

GAS FLUX ESTIMATION FROM SURFACE GAS CONCENTRATIONS

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Presented to
The Academic Faculty

By

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GAS FLUX ESTIMATION FROM SURFACE GAS CONCENTRATIONS

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EPIGRAPH

In physical science a first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it.

— Baron William Thomson Kelvin

Lecture to the Institution of Civil Engineers, London (3 May 1883)

DEDICATION

To my father, M. Nurul Amin

PREFACE

A gradient-independent model of gas fluxes was formulated and tested. The model is built on the relationship between gas flux and the time history of surface gas concentration, known as half-order derivative (HOD), when the transport of the gas in the boundary layer is described by a diffusion equation. The eddy-diffusivity of gas is parameterized based on the similarity theory of boundary layer turbulence combined with the MEP model of surface heat fluxes. Test of the new model using in-situ data of CO₂ concentration and fluxes at several locations with diverse vegetation cover, geographic and climatic conditions confirms its usefulness and potential for monitoring and modeling greenhouse gases. The proposed model may also be used for estimating other GHGS fluxes such as methane (CH₄) and Water vapor flux. This proof-of-concept study justifies the proposed model as a practical solution for monitoring and modeling global GHGS budget over remote areas and oceans where ground observations of GHGS fluxes are limited or non-existent. One focus of the on-going research is to investigate its application to producing regional and global distributions of carbon fluxes for identifying sinks and sources of carbon and re-evaluating the regional and global carbon budget at monthly and annual time scales.

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Most Sincerely,

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LIST OF ABBREVIATIONS

B	Bowen Ratio
C	Gas Concentration
CMDL	Climate Monitoring and Diagnostic Laboratory
c_p	Specific Heat of Air at Constant Pressure
CSIRO	Commonwealth Scientific and Industrial Research Organization
D	One Dimensional Diffusion Coefficient
E	Latent Heat Flux
EMEP	MEP Model Latent Heat Flux
e_0	Saturation Vapor Pressure at Reference Temperature
EOBS	Observed Latent Heat Flux
F	Gas Flux
FC	CO ₂ Flux
G	Ground Heat Flux
GHGS	Green House Gases
H	Sensible Heat Flux
HMEP	MEP Model Sensible Heat Flux
HOBS	Observed Sensible Heat Flux
HOD	Half Order Derivative
I_0	Apparent Thermal Inertia of the Air
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
I_s	Thermal Inertia of Soil
κ	Von Karman Constant
λ	Latent Heat of Vaporization of Liquid Water
MEP	Maximum Entropy Production
NOAA	National Oceanic and Atmospheric Administration
NRMSE	Normalized Root-Mean-Square Error
Pg C	Petagram Carbon
P_s	Surface Atmospheric Pressure
q_s	Specific Humidity at Ground (or Canopy) Surface
ρ	Density of Air
RMSE	Root-Mean-Square Error
Rn	Net Radiation
Rv	Gas Constant of Water Vapor
Ta	Air Temperature
Ts	Canopy (or Soil Skin) Surface Temperature
T ₀	Reference Temperature (in Kelvin)
u_*	Friction Velocity
z	Vertical distance between Canopy Top (Ground) and Point of Measurement

SUMMARY

The goal of this study is to develop a gradient-independent method for modeling surface gas flux using surface gas concentration data. The proposed method is built on the relationship between gas flux and the time history of surface gas concentration, known as half-order derivative (HOD), when the transport of gas in the boundary layer is described by a diffusion equation. A new parameterization of the eddy-diffusivity of gas is based on the similarity theory of boundary layer turbulence combined with the MEP model of surface heat fluxes reduces the sensitivity of the modeled fluxes to model parameters. The proposed model is tested using in-situ data of CO₂ concentration time series, net radiation and surface temperature at canopy (or ground) surface at half hour (or hour) intervals from Ameriflux Network at several locations with diverse vegetation cover, geographic and climatic conditions to test the applicability of model within reasonable endeavor. The study sites are Santarem KM67 Primary Forest, Brazil; Cedar Bridge, New Jersey, USA; Delta Junction 1920 Control, Alaska, USA and Walnut Gulch Lucky Hills Shrubland, Arizona, USA. The modeled CO₂ flux demonstrates close agreement with field observations with high value of correlation coefficient and regression coefficient (using observed flux as regressor) between modeled and observed CO₂ fluxes. The modeled CO₂ fluxes well capture the diurnal variation and magnitude of the observed fluxes. The magnitudes of modeled fluxes are comparable to the observed fluxes except for a small number of points due to the linear interpolation of the missing CO₂ concentration data points. The sensible heat flux used in parameterization of diffusion coefficient of CO₂ is estimated using MEP model with other energy fluxes

(such as ground heat flux and latent heat flux) using net radiation and canopy (or ground) surface temperature. The estimated energy fluxes using MEP model compared with observed energy fluxes for the study sites shows high correlation and captures diurnal variation and magnitude of the observed energy fluxes. Agreement between modeled and observed CO₂ flux is solid during growing season especially at forested sites.

The study demonstrated the usefulness and potential of the proposed gradient independent model of surface gas fluxes using surface gas concentration for monitoring and modeling of regional and global GHGS budget. The parsimony of model input makes it ideal for estimating fluxes of GHGS including CO₂ and methane given limited data availability and space-time coverage and resolution. Further field scale tests of the proposed model at daily and longer time scales are underway.

CHAPTER 1

INTRODUCTION

Increase in the atmospheric CO₂ concentration since 1750 has the largest contribution in climate change and surface warming (IPCC, 2013). Understanding and predicting the impact of increasing CO₂ and other greenhouse gases (GHGS) in the atmosphere on climate change requires accurate global CO₂ and other GHGS fluxes data. The uncertainties in the existing CO₂ fluxes data are arguably responsible for the unbalanced carbon budget at regional and global scales causing missing carbon sink problem (Schimel, 1995). A recent modeling study of the global carbon cycle suggests that the northern hemisphere terrestrial sinks are overestimated while tropical ecosystem sinks are underestimated (Stephens's et al., 2007). This finding implies that imbalance of global carbon budget causes the missing carbon sink in northern hemisphere. Global carbon budget was obtained using the mass balance equation of carbon emissions from fossil fuel and cement production and their partition among land, ocean and atmosphere (Le Quéré et al., 2013). Such derived global carbon budget has large uncertainties especially for terrestrial land, on the order of $\pm 0.8 \text{ Pg C yr}^{-1}$ when calculated using residual of mass balance equation and on the order of $\pm 1 \text{ Pg C yr}^{-1}$ when estimated using Dynamic Global Vegetation Models (Le Quéré et al., 2013).

Uncertainty of the current global carbon budget is closely related to the models of CO₂ fluxes. Reliable regional and global estimates of trace gas emissions depend on improved methodologies to reduce the uncertainty in the current estimates, which may be alleviated by developing new flux models for different processes, different gas species and on different space-time scales. Gas fluxes estimates of both terrestrial and aquatic systems have substantial uncertainties. In aquatic systems gas fluxes are generally modeled in terms of gas transfer velocity and concentration gradient in the atmosphere. Gas transfer velocity is parameterized in terms of wind speed with large measurement errors. There are large uncertainties in measurement of CO₂ concentration due to Webb effect, e.g. signal is sensitive to water vapor by overlapping CO₂ and H₂O IR peaks, pressure broadening effects and air density effects of sensitive and latent heat fluxes on the CO₂ gas (Reference) which causes measured flux an order of magnitude greater than actual flux over ocean. The uncertainty in the global emission rate is illustrated by the difference of more than a factor of 4 between the lowest and highest global emission rate (Boumann et al., 1999).

Current modeling and measurement methods of gas flux estimation in terrestrial ecosystem include: Chamber methods, Flux gradient methods, Eddy Correlation Methods, Mass Balance methods, Energy Balance methods, Convective Boundary Layer Budget methods, Nocturnal Boundary Layer Budget methods and Inverse Lagrangian model. Uncertainties in flux estimation in terrestrial ecosystem depend on specific measurement or modeling methods. For example, Chamber method is used for process level studies measuring trace gas fluxes and uncertainties result from chamber effects on

perturbation of the original natural environment (Hutchinson and Moiser, 1981; Moiser, 1989; Livingston and Hutchinson, 1995). Gradient method uses air samples from different levels having different foot prints causing potential problems to flux measurement (Denmead and Raupach, 1993). Although eddy correlation methods provide the most direct measurement of fluxes but, using fast response sensors make this method to technically demanding and expensive (Lapitan et al. 1999). Mass balance method works well for homogeneous ecosystems with known geometry of study area. The uncertainties of flux estimates result from surface roughness, horizontal wind velocity, mean background concentration and atmospheric stability conditions (Denmead and Raupach, 1993; Lenschow, 1995). Energy balance method has difficulty in making accurate measurements during nighttime and rainy events (Wagner-Riddle et al, 1996 a, b). Sensitivity to weather conditions limits the applicability of Convective Layer Budgeting methods (Denmead et al., 1996). Nocturnal Layer Budgeting method also has difficulties during nighttimes due to reduced height of nocturnal layer. Uncertainties of Inverse Lagrangian Dispersion modeled fluxes are caused by heterogeneous canopies such as re-growth forests as this model assumes homogeneous canopies with uniform distribution of source and sink horizontally (Raupach, 1989a, b). Although models developed for specific ecosystems may have less uncertainty but when extrapolating for a larger area with spatial and temporal variability, limited data availability may increase uncertainty (Mosier and Parton, 1985).

