Abstract

CHANG, HSIN-I. Observations of the effects of aerosol loading on carbon and water cycles over various landscapes under the direction of Dr. Dev Niyogi and Dr. Vin Saxena.

I present multi-site observational evidence that atmosphere aerosols affect regional terrestrial carbon and water cycle. Past studies have indicated that increase in diffuse irradiance due to cloudiness and aerosols could increase net ecosystem exchanges. Though the effect of clouds on terrestrial CO_2 and LHF exchanges have been reported, there have been no field scale, direct observations relating aerosol loading and CO_2 /LHF fluxes. We present first direct observations in support of the hypothesis that atmospheric aerosols affect the regional terrestrial carbon cycle. Observations from six CO_2 flux and latent heat flux monitoring sites (forest, grasslands, and croplands) with collocated aerosol and surface radiation measurements were analyzed. The daytime (10AM to 4PM) growing season (summer, June to August) CO_2 flux observations were subject to three clustering: (1) high and low diffuse radiation fraction (DRF) of the global radiation; (2) DRF changes with and without cloud cover; and (3) high DRF, no-cloud cover regimes for high and low aerosol optical depths (AOD). Results suggest that, aerosols exert a significant impact on potentially increasing the CO_2 fluxes, and their effect may be even more advantageous than that due to clouds (which reduced the total radiation). For the data analyzed, the response of increasing aerosol loading on landscape CO_2 fluxes,

appears to be a general feature irrespective of the landscape (forest, crops, or grasslands) and photosynthesis pathway (C3 or C4). The CO_2 sink increased with aerosol loading for forest and crop lands, and decreased for grassland. The slope of the AOD - CO_2 flux correlation however, was wavelength dependent and appeared to affect the woody trees more than the crops or grasslands. The analysis of the direct field measurements indicate; aerosol loading could play a significant role in the variability of the regional terrestrial carbon exchange by altering the amount of diffuse solar radiation.

As for water cycle, we examined latent heat flux (LHF) using the same time periods and locations. But instead of analyzing DRF and CO2 correlation, we were more focus on (1) heat fluxes and aerosol-loading correlation; (2) whether leaf area would affect the heat fluxes during aerosol loading; (3) soil moisture effect and (4) air temperature effect on the heat fluxes. Results indicate: (1) for corn, soybean croplands and forest sites, aerosol loadings had little impact on latent heat fluxes, but it had more impact in winter wheat and grassland sites; (2) after accounting for the leaf area index (LAI), our analysis results showed that aerosol loading had more significant impact in the heat fluxes for agriculture sites, where there were still no obvious trend for forest sites; (3) for agricultural site, latent heating tend to be affected more under low LAI condition; (4) grassland sites are more sensitive to soil moisture changes than agricultural sites; (5) agricultural sites have more obvious heat flux changes when air temperature changes than grassland site.

Observations of The Effects of Aerosol Loading on Carbon and Water

Cycles Over Various Landscapes

by

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Biography

Hsin-I Chang was born on May 22nd, 1977, in Chia-Yi, Taiwan, the first of the two children of Ta-Li Chang and Yu-Hua Tzen. I lived in the southern part of Taiwan until my college years; I went to Taipei to enroll Chinese Culture University majoring Atmospheric Sciences. Since growing up in the country side with grandfather as a farmer and always be amazed by the atmospheric activities, studying meteorology was not a tough decision. After graduated from college, I decided to continue my graduate study in United States. Not only because there have more options and opportunities in the U.S., but being a Chinese living in a small island at the Pacific Ocean to experience a totally different culture and maybe I could learn some of the greatness of this country. Initially, I was enrolled in the Atmospheric Science program in University of Missouri-Columbia in 2001. After a year of study, due to the change of my interest from forecasting to air quality, I decided to transfer to North Carolina State University. Because this research result is mainly based on the observed data, I'd like to focus on model simulation for my future work. By developing a land surface- atmospheric model and compare with the observed data results, to assimilate the air-land interaction.

Acknowledgment

I'd like to thank my Graduate Advisory Committee members Dr. Dev Niyogi and Dr. V.K. Saxena (Co-Chairs) and Dr. Fredrick Semazzi, without your guidance, I could never finish this paper.

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Chapter 1. Introduction

Regional climate change could be affected by various factors; it would due to natural or anthropogenic activities. Solar irradiance is the most important source for the Earth's energy exchanges. It affects weather and climate changes, and all living creatures on the planet. Global radiation could be divided into direct and diffuse radiation. Direct radiation comes directly from the sun. But there are various sources of diffuse radiation; it could be radiations that diffused by clouds, aerosols, water, or Earth's surface, etc. The changes in diffuse radiation fraction (DFR) could affect energy fluxes exchanges in carbon and water cycles and then affect the plant productivity.

1.1 Factors affect net ecosystem and water exchanges:

(1) Radiation/cloudiness:

When incoming solar radiation reaches the plant leaves, it creates shadows at the surface. One can describe these shadows in terms of the volumes of umbra (full shade), sunflecks (full sun) and penumbra (part sun- part shade). During cloudy days, the irradiances are mostly diffuse and there are only very small volumes of shade within canopies. During sunny days, because solar radiation mostly comes from a single direction, the length of the umbra is much longer under each leaf. It is hard to estimate the volume of penumbra on sunny days because penumbra is mostly depends on the spatial arrangement of the leaves. More than an order of magnitude reduces the volume of shaded area within vegetation canopies during cloudy days compare to sunny days because of the increase in diffuse fraction of the solar radiation at cloudy days. With this increase in diffuse fraction, there will have more efficient canopy photosynthesis and have more CO_2 uptake. Therefore, one can say that clouds and other atmospheric parcels have important direct effects on vegetation productivity due to changes in the diffuse radiation, which may come from variations in cloudiness and aerosol concentrations, lead to large changes in the volume of shaded area within vegetation (Roderick et al. 2001). Light responses of sunlit and shaded leaves are distinctively different with each other and usually there are a lot more amount of shaded area than sunlit area within a plant. Stanhill et al. 2001 indicated that photon flux densities are 30% less at high light intensity then at low light intensity. Plants would be insensitive to CO_2 flux changes under high light intensity- less photosynthesis when there has more sunlight. Light response for sunlit leaves saturates quickly with increasing sunlight, and with increasing radiation, photosynthesis will decrease because of increasing air temperature and enhanced respiration. Stoma will be closed to prevent losing moisture within the plant. On the contrary, plants tend to have more photosynthesis under low light intensity condition and any decrease in solar radiation may be expected to decrease plant productivity.

(2) Aerosol Optical Depth (AOD):

But it is difficult to define whether the low light intensity condition is due to clouds or aerosol concentrations. In order to eliminate could effects, I used Aerosol Optical Depth (AOD) to indicate of aerosol loading. Usually, AOD data would only be collected during no cloud/sunny conditions. AOD is the vertical integral of aerosol concentration weighted with the effective cross-sectional area of the particles intercepting the solar radiation (by scattering and absorbing) at multiple wavelengths (300nm, 430nm, 500nm, 670nm, 870nm and 1020nm). The lifetime of aerosols is very short, about a week or less, compare to green house gases. Therefore, to study the impact of aerosols, one needs to gather the data during the peak aerosol concentration near the source. Aerosols may come from natural and anthropogenic sources. The anthropogenic aerosol sources are almost as much as natural sources. The change of longwave outgoing radiation (Top Of Atmosphere radiative forcing) due to increases of green house gases is about 2.4 W/m^2, where change due to aerosol loadings is about –0.5 to –2.5 W/m^2 (negative sign indicates a cooling effect). Carbonaceous aerosols (Black Carbon and organics) absorb and scatter solar radiation, and even a trace amount of BC could result in large atmosphere solar absorption, which reduces the solar radiation reaching the surface. BC also absorbs outgoing solar radiation and reduces radiations reflected to the space; this could cause a positive TOA radiative forcing. All aerosols have cooling effects at Earth's surface (reduce solar radiation reaches the surface); at the TOA, BC will have warming effects by absorbing solar radiation, where sulfates and organics have cooling effects. Results indicate that global temperature changes are mostly determined by TOA forcing. And the warming effects due to GHG exceed the cooling due to aerosols, and vise versa (Ramanthan et al. 2001). Earlier model researches tend to overestimate global warming, which did not include negative shortwave radiative forcing (Stanhill et al. 2001). Further studies in the indirect effects of aerosols may improve this overestimating result.

(3) Leaf area:

This research is focused on aerosol effects on carbon and water cycles through different canopies. I used multiple sites with various vegetations including hardwood forests, corn, soybean and grasslands (detailed site descriptions in Chapter 2). Carbon and water cycles are very sensitive to radiations. Because of various vegetation canopies, leaf area factor needs to be considered. Leaf area is an important factor that needed to model the radiation regime and to compute the energy exchange between ground canopy and the atmosphere. The more leaves that intercept light, the greater the potential for carbon assimilation and water vapor transfer. Leaves intercepting lights may become a source or sink for carbon, water vapor or energy exchange between ground canopy and the atmosphere through stomatal conductance (photosynthesis, respiration and transpiration). But these relations are nonlinear. Law et al. 2001b evaluated LAI data collecting methods in an open-canopy ponderosa pine site. At low LAI, canopies are mostly sunlit, so that redistribution of light has little effect on net photosynthesis, whereas the effect on net photosynthesis is much greater at high LAI (Law et al. 2001a). Many of the previous studies were focused on single type of vegetation (Hollinger et al.1999- boreal forest; Law et al. 2000- ponderosa pine) to study the observed CO2 and water cycles. In this paper, I tried to compare the net ecosystem exchanges and water exchanges in various ground vegetations (hardwood forests, agricultural crops and grasslands).

(4) Leaf age:

Anthoni et al. 2002 compared the energy fluxes differences for both young and old growth pines. During early growth, trees partition more assimilate into foliage than into stems (Law et al. 2001a). This creates a hydraulic system that is vulnerable to water stress. As the trees reach maturity, roots extend deeper and access more water, the water storage capacity in stems increases to provide a buffer against short-term water stress, and stomatal conductance decreases. Results found that the young site experienced more water stress, and lead to a significant reduction in transpiration. Wilson et al. 2001 used a biophysical model (CANOAK) to assimilate the seasonal changes in net ecosystem exchange in carbon (NEE) and photosynthesis due to leaf age. In general, carbon fluxes intake increased at the beginning of the growing season and started to decrease after the peak-growing season. CANOAK model has a tendency to overestimate NEE compared to the observed CO_2 intake.

(5) Soil moisture and air temperature:

Energy fluxes, especially latent heat and sensible heat fluxes, determine the water vapor and heat content of the atmosphere and may affect regional and global scale climatological processes. This energy partitioning (evapotranspiration) determines the vegetation growth rate, long-range transport of heat, humidity and pollutants, and properties of the planetary boundary layer. It also affects streamflow, nutrient loss, soil moisture content and forest productivity. Evapotranspiration is a combination of evaporation and transpiration. Evaporation is the process when liquid water changes to a gaseous stage, which occurs from water surfaces, raindrops and moisture in the soil and vegetations. Evaporation could be affected by air temperature, solar radiation, wind and pressure. Transpiration occurs when water vapor transfers from the vegetation to the atmosphere through the leaf openings- stomata, which could be found at the under side of the leaves. The transpiration rate varies with different kind of vegetation, solar radiation, temperature, relative humidity, winds, soil moisture and time of the year. When there is more shaded area under a plant, here will be more moisture transfer in transpiration and less in evaporation than bare ground soil. With the beginning of growing season (start of leaf expansion), moisture content starts to decrease in temperate broadleaved forests (also in southern boreal aspen stand, deciduous forests, but less dramatic in Japanese grassland)

and increase in the late summer. Latent heat flux started to decrease during mid and late summer with the increase of soil moisture (Wilson e al. 2000).

1.2 Relations between aerosols and carbon cycle:

The effects of aerosols on regional climate have largely concerned the warming or cooling potential of the earth's surface (IPCC 2001). In this research, I am trying to seek the importance of aerosol feedback on regional climate via the biogeochemical pathways by affecting the terrestrial carbon cycle.

About half of all CO2 emitted by fossil fuel combustion is absorbed by the terrestrial and marine ecosystems (IPCC 2001). Photosynthesis continues to be a major terrestrial process that removes large amounts of CO2 from the atmosphere. Global gross primary production or photosynthesis on land fixes about 20 times more carbon than is released by fossil fuel combustion (120 Pg Cyr^{-1} through gross assimilation and 54.6 Pg Cyr^{-1} through net assimilation (Field 2001)). Net global terrestrial carbon exchange was nearly neutral in the 1980's, but resulted in a net carbon sink in the 1990's (Schimel et al. 2001). The contributing factors behind this increase in terrestrial carbon storage and the potential of the terrestrial biosphere as a carbon sink in the future still remains uncertain.

It is therefore becoming increasingly important to understand the physical processes that contribute to the uncertainty and variability of the terrestrial carbon exchanges. CO_2

fertilization, land cover/ land use change, nitrogen loading, forest fires, and regional hydrological cycle are some of the known factors affecting the carbon cycle (Nemani et al. 2002). Recently, Gu et al. 2003 and Farquhar and Roderick 2003 conclude that aerosols released in the atmosphere due to volcanic eruptions could also affect the terrestrial carbon cycle through enhanced photosynthesis. Given that though the past studies cite significant geological events such volcano as the cause for variability in the carbon cycle, and that the mechanisms causing the increased photosynthesis rate are modulated by aerosol loading that are available abundantly in the atmosphere, we ask the question: can we detect the effect of relatively routine aerosol variability on field measurements of CO_2 fluxes, and if so, how does the variability in aerosol loading affect the changes in CO_2 fluxes over different landscapes? That is, we seek to investigate using direct field measurements, whether routine (typically order of week) changes in the atmospheric aerosol loading can significantly contribute to the CO_2 flux variability; and whether the responses are similar over different landscapes such as woody forests, and agricultural or grasslands.

1.3 Relations between aerosols and hydrological cycle:

At the past 50 years, Earth surface temperature has increased about 0.15 degrees per decade. With the increase of surface temperature, it is expected that the evaporation rate from terrestrial open water bodies would also increase. But on the contrary, observations show that the evaporation rate decreases steadily at the past 50 years. This decreasing trend is due to the decrease in solar irradiance and the associated changes in diurnal temperature range (DTR) (Roderick et al. 2002; Cohen et al. 2002). In the hydrological cycle, the warming effects due to green house gases could lead to an increase in global precipitation. On the other hand, because aerosols could prevent large amount of solar irradiances reach to the surface by producing brighter clouds, these brighter clouds may produce less precipitation. At Earth's surface, about 60 to 70% of the absorbed solar radiation is balanced by evaporation. Therefore, there may have major fraction of reduction of surface solar radiation is balanced by reduced evaporation. This would lead to a weaker hydrologic cycle. More studies showed that this reduction of hydrologic cycle due to aerosol loadings is large enough to reverse the increasing precipitation due to green house gases.

