2008: The energy balance closure problem: An overview. *Ecol. Appl.*, **18**, 1351–1367.
- Forster, P., and Coauthors, 2007: Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007: The Physical Science Basis*, S. Solomon et al., Eds., Cambridge University Press, 129–234.
- Franssen, H. J. H., R. Stockli, I. Lehner, E. Rotenberg, and S. I. Seneviratne, 2010: Energy balance closure of eddy-covariance data: A multisite analysis for European FLUXNET stations. *Agric. For. Meteorol.*, **150**, 1553–1567.
- Gu, L. H., D. D. Baldocchi, S. C. Wofsy, J. W. Munger, J. J. Michalsky, S. P. Urbanski, and T. A. Boden, 2003: Response of a deciduous forest to the Mount Pinatubo eruption: Enhanced photosynthesis. *Science*, **299**, 2035–2038.
- Hansen, J., M. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res.*, **102**, 6831–6864.
- Holben, B. N., and Coauthors, 1998: AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sens. Environ.*, **66**, 1–16.
- Hollinger, D. Y., and Coauthors, 2010: Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration. *Global Change Biol.*, **16**, 696–710.
- Huang, Y., W. L. Chameides, and R. E. Dickinson, 2007: Direct and indirect effects of anthropogenic aerosols on regional precipitation over east Asia. *J. Geophys. Res.*, **112**, D03212, doi:10.1029/2006JD007114.
- Hui, D., S. Wan, B. Su, G. Katul, R. Monson, and Y. Luo, 2004: Gap-filled missing data in eddy covariance measurements using multiple imputation (MI) for annual estimations. *Agric. For. Meteorol.*, **121**, 93–111.
- Jaeger, E. B., R. Stockli, and S. I. Seneviratne, 2009: Analysis of planetary boundary layer fluxes and land-atmosphere coupling in the regional climate model CLM. *J. Geophys. Res.*, **114**, D17106, doi:10.1029/2008JD011658.
- Kaufman, Y. J., D. Tanre, and O. Boucher, 2002: A satellite view of aerosols in the climate system. *Nature*, **419**, 215–223.
- Knohl, A., and D. D. Baldocchi, 2008: Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. *J. Geophys. Res.*, **113**, G02023, doi:10.1029/2007JG000663.

- Kondo, F., and O. Tsukamoto, 2008: Evaluation of Webb correction on CO₂ flux by eddy covariance technique using open-path gas analyzer over asphalt surface. *J. Agric. Meteor.*, **64**, 1–8.
- Krakauer, N. Y., and J. T. Randerson, 2003: Do volcanic eruptions enhance or diminish net primary production? Evidence from tree rings. *Global Biogeochem. Cycles*, **17**, 1118, doi:10.1029/2003GB002076.
- Leuning, R., and K. M. King, 1992: Comparison of eddy-covariance measurements of CO₂ fluxes by open-path and closed-path CO₂ analyzers. *Bound.-Layer Meteor.*, **59**, 297–311.
- , E. van Gorsel, W. J. Massman, and P. R. Isaac, 2012: Reflections on the surface energy imbalance problem. *Agric. For. Meteor.*, **156**, 65–74.
- Levy, R. C., L. A. Remer, S. Matoo, E. F. Vermote, and Y. J. Kaufman, 2007: Second generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance. *J. Geophys. Res.*, **112**, D13211, doi:10.1029/2006JD007811.
- Li, B., H. Yuan, N. Feng, and S. Tao, 2009: Comparing MODIS and AERONET aerosol optical depth over China. *Int. J. Remote Sens.*, **30**, 6519–6529.
- Liepert, B., and I. Tegen, 2002: Multidecadal solar radiation trends in the United States and Germany and direct tropospheric aerosol forcing. *J. Geophys. Res.*, **107**, doi:10.1029/2001JD000760.
- Matsui, T., A. Beltran-Przekurat, D. Niyogi, R. A. Pielke, and M. Coughenour, 2008: Aerosol light scattering effect on terrestrial plant productivity and energy fluxes over the eastern United States. *J. Geophys. Res.*, **113**, D14S14, doi:10.1029/2007JD009658.
- Mercado, L. M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, and P. M. Cox, 2009: Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, **458**, 1014–1087.
- Miller, G. R., D. D. Baldocchi, B. E. Law, and T. Meyers, 2007: An analysis of soil moisture dynamics using multi-year data from a network of micrometeorological observation sites. *Adv. Water Resour.*, **30**, 1065–1081.
- Misson, L., M. Lunden, M. McKay, and A. H. Goldstein, 2005: Atmospheric aerosol light scattering and surface wetness influence the diurnal pattern of net ecosystem exchange in a semi-arid ponderosa pine plantation. *Agric. For. Meteor.*, **129**, 69–83.
- Monson, R. K., A. A. Turnipseed, J. P. Sparks, P. C. Harley, L. E. Scott-Denton, K. Sparks, and T. E. Huxman, 2002: Carbon sequestration in a high-elevation, subalpine forest. *Global Change Biol.*, **8**, 459–478.