Except for limited number of ground observation stations where carbon fluxes are measured directly, CO₂ fluxes are commonly derived using the bulk transfer model requiring remote sensing or reanalysis data of near-surface CO₂ concentration gradient and wind speed are subject to large measurement errors. CO₂ fluxes over oceans are routinely derived using the bulk transfer model from the concentration gradient of CO₂ across the air-sea interface with the gas transfer coefficient parameterized in terms of wind speed. However, CO₂ concentration gradient in sea-water boundary layer cannot be measured directly, usually inferred from in partial pressure of CO₂, $\Delta p\text{CO}_2$, which is difficult to estimate (McGillis, 2006). Changes in wind speed have pronounced effect on the parameterization of gas transfer coefficient hence estimation of CO₂ flux (Wanninkhof, 2007). The overall uncertainty in the global air-sea CO₂ flux is on the order of -19% to +22% due to wind speed (Takahashi, 2002) and on the order of 25% due to the measurement errors of $\Delta p\text{CO}_2$ (Wanninkhof, 2007).

Reducing the uncertainty of the estimated CO₂ fluxes for solving the mystery of the missing carbon sink in the study of regional and global carbon budget needs a more suitable model of carbon fluxes. The goal of this study is to formulate and test a new model of carbon fluxes that does not use CO₂ concentration gradient and wind speed data. The basic idea is to express the CO₂ flux in terms of near-surface CO₂ concentration time-series, analogous to ground heat flux expressed as a functional of ground temperature (Wang and Bras, 1999), to avoid the use of CO₂ concentration gradient. The eddy diffusivity in the governing equation describing the transport of CO₂ in the boundary layer is parameterized in terms of sensible heat flux according to a similarity model of

atmospheric turbulence (Wang and Bras, 1999) to avoid the use of wind speed. The proposed model was tested using field observations of CO₂ concentration, CO₂ fluxes and sensible heat flux. Using the MEP model of surface heat fluxes (Wang and Bras, 2011), sensible heat flux may be derived from net radiation and surface temperature without using wind speed data, paving the way for remote sensing application of the proposed model.

CHAPTER 2

LITERATURE REVIEW

2.1 Gas Flux Measurement in Terrestrial Ecosystems

Current measurement methods of gas flux estimation in terrestrial ecosystem include Chamber methods and Micrometeorological methods (Lapitan et al., 1999).

Chamber techniques are of two types: Closed Chamber and Open Chamber.

Micrometeorological methods include: Flux gradient methods, Eddy correlation, Eddy accumulation, Bowen ratio methods, Mass balance methods, Convective boundary layer budget methods. Tracer method is used to measure diffusion coefficient which is a significant source of uncertainties in Flux gradient and Energy Balance (Bowen Ratio) methods. The Micrometeorological methods can also be applied for aircraft mounted measurements to provide spatially averaged, aerial assessments of gas fluxes.

Above methods are described in the following sections.

2.1.1 Chamber Methods

Chamber methods are used for measuring small gas fluxes in process-level studies, identifying sources of spatial variations controlling gas fluxes (Hutchinson and Moiser, 1981; Moiser, 1989; Livingston and Hutchinson, 1995). The chamber methods are of two types: Closed Chamber and Open Chamber. The closed chamber restricts exchange of heat and water vapor between inside and outside of chamber.

In open chamber method, a steady state gas concentration gradient is established by maintaining concentration of gas in the enclosed volume of air at ambient level through continuous air flow of external air. The Formulations for closed and open chamber methods are shown in equation (2.1) and (2.2), respectively,

$$F = \frac{V}{A} \frac{dC_g}{dt} , \quad (2.1)$$

$$F = \frac{f}{A} (C_{g(o)} - C_{g(i)}) , \quad (2.2)$$

where F is the gas flux, V the chamber volume, A the chamber area, C_g the gas concentration in the chamber, t the time, f the air flow rate, $C_{g(o)}$ the concentration in the air going out of the chamber and $C_{g(i)}$ the concentration in the air coming into the chamber.

Changes in gas concentration due to emission magnified in a closed chamber provides better precision relative to open chamber for detecting small fluxes. Errors in flux measurement primarily caused by chamber effects on perturbation of the original natural environment (Denmead, 1979; Hutchinson and Mosier, 1981; Mosier, 1990; Hutchinson and Livingston, 1993; Livingston and Hutchinson, 1995). Gas flux over an area is obtained by taking spatial averages of chamber fluxes aligned at grid points along wind direction.

2.1.2 Flux Gradient Method

The flux gradient method measures gas flux from concentration gradient and eddy diffusivity of the gas. Eddy diffusivity of a gas is inferred using tracers (e.g. heat and water vapor). Fluxes and concentration gradients are measured simultaneously with gas concentration gradient (Denmead and Raupach, 1993). Eddy diffusivity of gas corrected for atmospheric stability condition is estimated from temperature and wind profile measurements (Paulson, 1970; Businger et al., 1971). The Formulation of flux gradient method is shown in equation (2.3).

$$F = \frac{\kappa U_* z}{\varphi_h} \frac{dC_g}{dz} , \quad (2.3)$$

where, F is the flux, κ the Van Karman's constant, U_* the friction velocity, $\frac{dC_g}{dz}$ the concentration gradient between two layers, z the sensor height and φ_h the atmospheric correction for heat. The uncertainty in the estimated flux results from the measurement of concentration gradient and wind velocity, which have uncertainty themselves. Another potential problem with this method is that air samples from different level have different foot prints.

2.1.3 Eddy Correlation Method

Eddy correlation method relates the covariance of instantaneous vertical wind velocity with the instantaneous fluctuations of gas concentration to estimate vertical flux density from (in case of deposition to) the surface. The formulation of Eddy Correlation methods is shown in equation (2.4).

$$F = \overline{w'c_g'} + \frac{\overline{c_g}}{\overline{\rho_a}} \left(\frac{\eta}{1+\eta\beta} \right) E + \frac{\overline{c_g}}{(\overline{\rho_a} + \overline{\rho_v})} \left(\frac{H}{c_p T} \right) , \quad (2.4)$$

where, F is the gas flux, $\overline{w'c_g'}$ the time averaged instantaneous fluctuations of vertical wind velocity and instantaneous fluctuations of gas concentration, $\overline{c_g}$ the time averaged concentration, $\overline{\rho_a}$ the time averaged density of dry air, $\overline{\rho_v}$ the time averaged density of moist air, c_p the specific heat of air at constant pressure, T the air temperature, H the sensible heat flux, E the latent heat flux, η the ratio of molecular weights of dry and moist air and β the ratios of the mean densities of dry and moist air. Eddy correlation method is the most direct method of gas flux measurement but it is technically demanding considering the logistics before and during data acquisition (Lapitan et al. 1999). These include check on instrument drifts, transient errors, vertical alignment and sitting geometry relative to mast and other sensors (Businger, 1986). The sensor sampling height and fetch are also important factors affecting measurement of flux. The minimum sensor (wind and temperature) of 2 m requires a fetch of 200 m (Denmead and Raupach, 1993). Decrease in gas concentration with height and thermal stratification affects gas flux density (Lapitan et al. 1999).

Gas flux obtained in this method is averaged over a period 15 min to 1 hour. Fast response analytical instrumentation (TDL and FTIR spectrometers) can increase the cost but sensitively measure a range of gas fluxes within spatial variability among terrestrial ecosystems (Edwards et al. 1994; Simpson et al. 1995).

2.1.4 Eddy Accumulation Method

Eddy accumulation method is similar to eddy correlation, but accumulated instead of instantaneous air samples are measured in two reservoirs for concentration of gas species, slow response and high resolution spectrometer can be used. The Formulation of Eddy Accumulation methods is shown in equation (2.5).

$$F = b(\overline{C_g^+} - \overline{C_g^-}) , \quad (2.5)$$

where, F is the flux, b the proportionality coefficient has a value close to 0.6 (Denmead, 1994), $\overline{C_g^+}$ and $\overline{C_g^-}$ the average gas concentrations in the air reservoir at ‘up’ position and ‘down’ position respectively. Advantages for this method includes: it does not require fast response sensors and need not to be in the field so that high resolution laboratory based instruments can be used, measurements do not need density corrections and it provides direct point measurement (Denmead, 1994). Potential sources of error for this method results from offsets in vertical wind velocity, mechanical failures of fast switches and flow rate circuitry and low resolution of gas analyzer (Hicks and Mcmillen, 1984), especially when updraft and downdraft changes in gas concentration is small.

2.1.5 Energy Balance Method

This method measures air temperature, water vapor pressure and gas concentration at two heights above surface. The sensible heat flux and latent heat flux components of energy balance is measured separately from the finite difference of temperature gradient and vapor pressure gradient respectively or by residual knowing total net radiation, ground heat flux, and either sensible heat flux or latent heat flux. The eddy diffusivity coefficient can be derived from ratio between sensible heat flux and temperature gradient and by invoking the similarity assumption, diffusivity of desired gas is obtained. Using this assumption alleviates the need for atmospheric stability correction for energy balance approach. Flux is estimated from product of concentration gradient and diffusivity or from the ratio of measured gas concentration and temperature gradient given net radiation and ground heat flux. The Formulation of Energy balance method is shown in equation (2.6),

$$F = \frac{(R_n - G)(C_g^+ - C_g^-)}{c_p(1 + \gamma)(T^+ - T^-)} , \quad (2.6)$$

where F is the flux, R_n the net radiation, G the ground heat flux, C_g^+ the gas concentration measured by sensor in the air reservoir at ‘up’ position, C_g^- the gas concentration measured by sensor in the air reservoir at ‘down’ position, c_p the specific heat of air at constant pressure, γ the ratio of mean densities of water vapor and air, T^+ the air temperature measured at ‘up’ position and T^- the air temperature measured at ‘down’ position.

Energy balance method does not provide good agreement during nighttime and rainy condition due to low available energy (Wagner-Riddle et al, 1996 a,b). Other sources of error include transient error in heat and moisture sensors, sampling errors during low available energy (Fritschen and Gay, 1979), inequalities in exchange coefficients (Dugas et al., 1997; Meyers et. al., 1996), and differences in horizontal length scale of air sampled at different heights.