In this research, I use latent heat flux (LHF) representing the water cycle exchanges between vegetation canopies and the atmosphere. Our hypotheses are (1) Heat fluxes decrease with aerosol loading due to decreasing solar irradiance. (2) Under high LAI condition: LHF increase with AOD. Increasing aerosols would increase diffuse radiation and decrease air temperature; this would cause the increase of transpiration rate and increase the heat fluxes, when transpiration changes are mostly due to radiation changes.

(3) Under low LAI condition: LHF decrease with AOD. With increase of diffuse radiation and decrease of air temperature, it would decrease the evaporation rate and decrease the heat fluxes, because evaporation rate varies with temperature.

Chapter 2 Data and Methodology

2.1 Site description:

We used continuous CO_2 flux and latent heat flux field measurements as part of the AmeriFlux network (Baldocchi et al., 2001), and NASA Aerosol Robotic Network or the AERONET (Holben et al., 2001) aerosol optical depth (AOD) data for assessing the effect of aerosol loading on terrestrial carbon exchange. Six locations could be identified which had concurrent CO_2 flux and AOD observations. The landscapes range from broadleaf eastern deciduous forest (Walker Branch (TN)), mixed forest (Willow Creek/ Lost Creek (WI)), agricultural crops (winter wheat: Ponca (OK); alternate soybean or corn: Bondville (IL)) and grassland (Barrow (AK) and Shidler (AK)). Detailed site descriptions are listed below:

(1) Bondville (IL): Latitude: 40° 0.366' N, Longitude: 88° 17.512' W. Vegetation type: Annual rotation between Corn (C4) and Soybeans (C3) (Corn years-1999 and 2001; Soybean years-1998, 2000, 2002). Available: 1998-2001.

(2) Walker Branch (TN): Latitude: 35° 57' 31.56" N, Longitude: 84° 17' 14.76" W. Vegetation type: Mixed-species, broad-leaved forest, deciduous forest. Available: 2000.

(3) Willow Creek (WI): Latitude: 45° 48' 21.336" N, Longitude: 90° 04' 47.493" W. Vegetation type: Temperate/Boreal forest, lowland and wetland forest, upland hardwoods. Available: 1999-2001.

(4) Lost Creek (WI): Latitude: 46° 4' 57.648" N, Longitude: 89° 58' 45.084" W. Vegetation type: Alder-willow wetland. Available: 2001.

(5) Park Falls/WLEF: Latitude: 45° 56' 45.16" N, Longitude: 90° 16' 20.295" W. Vegetation type: Mixed evergreen and deciduous forests, boreal, lowland and wetland forest, temperate/boreal forests. Only CO2 flux available in 1999-2001 and no LHF data available.

(6) Ponca City (OK): Latitude: 36° 46' N, Longitude: 97° 08' W. Vegetation type: Winter wheat (C3), crops, grasslands. During our research period (June-August 2000), the ground cover was winter wheat. Available: 1999.

(7) Shidler (OK): Latitude: 36° 56' N, Longitude: 96° 41' W. Vegetation type: Native tall grass prairie, almost all plants are warm season C4 species, grasslands. Available: 1999.

(8) Barrow (AK): Latitude: 71° 19' 21. 09" N, Longitude: 156° 37' 33.17" W. Vegetation type: Arctic tundra. Available: 1999.

2.2 Data description:

At all the study sites, CO_2 fluxes were measured using eddy covariance technique and reduced to 30-minute averages, so were latent heat fluxes. Used data (CO2 flux, LHF, air temperature and soil moisture) were converted from 30-mintues to daily averaged values, taking the time period from 10am to 4pm. AOD observations were made using a robotic multispectral radiometer. Measurements were taken at variable intervals from 0700 to 1900 local time and daily averaged. As part of the AERONET analysis, attenuation due to Rayleigh scattering, and absorption by ozone and other gaseous pollutants are removed to obtain aerosol optical depths. The AOD measurements were available for cloud free conditions since they are cloud screened by analyzing a sequence of three sets of measurements taken 30 seconds apart as described in Holben et al. 2001. In addition to the CO_2, LHF and AOD data, radiation observations were obtained from Integrated Surface Irradiance Study (ISIS) / Surface Radiation Budget Network (SURFRAD) (Hicks et al., 1996). Global irradiance and diffuse radiation observations (1-second scans, averaged over 30 minutes) were obtained from a Precision Spectral Pyranometer (PSP) and shadow band with a spectral range of 280 to 3000 nm (Hicks et al., 1996).

All data were compiled and checked for consistency and quality assured by graphical and statistical means. Periods for which CO2 flux, latent heat flux or AOD measurements were missing were eliminated from further analysis. Additionally, to obtain data that would correspond to the growing season, as well as peak photosynthetic activity and capacity of the canopy, daytime observations for period corresponding from June through August were selected for this study.

The data analysis for CO_2 flux was performed following a flowchart as shown in Figure 2.1.1. Observations were clustered into three pairs of data sets: (i) high and low diffuse radiation regimes (irrespective of cloud cover); (ii) clear sky and cloudy days; and (iii) high and low aerosol loading (AODs) for days for which there were no clouds affecting the measurements. This clustering was thus designed so as to test the sensitivity of the CO_2 fluxes to the diffuse radiative flux fraction, and then to determine the potential impact of clouds as well as aerosol loading on the flux values using direct observations. Also, we clustered the latent heat flux data considering high and low leaf area index (LAI) conditions to indicate the beginning and the peak of the growing season. The purpose of this set up is for us to identify whether change of the percentage of the sunlit and shaded part of ground vegetations would be a factor for water cycle exchanges.

CO2 (umol/m^2/s):

It is the rate of vertical transfer of CO_2 calculated from measurements above the canopy. Different ground vegetation will release different type of CO_2 fluxes. Even at the same measuring site, the rotation of ground crops provides different carbon sources, for example, we are having CO_2 fluxes from corn (C3), soybean (C3) and winter wheat (C3) in this paper. And different type of carbon may have different photosynthesis processes.

LHF (W/m2):

Rate of vertical transfer of latent heat {heat (energy) released by evapotranspiration or absorbed by the condensation or frost of water)} from measurements above the canopy (NOTE latent heat is the heat released or absorbed per unit mass by a system in a reversible isobaric-isothermal phase change).

AOD:

Aerosol Optical Depth data from AERONET (AErosol RObotic NETwork) website are collected by automatic sun-sky scanning spectral radiometers, which provide near real time observations (real time data, data calibration(up to six months), quality assurance and archiving and distribution from NASA Goddard Space Flight Center master archive and several identical data bases maintained globally). The direct sun measurements are operated in eight different spectral bands- 340, 380, 440, 500, 670, 870, 940 and 1020 nm, where the direct sky measurements only measure four spectral bands- 440, 670, 870 and 1020 nm. AOD data mainly used here are at wavelength 500nm, but procedures comparing CO_2 flux changes in all wavelengths are performed.

Diffuse to Direct Radiation Ratio (DDR):

This is the ratio that using direct radiation as the fraction of the diffuse radiation. Both direct and diffuse radiations are in units of W/m^2.

Soil moisture:

The soil moisture data from AmeriFlux sites are measured in six different layers - 10cm, 20cm, 30cm, 40cm, 60cm and 100cm below the surface. But the data availability of each layer though different sites varies. The soil moisture is based on the difference between the soil wet and dry weight, measured once per time period in % by volume. Here we are using the top layer (0-15cm) soil moisture data for our analysis.

Leaf Area Index (LAI):

LAI is defined as the one sided green leaf area per unit ground area in units of m^2/m^2. LAI varies with the growth of vegetations. But it will have more dramatic changes in commercial crops (e.g. corn and soybean), because the leaf area index will become maximum during the peak growing season and minimum at harvest season. Compare to hardwood forests, where the LAI doesn't very too much through out the entire year. Here we use both measured LAI and annually averaged LAI, details list below:

(1)Bondville (IL) (Agricultural site): LAI data provided by AmeriFlux, file attached.

(2)Walker Branch (TN) (Broad-leaved forest): LAI: Max: 8.8 Min: 1.1 <Mean: 5.1> (The forest has a leaf area index in the range between 5 and 6)

(3)Willow Creek (WI) (Temperate/Boreal forest): LAI: 4.18

(4)Lost Creek (WI) (Wetland): Max: 8.4 Min 2.5 <Mean: 6.3> (Asner et al. 2003)

(5)Park Falls/WLEF (WI) (Temperate/Boreal forest): Mean LAI: 5 (Ameriflux)

(6)Ponca City (OK) (winter wheat (C3)): for June-Aug period, ground vegetation is winter wheat (C3). LAI: Max: 4.7 Min: 0.0(from AmeriFlux) <Mean: 1.2>

(7)Shidler (OK) (Tall grass (C4)): LAI: Max: 2.9 m2 m-2 Min: 0.0 (1997-1999)

(AmeriFlux)

(8)Barrow (AK): Tundra. LAI: Max: 5.3 Min: 0.21<Mean: 1.9> But here we assume the leaf are index=1

Air temperature:

Measure of the thermal energy of the atmosphere measured above the canopy in degrees C.

Chapter 3 Effects of aerosols on carbon cycle

Since similar analysis was conducted for each site, we will discuss the results for one site (Walker Branch, TN eastern deciduous forest) in detail and summarize the results for all the sites. The Walker Branch site is located in the southeastern United States, where aerosols have been shown to have a significant impact on the regional climate causing a net cooling effect in the surface temperature records (Saxena and Menon, 1999; IPCC, 2001). It is also one of the oldest AmeriFlux sites with significant background studies to understand the different biogeographical feedbacks active in this region (Wilson and Baldocchi, 2000).

3.1 Effect of Diffuse Radiation on Measured CO_2 Fluxes

Figure 3.1.1a shows the observed daytime CO_2 fluxes clustered for high (Rd/Rg > 0.6) and low (Rd/Rg < 0.4) diffuse regimes over a period for the summer (June through August) months of 1996 through 2000 (corresponding to Analysis I). The CO_2 fluxes increase (in the figures, the negative value indicates flux is towards the vegetation, i.e. a sink) as a function of surface global radiation. Additionally, for the same global irradiance, when the DRF is larger, the corresponding surface CO_2 flux is larger in magnitude. For example, for a global irradiance of 500 Wm^{-2}, the low diffuse regime would correspond to about 13 μmol $m^{-2}s^{-1}$, while the high diffuse regime could lead to a

CO_2 flux of about 20 μmol m^{-2} s^{-1} i.e. about 50% higher. Observations for the three summer months over five years clearly indicate a significant increase in carbon assimilation rates over the study site for larger DRF for similar global irradiance.

The data shown in Figure 3.1.1a, which are based on 30-min averages, were averaged further by taking the values from approximately 1000 to 1600 LT. We chose this period to avoid confounding with low solar elevation angles, since the DRF could be significantly large under these conditions, and it is generally neither a function of cloud cover or aerosol loading (Gu et al., 1999). These 'daily' averaged data are plotted in Figure 3.1.1b, with the CO_2 flux values normalized by the global irradiances. This was done because carbon assimilation rates are a function of global irradiance as well. With this normalization, the effect of the differences in the fraction of the total radiative flux attributed to the diffusive flux on the CO_2 flux values are clearly delineated. A linear relation is obtained between higher DRF and the CO_2 flux values (both normalized for global radiative flux values). The slope of the linear fit indicates that for a given radiation level, increase in DRF is about 30% more efficient in enhancing the carbon fluxes over the study site.

3.2 Effect of Clouds on Measured CO_2 Fluxes

The effect of increased diffuse radiation on CO_2 flux values, as seen in Figures 3.1.1a-b, can be related to both increased cloud cover and/or due to aerosol loading. Indeed, clouds lead to significantly larger DRF, and under overcast conditions the diffuse radiative flux fraction can be close to one. Hence the data were clustered into 'clear' and 'cloudy' regimes (corresponding to Analysis II) and the resulting CO_2 flux variations are shown in Figure 3.2.1a. This variability is similar to the one obtained in studies by Hollinger et al. 1994, Gu et al. 1999, and Roderick et al. 2001. That is, under cloudy conditions the CO_2 flux values are larger for similar global irradiance values. As in Analysis I, the data were then averaged (between 1000 and 1600 LT) and the CO_2 flux values were normalized by the global irradiances, and are plotted as Figure 3.2.1b. The normalized data show two distinct clusters for CO_2 flux values corresponding to cloudy and clear sky conditions. The slope of the best fit indicates a value similar to that obtained in Figure 3.1.1b. Again the results clearly show that CO_2 fluxes under cloudy conditions (corresponding to high DRF) are significantly larger than those under clear sky conditions with the same total irradiance (corresponding to lower DRF).

3.3 Impact of Aerosol Loading on Measured CO_2 Fluxes

As seen in Figure 3.2.1b, some 'clear' days also have relatively high (around 0.6 or higher) DRF. This high DRF, under clear sky conditions can be due to aerosols. Hence, the clear sky conditions data were analyzed further as a function of aerosol loading (through AOD values). Aerosol optical depth (AOD), a measure of aerosol loading, was available for June and July 2000 for the Walker Branch site.

Figure 3.3.1 shows the effect of AOD on surface CO_2 fluxes. The results indicate that the surface CO_2 flux is typically larger in magnitude for larger aerosol loading. Another noteworthy feature of Figure 3.3.1 is that even under high aerosol loading, the global irradiance values can be very high (~ 900 Wm^{-2}).

The increase in CO_2 flux due to aerosol loading is considered to be a feedback of larger diffuse radiative flux fraction due to aerosol loading. Consistent with this hypothesis, the variation of diffuse fraction as a function of AOD was also studied. With increasing aerosol loading, the DRF increases in a nearly linear manner (not shown). Therefore, the variation in CO_2 fluxes can be considered to be an indirect feedback of the regional aerosol loading. Consequently, a nearly linear relation is obtained between AOD and the surface CO_2 fluxes under the clear sky conditions, as shown in Figure 3.3.2. With increasing AOD, the surface CO_2 fluxes are consistently larger, indicating the atmospheric aerosols indeed have a significant impact on the surface carbon fluxes, and hence the terrestrial carbon cycle.

3.4 Comparing Results of Aerosol Loading on CO_2 Fluxes over Different Landscapes:

The analysis described above for an eastern deciduous forest site was repeated for the five other sites, to investigate the regional effect of aerosol loading on the field scale net ecosystem CO_2 exchange. The five sites represented following landscapes: winter wheat (C3), corn (C4), soybean (C3), grassland (C3/C4), and mixed hardwood forest. Figure 3.4.1 shows the results.