- Niyogi, D., and Coauthors, 2004: Direct observations of the effects of aerosol loading on net ecosystem CO₂ exchanges over different landscapes. *Geophys. Res. Lett.*, **31**, L20506, doi:10.1029/2004GL020915.
- Oliphant, A. J., and Coauthors, 2004: Heat storage and energy balance fluxes for a temperate deciduous forest. *Agric. For. Meteor.*, **126**, 185–201.
- , D. Dragoni, B. Deng, C. S. B. Grimmond, H. P. Schmid, and S. L. Scott, 2011: The role of sky conditions on gross primary production in a mixed deciduous forest. *Agric. For. Meteor.*, **151**, 781–791.
- Oncley, S. P., and Coauthors, 2007: The Energy Balance Experiment EBEX-2000. Part I: Overview and energy balance. *Bound.-Layer Meteor.*, **123**, 1–28.
- Péré, J. C., M. Mallet, V. Pont, and B. Bessagnet, 2011: Impact of aerosol direct radiative forcing on the radiative budget, surface heat fluxes, and atmospheric dynamics during the heat wave of summer 2003 over Western Europe: A modeling study. *J. Geophys. Res.*, **116**, D23119, doi:10.1029/2011JD016240.
- Remer, L. A., and Coauthors, 2005: The MODIS aerosol algorithm, products, and validation. *J. Atmos. Sci.*, **62**, 947–973.
- Rocha, A. V., H.-B. Su, C. S. Vogel, H. P. Schmid, and P. S. Curtis, 2004: Photosynthetic and water use efficiency responses to diffuse radiation by an aspen-dominated northern hardwood forest. *For. Sci.*, **50**, 793–801.

- Roderick, M. L., G. D. Farquhar, S. L. Berry, and I. R. Noble, 2001: On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation. *Oecologia*, **129**, 21–30.
- Schwartz, S. E., 1996: The Whitehouse effect—Shortwave radiative forcing of climate by anthropogenic aerosols: An overview. *J. Aerosol Sci.*, **27**, 359–382.
- Steiner, A., and W. Chameides, 2005: Aerosol-induced thermal effects increase modelled terrestrial photosynthesis and transpiration. *Tellus*, **57B**, 404–411.
- Stoy, P. C., and Coauthors, 2006: Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US. *Global Change Biol.*, **12**, 2115–2135.
- Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology*. Springer, 666 pp.
- Thompson, S. E., C. J. Harman, A. G. Konings, M. Sivapalan, A. Neal, and P. A. Troch, 2011: Comparative hydrology across AmeriFlux sites: The variable roles of climate, vegetation, and groundwater. *Water Resour. Res.*, **47**, W00J07, doi:10.1029/2010WR009797.
- Trenberth, K. E., J. T. Fasullo, and J. Kiehl, 2009: Earth’s global energy budget. *Bull. Amer. Meteor. Soc.*, **90**, 311–323.
- Twine, T. E., and Coauthors, 2000: Correcting eddy-covariance flux underestimates over a grassland. *Agric. For. Meteorol.*, **103**, 279–300.
- Urban, O., and Coauthors, 2012: Impact of clear and cloudy sky conditions on the vertical distribution of photosynthetic CO₂ uptake within a spruce canopy. *Funct. Ecol.*, **26**, 46–55.
- Wang, J., and S. Christopher, 2006: Mesoscale modeling of Central American smoke transport to the United States: 2. Smoke radiative impact on regional surface energy budget and boundary layer evolution. *J. Geophys. Res.*, **111**, D14S92, doi:10.1029/2005JD006720.
- Wang, K. C., R. E. Dickinson, and S. L. Liang, 2008: Observational evidence on the effects of clouds and aerosols on net ecosystem exchange and evapotranspiration. *Geophys. Res. Lett.*, **35**, L10401, doi:10.1029/2008GL034167.
- Wilson, K. B., and Coauthors, 2002: Energy partitioning between latent and sensible heat flux during the warm season at FLUXNET sites. *Water Resour. Res.*, **38**, 1294, doi:10.1029/2001WR000989.
- Zhang, M., and Coauthors, 2011: Effects of cloudiness change on net ecosystem exchange, light use efficiency, and water use efficiency in typical ecosystems of China. *Agric. For. Meteorol.*, **151**, 803–816.
- Zhang, Y., R. Fu, H. Yu, R. E. Dickinson, R. N. Juarez, M. Chin, and H. Wang, 2008: A regional climate model study of how biomass burning aerosol impacts land-atmosphere interactions over the Amazon. *J. Geophys. Res.*, **113**, D14S15, doi:10.1029/2007JD009449.
- , X. Y. Wen, and C. J. Jang, 2010: Simulating chemistry–aerosol–cloud–radiation–climate feedbacks over the continental U.S. using the online-coupled Weather Research Forecasting Model with chemistry (WRF/Chem). *Atmos. Environ.*, **44**, 3568–3582.