2.2. Gas Flux Modeling Methods in Terrestrial Ecosystems

Current modeling methods of gas fluxes in terrestrial ecosystem include Inverse Lagrangian model (Raupach, 1989b) to identify sources and sinks of scalars in the canopy space from mean concentration, mass balance method, convective boundary layer budget model (Raupach et al., 1992; Denmead et al., 1996) and nocturnal boundary layer budget model. Descriptions of above models are as follows:

2.2.1 Inverse Lagrangian Dispersion Model

Inverse Lagrangian Dispersion model of gas flux proposed by Raupach (1989a, b) infers fluxes of trace gases and their source sink distribution over canopies by building relationship between chamber measurements and canopy measurements at field scale. This method requires a mean concentration profile of gas within the canopy and some knowledge of turbulence and lagrangian time scales of that region. Within the canopy, the source or sink strength of the gas at level z $S(z)$ is related to vertical flux density $F(z)$,

$$S(z) = \frac{dF(z)}{dz}, \quad (2.7)$$

Integrating (2.7) gives

$$F(h) = F(0) + \int_0^h S(z)dz, \quad (2.8)$$

where $F(0)$ is the flux density at surface, and h the height of canopy above the surface. Lagrangian dispersion theory (Raupach, 1989a) enables a prediction of mean concentration profile $C(z)$ from $S(z)$. Adding Emissions from all source layers, gas concentration at any height is given by

$$C_i - C_R = \sum D_{ij} S_j \Delta Z_j , \quad (2.9)$$

where, C_R , is the concentration at a reference height above the canopy and D_{ij} are the coefficients of the dispersion matrix. These coefficients are calculated from profiles of standard deviation of vertical wind speed, σ_w , and lagrangian time scale within canopy, T_L (Raupach, 1989a). Using values of D_{ij} , in (2.9) yields a system of linear equations from which $C_i - C_R$ can be solved for source densities S_j with known values of concentrations, C_i . Redundant concentration data should be included so that source densities S_j are sought in m layers with n measured concentration values such that $n > m$. This method is based on the assumption of homogeneous canopies where the source and sink pattern is uniform horizontally. It may not work as well in heterogeneous canopies such as regrowth forests. The method showed some discrepancies with conventional micrometeorological methods during earlier part of day (Denmead and Raupach, 1993).

2.2.2 Mass Balance Model

Mass balance model is suitable for small fetches. This method is used to estimate gas flux density at the height of boundary layer developed over a given fetch from the height integral of the product of mean horizontal wind and upwind gas concentration corrected by the mean background concentration. The Formulation of mass balance method is shown as,

$$F = \frac{1}{X} \int_0^z u(C_{g(u)} - C_{g(b)}) dz , \quad (2.10)$$

where, F is the flux, X the length of upwind fetch, u the horizontal wind speed, z is the depth of modified layer (1/10 of fetch), $C_{g(u)}$ and $C_{g(b)}$ are the upwind and background gas concentration respectively. The uncertainties of flux estimation result from surface roughness, horizontal wind velocity, atmospheric stability conditions and mean background concentration (Denmead and Raupach, 1993; Lenschow, 1995). Formulation of mass balance method neglects diffusion transport that is 10% of the contribution due to convective transport (Raupach and Legg, 1984). Another possible sources of error involves subtraction of experimentally determined upwind and downwind concentration profiles, an error prone process due to logistic difficulty of measuring two concentration profiles. A third difficulty arises from lack of knowledge about wind speed dependent fetch length. This method becomes unreliable under the condition of variable wind directions.

2.2.3 Convective Boundary Layer Budget Model

Convective Boundary Layer (CBL) is a shallow surface layer (about 100m depth) with large concentration gradients. The vertical gas fluxes is nearly constant with height with in this layer. CBL is topped by a mixed layer containing slowly varying fluxes with height and uniform concentrations. CBL is capped by sharp temperature inversion. The mixed layer grows during day time through the input of heat at the ground, entraining air above the inversion extends up to 1-2 km. CBL budgeting methods are based on the rate of change of gas concentration in the mixed layer which acts like a giant mixing chamber moving with mean wind. CBL model is formulated as (Denmead et al., 1996),

$$F = h \frac{dC_m}{dt} (C_+ - C_m) \left(\frac{dh}{dt} - W_+ \right) , \quad (2.11)$$

where, F is the surface flux density, h the height of CBL, C_m the gas concentration in CBL, C_+ the free atmosphere just above CBL, t the time and W_+ the subsidence velocity. Integrating (2.11) gives cumulated regional flux, I,

$$\begin{aligned} I(t) &= \int_0^t F(\tau) d\tau \\ &= h(t)[C_m(t) - C_+(t)] - h(0)[C_m(0) - C_+(0)] \\ &\quad + \frac{\gamma}{2}(h_t^2 - h_0^2) - \int_0^t W_+(\tau)[C_m(\tau) - C_+(\tau)] d\tau , \end{aligned} \quad (2.12)$$

In (2.12) $\gamma = \frac{dC_+}{dz}$ is the rate of change of concentration with height just above the mixed layer (h_+), C_m is obtained from near surface concentration C_s measured at height z_s with an aerodynamic resistance r_a at unstable conditions according to similarity theory,

$$C_m = C_s - r_a F , \quad (2.13)$$

$$r_a = \frac{\ln\left[\frac{(z_m-d)}{(z_s-d)}\right] - 2 \ln\left[\frac{1 + \sqrt{1 - \frac{16(z_m-d)}{L}}}{1 + \sqrt{1 - \frac{16(z_s-d)}{L}}}\right]}{ku_*} , \quad (2.14)$$

where $k = 0.41$ is von Karman's constant, u_* the friction velocity, d zero displacement distance, z_m the height from the ground to the bottom of the mixed layer and L is the Monin–Obukhov length. Assuming W_+ is small and $\gamma = 0$ (step change from C_m to C_+ at h) gives,

$$I(t) = \frac{h(t)[C_s(t) - C_+(t)] - h(0)[C_s(0) - C_+(0)]}{1 + \frac{[h(t)r_a(t) - h(0)r_a(0)]}{t}} , \quad (2.15)$$

Use of near surface concentration instead of mixed layer concentration may bias the estimates toward local flux values. Measurement at more than one location in regions of heterogeneous landscape will provide better flux estimates. Changing wind conditions, unsuitable weather and high precision gas concentration measurements are limitations of this method. This method is an effective scheme of gas flux estimation scheme at regional scale.

2.2.4 Nocturnal Boundary Layer Budget Model

Nocturnal Boundary Layer (NBL) occurs at night as convective heating stops. It is a shallow weakly turbulent layer bounded with a low level radiative inversion. Inversion inhibits vertical mixing so that emission of gases from surface are contained in shallow aerial layer whose concentration changes appreciably. The formulation of nocturnal boundary layer budget model is shown in equation (2.16),

$$F = \int_0^z \frac{dC}{dt} dz , \quad (2.16)$$

where, F is the surface flux, z the height of NBL and C the concentration at the top of the inversion layer (NBL). The growth and height of NBL are not easily predicted especially when radiative inversion layer is deep or absent so application of this method may not be possible.

2.3 Gas Flux Measurement and Modeling in Aquatic Ecosystems

Direct measurement of gas fluxes by eddy correlation, relaxed eddy accumulation and flux gradient methods are difficult over water because of small magnitude of net fluxes and large uncertainties in the measurements of temperature and concentration gradients. The flux across the air water interface F can be expressed as,

$$F = kr(C_w - \alpha' C_a) = krK_0 (pX_w - pX_a), \quad (2.17)$$

where, k is the gas transfer velocity for a nonreactive gas, r the enhancement factor by chemical reaction of the gas at interface, α' the Ostwald solubility coefficient, C_w the gas concentration near water surface, C_a the gas concentration in the air immediately above the water surface given the concentration gradient across the interface $(C_w - \alpha C_a)$. The concentration gradient equals $K_0 (pX_w - pX_a)$ when expressed in terms of partial pressure, where, K_0 is the solubility of gas in water, pX_w the partial pressure of gas in water and pX_a the partial pressure of gas in air. The gas transfer velocity k is frequently parameterized in terms of wind speed (Liss and Merlivat, 1986; Wannikhof, 1992) obtained using the following equation,

$$k_1 = k_2 \left(\frac{Sc_1}{Sc_2} \right)^n, \quad (2.18)$$

where, k_1 is the transfer velocity of gas in question, k_2 the transfer velocity of a reference gas, Sc_1 and Sc_2 the Schmidt numbers of gas in question and reference gas, respectively and n is the Schmidt number equal to -0.66 for smooth surfaces and -0.5 for rough surfaces.

The relative homogeneity of aqueous systems causes the flux to be less scale dependent in comparison to terrestrial systems. Gas concentration in lakes varies less than 5% from the mean suggests smaller spatial variation of fluxes which will be larger on global oceanic scales due to large differences in production and consumption rates. Generally, subtropical and polar gyres on average will be sinks and tropical regions the sources due to equatorial upwelling and heating of surface water. Temporal variation of fluxes on short time scales controlled by changes of environmental forcing on gas transfer velocity k and change in solubility due to temperature change. Simple parameterization of k suggests that it has a quadratic dependence on wind speed. Diurnal change in surface water temperature can be up to 2°C while annual changes in inland waters can be as large as 25°C and 5°C to 10°C over the ocean.

Methods of measurement gas flux F and/or gas transfer velocity k across air water interface include: natural ^{14}C method, bomb ^{14}C method, natural ^{222}Rn method, enclosure methods, opportunistic mass balance methods and deliberate tracer method briefly described in following sections.

2.3.1 Natural ^{14}C Method

Natural ^{14}C method uses radioisotope of Carbon -14 in water and air and mean depth of ocean and decay constant of ^{14}C to measure global average gas transfer velocity k which is about 21cm/hour with 25% uncertainty (Broecker and Peng, 1982).

2.3.2 Bomb ^{14}C Method

Bomb ^{14}C method uses radioisotope of Carbon -14 inputs from nuclear bomb tests to measure global average gas transfer velocity, which is about 22 cm/hour with less than 15% uncertainty (Broecker et al., 1985). Current observations of atmospheric ^{14}C require large sampling of ^{14}C from World Ocean Circulation Experiments (Duffy and Caldeira, 1995).