As seen from Figure 3.4.1, all the sites/ landscapes show field scale CO_2 fluxes respond to changes in the AOD. Each site/ landscape has a different response as quantified by the net ecosystem CO_2 exchange to the changes in the atmospheric aerosol loading (AOD). The woody and agricultural landscapes show an increase in the field scale CO_2 flux 'sink' as a response to atmospheric aerosol loading. Interestingly, both the grassland sites show an opposite response as compare to the woody and agricultural sites, and indicate a decreased field scale CO_2 flux 'sink' with aerosol loading. Reviewing the slope of the best-fits, the effect of aerosol loading on CO_2 fluxes appears to be largest for C4 grassland (Shidler, OK), and crops (corn; Bondville, IL 1999, 2001), and relatively least on C3 crops (winter wheat, Ponca, OK; and soybean, Bondville, IL 1998, 2000, 2002). The CO_2 flux measurements over trees (forest sites) also appear to be sensitive to the aerosol loading. Thus, both the canopy architecture (and hence the canopy scale radiative feedback on photosynthesis) as well as the photosynthesis pathway appears to be important factors. Additionally, there is significant scatter in the relationship between AOD and CO_2 flux, indicating other environmental variables (beyond aerosol loading) also influence the results. Indeed for all the landscapes, those variables that are known to affect photosynthesis rates (such as leaf area index and soil moisture availability) were also found to be significant in modulating the CO_2 fluxes (results not shown). The results, however, clearly indicate that aerosol loading has a significant impact on the net ecosystem CO_2 exchange over terrestrial landscapes.

3.5 Wavelength Dependence of Aerosol Optical Depth Results:

For the AERONET data used in this study, AOD are centered on seven wavelengths (between 340 nm and 1020 nm). Results from the 500 nm AOD data were chosen since it corresponded to the PAR wavelength. The analysis was extended to assess the effect of wavelength dependent AOD estimates and hence the AOD – CO_2 relation. The relation is sensitive to the choice of AOD wavelength used (not shown) and could be important in considering the effect of aerosol loading in developing satellite estimates of surface CO_2 flux mapping. Additionally, different landscapes may show sensitivity to different wavelengths. For example, for the deciduous forest site, the slope of the CO_2 flux – AOD relation, which can be an indicator of the sensitivity of the aerosol loading on landscape carbon sink potential, is a function of the AOD wavelength. The wavelength dependence (of the AOD – CO_2 flux relation) is relatively lesser for the cropland. Thus the CO_2 fluxes over a woody landscape could be even more sensitive to the aerosol loading than discussed in the analysis above, depending on the wavelength one would choose for assessing the relation. The AOD wavelength – CO_2 flux results could also depend on the soil moisture availability and this feature should be studied further using regional satellite data. However, this wavelength dependence does not alter the conclusion that aerosol loading can significantly influence the variability in the terrestrial CO_2 fluxes.

Chapter 4 Effect of Aerosols on Water Cycle

The Earth temperature has a steady increase trend in the past 50 years. This increasing of temperature was assumed to cause the increase in evaporation rate. But on the contrary, we have a decreased evaporation rate. Because aerosols would prevent solar irradiances reach to the surface by producing brighter clouds. These brighter clouds produce less precipitation. Less precipitation and less evaporation rate cause a weaker hydrological cycle (Ramanthan et al. 2001). But the direct relations between aerosols and water cycle remain unclear. Previous studies discussed mostly for effects with more diffuse radiations (caused both by clouds and aerosols) on carbon and water cycles (Roderick et al. 2002; Gu et al. 2002). Some of the researches focused on one single ground vegetation (Anthoni et al. 2002; Baldocchi et al. 2001b; Gu et al. 1999, etc.). In our research, we tried to compare the water cycle differences for various ground vegetations (corn, soybean, hardwood forest and grassland) in multiple sites and the correlations with aerosol loadings. Here we'd like to examine the aerosol effects on water cycle by using latent heat flux (LHF) data. The transfer of water vapor between ground canopy and the atmosphere may be affected by radiation, temperature and moisture itself. In order to study the aerosol loading effects on the heat fluxes, we performed analyses on leaf area, moisture and temperature to see the impacts of those factors on heat fluxes, and then tried to eliminate those effects and focus only on the aerosol effects. Similar analyses were performed on all the sites previously mentioned in Chapter 2. Because we have multiple sites with various ground vegetations, we will have more discussion on some of the much obvious results.

4.1 Effect of Aerosol Loading on Latent Heat Fluxes (LHF)

4.1.1 LHF vs. AOD for agriculture site:

Bondville (IL) is an agricultural site with annual rotation of crops (corn and soybean); it is a good candidate for comparing the changes of water cycle between different vegetations. Because crops have a shorter growing period and data are usually only available from spring to fall. We used data period from June through August during crops' peak growing season.

(A) Soybeans-1998, 2000, 2002

Plots for soybean data indicates that there was a slight trend of decreasing latent heart flux with increasing of AOD. For both 1998 (Figure 4.1.1a) and 2002 (Figure 4.1.1c), the amount of LHF were concentrated no less than 150 W/m2, but for year 2002 (Figure 4.1.1b), the data were more scattered and LHF could be as low as nearly 50 W/m2. Despite the general value differences of the heat fluxes for each year, there are no significant changes in fluxes with aerosol loadings.

(B) Corns-1999, 2001

Comparing to soybean years and corn years, the amount of LHF maintains above 150 W/m2 or even higher during corn years. But the question about whether LHF increases/decreases with AOD is still not clear for corn years. For 1999 (Figure 4.1.1d), there was a slight decrease trend for LHF, but the LHF data from 2001 (Figure 4.1.1f) were more scattered between the ranges of 200-450 W/m2, and does not indicate if AOD would affect latent heat flux.

Although the analyses results indicate that heat fluxes slightly decrease with aerosol loading for most of the agricultural site study periods, some of the study periods show that LHF were not affected directly by aerosols at all (no changes of heat fluxes with aerosol loading). The correlations for heat fluxes and aerosol loading are still uncertain for both corn and soybean ground covers. Therefore, further analyses on other meteorological factors will be added.

4.1.2 LHF vs. AOD for forest sites

We are using several forest sites in this study, including Walker Branch (Deciduous forest), Willow creek (WI) (Temperate/Boreal forest), Lost creek (WI) (Alder-willow wetland) and Park Falls/WLEF (WI) (Temperate/Boreal forest). Because the environment for hardwood forests wouldn't change as much as agricultural sites, therefore, we could see if various types of forests would have different impact on heat fluxes. As we mentioned before, we used three forest sites in Wisconsin: Willow creek, Lost creek and Park Falls. The location of these three sites are very close to each other, and due to the limitation of the aerosol data (only available for Willow creek), I decided to use the same AOD data for all three sites with different latent heat fluxes.

From Figure 4.1.2a, we can see that the heat fluxes didn't change too much with aerosols, the LHF value at Walker Branch (TN) in year 2000 remained mostly between 200 to 400 W/m2, but this may be the exception of one particular year. For Willow creek site, we analyzed the data from 1999 to 2001 and have significantly different results (see Figure 4.1.2b, 4.1.2c and 4.1.2d). At year 1999, even the aerosol optical depth (AOD) is relatively shallow (between 0 to 0.3), heat fluxes were affected dramatically by aerosol loading (see Figure 4.1.2b, and similar result could be seen in Figure 4.1.2e for Lost creek site). There were similar AOD values in year 1999 and 2001 for Willow creek, but the heat fluxes ranged from 0 to 400 W/m2 in year 2001 and the fluxes did not very with aerosol loading (Figure 4.1.2d). As for Willow creek 2000, the AOD values were much higher than other research periods, but we still see very scattered LHF data and no significant trend of increasing/decreasing LHF (Figure 4.1.2c). These results prove that even at hardwood forest sites (a relatively constant environment), higher aerosol loading may not cause larger increase/decrease of heat fluxes and the changes in heat fluxes would be a result of very small amount changes of aerosols. Because aerosol effects on the heat flux changes vary from year to year without a consistent result for hardwood forests (LHF may decrease in one year and have a nonlinear relation in another year). Factors other than aerosols that would affect the water cycle need to be considered.

4.1.3 LHF vs. AOD for winter wheat site

Ponca City (OK) is the only winter wheat site we are using for our analysis. From Figure 4.1.3, we can see the most significant difference between this winter wheat site and other agricultural and forest sites is that the latent heat flux values increase with aerosol loading, which means there have latent heat “sink” effect at this winter wheat site. And with the increase of aerosol loading, there were more heat flux intake by the surface canopy. This is very different from our results for agricultural sites and forest sites.

4.1.4 LHF vs. AOD for grassland site

Here we have two different grassland sites: Shidler (OK) and Barrow (AK). Shidler site is located very close to Ponca City site. LHF decreases with aerosol loading in both Shidler (Figure 4.1.4a, Figure 4.1.4b). Compare with result from Figure 4.1.3 (winter wheat site), despite the closeness of the locations of Ponca City and Shidler, heat fluxes have very diverse results for these two sites. 0ne can say that heat flux exchanges could vary from sink to source due to the differences of ground cover. As for Barrow site (see

Figure 4.1.4c), although it is a tundra site, similar to the grassland site, it has very shallow aerosol optical depth data (less than 0.2) and the heat fluxes increase with aerosol loading, which means there has heat flux "source" at Barrow. Aerosol loading effects are more efficient here in Barrow. Latent heat fluxes are about one order smaller than other sites, but heat fluxes doubled even tripled with very little aerosol increase.

Figure 4.1.5 is the plot for all available sites indicating the correlations between latent heat fluxes and aerosol optical depth.

4.2 Effects of AOD without Leaf Area Index on Latent Heat Fluxes

Radiation could affect the heat fluxes directly and indirectly. Global radiation = diffuse + direct radiation, direct radiation comes directly from the sun, and diffuse radiation is from the radiation diffused by clouds, aerosols, water, and ground covers, etc. Here we are interested in whether the direct-to-diffuse radiation ratio (DDR) would be affected by aerosols with the change of leaf area.

Because we are using data from various ground covers (agricultural crops, forest, grassland, wheat), the leaf area varies with different vegetation. For agriculture site (Bondville, IL), the leaf area index (LAI) varies from season to season (during the growing season, it tends to have larger LAI than after the harvest season). On the contrary, LAI remains a relatively constant value through out the year for forest and grassland sites.

We use actual measured LAI data for Bondville, IL from AmeriFlux website, and averaged LAI values for other sites from Asner et al. 2003.

Previously, we analyzed the latent heat data with change of aerosol optical depth (AOD) and got the results that LHF may slightly decrease with AOD for both soybean and corn years from the agriculture site. Here we would like to add another possible factor-Leaf, using leaf area index (LAI). Because there are different leaf surface areas in different vegetation, and with the change of leaf area, the percentage of sunlit and shaded parts of the vegetation would very. Sunlit leaves receive direct radiations and shaded leaves contribute more diffuse radiations into the atmosphere. This may cause the change of diffuse-to-direct radiation ratio (DDR) and heat fluxes may also very with DDR changes. Figure 4.2.1a and 4.2.1b show the latent heat change with aerosol loading after eliminating the leaf area factor. Comparing Figure 4.1.1b with Figure 4.2.1a, it shows that after accounting for LAI, latent heat fluxes respond with aerosol loading more significantly. This indicates that LAI does affect the heat flux for agriculture site. But for forest site (Walker Branch) and grassland (Ponca City), there are no significant changes after accounting for the leaf area change (see Figure 4.2.2 and Figure 4.2.3). This is mainly because the LAI value for forest site and grassland site almost remain a constant value, and there we use average LAI=5.1 for Walker Branch site and consider LAI=1.2 for grassland (Asner et al. 2003). Therefore, we must consider other factors that would affect the heat fluxes for forest sites.

4.3 Effects of Leaf Area on Latent Heat Fluxes

From our previous discussion, we know that changes in leaf area could affect the heat fluxes for agriculture site. At the same agriculture site, different crops have different LAI changes (see Figure 4.3.1a (soybean) and Figure 4.3.1b (corn)). During the peak-growing season, crops tend to have the maximum capacity of leaf area. Compare with Figures 4.3.a and 4.3.b, during the summer season (June-August), we can see that the maximum leaf area index during soybean year is higher than corn year. And LAI increased gradually from 0 up to 6 (maximum) in about 20 days for corn year, while it increased stage by stage for soybean year. In order to have a more precise comparison between different years of data, I tried to keep the plot scales the same within each comparison. After considering leaf area as a factor according to my analyses in section 4.2, I clustered those LHF and AOD data, based on high and low leaf area index. Here I categorized LAI<2.5 as low LAI and LAI>3.0 as high LAI. Law et al. 2001a concluded that comparing with different forests with different maximum leaf area index (LAI), the proportion of total latent heat fluxes derived from the forest floor increased with sparser leaf area (lower LAI), and LHF has little changes when LAI is above 3. Latent heat flux values were higher with less leaf area in open-canopy forests. I did the analyses for latent heat fluxes and aerosol loadings after clustering leaf area into high (LAI>3) and low (LAI<2.5) conditions for both corn and soybean site in Bondville (IL). There are higher latent heat values during high LAI condition for both corn and soybean sites within the same year, which is contrast to conclusion from Law et al. 2001a for open-canopy forest sites.

Considering the correlations between latent heat fluxes and aerosol loadings. At corn site, LHF has a greater decreasing tendency with aerosol loading when leaf area index is below 2.5 than higher LAI values (LAI>3) (see Figure 4.3.2a and 4.3.2b) for agricultural sites. LHF and AOD correlation is not linear for soybean site during high LAI condition at corn site (Figure 4.3.3a) when it has a decreasing trend at low LAI (Figure 4.3.3b). And LHF values were higher in corn year (1999). Under low LAI condition for both 1998 (soybean) and 1999 (corn), the plots show a more significant trend of LHF decreasing with AOD. But for high LAI period the results are not consistent. At 1998, heat fluxes decreased with aerosol loading while LHF had a non-linear relation with AOD at 1999 (increasing in the beginning of our research period but decreasing later on).

In short, heat fluxes are higher under high LAI condition for both corn and soybean years (opposite to forest). Heat fluxes react better with aerosol loadings at low LAI for both soybean and corn years; fluxes both decrease more with aerosol loadings at low LAI condition in corn and soybean sites.

4.4 Correlations between latent heat fluxes and aerosol loading under different soil moisture content

The direct correlations between aerosols and latent fluxes are not consistent for all studied sites: latent heat fluxes decrease with aerosol loading in most of the agricultural sites and some of the forest sites. In previous sections, we've discussed the leaf area factor in the water cycle. Here we would like to consider other important factor - soil moisture.

Water plays an important role in the energy of balance of soils and plants. Baldocchi 1997 indicated that the existence of drought could reduce CO2 and water exchange. Water sources for plants come from both precipitation and moisture content within the soil. Plant water uptake is a process that liquid water moves from soil into plants through roots, through the xylem of plants to the leaves, and evaporates in the substomatal cavities of the leaf. This is a very important step during photosynthesis. Plants need the oxygen and nitrogen from water to convert them into carbohydrate. Moisture content within soil is a main source of water for plants in order to perform photosynthesis.

In this section, I tried to examine the effects of soil moisture using only the top layer soil data (0-15cm below the surface). Generally speaking, moisture at the top layer of the soil (0-15cm) decreases with time in the summer (see Figures 4.4.1a and 4.4.1b).