2.3.3 Natural ^{221}Rn Method

The limitation of Natural ^{14}C method due to from limited information on variability gas transfer velocity at regional scale may be overcome by Natural Radon (^{221}Rn) method even though this method is not applicable to inland waters. Global average gas transfer velocity by ^{221}Rn method is 20% lower than ^{14}C method (Roether et al., 1984).

2.3.4 Enclosure Methods

For inland waters, gas transfer velocity is measured by Enclosure (Chamber) method (MacIntyre et al., 1995). The difficulty with this method is that the surface turbulence controlling gas exchange under the chamber differs from the surrounding water, leading to higher values of gas transfer velocity than other methods.

2.3.5 Opportunistic Mass Balance Methods

Opportunistic mass balance methods are used to estimate gas transfer velocities in the subtropical gyres by determining air-water disequilibrium of man-made halo carbons, which can be used to measure daily cycle of reactive trace gases (Yvon et al., 1996).

2.3.6 Deliberate tracer method

Deliberate tracer method is used to perturb a mass balance by adding a known amount of gas to the water and subsequently follow the mass decrease through time. This method is used in lakes, rivers and coastal waters by injecting Sulfur Hexafluoride (SF_6) as tracer in epilimnion. Once the trace gas is homogeneous, samples are taken to determine decrease in concentration over time to measure gas transfer velocity.

One limitation of the methods for measuring gas transfer velocities (k) using the waterside perturbation is caused by slow response time relation to variability in environmental forcing. By using air side measurements such as eddy correlation, eddy accumulation and flux gradient method with faster response times, this problem can be resolved. An alternate method of direct flux measurements over air-water interface is the controlled flux technique in which heat is used as proxy for a gas (Haussecker et al., 1995). In general gas flux measurement across air water interface is favorable using air-side measurement due to short response time. Performing air side measurement aside with water side measurement will resolve the discrepancies between low k values in water side measurements to higher k values in air-side measurements and to use active and passive radiometry remote sensing data to extrapolate gas transfer velocities.

2.4 Gas Flux Modeling in Methods in Global Systems

Global models are developed for assessment of main pathways and distribution of emissions and depositions and interaction between the Northern and Southern hemisphere. During recent decades several global networks of trace gas monitoring stations have been developed: for example; by the Climate Monitoring and Diagnostics Laboratory of U.S. National Oceanic and Atmospheric Administration (NOAA/CMDL), the Scripps Institution of Oceanography, CSIRO of Australia routinely monitoring atmospheric composition with comprehensive efficiency and finer temporal and spatial resolution. Atmospheric transport models are used to derive global fluxes applying two methods: 1) Forward Atmospheric Model, 2) Inverse Atmospheric Model.

2.4.1 Forward Atmospheric Model

The concentration and deposition fields simulated with Forward Atmospheric Modeling are validated by comparing the model results with measured concentrations and fluxes. After validation model is used for spatial and temporal interpolation between measurement sites with proper spatial and temporal scale (Sofiev, 1999).

2.4.2 Inverse Atmospheric Model

Inverse Atmospheric Model uses observations of atmospheric concentration to estimate gas fluxes. The inverse problem is formulated as:

$$\overleftarrow{\Delta C} = T (\overleftarrow{q}) , \quad (2.19)$$

Where, $\overleftarrow{\Delta C}$ is the temporal change in vector of observed concentrations; \overleftarrow{q} is the vectors of sources and sinks and T is the atmospheric transport model. Transport model cannot be used to describe backward transport due to not being able model backward diffusion. The unknown sources and sinks are found by minimizing differences between measured and modeled concentrations by varying sink/source strengths. Similar to forward atmospheric model, spatial and temporal interpolation between measurement sites with proper spatial and temporal scale is applied after comparison of modeled and measured fluxes. Inverse method provides error covariance matrix quantifying uncertainty of model fluxes. For trace gases such as CO₂, methane transport and chemistry of equation (2.18) can be linearly approximated.

Bayesian approach to inverse problem provides a means to include a priori information on unknown source components in the inversion procedure (Tarantola, 1987). The priori information is based on a formulation of the problem in terms of Gaussian probability distribution in the joint space of sources and concentrations. An optimal posteriori source estimate is derived by inverse model which is as close as possible to the priori sources and resulting concentrations as close as the observed concentrations. Bayesian inversions trace gases such as CO₂ and methane are carried out in many experiments (Enting et al., 1995; Bousquet, 1997; Rayner et al., 1998; Kaminski, 1998; Hein and Heimann, 1994).

CHAPTER 3

PROPOSED METHOD OF GAS FLUX ESTIMATION

3.1 Model Formulation

Turbulent Dispersion of passive contaminants can be described by a diffusion equation (Monin and Yaglom, 1971; Pasquill, 1974),

$$\frac{\partial \chi}{\partial t} + u \frac{\partial \chi}{\partial x} + v \frac{\partial \chi}{\partial y} = K_x \frac{\partial^2 \chi}{\partial x^2} + K_y \frac{\partial^2 \chi}{\partial y^2} + K_z \frac{\partial^2 \chi}{\partial z^2} , \quad (3.1)$$

where, t is time, x , y and z the space co-ordinates, K_x , K_y and K_z diffusion coefficients in x , y and z directions, χ the concentration of a passive contaminant and u and v the component of the horizontal mean wind, while vertical mean wind is assumed to be zero. When horizontally homogeneous concentration distribution is assumed, turbulent diffusion coefficients K_x and K_y become zero (Nieuwstadt, 1980). (3.1) reduces to,

$$\frac{\partial \chi}{\partial t} = K_z \frac{\partial}{\partial z} \left(\frac{\partial \chi}{\partial z} \right) , \quad (3.3)$$

(3.2) has been frequently used to model turbulent transport including turbulent transfer of heat in the lower atmosphere over a homogeneous land surfaces (Wang and Bras, 1998). The transport of CO_2 over a homogeneous surface in the atmospheric

boundary layer is predominantly vertical hence may be described by one dimensional diffusion equation,

$$\frac{\delta C}{\delta t} = \frac{\delta}{\delta z} \left(D_c \frac{dC}{dz} \right) , \quad (3.3)$$

where, C (kg m^{-3}) is the mean atmospheric CO_2 concentration, $D_c(z, t)$ ($\text{m}^2 \text{s}^{-1}$) the turbulent diffusion coefficient or eddy diffusivity of CO_2 and z (m) the distance above the (ground or canopy) surface. The Proposed study assumes that the turbulent flow in the boundary layer responsible for transport of heat is also responsible for the transport of other passive tracers such as water vapor and CO_2 (Yakir and Wang, 1996). Following initial profile and boundary condition is applicable in deriving the solution of (3.3)

$$\text{Initial Condition,} \quad C = C_0 , z > 0 , t = 0 \quad (3.4)$$

$$\text{Boundary Condition,} \quad C = C_0 , z \rightarrow \infty , t > 0 \quad (3.5)$$

The full solution of C as a function of z and t requires an additional boundary condition at surface. Use of a mathematical tool called fractional calculus (presented in **Appendix A**) will facilitate the derivation of a solution of (3.3)

3.2 Parameterization of Diffusion Coefficient

Eddy diffusivity of CO₂ D_c in (3.3) may be parameterized (Wang and Bras, 2010) as

$$D_c = C_k \kappa z u_* , \quad (3.6)$$

where, z is the distance between height of measurement and that of canopy top or ground surface, κ (≈ 0.4) the Von Karman constant, u_* the friction velocity, C_k the empirical coefficient characterizing representing the stability of the surface layers. Friction velocity, u_* is parameterized using extremum solution of Monin-Obukhov similarity equations (Wang and Bras, 2010) expressed as

$$u_* = - \left(\frac{2\beta g \kappa H z}{\rho c_p T_o} \right)^{\frac{1}{3}} , \quad H < 0 \quad (3.7)$$

$$u_* = \left(\frac{\gamma_2 g \kappa H z}{2\rho c_p T_o} \right)^{\frac{1}{3}} , \quad H > 0 \quad (3.8)$$

where, H is the sensible heat flux parameterized using Maximum Entropy Production (MEP) Model (Wang and Bras, 2009, 2011) in terms of surface net radiation and surface temperature (details of MEP model is presented in **Appendix B**). H is positive when heat transfer in upward direction from ground surface to atmospheric boundary layer characterizing unstable condition of atmosphere. H is negative when heat transfer in downward direction from atmospheric boundary layer to ground surface characterizing stable condition of atmosphere. T_o (≈ 300 K) is the representative

environmental temperature, ρ ($\approx 1.2 \text{ kg m}^{-3}$) the representative density of air, c_p the specific heat at constant pressure, g (9.8 m s^{-2}) the gravitational acceleration and the universal empirical coefficients $\alpha \approx 0.75$, $\beta \approx 4.7$, $\gamma_2 \approx 9$ (Businger et al. 1971).