This may be caused by the growth of the vegetation in the summer time, which requires a lot of moisture uptake when growing either from precipitation or from soil. According to the soil moisture time series (Figures 4.1.1a and 4.1.1b), higher soil moisture content occurred during the early research period of each year, which means it has higher moisture content in the early summer, but because with the increase of solar radiation and air temperature, there will have more evaporation and transpiration rates and decrease the soil moisture content. Or one can say that high soil moisture coincides with low leaf area index during our research periods; in the early summer with lower LAI value (before peak growing season), there has more soil moisture in the soil.

I clustered the latent heat fluxes into high (soil moisture > 0.3) and low (soil moisture < 0.3) soil moisture conditions. Results show that for both high and low soil moisture content, latent heat fluxes decrease with aerosol loading in Bondville agricultural site (compare Figure 4.4.2a with 4.4.2b; Figure 4.4.2c with 4.4.2d). It is also similar for both corn and soybean years (compare Figure 4.4.2a with 4.4.2c; Figure 4.4.2b with 4.4.2d). One can say that heat fluxes decrease with aerosol loadings in both high and low soil moisture contents; this tells us that the changes in soil moisture may not affect the heat fluxes in corn and soybean sites. But this decreasing trend is not as obvious for Ponca City, the grassland site (see Figure 4.4.3a and 4.4.3b). At high soil moisture content, latent heat fluxes have a very slight increase trend with aerosol loading, where there are no signs of increasing or decreasing at low soil moisture content. Compare with the results in sections 4.1 and 4.3, where there have significant increasing heat fluxes with increasing aerosols, one can say that soil moisture has a great influence in latent heat fluxes for grassland site.

4.5 Effects of air temperature on heat flux

Rates of biochemical reactions within an organism are strongly dependent on its temperature. The rates of reactions may be doubled or tripled for each 10 degrees temperature increase (Campbell and Norman 1998). As mentioned in section 4.2, latent heat fluxes have much obvious decrease with aerosol loading after accounting for leaf effects (see Figure 4.2.1a). After eliminating leaf effects, we no longer consider the increase of diffuse radiation caused by shaded leaves. In this section, we would only consider the temperature change effects caused by direct solar radiation and how latent heat fluxes were affected with aerosol loadings considering the air temperature changes. Figures 4.5.1a and 4.5.1b are the averaged air temperature time series for soybean site and grassland site in the summer time. Note that the averaged daily maximum and minimum air temperature data for grassland site are higher than soybean site. With these temperature differences, one would expect different reactions in the heat fluxes exchanges; see Figures 4.1.1b and 4.1.3a, if ignoring the increase/decrease trend of latent heat fluxes, the overall heat flux values for Ponca City (grassland) are lower than Bondville soybean site. The maximum LHF for grassland is about 250 W/m^2, where maximum LHF for soybean was close to 400 W/m^2. From our previous discussion we've already known that latent heat fluxes have direct relations with aerosol loadings for grassland site (see section 4.1 and 4.2), but not consistent for corn and soybean sites. We will have further analyses for those agricultural sites and also use grassland site analyses as comparison.

4.5.1 Changes of latent heat fluxes without leaf effects and temperature effects

Changes of air temperature in one single ground canopy site may due to the direct radiative heating or the diffused radiation reflected by the ground leaf area. According to previous discussions, we indicated that leaf area varies much dramatically in agricultural sites than hardwood forest sites and grassland sites, which is because agricultural vegetations have much shorter growing period; their peak growing season is concentrated in the spring and summer; and there will be no leaf area after harvest. Changes in leaf area could affect the heat flux changes; latent heat fluxes tend to decrease more with aerosol loading during low leaf area period (Law et al. 2001a). Although the air temperature time series indicated that for grassland and soybean site, the temperature profiles (Figures 4.5.1a and 4.5.1b) during the summer time are relatively consistent, no very dramatic increase or decrease at the researched period even with more leaf area index. The regular temperature changes could still have an impact in heat flux exchanges. In soybean site, comparing the heat flux changes with and without air temperature effects (see Figures 4.2.1a, 4,2,1b and 4.5.2a, 4.5.2b), results indicate that temperature changes may not have significant impact on latent heat fluxes. Those plots all have similar decreasing trend of heat fluxes with aerosols. Also in grassland site (see Figures 4.2.1c and 4.5.2c), the heat fluxes increase with aerosol loadings with and without air temperature effects. Therefore, one may say that air temperature changes may not have direct effects in heat flux changes with aerosol loadings for soybean and grassland sites.

4.5.2 soil moisture effects on latent heat fluxes without considering temperature and leaf changes

With higher air temperature, one would expect there would have more evaporation and transpiration rate and more moisture transferred from the soil into the atmosphere. Since results from section 4.5.1 show that air temperature does not have significant effects on heat fluxes for grassland and agricultural sites, but soil moisture is considered an important factor when analyzing the heat flux changes for grassland site, we would like to eliminate the temperature factor from the heat flux data and still considering the soil moisture changes to our analyses by dividing the heat flux data with air temperature data. Figure 4.2.1a is the heat fluxes correlated with aerosol after accounting for the leaf effects, which shows that latent heat fluxes decrease with aerosols when not considering leaf area changes. After clustering the latent heat exchange data (with no leaf area effects and air temperature effects) into high and low soil moisture conditions for both agricultural and grassland sites, we had very diverse results for low soil moisture condition. Figure 4.5.3a and Figure 4.5.4a are the correlations between heat flux changes and aerosol loading during higher soil moisture content in soybean and grassland sites. Comparing Figures 4.2.1a and 4.5.3a,b, it is much clear to see the soil moisture effects at soybean site. With no leaf effects and temperature effects, latent heat fluxes have a non-linear relation with aerosols with low soil moisture content, where fluxes still decrease with aerosols at high soil moisture content, which means the heat fluxes are more sensitive with aerosols at low soil moisture content at soybean site with no effects from leaf area and temperature changes. Note that this result is different from section 4.4, when we considered leaf area changes within the heat flux changes. This also confirmed with our results from sections 4.1 and 4.2, saying that leaf area changes could be a factor of heat flux changes.

In comparison, we performed similar analyses in grassland site (see Figures 4.5.4a and 4.5.4b). Latent heat fluxes increase slightly at high soil moisture content, but no significant trend at low soil moisture content. These plots are similar to Figures 4.4.3a and 4.4.3a, when only we only clustered the heat fluxes into high and low soil moisture content including all leaf effects and temperature effects. One can say that leaf and air temperature changes do not have significant influences in latent heat flux changes for grassland.

Chapter 5 Summary and Conclusions:

In this study, we are focusing on aerosol loading affecting both CO2 and water cycles in different ground covers. One all know that CO2 fluxes could very mainly due to plant photosynthesis; and water vapor exchanges may affected by radiation, leaf area, cloudiness, moisture and temperature. Therefore, we chose summer season from June to August with peak growing season, more dramatic leaf area changes, higher air temperatures and much activated plant photosynthesis, for our research period.

The results of our study suggest a positive test of the hypothesis that aerosol induced radiative feedback is an important modulator of the regional terrestrial carbon cycle. For the different study sites, the diffuse radiative flux fraction (DRF) impacted the field measurements of CO_2 fluxes, with the increase in the DRF correlating with the higher CO_2 flux values (sink) for woody trees and agricultural crops; but a lower sink potential for grasslands. The effect was clearly seen under cloudy conditions, during which the DRF constituted the majority of the total radiative flux. The effect was also identified under larger aerosol loading in clear (no–clouds) sky conditions, which caused higher DRF. Aerosols can therefore routinely influence surface radiative flux and hence the terrestrial CO_2 flux and regional carbon cycle. In addition, although an increase in cloud cover leads to an increase in the DRF, there is a concurrent decrease in the total radiative flux, which can reduce the rate of carbon assimilation. However, under clear sky conditions, and high aerosol loading, the total radiative flux still remains relatively large (as seen from the dataset presented and cf. Garrison, 1995; Jacovides et al., 1997). Hence, the aerosol loading effect could be more important than the effects of clouds in terms of its role in modulating the regional carbon cycle.

The reason for the increase in the CO_2 fluxes with increasing DRF for woody and croplands is considered a result of a larger fraction of vegetation canopy participating in its interaction with the radiative flux (without photosaturation), and leading to higher carbon assimilation rates (Campbell and Norman, 1998; Gu et al. 2002). This advantage of increasing diffuse radiation interacting with leaf area does not appear to be available to grasslands due to the canopy architecture, under no – clouds, high aerosol conditions. Additional confounding of the effect of air and soil temperature for conditions with high DRF or AOD, and changes in the vapor pressure deficits are also possible and should be explored through dedicated field measurements and detailed modeling studies.

Aerosols are abundant in the environment as a result of both natural and anthropogenic sources, and the 'direct' and 'indirect' effects of aerosols on climate are only poorly understood (Kabat et al. 2002, Ramanathan et al. 2001). Considering that aerosols are known to both absorb and scatter incoming solar radiation, an increase in aerosol loading can lead to more diffuse radiation in the atmosphere (Cohan et al. 2002). These aerosols can affect the radiative flux at the top of atmosphere and even more profoundly at the surface and thus affect the biospheric processes. Therefore, changes in the diffuse radiation fraction, due to aerosol loading, appear to have the potential to impact the efficiency of the terrestrial carbon exchange.

Past studies on the impact of diffuse radiation on CO_2 flux focused on either investigating the effect of cloudiness (*e.g. Hollinger et al. 1998*) or episodic analysis of the impact of aerosol occurrence (*Gu et al. 2003*) such as from the Mt. Pinatubo volcanic eruption on CO_2 flux exchange at a Harvard Forest AmeriFlux site. Additionally, *Gu et al.* 2002 analyzed field measurements across the United States and showed that net ecosystem exchanges are larger for a higher diffuse fraction of the incoming radiation. Thus, even though field and model studies provide increasing evidence that plant photosynthesis rates and field scales CO_2 sink potential will increase with diffuse radiation fraction, the majority of these studies have been based on either episodic analysis of aerosol loading (i.e., effect of the Mt. Pinatubo eruption) or as the effect of cloudiness (which are conditions of high diffuse radiative fraction). Thus an observational analysis investigating effects of persistent regional aerosol loading (which typically has a lifetime on the order of a week) on fieldscale CO_2 fluxes, as conducted in this study, was lacking. Such an analysis is important because of several reasons. First, the results provide evidence that routine aerosol loading due to natural or anthropogenic sources (as against outstanding geophysical events such as volcanic eruptions) have the potential to cause variability in the regional CO_2 flux. This could help explain a high-frequency (order of a week) variability in the CO_2 fluxes observed over different landscapes. Second, even though past studies have shown that for a given radiative flux, CO_2 exchange would be higher under cloudy conditions; cloudiness in itself may not be a dominant forcing which would increase the ability of a region to be a carbon 'sink'. This is because, even though the radiation under cloudy conditions has a large diffuse fraction, the total radiation itself is dramatically reduced. Hence as a feedback this could even lead to lower, rather than higher, CO_2 fluxes over the region (cf. Krakauer and Randerson, 2004). On the other hand, our results indicate that increasing aerosol loading will increase the diffuse fraction of the radiation without significantly reducing the total radiation itself, and would be a prominent forcing affecting the atmospheric CO_2 flux variability over a region. Thus, the potential of the vegetated land surface to be a sink for atmospheric carbon could increase with regional aerosol loading.

Past studies on impacts of diffuse radiation on CO2 flux focused on either investigating the effect of cloudiness (Hollinger et al. 1998) or episodic analysis of the impact of aerosol occurrence (Gu et al. 2003). Additionally, Gu et al. 2002 analyzed field measurements across US and showed that net ecosystem exchanges are larger for higher diffuse radiation fraction of the incoming radiation. Even both field and model studies provide increasing evidence that plant photosynthesis rates and field scales CO2 sink potential will increase with diffuse radiation fraction, the majority of these studies have been based on either episodic analysis of aerosol loading (i.e. effect of Mt. Pinatubo eruption) or the effect of cloudiness (high diffuse radiative fraction). Researches based on observational analysis investigating effects of persistent regional aerosol loading (typically has a lifetime of order of week) on field scale CO2 fluxes as conducted in this study were lacking.

We performed similar data analyses on latent heat fluxes with aerosol loading over different ground cover. For agricultural crop site (corns and soybeans), leaf area changes have influences on water vapor cycle. Law et al. 2001a concluded that comparing with different forests with different maximum leaf area index (LAI), the proportion of total latent heat fluxes derived from the forest floor increased with sparser leaf area (lower LAI), and LHF has little changes when LAI is above 3. I did the similar analyses clustering leaf area into high (LAI>3) and low (LAI<2.5) conditions. Latent heat flux values were higher with higher LAI value in both corn and soybean sites. But heat fluxes tend to be more sensitive with aerosol changes during low LAI condition. LHF has a more significant decreasing trend with aerosol loading with less leaf area than with higher LAI content. At both high and low soil moisture contents; heat fluxes decrease with aerosol loadings in corn and soybean site. But there are not significant latent heat changes in grassland site after clustering the data into high and low soil moisture, compare with an obvious increasing trend of heat fluxes with aerosol loadings (not considering soil moisture effects). We conclude that soil moisture has a great influence in latent heat flux in Ponca City (OK) with grass ground cover; but leaf area and air temperature changes both have little effects in latent heat exchanges. For agricultural sites, air temperature changes have less impact on heat fluxes then leaf area and soil moisture. Heat fluxes decrease with aerosols at both high and low leaf area conditions, but are more sensitive when there is less leaf area. LHF decrease more while at lower LAI condition. After accounting for the leaf area and temperature effects, heat fluxes have a non-linear relation with aerosols at low soil moisture content.

Observational analyses are important because (1) providing evidences that routine aerosol loading due to natural or anthropogenic sources could cause regional CO2 and latent heat fluxes changes (eliminating abnormal geophysical events such as volcanic eruptions and forest fires). This could help explain high frequency (order of week) variability in the CO2 fluxes and latent heat fluxes observed over different landscapes. (2) even though past studies show that for a given radiative flux, CO2 exchange could be higher under cloudy conditions, but cloudiness may not be a dominant forcing which could increase the ability of a region to be a carbon sink. It is because that even the diffuse radiation fraction during cloudy days is large; the total radiation is dramatically reduced. Therefore, this could lead to lower, rather than higher, CO2 exchange over the region. Our research results indicate that increasing aerosol loading will increase diffuse radiation fraction without significantly reducing the total radiation, and this would be a prominent forcing affect the atmosphere CO_2 variability over a region. Thus, the potential of the vegetated land surface to be a sink for atmospheric carbon could depend on aerosol loading.

Future work:

In this research, I examined the net ecosystem exchanges and water exchanges due to aerosol loadings. But CO_2 fluxes and latent heat fluxes changes are not only affected by aerosols. Through previous studies (Roderick et al. 2001), some major volcanic eruptions were examined and considered an important effect in changing the CO_2 and water fluxes exchanges. I'd like to include the volcanic effects in the future research. Also, there is another important factor that I'd like to consider- forest fires. During the researched periods, there were a number of major forest fires occurred not only in United States, but also in Canada and Asia. Some of the abnormal carbon dioxide concentrations were detected in United States even the CO_2 sources were hundreds or thousands of miles away. In some places, forest fires may occur annually and were considered as natural events. Fire season usually begins in late spring/early summer when air temperature starts to increase and low in humidity. First, we need to determine those forest fires were normal events through out the entire researched periods or were abnormal activities. Then perform further examinations on CO_2 concentrations after those abnormal forest fires.

In this research, I used aerosol optical depth data collected by automatic-tracking Sun and sky scanning radiometers from AERONET and some annually averaged AOD data for which measured aerosol data were not available. In order to have more accurate aerosol loading information, satellite collected AOD data from MODIS should be considered using in the future. MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. The MODIS Aerosol Product (MOD 04) monitors the ambient aerosol optical thickness over the oceans and over a portion of the continents and displays the aerosols on a color-coded global map. Since some of my AOD data for our studied sites are averaged annual value, with the usage of MODIS aerosol data, we could study the aerosol effects more realistically.

Further more, I'd like to perform some model assimilations for our research. In this paper, results are all from converting those raw carbon dioxide, latent heat fluxes, moisture, and temperature data for every 30 minutes or every hour into daily averaged data and analyzing the correlations with aerosol loadings. Previous studies used different models such as Big-leaf model (De Pury et al. 1997) or CANOAK (Wilson et al.2001 and Baldocchi et al. 1995, 2002) model to simulate the behaviors of the fluxes. Big leaf model treats the researched canopy area as one very big leaf regardless the actual canopy structure and no differences from individual chloroplasts across a leaf. When using Big leaf model for a canopy site, the time-averaged profile of absorbed irradiance and the spatially averaged instantaneous show an exponential decline with cumulative leaf area index by the model, but the actual instantaneous profiles of the absorbed irradiance do not follow Beer's law because of both sunfleck penetration and leaf angles. CANOAK model is a one-dimensional, multi-layer biosphere-atmosphere gas exchange model that computes water vapor, carbon dioxide, and sensible heat flux densities and the microclimate within and above the forest. Compare to Big leaf model, CANOAK model is more complicated and realistic. Later on, a general energy and mass transport model (GEMTM) was developed to predict the atmosphere and land surface interactions. The plant canopy in the GEMTM model is divided into sunlit and shaded layers, and the stomatal conductance and photosynthesis of sunlit and shaded leaves are simulated separately. Compare with the Big-leaf model and CANOAK model, GEMTM model simulates the most realistic canopy structure.

I would be using the Regional Atmospheric Modeling System (RAMS) to assimilate the analyzed research results. RAMS model, similar to MM5 and Eta model, is designed for mesoscale or higher resolution grid scales, but it can also be used as a global scale model for large-scale systems. In other words: RAMS works on both meso and large scales. With data of radiation, moisture transfer processes in the hydrological cycle, kinematic effects and heat exchange between the atmosphere and the surface, which includes multiple layers of soil and different ground covers, RAMS model would simulate the atmospheric dynamic and thermodynamic processes with non-hydrostatic and compressible equations. With the comparison of our research results and model simulations, we would have an opportunity to examine the accuracy of the model and improve the model forecast. And our future studies will continue looking for the dynamical feedback between land surface and the atmosphere.

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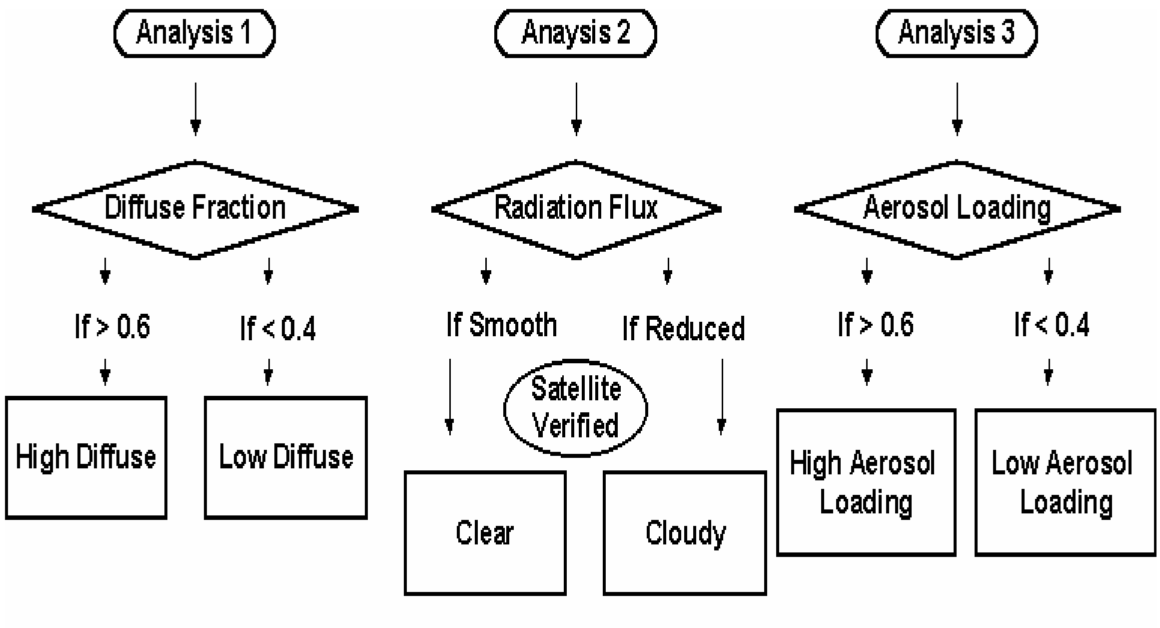
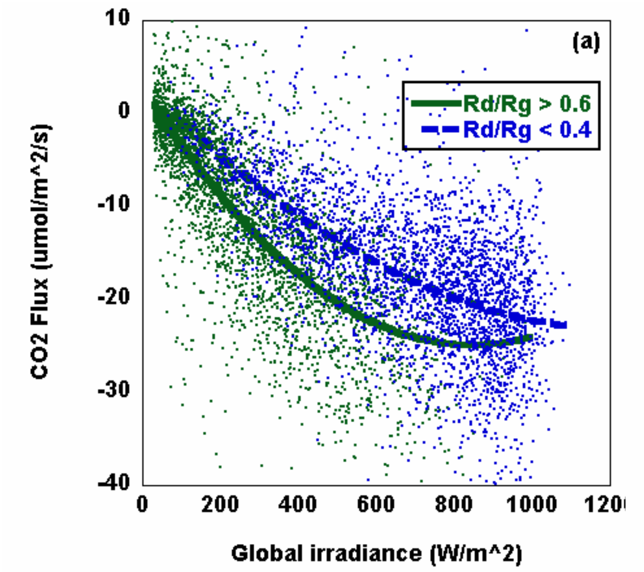


Figure 2.1

Schematic showing method of clustering data adopted for analysis. For analysis I, data were clustered according to diffuse radiative flux fraction (Rd/Rg). For analysis II, data was clustered according to 'Clear' and 'Cloudy' sky conditions based on diurnal radiation flux characteristics and GOES satellite imagery. For analysis III, data were clustered according to aerosol loading quantified through aerosol optical depths (AOD). Each pair of clustered data was then compared for differences in observed carbon exchange (CO_2 flux observations).



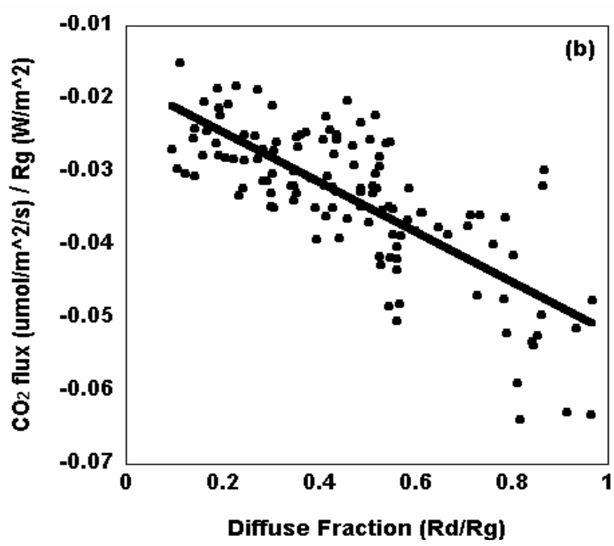
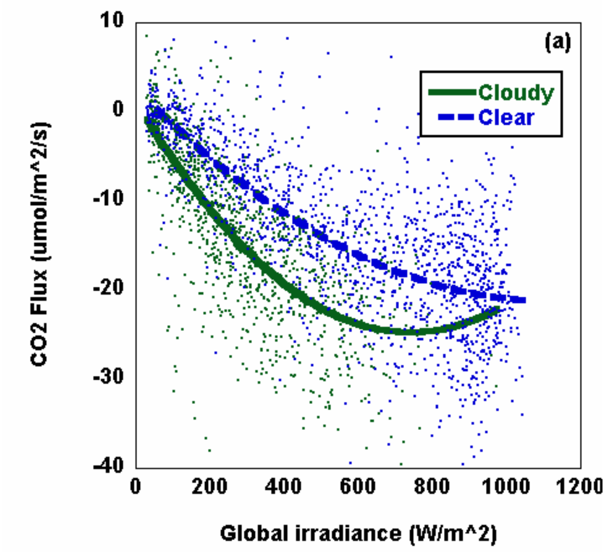


Figure 3.1.1a

Observed 30-minute averaged daytime observations of CO_2 flux (μmol$m^{-2}s^{-1}$) and global irradiance (Wm^{-2}) during summer months (June through August) of 1996-2000. Solid line corresponds to 'high' diffuse regimes (Rd/Rg > 0.6), and dashed line corresponds to 'low' diffuse radiation regime (Rd/Rg < 0.4). Generally higher diffuse radiative flux fraction corresponds to larger CO_2 flux values to the vegetation / landscape.

Figure 3.1.1b

Normalized daily CO_2 flux and diffuse fraction from the same period as data in Figure 3.1.1a.



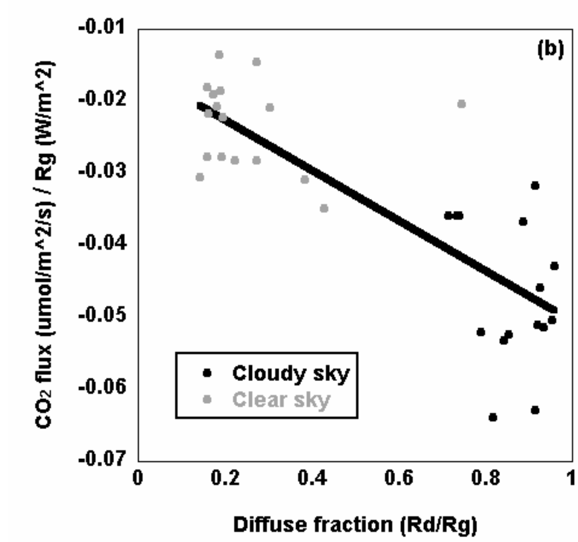


Figure 3.2.1a

Effect of cloudiness on CO_2 flux observations shown in Figure 3.1.1a-b. Solid line corresponds to 'Cloudy' sky conditions, while dashed line corresponds to the 'Clear' sky conditions. The CO_2 flux values are generally higher for cloudy conditions.

Figure 3.2.1b

Normalized daily averaged CO_2 flux and daily averaged diffuse fraction from the same time period as data in Fig. 2a. The CO_2 fluxes are larger for cloudy conditions as a result of higher diffuse radiation fraction.

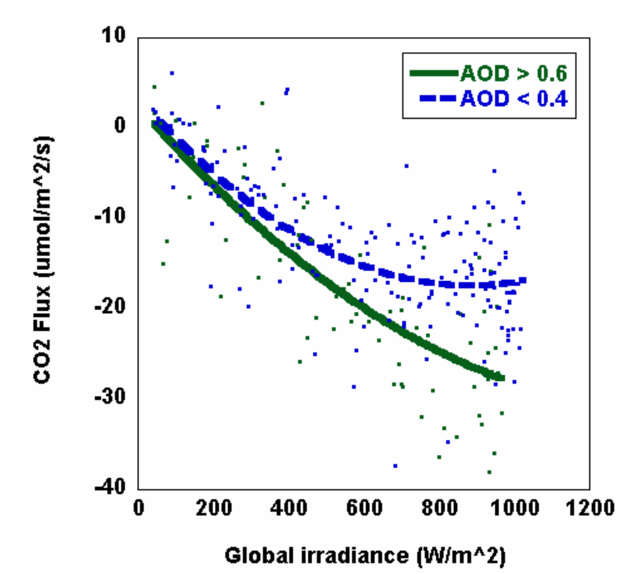


Figure 3.3.1

Scatter plots and 2nd order regressions between 30-minute averaged daytime observations of canopy CO2 flux and global irradiance during June-July of 2000 (Solid = AOD > 0.6; Dashed = AOD < 0.4).

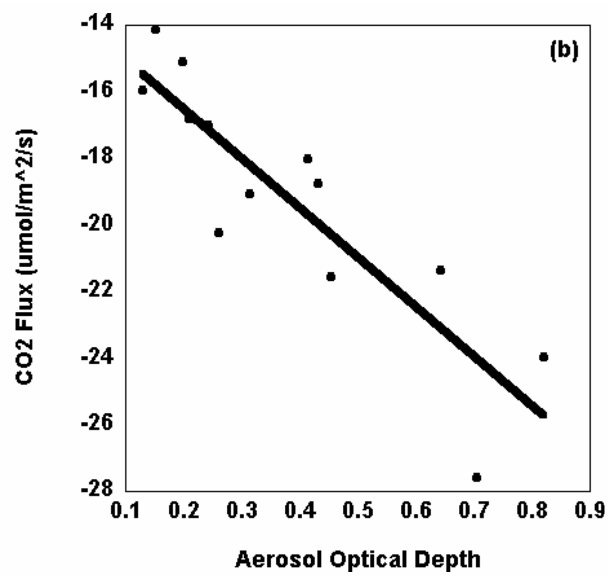


Figure 3.3.2

Daily averaged observations of aerosol optical depth and observed CO_2 flux at the Walker Branch Forest site during June – July 2000. With increased aerosol optical depths (that is, increased aerosol loading), the landscape appears to be a larger 'sink' for CO_2.