Empirical coefficients C_k characterizing the boundary stability in the Monin-Obukhov similarity equations representing the stability of the surface layers (Businger et. al.1971) given as follows

$$C_k = \frac{2}{1+\alpha} , H < 0 \quad (3.9)$$

$$C_k = \frac{\sqrt{3}}{\alpha} , H > 0 \quad (3.10)$$

Substituting (3.7) - (3.10) into (3.6) D_c can be expressed as:

$$D_c = \left(\frac{2}{1+\alpha} \right) \left\{ - \left(\frac{2\beta g \kappa H z}{\rho c_p T_o} \right)^{\frac{1}{3}} \right\} \kappa z , H < 0 \quad (3.11)$$

$$D_c = \left(\frac{\sqrt{3}}{\alpha} \right) \left\{ \left(\frac{\gamma_2 g \kappa H z}{2\rho c_p T_o} \right)^{\frac{1}{3}} \right\} \kappa z , H > 0 \quad (3.12)$$

Combining terms independent of t and z in (3.11) and (3.12), the expression of turbulent diffusion equation is parameterized as

$$D_C(z, t) = D_o z^{\frac{4}{3}} |H|^{\frac{1}{3}}, \quad (3.13)$$

where, D_o is the empirical constant,

$$D_o = \frac{2(2\beta)^{\frac{1}{3}}}{1+\alpha} \left(\frac{g\kappa^4}{\rho c_p T_o} \right)^{\frac{1}{3}}, \quad H < 0 \quad (3.14)$$

$$D_o = \frac{\sqrt{3}}{\alpha} \left(\frac{\gamma_2}{2} \right)^{\frac{1}{3}} \left(\frac{g\kappa^4}{\rho c_p T_o} \right)^{\frac{1}{3}}, \quad H > 0 \quad (3.15)$$

3.3 Derivation of Surface Flux

The surface CO₂ Flux, F_C (defined positive for upward transport of CO₂) at a distance z from ground (or canopy) surface can be expressed as,

$$F_C(z, t) = D_C(z, t) \frac{\partial C(z, t)}{\partial z} , \quad (3.16)$$

where, $D_C(z, t)$ is the eddy diffusivity of CO₂ parameterized in (3.13). Derivation of F_C involves solution of (3.3) with boundary conditions described in (3.4) and (3.5). In order to incorporate $D_C(z, t)$ in (3.13) three new variables \acute{t} (functions of time t), ξ (functions of height z) and A (function of D_0) are introduced assuming H invariant within height (z) of within surface layer then (3.3) is rewritten as,

$$\frac{\delta C}{\delta \acute{t}} = A \left(\frac{2}{\xi} \frac{\delta C}{\delta \xi} + \frac{\delta^2 C}{\delta \xi^2} \right) , \quad (3.17)$$

where,

$$\acute{t} = \int_0^t |H(\tau)|^{\frac{1}{3}} d\tau , \quad (3.18)$$

$$\xi = z^{\frac{1}{3}} , \quad (3.19)$$

$$A = \frac{D_0}{9} , \quad (3.20)$$

Analytic solution of (3.17) follows Oldham and Spanier (2002, page 204) given by,

$$\frac{\delta C(\xi, \acute{t})}{\delta \xi} = -\frac{1}{\sqrt{A}} \frac{\delta^{\frac{1}{2}}}{\delta \acute{t}^{\frac{1}{2}}} (C(\xi, \acute{t}) - C_0) - \frac{C(\xi, \acute{t}) - C_0}{\xi + R} , \quad (3.21)$$

Initial and boundary condition given in terms of new variables

$$\text{Initial condition,} \quad C = C_0 \quad \text{as } \acute{t} = 0 \text{ at } \xi > 0 \quad (3.22)$$

$$\text{Boundary condition,} \quad C = C_0 \quad \text{as } \acute{t} > 0 \text{ at } \xi \rightarrow \infty \quad (3.23)$$

For horizontal surface $\xi = 0$ and $R \rightarrow \infty$, (3.21) becomes,

$$\frac{\delta C(\xi, \acute{t})}{\delta \xi} = -\frac{1}{\sqrt{A}} \frac{\delta^{\frac{1}{2}}}{\delta \acute{t}^{\frac{1}{2}}} (C(\xi, \acute{t}) - C_0) , \quad (3.24)$$

where, the half order derivative (see appendix A for details) of a function $f(t)$ is defined as,

$$\frac{d^{\frac{1}{2}} f(t)}{\delta t^{\frac{1}{2}}} = \frac{1}{\sqrt{\pi}} \frac{d}{dt} \int_0^t \frac{f(\tau) d\tau}{\sqrt{t-\tau}} , \quad (3.25)$$

Replacing the variables ξ and \acute{t} and A by the original variables in (3.24) leads to,

$$\frac{\delta C(z, t)}{\delta z} = \frac{1}{\sqrt{\pi}} \int_0^t \frac{\delta C(z, \tau)}{\delta \tau} \left[\int_{\tau}^t D_C(z, \eta) d\eta \right] d\tau , \quad (3.26)$$

The CO₂ Flux, F_C is given as,

$$F_C(z, t) = \frac{D_C(z, t)}{\sqrt{\pi}} \int_0^t \frac{\delta C(z, \tau)}{\delta \tau} \left[\int_\tau^t D_C(z, \eta) d\eta \right]^{-\frac{1}{2}} d\tau \quad , \quad (3.27)$$

where, τ and ξ are integration (dummy) variables. Theoretically the starting time ($t = 0$) is the time when CO₂ concentration is constant in z in order to obtain the analytic solution of (3.27). Case studies indicate that F_C is not sensitive to this initial condition as long as t is on the order of hours. According to (3.27) surface CO₂ flux (F_C) at a given time (and a certain height above surface) is expressed as the weighted average of the time history of CO₂. The weighting function is expressed as an integrated time history of diffusion coefficient of CO₂ (D_C). In fact, F_C over the entire period can be obtained according to (3.27) from the time history data of surface (or canopy) CO₂ concentration and the time history data of D_C . Calculation of F_C using (3.27) involves numerical computation of a singular integral as the weighting function is divergent at $\tau = t$. The input variables for computation of F_C include time series of CO₂ concentration data and time series of diffusion coefficient using net radiation and surface (or near surface air) temperature data to compute sensible heat flux H .

3.4 Numerical Algorithm for Computing Surface Flux

Given the time-series data of CO₂ concentration at height z from canopy surface $C(t_i, z)$, net radiation $R_n(t_i)$ and surface temperature at canopy $T_s(t_i)$ measured at discrete times t_i ($i = 1, \dots, N$, $t_1 = 0$) surface CO₂ flux $F_C(z, t_i)$ may be calculated using the following numerical algorithm. To remove singularity of the integrand, the double integral in (3.27) can be rewritten as

$$\int_0^t \frac{\delta C(z, \tau)}{\delta \tau} \left[\int_\tau^t D_C(z, \eta) d\eta \right]^{-\frac{1}{2}} d\tau = -2 \int_0^t \frac{\delta C(z, \tau)}{\delta \tau} \frac{1}{D(z, \tau)} d \left[\int_\tau^t D_C(z, \eta) d\eta \right]^{\frac{1}{2}}, \quad (3.28)$$

The integral on right hand side of (3.28) is the Riemann-Stieltjes integral

$$\int_0^t f(\tau) d[g(\tau)], \quad (3.29)$$

where,

$$f(\tau) = \int_0^t \frac{\delta C(z, \tau)}{\delta \tau} \frac{1}{D(z, \tau)}, \quad (3.30)$$

$$g(\tau) = \left[\int_\tau^t D_C(z, \eta) d\eta \right]^{\frac{1}{2}}, \quad (3.31)$$

The Riemann-Stieltjes integral may be numerically computed as

$$\int_0^t f(\tau) d[g(\tau)] = \sum_{i=1}^N f(t_i) [g(t_i) - g(t_{i-1})] , \quad (3.32)$$

where,

$$f(t_i) = \frac{C(z, t_i) - C(z, t_{i-1})}{t_i - t_{i-1}} \frac{1}{D(z, t_i)} , \quad (3.33)$$

$$g(t_i) = \left[\sum_{j=i+1}^N D_C(z, t_j) (t_j - t_{j-1}) \right]^{\frac{1}{2}} , \quad (3.34)$$

$$g(t_{i-1}) = \left[\sum_{j=i}^N D_C(z, t_j) (t_j - t_{j-1}) \right]^{\frac{1}{2}} , \quad (3.35)$$

3.5 Computing Turbulent Diffusion Coefficient

Computation of turbulent diffusion coefficient of CO₂, $D_C(z, t_i)$ at height z from canopy surface at discrete times t_i ($i = 1, \dots, N$, $t_1 = 0$) requires surface sensible heat flux $H(t_i)$ which is calculated using surface temperature at canopy $T_s(t_i)$ and net radiation $R_n(t_i)$ MEP Model described in Appendix B. According to (B9) sensible heat flux over canopy is expressed as,

$$H(t_i) = \frac{R_n(t_i)}{1+B(\sigma)} , \quad (3.36)$$

$$B(\sigma) = 6 \left(\sqrt{1 + \frac{11}{36} \sigma} - 1 \right) , \quad (3.37)$$

$$\sigma = \frac{\lambda^2 q_s [T_s(t_i)]}{c_p R_v [T_s(t_i)]^2} , \quad (3.38)$$

where, $T_s(t_i)$ is the temperature at canopy surface (K), λ the latent heat of vaporization of liquid water ($2.5 \times 10^6 \text{ J kg}^{-1} \text{ K}^{-1}$), c_p the specific heat of air at constant pressure ($10^3 \text{ J kg}^{-1} \text{ K}^{-1}$) and R_v is the gas constant of water vapor ($461 \text{ J kg}^{-1} \text{ K}^{-1}$). q_s is the specific humidity at ground (or canopy) surface (kg kg^{-1}). q_s is expressed in terms T_s according to Clausius-Clapeyron equation

$$q_s [T_s(t_i)] = 0.62 \left(\frac{e_0}{P_s} \right) \exp \left[\frac{\lambda}{R_v} \left(\frac{1}{T_0} - \frac{1}{T_s} \right) \right] , \quad (3.39)$$

where, e_0 is the saturation vapor pressure at (an arbitrary reference temperature T_0 , P_s is the surface atmospheric pressure ($\sim 10^5 \text{ Pa}$). At $T_0 = 273 \text{ K}$, $e_0 = 611 \text{ Pa}$.

3.6 Advantages of Proposed Model

The proposed model has several advantages. The model uses a single level CO₂ concentration data (at surface or canopy level) instead of CO₂ concentration gradient data that are subjected to greater measurement errors and modeling complexity. Second, the modeled CO₂ fluxes (3.27) is not sensitive to uncertainties of CO₂ diffusion coefficient (3.17). As parameterization of the CO₂ diffusion coefficient is has one-sixth power dependence of sensible heat flux. Third, the model is parsimonious not using near surface wind speed, surface roughness and vegetation specific data. Fourth, the model formulation facilitates its generalization from field scale to regional and global scale as all model input parameters namely, CO₂ concentration time series, net radiation time series and surface (or near surface air) temperature may be obtained from remote sensing observations.