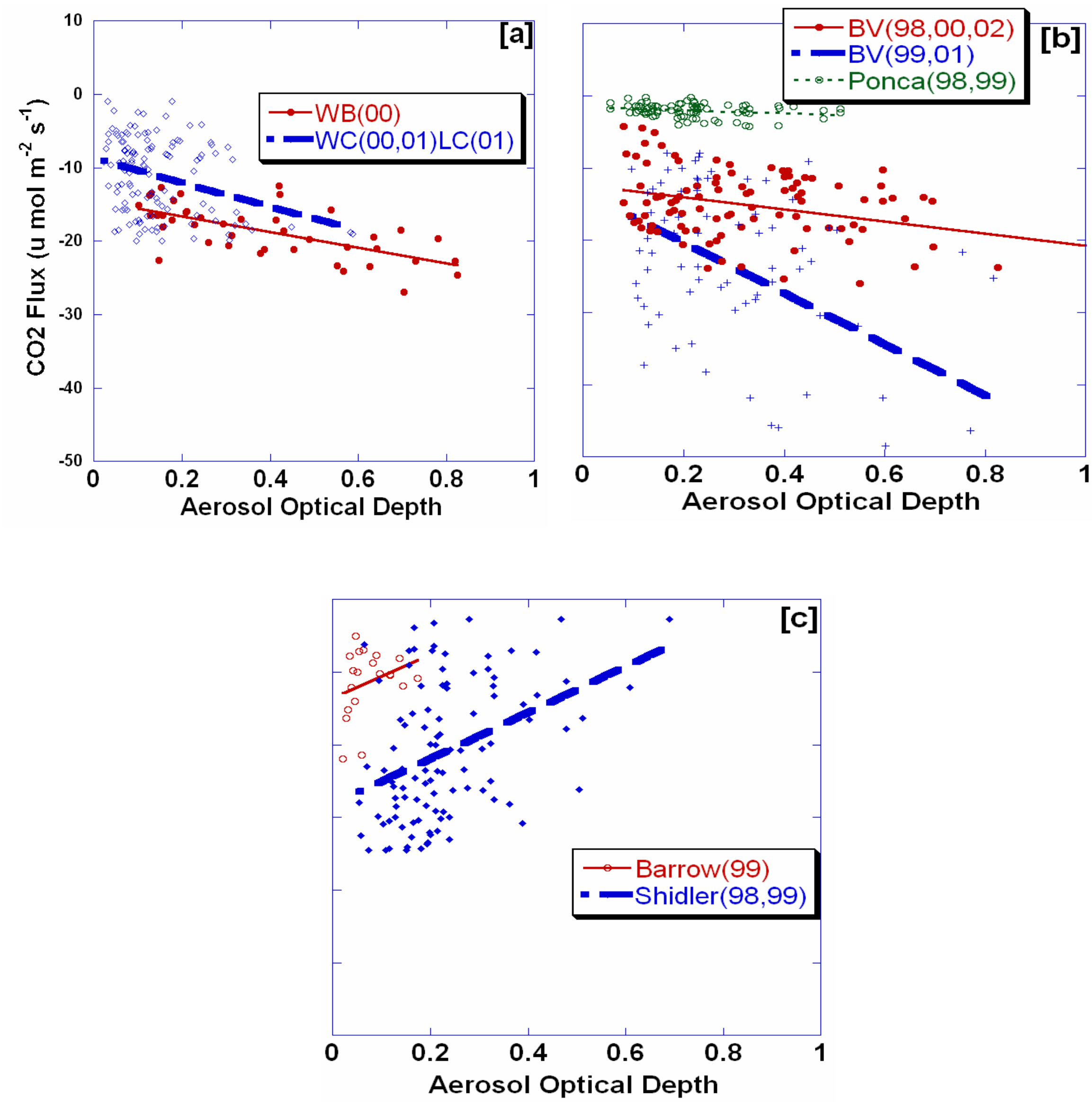
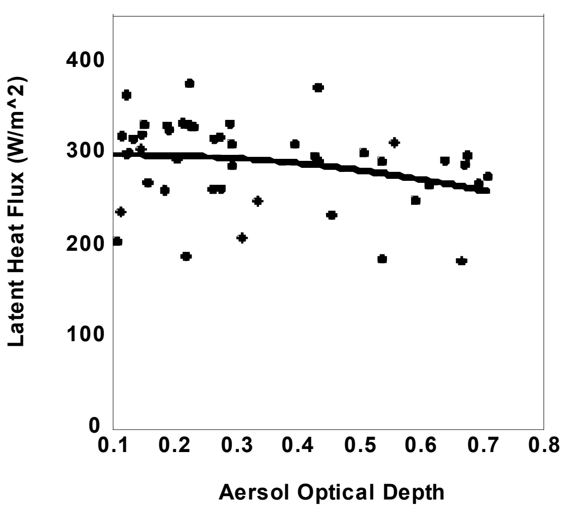


Figure 3.4.1a, b, c

Relation between 500 nm Aerosol Optical Depth (AOD) and measured CO_2 flux at different sites and landscapes. WB: Walker Branch; BV: Bondville, WC,LC: Willow Creek . Lost Creek. The period for which data were used are also indicated. Results indicate that aerosols have a significant impact on increasing (decreasing) terrestrial CO_2 fluxes / sink potential over forest and croplands (grasslands, cf. Barrow and Shidler). C4 vegetation [cf Shidler and BV(99, 01)] appear to have the largest sensitivity, while C3 crops/grasslands have the least, and hardwood trees show a moderately high influence of aerosol loading on the field-scale CO_2 fluxes for the data considered.



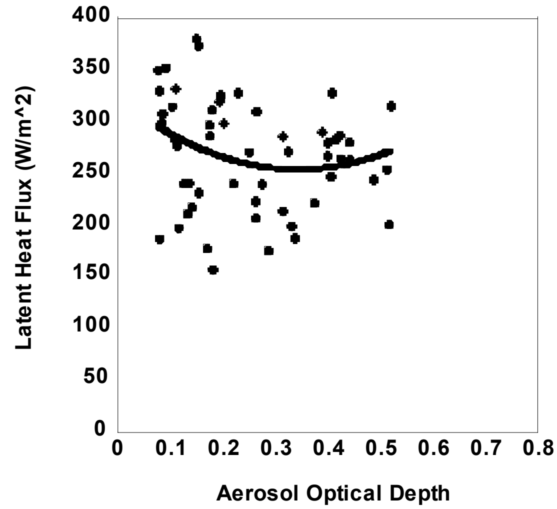


Figure 4.1.1a

Bondville LHF vs. AOD 1998

Heat fluxes did not very with aerosol loading at soybean ground cover in 1998.

Figure 4.1.1b

Bondville LHF vs. AOD 2000:

Similar to Figure 4.1.1a, aerosols had little impact in latent heat flux in 2000.

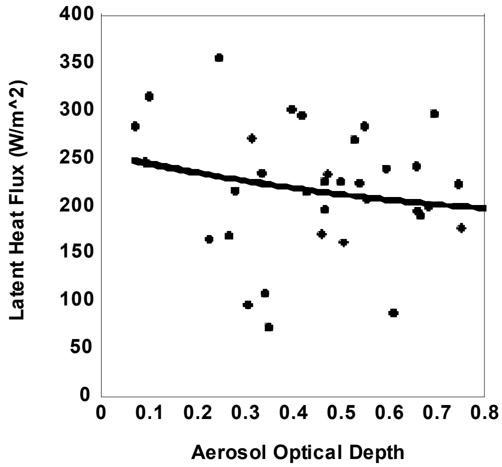


Figure 4.1.1c

Bondville LHF vs. AOD 2002:

Latent heat flux values for year 2002 were lower than previous soybean years (1998 and 2000), and still no significant relationships between aerosols and LHF.

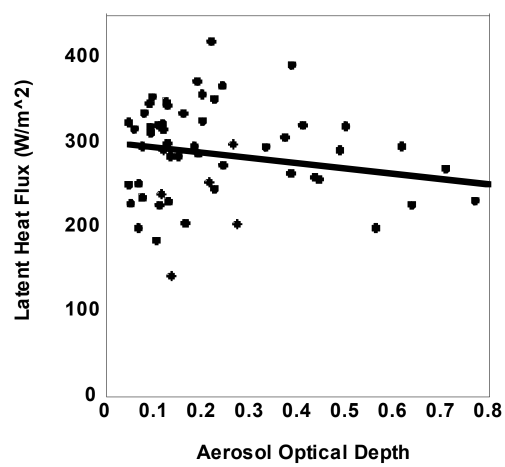
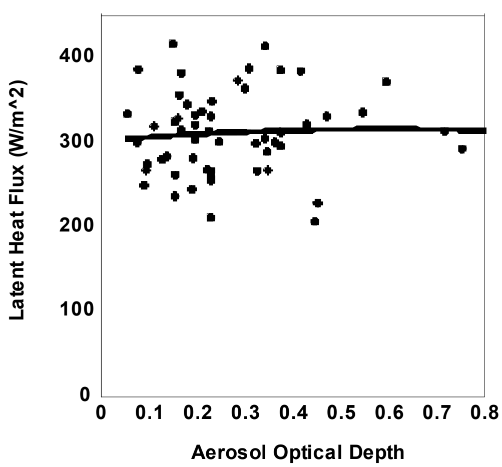


Figure 4.1.1d

Bondville LHF vs. AOD 1999:

Aerosol loading did not have major impact in latent heat flux in corn year (related to Figure 4.1.a, b, and c).



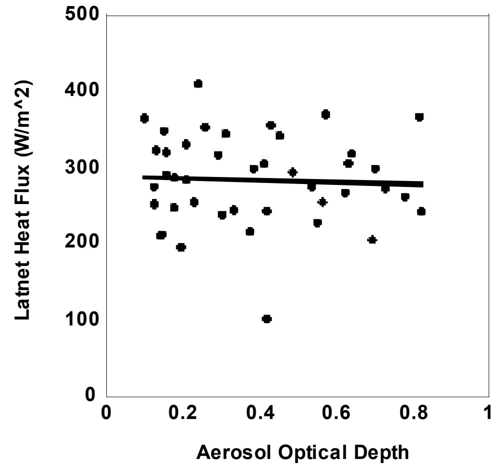


Figure 4.1.1e

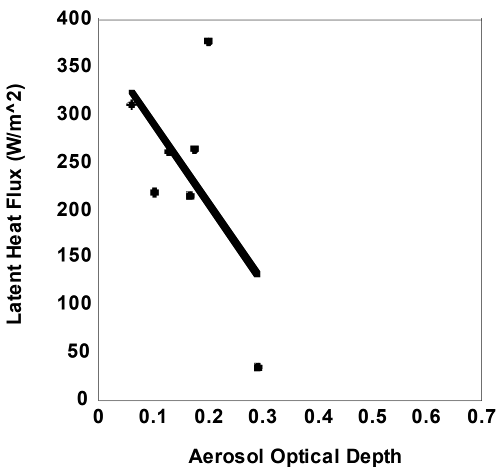
Bondville LHF vs. AOD 2001:

The trend for heat flux was not obvious and the LHF values were between 200 to 400 W/m2.

Figure 4.1.2a

Walker Branch LHF vs. AOD 2000:

Heat flux values didn’t vary with increasing AOD at this broad-leaved, deciduous forest.



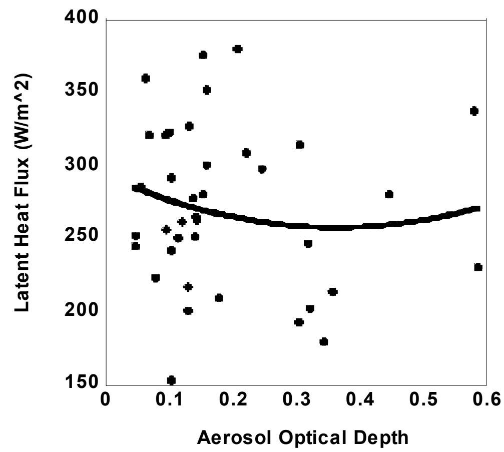


Figure 4.1.2b

Willow creek LHF vs. AOD 1999:

LHF decreased significantly with the increase of aerosol loading at this temperate forest.

Figure 4.1.2c

Willow creek LHF vs. AOD 2000:

Latent heat flux values were much scattered and more aerosol loadings at year 2000. But this plot indicates that heat fluxes did not very with increasing AOD (related to Figure 4.1.2b).

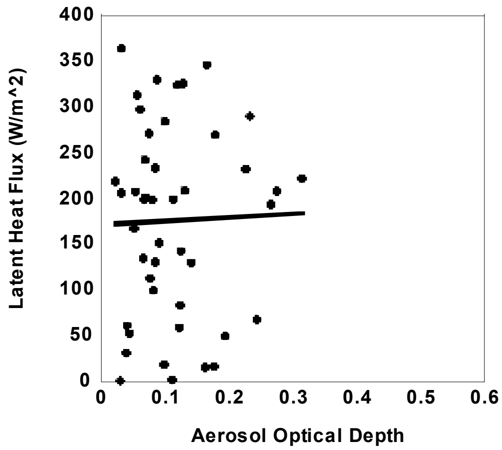


Figure 4.1.2d

Willow creek LHF vs. AOD 2001:

Similar to Figure 4.1.2c, no significant trend in heat fluxes in 2001 for Willow creek site.

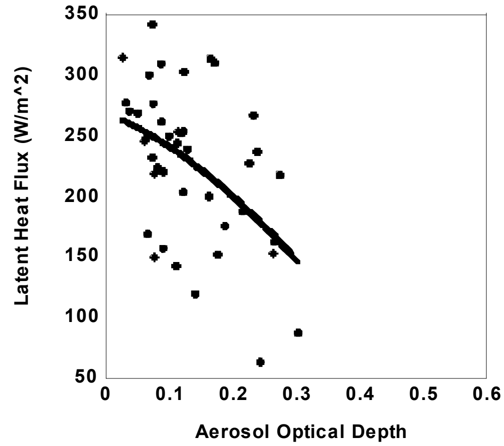
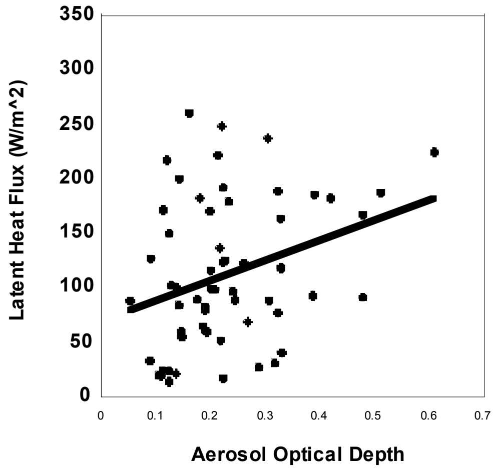


Figure 4.1.2e

Lost creek LHF vs. AOD 2001:

For nearby Lost creek site (Alder-willow wetland), heat fluxes decreased with aerosol loading (related to Figure 4.1.2d).