These advantageous features results mainly from the parameterization of eddy diffusivity of CO₂ (3.17). The MEP model allows sensible heat flux to be derived from surface net radiation, surface temperature (and / or humidity) data. When field observations of these variables are not available a recently developed method (Moghim et al., 2014) may be used to obtain the field to regional scales from visible images of satellite data. Due to reduced sensitivity of the diffusion coefficient to sensible heat flux especially for the case of dense canopy, it would be sufficient to assume wet condition to calculate sensible heat flux only from net radiation and surface (or near surface air) temperature time series using MEP the model.

CHAPTER 4

MODEL TESTING

4.1 Test Sites

Field data of CO₂ concentration, net radiation and surface temperature over canopy measured at four sites (Clark et al., 2010; Liu et al., 2005; Saleska et al., 2003; and Scott et al., 2006) from AmeriFlux network provide the input of the proposed CO₂ flux model. The modeled CO₂ flux is compared with eddy-covariance CO₂ flux data. AmeriFlux sites are managed by the AmeriFlux Management Project (AMP) at Lawrence Berkeley National Laboratory (LBNL) supported by U.S. Department of Energy (DOE).

The test sites are selected with contrasting climatic, geographic, vegetation condition to assess the applicability of the model in diverse environments. The four sites are: Santarem KM67 Primary Forest, Brazil; Cedar Bridge, New Jersey, USA; Delta Junction 1920 Control, Alaska, USA and Walnut Gulch Lucky Hills Shrubland, Arizona, USA. Description of the sites are presented in Table 4.1.

Table 4.1 Description of the study sites.

Sites	Latitude, Longitude	Climate Condition	Vegetation Type
1. Santarem KM67 Primary Forest, Brazil	-2.86°, -54.96°	Tropical monsoon, with mean annual temperature 26.13 °C and mean annual precipitation 2075 mm.	Evergreen Broad Leaf Forest
2. Cedar Bridge, New Jersey, USA	39.84°, -74.38°	Cool temperate, mean annual temperature 11.04 °C (with mean monthly temperatures of 0.3 °C in January and 23.8 °C in June) and mean annual precipitation is 1123 mm (S.D. 82 mm).	Mixed Forest
3. Delta Junction 1920 Control, Alaska, USA	63.89°, -145.74°	Dry continental, mean annual temperature - 2.3 °C, mean annual Rainfall : 304 mm, mean annual Snowfall: 940 mm	Evergreen Needle Leaf Forest
4. Walnut Gulch Lucky Hills Shrubland, Arizona, USA	31.74°, -110.052°	Temperate semi- arid with mean annual temperature 17.6 °C and mean annual precipitation 320 mm.	Open Shrub lands

4.2 Results and Discussion

4.2.1 Site 1

Santarem KM67 Primary forest site (2.86°S, 54.96°W) is located in the Tapajos National Forest. This is a 450,000 ha closed-canopy upland forest in Brazilian Amazon with evergreen broad leaf vegetation class and 45 m mean canopy height. The tropical climate is strongly influenced by the monsoon with annual mean temperature of 26.13°C and mean precipitation of 2075 mm. A 5-month dry season (months with <100 mm of rainfall) that extends from July to December. The 64-m eddy covariance tower is located on a flat plateau (or planalto) that extends up to 150 km to the north, south, and east. Within the National Forest, anthropogenic disturbances are limited to a few small hunting trails. The surrounding stand is classified as primary or "old-growth" predominantly by its uneven age distribution, emergent trees, numerous epiphytes and abundant large logs.

The model uses hourly time-series data of CO_2 concentration ($\mu\text{mol mol}^{-1}$), canopy surface temperature T_s (°C) and net radiation R_n (W m^{-2}). Downward CO_2 flux (FC) as well as latent (E) and sensible (H) heat flux from the atmosphere to canopy surface are defined as negative. Ground heat flux (G) is defined negative from the surface into the soil layer. Due to dense canopy cover at this site the observed ground heat flux is very small. The MEP model as in (B8) – (B10) of appendix B is used to estimate H, which is used in parameterization of diffusion coefficient of CO_2 , D_c . The distance above the canopy surface z is measured by the difference of mean canopy height

(45 m) and height of CO₂ measurement (64 m) is 19 m. Scattered missing data are filled using linear interpolation when the time interval between missing data are not very large (< 3 hours). The dataset is re-grouped into multiple no-gap time series to avoid larger gaps (> 3hrs) of the time-series records.

The comparison of modeled CO₂ flux using equation (3.27) with the observed eddy-covariance flux is characterized by the root-mean-square error (RMSE), the normalized root-mean-square error (NRMSE defined as the RMSE divided by the magnitude of the observed fluxes), correlation coefficient (covariance of the observed and modeled CO₂ fluxes divided by the product of their standard deviations) and regression coefficient (covariance of the observed and modeled CO₂ fluxes divided by the variance of observed CO₂ fluxes). The maximum and minimum observed fluxes over the test period and maximum and minimum modeled fluxes over test period are reported. As the MEP modeled sensible heat flux is used in the parameterization of eddy diffusivity of CO₂, the MEP modeled energy fluxes are compared with observed energy fluxes from eddy covariance measurements. This includes: root-mean-square error (RMSE), normalized root-mean-square error (NRMSE), correlation coefficient, maximum and minimum flux of the observed and MEP modeled heat fluxes over the test period. The results are shown in figures and tables followed by summary tables.

Test Period 1: Day 1-8, 2003, Santarem KM67 Primary Forest, Brazil

Table 4.2.1 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 1-8, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.935	Correlation Coefficient	0.937
RMSE (W m^{-2})	27.62	RMSE (W m^{-2})	65.64
NRMSE	0.1209	NRMSE	0.1585
Max HOBS (W m^{-2})	189.28	Max EOBS (W m^{-2})	404.83
Min HOBS (W m^{-2})	-39.07	Min EOBS (W m^{-2})	-9.195
Max HMEP (W m^{-2})	201.35	Max EMEP (W m^{-2})	552.50
Min HMEP (W m^{-2})	-13.12	Min EMEP (W m^{-2})	-33.74

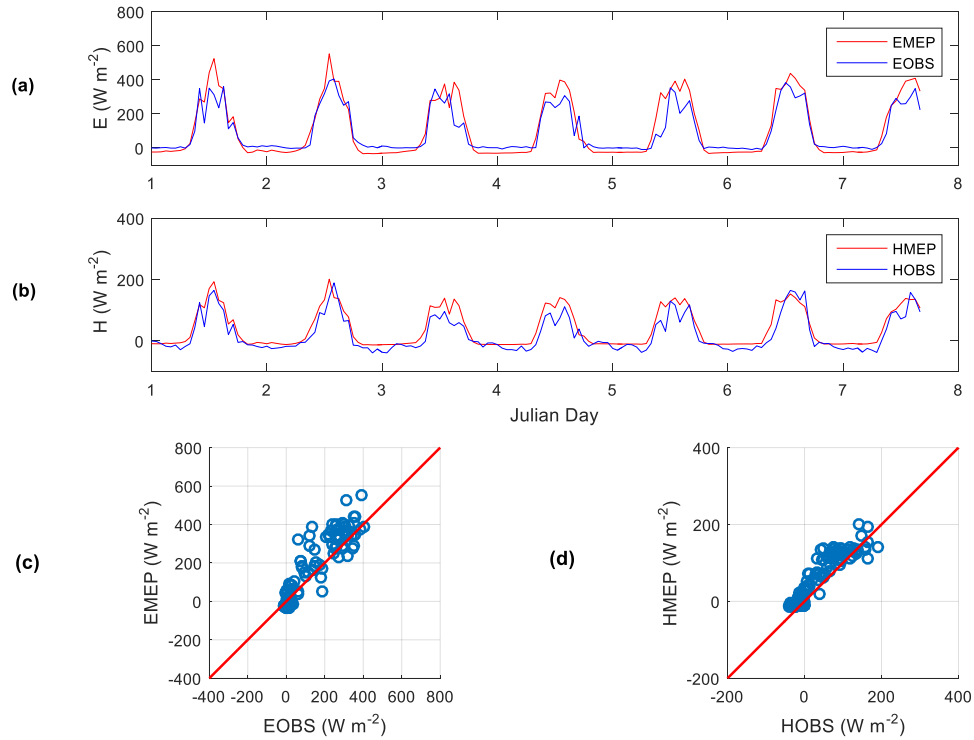


Figure 4.2.1 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 1-8, 2003.

Table 4.2.2 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 1-8, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	6.36
NRMSE	0.1285
Correlation Coefficient	0.73
Regression Coefficient	0.66
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	44.30
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-35.49
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	23.76
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-25.77
Number of Data Points	168
SD Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	
MAE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	
Max Observed CO ₂ ($\mu\text{mol/mol}$)	
Min Observed CO ₂ ($\mu\text{mol/mol}$)	
SD Observed CO ₂ ($\mu\text{mol/mol}$)	
Mean Observed CO ₂ ($\mu\text{mol/mol}$)	

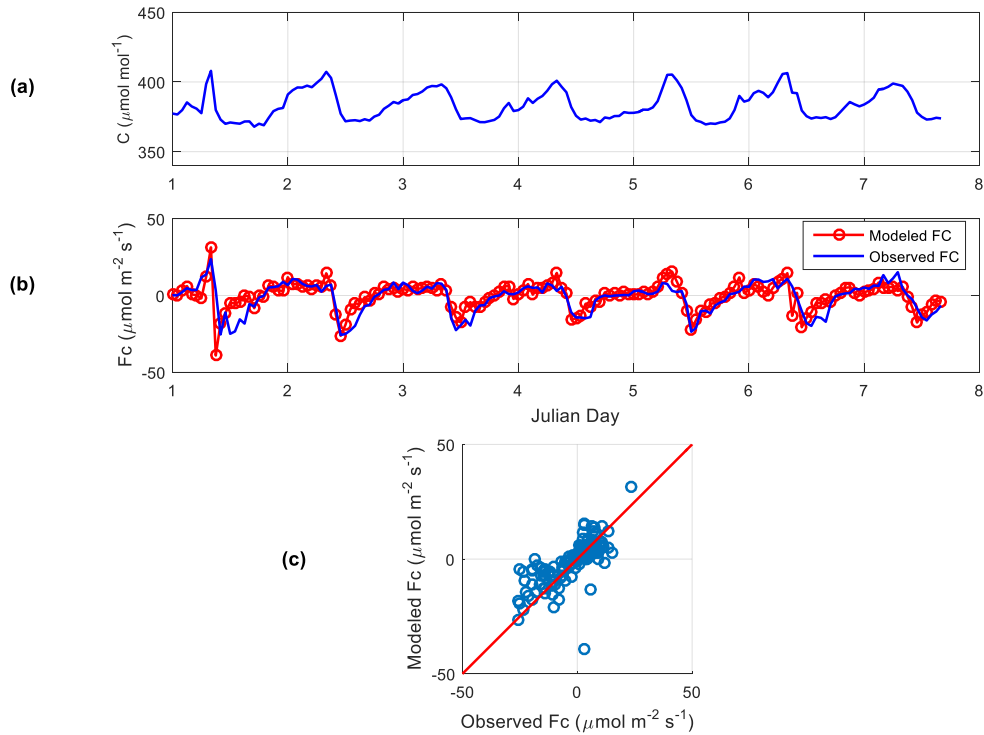


Figure 4.2.2 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 1-8, 2003.

The modeled CO₂ fluxes using equation (3.27) well capture the diurnal variation and magnitude of the observed fluxes (Figure 4.2.2 (b)) during test period 1 (day 1 to 8, 2003). The RMSE and the NRMSE of the modeled CO₂ fluxes are 6.36 $\mu\text{mol m}^{-2}\text{s}^{-1}$ and 12.85% respectively, with the CO₂ fluxes on the order of 49.53 $\mu\text{mol m}^{-2}\text{s}^{-1}$. The scatterplot of modeled vs. observed fluxes show good agreement (Figure 4.2.2 (c)) with correlation coefficient, 0.73 and regression coefficient, 0.66. The magnitudes of modeled fluxes are comparable to the observed fluxes except for a small number of points due to the linear interpolation of the missing CO₂ concentration data points (such as 398.54 $\mu\text{mol/mol}$ to 407 $\mu\text{mol/mol}$) causing relatively large numerical errors of the calculated derivative term in (3.27) associated with large value maximum modeled flux (44.3 $\mu\text{mol m}^{-2}\text{s}^{-1}$). The MEP energy fluxes have correlation coefficients 0.935 and 0.937 for sensible heat (H) and latent heat (E) fluxes, respectively. The RMSE and NRMSE for this test period are 27.62 W m^{-2} and 12% with the sensible heat fluxes on the order of 228.35 W m^{-2} . The RMSE and NRMSE for this test period are 65.64 W m^{-2} and 15.85% with the latent heat fluxes on the order of 414 W m^{-2} .

Test Period 2: Day 13-21, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.3 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 13-21, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.919	Correlation Coefficient	0.945
RMSE (W m^{-2})	27.94	RMSE (W m^{-2})	62.85
NRMSE	0.0819	NRMSE	0.1341
Max HOBS (W m^{-2})	298.95	Max EOBS (W m^{-2})	459.99
Min HOBS (W m^{-2})	-42.33	Min EOBS (W m^{-2})	-8.744
Max HMEP (W m^{-2})	188.98	Max EMEP (W m^{-2})	533.57
Min HMEP (W m^{-2})	-11.01	Min EMEP (W m^{-2})	-29.17

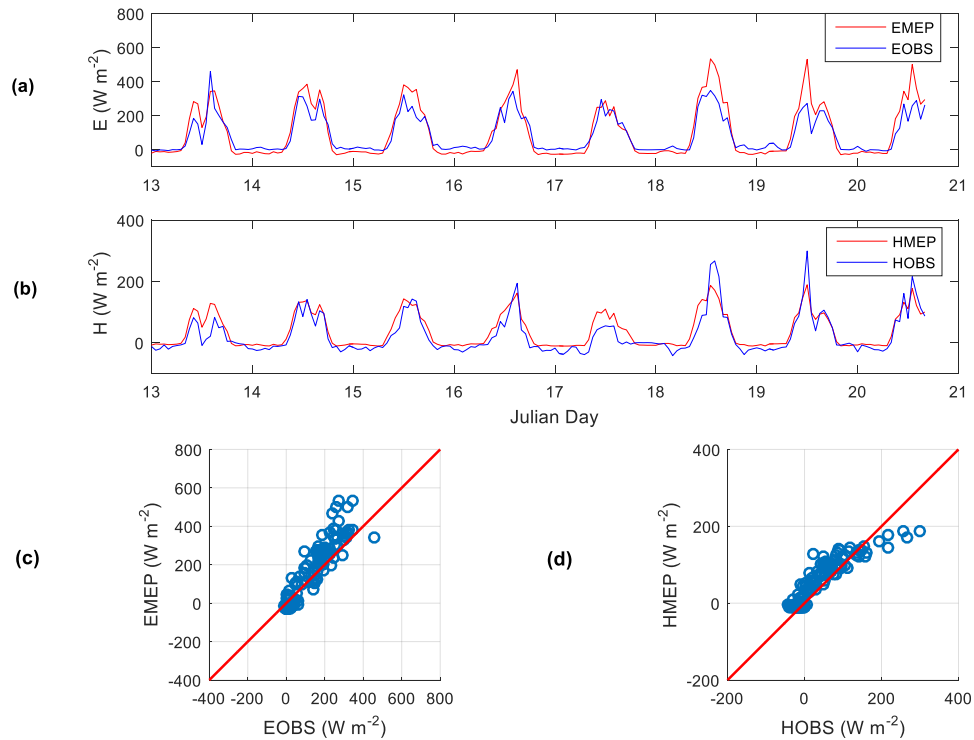


Figure 4.2.3 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem KM67 Primary Forest, Brazil. Day 13-21, 2003.

Table 4.2.3 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 13-21, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	8.386
NRMSE	0.1981
Correlation Coefficient	0.422
Regression Coefficient	0.396
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	59.71
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-27.97
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	17.01
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-25.33
Number of Data Points	189

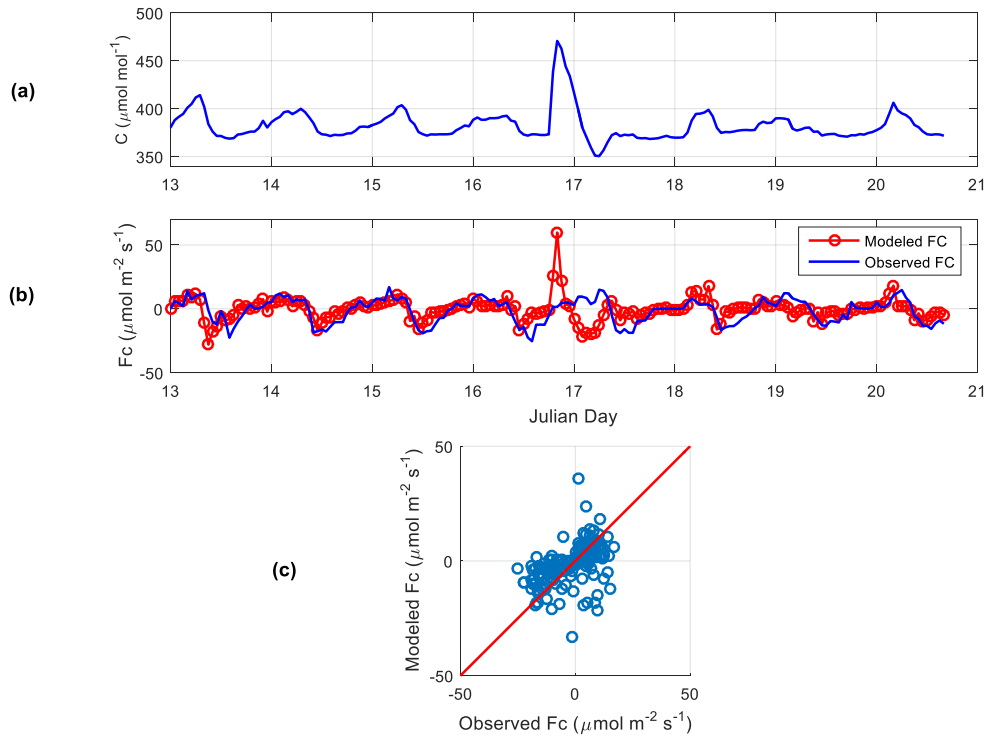


Figure 4.2.4 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 13-21, 2003.

Test period 2 (day 13 to 21, 2003) contains a large CO₂ concentration spike (470.65 $\mu\text{mol/mol}$) during day 16-17 (Figure 4.2.4 (a)) which causes large value maximum modeled flux (59.71 $\mu\text{mol m}^{-2} \text{s}^{-1}$) (Figure 4.2.4 (b)). The scatterplot shows outliers (Figure 4.2.4 (c)) causing reduced correlation coefficient, 0.422 and regression coefficient, 0.396. The RMSE and the NRMSE of the modeled CO₂ fluxes are 8.386 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and 19.81% with the CO₂ fluxes on the order of 42 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for this period. The MEP energy fluxes have correlation coefficients 0.919 and 0.945 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 27.94 W m^{-2} and 8.19% with the sensible heat fluxes on the order of 341 W m^{-2} . The RMSE and NRMSE for this test period are 62.85 W m^{-2} and 13.41% with the latent heat fluxes on the order of 468 W m^{-2} .