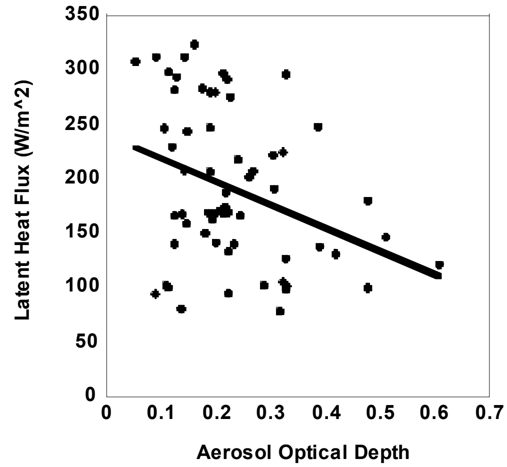


Figure 4.1.3

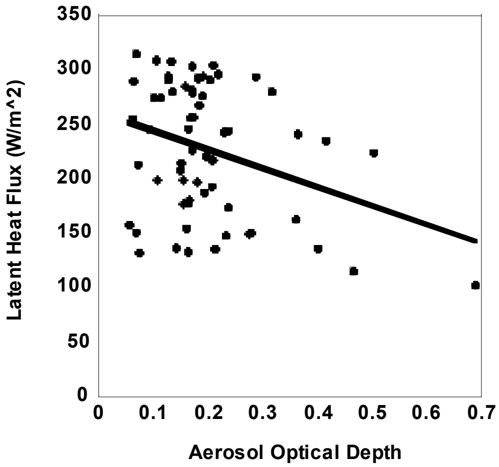
Ponca city LHF vs. AOD 1998

With increasing aerosols, the heat flux intake by the ground vegetation increased at this winter wheat site.

Figure 4.1.4a

Shidler LHF vs. AOD 1998

Similar to Lost creek (hardwood forest site, significant trend of latent heat fluxes decrease with aerosol loading at grassland site.



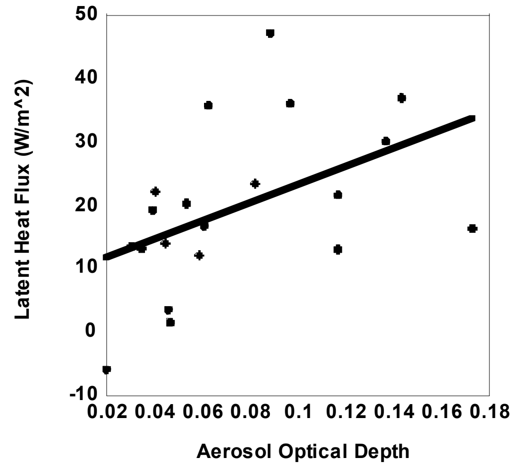


Figure 4.1.4b

Shidler LHF vs. AOD 1999:

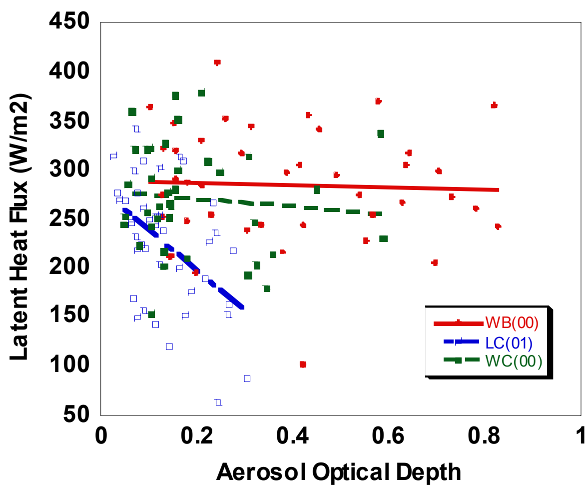
The minimum values of latent heat fluxes in Shidler 1999 were higher that the previous year (1998); bith maximum and minimum values were concentrated during lower aerosol decreasing trend of the heat fluxes similar to Figure 4.1.4a.

Figure 4.1.4c

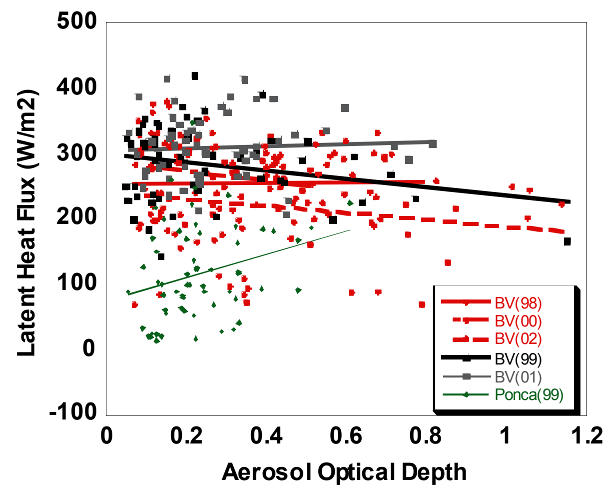
Barrow LHF vs. AOD 1999:

Similar to grassland site, the latent heat fluxes increase with aerosol loading in Barrow

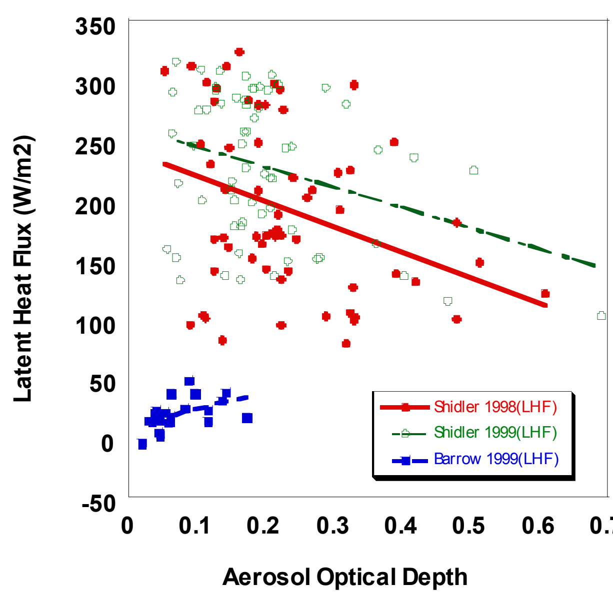
(AK) tundra site.



(a) forest



(b) cropland

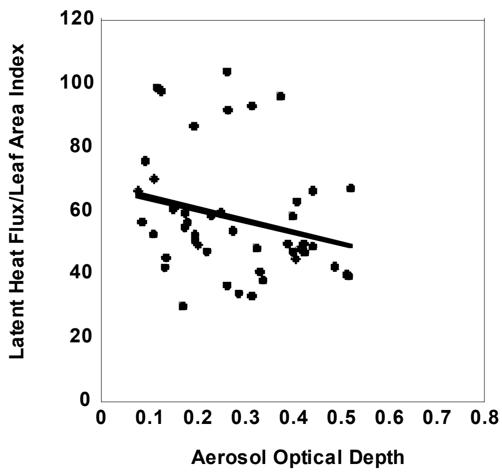


(c) grassland

Figure 4.1.5 a, b and c

Clustered latent heat fluxes and aerosol loading correlations for all researched sites and periods.

Unlike relations between CO2 fluxes and aerosols, latent heat flux appears to generally decrease with increasing Aerosol Optical Depths for most of the studied sites. But there are a few exceptions in one of the grassland site and one year in cropland.



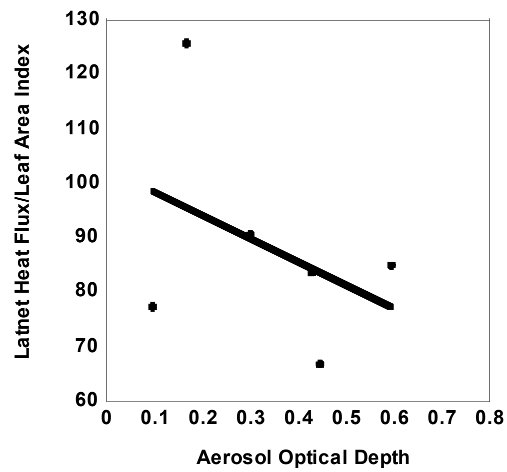
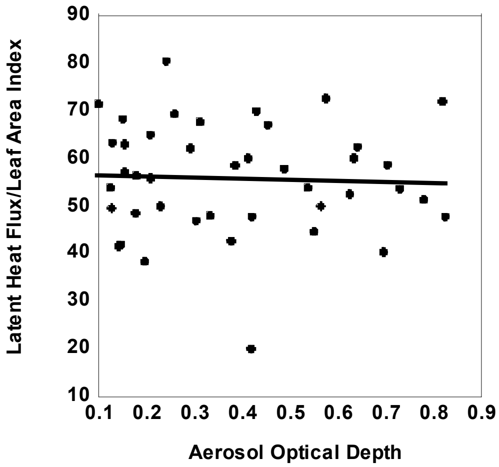


Figure 4.2.1a

Bondville (IL) LHF/LAI vs. AOD 2000 (soybean)

Figure 4.2.1b

Bondville (IL) LHF/LAI vs. AOD 2001 (corn)



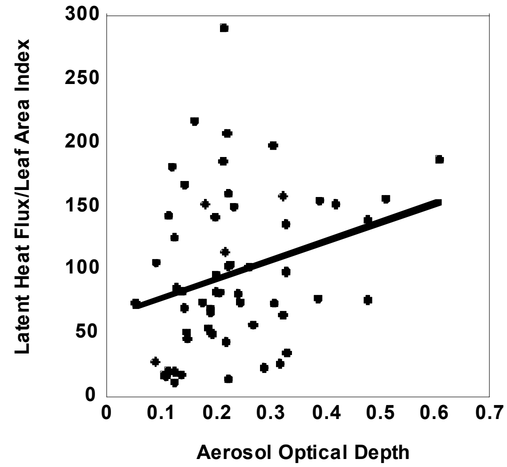
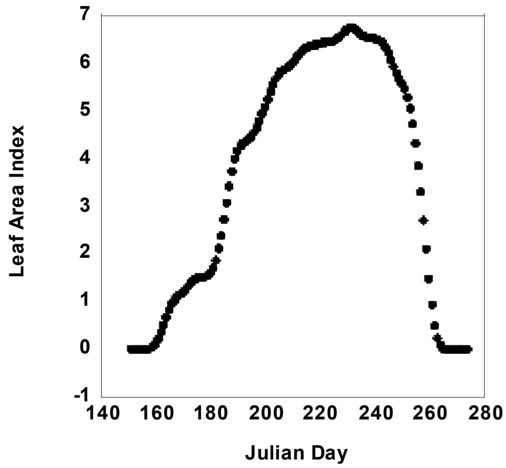


Figure 4.2.2

Walker Branch (TN) LHF/LAI vs. AOD 2000 (hardwood forest)

Figure 4.2.3

Ponca City LHF/LAI vs. AOD 1999 (grassland)



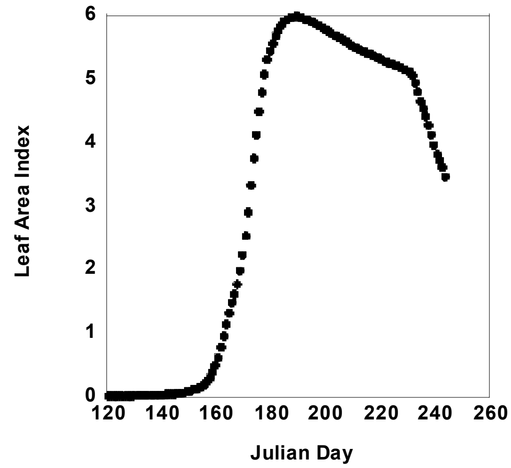
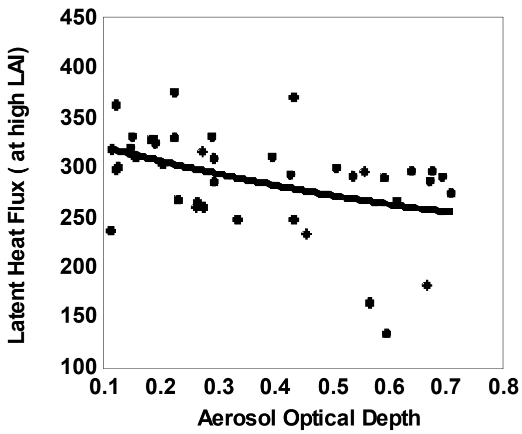


Figure 4.3.1a

Leaf area index (LAI) time series for Bondville 1998 (soybean) during the growing season (June to August).

Figure 4.3.1b

LAI time series for Bondville 1999 (corn) from June to August.



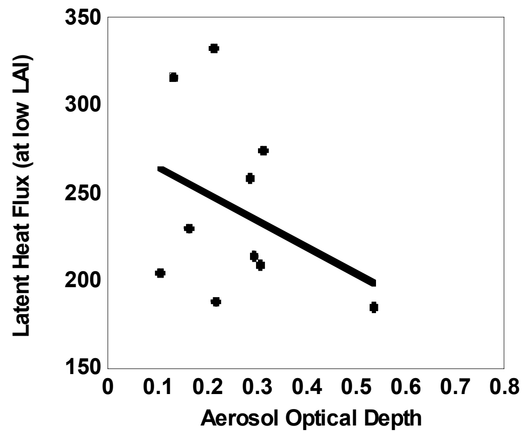


Figure 4.3.2a

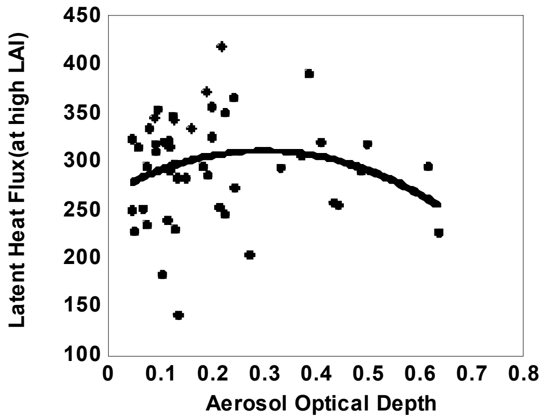
LHF vs. AOD for Bondville 1998 at high LAI condition (LAI > 3.0):

Latent heat fluxes slightly decrease with aerosol loading.

Figure 4.3.2b

LHF vs. AOD for Bondville 1998 at low LAI condition (LAI < 2.5):

One can see a dramatic decrease of heat flux values caused by aerosols.



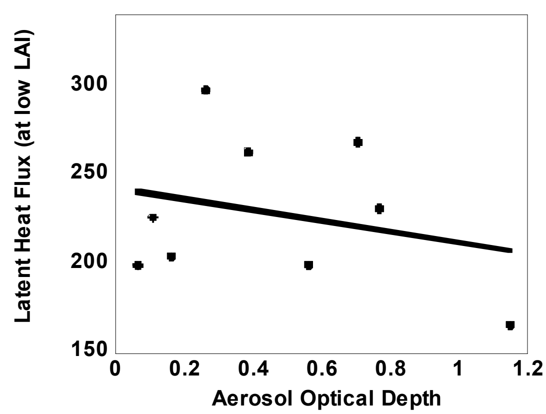


Figure 4.3.3a

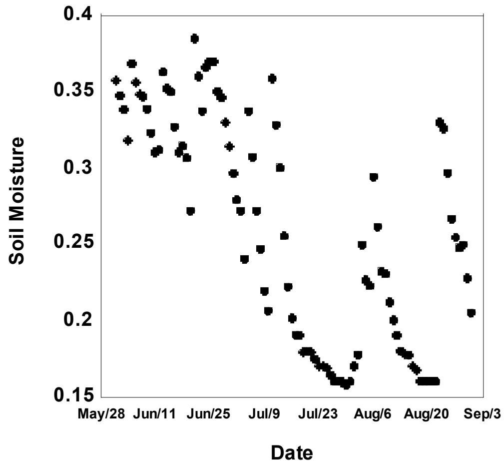
LHF vs. AOD for Bondville 1999 at high LAI condition (LAI >3.0):

No significant trend of increase/decrease of latent heat fluxes with aerosol loading.

Figure 4.3.3b

LHF vs. AOD for Bondville 1999 at low LAI condition (LAI < 2.5):

LHF decrease with increasing AOD.



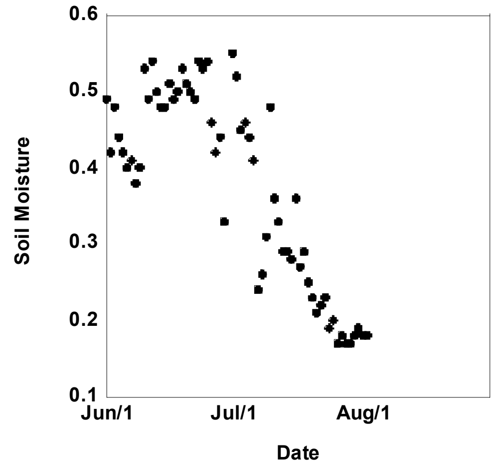


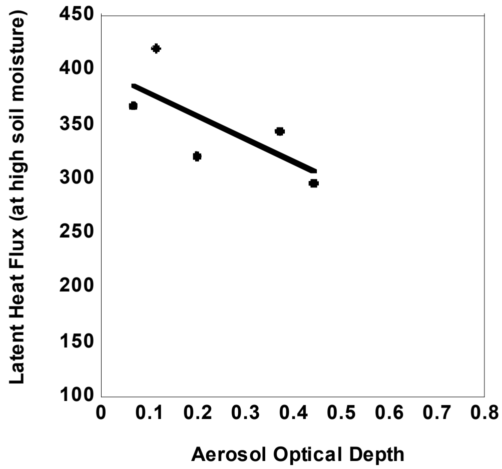
Figure 4.4.1a

Time series for Bondville soil moisture from June to August 2000 at layer 0-15cm.

Figure 4.4.1b

Soil moisture time series for Ponca City summer 1999 at layer 0-15cm.

Note that the soil moisture content is higher here in grassland site than the soybean site from Figure 4.4.1a.



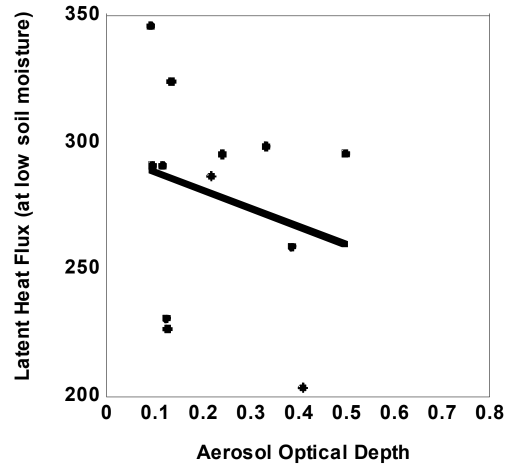


Figure 4.4.2a

Bondville LHF vs. AOD 1999 at high soil moisture content.

Figure 4.4.2b

Bondville LHF vs. AOD 1999 at low soil moisture content.

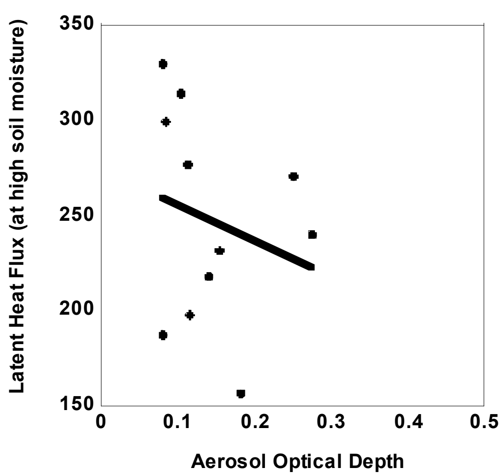


Figure 4.4.2c

Bondville LHF vs. AOD 2000 at high soil moisture content.

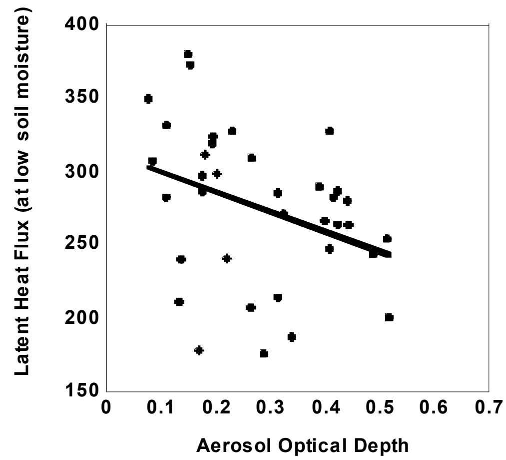
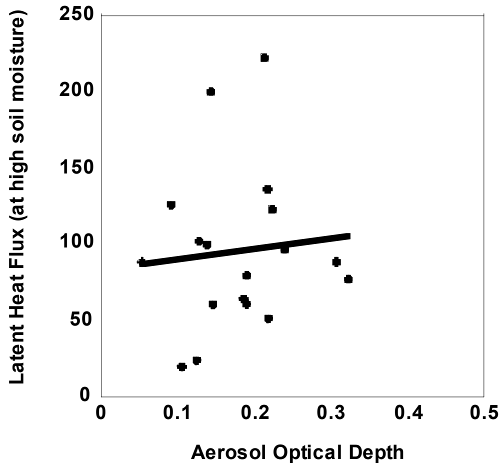


Figure 4.4.2d

Bondville LHF vs. AOD 2000at low soil moisture content.



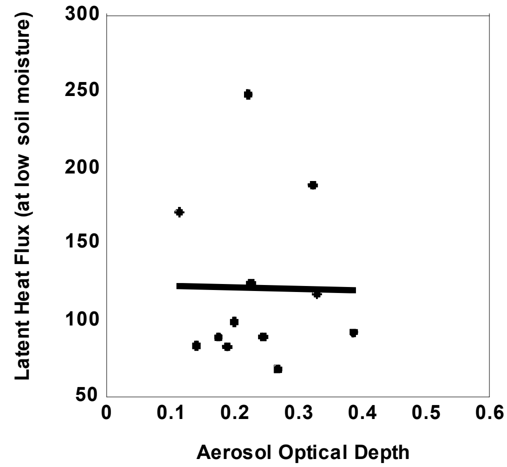
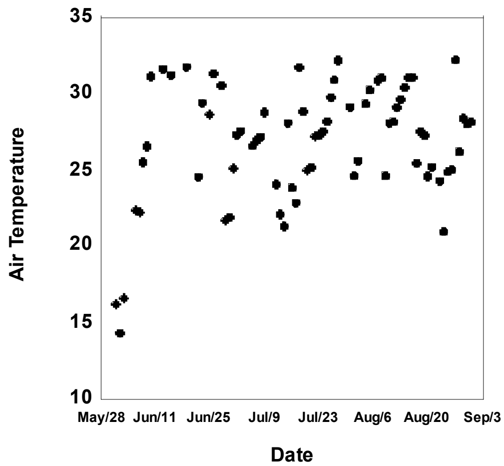


Figure 4.4.3a

Ponca city LHF vs. AOD 1999 at high soil moisture content.

Figure 4.4.3b

Ponca city LHF vs. AOD 1999 at low soil moisture content.



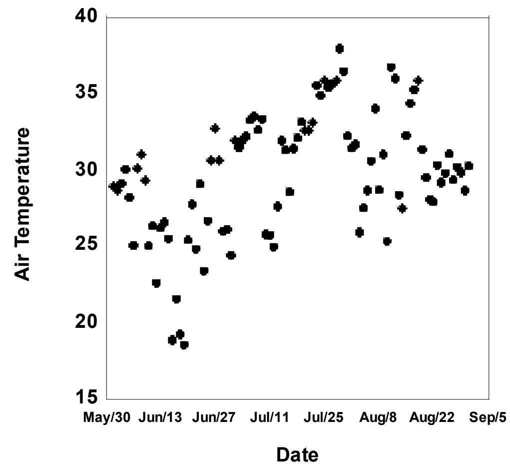
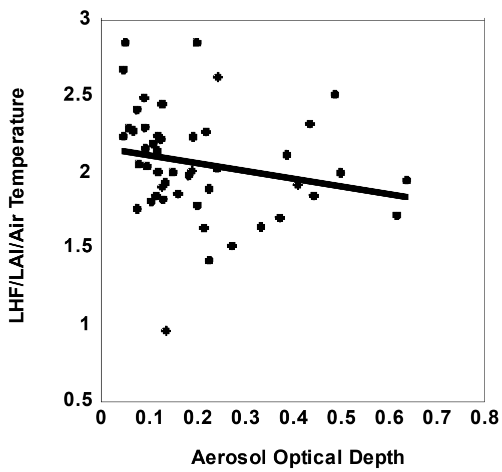


Figure 4.5.1a

Air temperature time series for Bondville in summer 2000 (soybean site) from June 1st to August 31st.

Figure 4.5.1b

Air temperature time series for Ponca City in summer 1999 (grassland site) from June1st through August 31st.



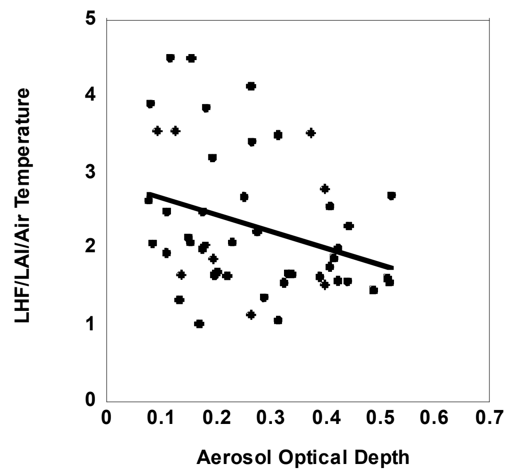


Figure 4.5.2a

Bondville LHF vs. AOD 1999 under no leaf area and no air temperature effects. (corn)

Figure 4.5.2b

Bondville LHF vs. AOD 2000 under no leaf area and no air temperature effects. (soybean)

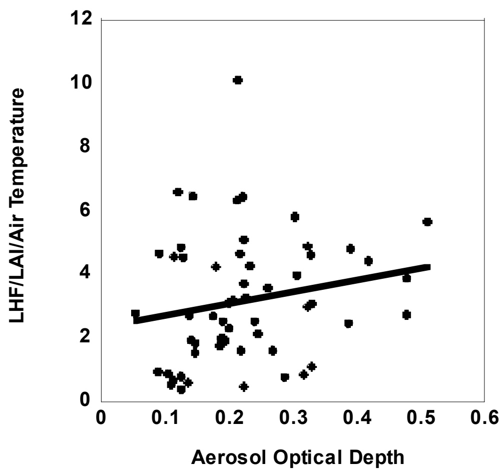
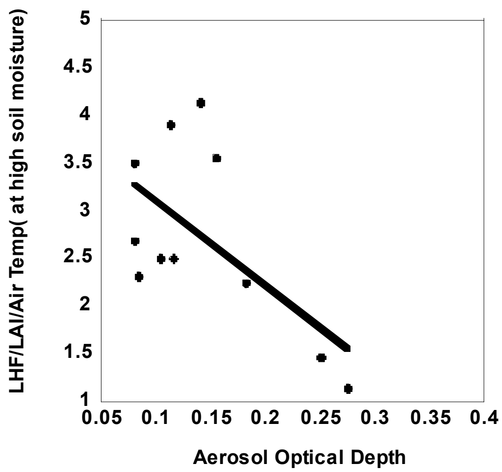


Figure 4.5.2c

Ponca city LHF vs. AOD 1999

under no leaf area and no air temperature

effects. (grassland)



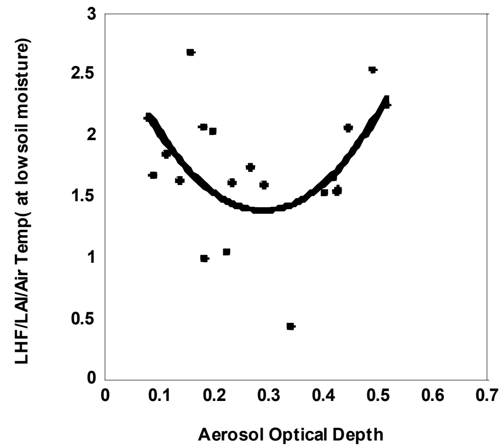


Figure 4.5.3a

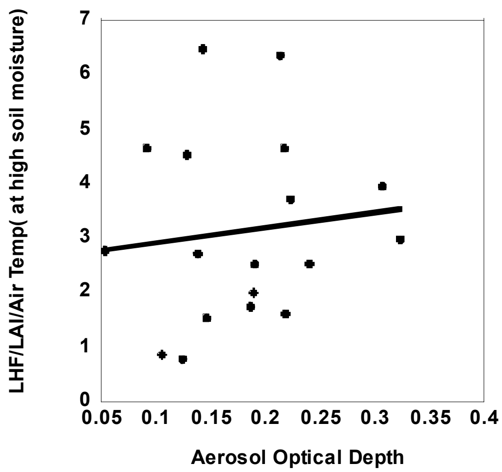
Bondville LHF/LAI/air temp vs. AOD.

At year 2000 under high soil moisture condition (soybean).

Figure 4.5.3b

Bondville LHF/LAI/air temp vs. AOD.

At 2000 under low soil moisture condition (soybean).



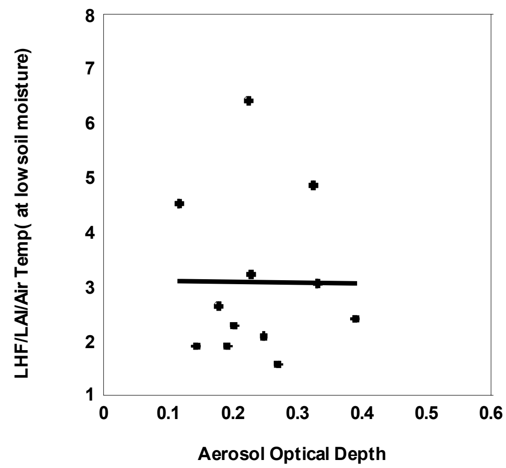


Figure 4.5.4a

Correlation between latent heat flux and aerosol loading without leaf area moisture content and air temperature effects at high soil moisture content in Ponca City 1999 (grassland).

Figure 4.5.4b

Correlation between latent heat flux and aerosol loading without leaf area and air temperature effects at low soil moisture content in Ponca City 1999 (grassland) (compare with Figure 4.4.3b).