Test Period 3: Day 33-43, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.5 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 33-43, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9351	Correlation Coefficient	0.9421
RMSE (W m^{-2})	26.21	RMSE (W m^{-2})	55.30
NRMSE	0.0869	NRMSE	0.1381
Max HOBS (W m^{-2})	239.50	Max EOBS (W m^{-2})	382.645
Min HOBS (W m^{-2})	-62.09	Min EOBS (W m^{-2})	-17.81
Max HMEP (W m^{-2})	187.96	Max EMEP (W m^{-2})	499.746
Min HMEP (W m^{-2})	-10.57	Min EMEP (W m^{-2})	-27.72

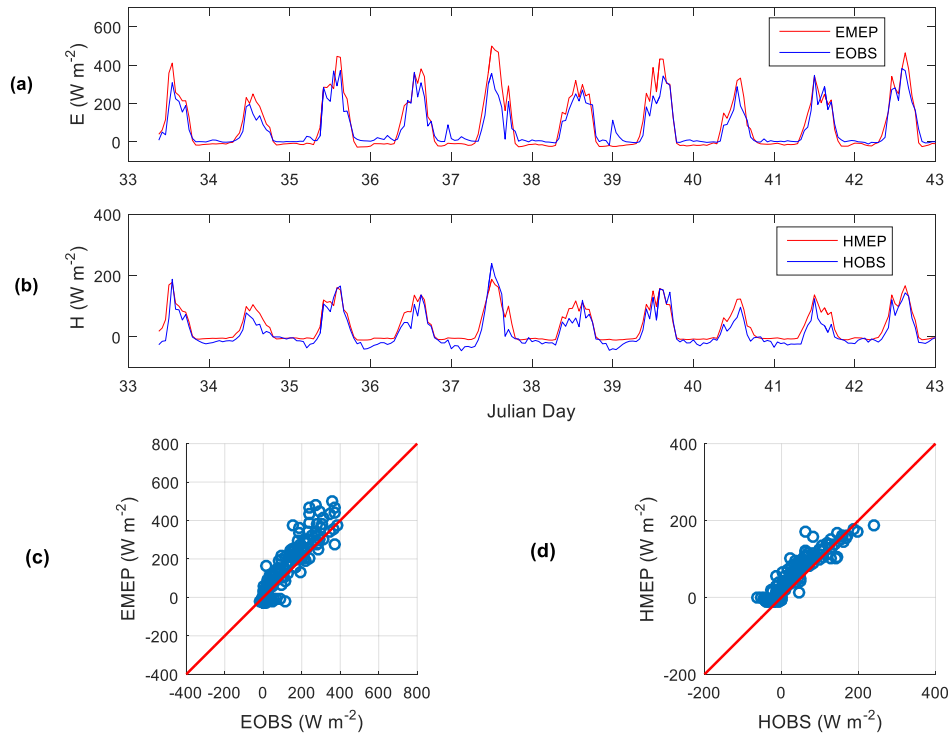


Figure 4.2.5 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 33-43, 2003.

Table 4.2.6 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 33-43, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	7.52
NRMSE	0.1263
Correlation Coefficient	0.71
Regression Coefficient	0.56
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	23.26
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-39.429
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	32.347
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-27.133
Number of Data Points	248

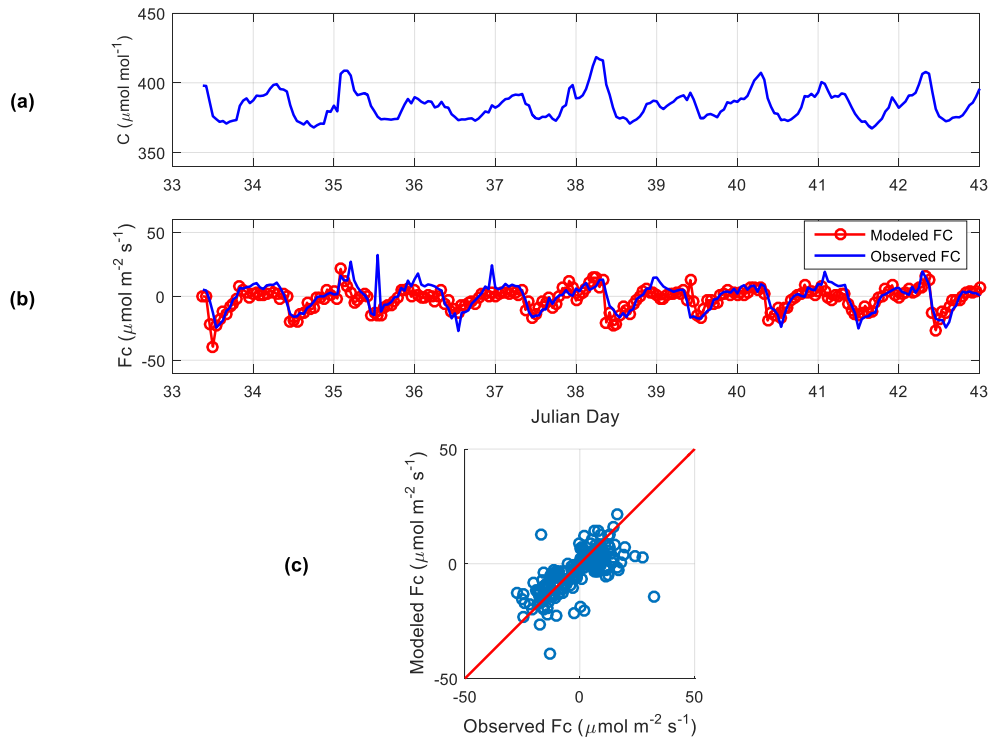


Figure 4.2.6 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 33-43, 2003.

Test period 3 starts from day 33 to 43, 2003. During this period modeled fluxes show good agreement with observation with the correlation coefficient, 0.71 and regression coefficient, 0.56. Except for day 35 the observed maximum CO₂ flux during this period, 32.347 $\mu\text{molm}^{-2}\text{s}^{-1}$ (Figure 4.2.6 (b)) is erroneous as it was measured at 1 PM during daytime (when the photosynthesis occurs) which is inconsistent with observed flux at 12 PM, -14.663 $\mu\text{molm}^{-2}\text{s}^{-1}$ and 2 PM, -11.921 $\mu\text{molm}^{-2}\text{s}^{-1}$. The modeled CO₂ flux at 1 PM (-13.761 $\mu\text{molm}^{-2}\text{s}^{-1}$) shows consistency with observed fluxes at 12 PM and 2 PM. The RMSE and the NRMSE of the modeled CO₂ fluxes during this period is 7.52 $\mu\text{molm}^{-2}\text{s}^{-1}$ and 12.63% respectively, with the CO₂ fluxes on the order of 59.48 $\mu\text{mol m}^{-2}\text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.9351 and 0.9421 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 26.21 W m^{-2} and 8.69% with the sensible heat fluxes on the order of 301.59 W m^{-2} . The RMSE and NRMSE for this test period are 55.30 W m^{-2} and 13.81% with the latent heat fluxes on the order of 400 W m^{-2} .

Test Period 4: Day 40-50, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.7 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 40-50, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.866	Correlation Coefficient	0.941
RMSE (W m^{-2})	30.16	RMSE (W m^{-2})	44.74
NRMSE	0.1225	NRMSE	0.1099
Max HOBS (W m^{-2})	165.77	Max EOBS (W m^{-2})	382.65
Min HOBS (W m^{-2})	-80.38	Min EOBS (W m^{-2})	-24.47
Max HMEP (W m^{-2})	173.99	Max EMEP (W m^{-2})	464.48
Min HMEP (W m^{-2})	-9.33	Min EMEP (W m^{-2})	-24.95

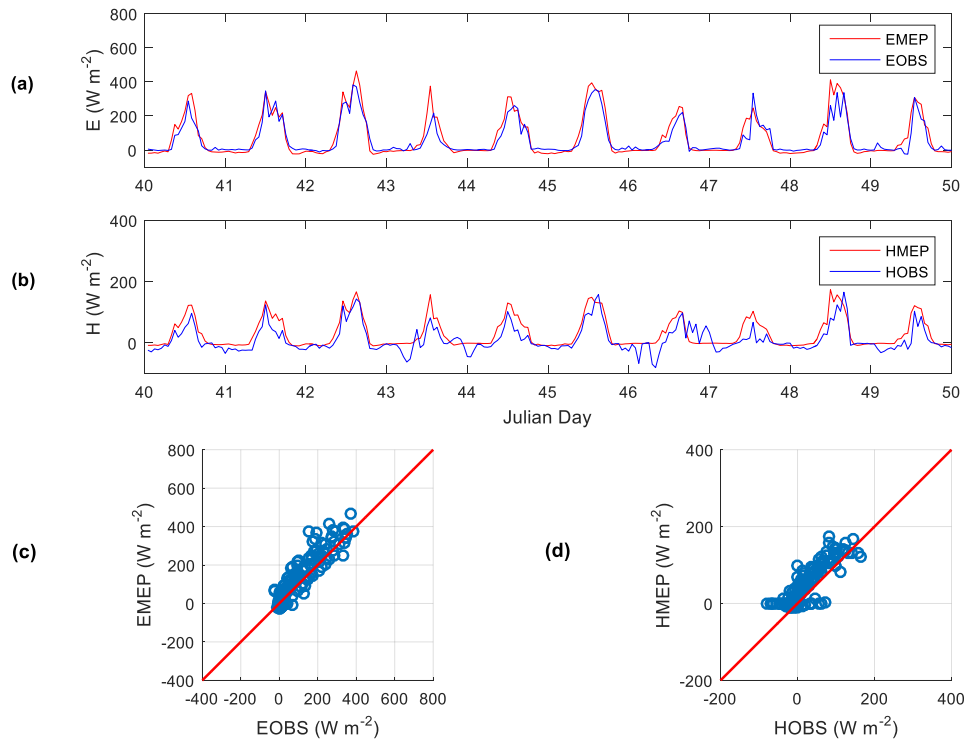


Figure 4.2.7 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 40-50, 2003.

Table 4.2.8 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 40-50, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	7.90
NRMSE	0.1646
Correlation Coefficient	0.55
Regression Coefficient	0.70
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	71.91
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-73.71
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	22.86
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-25.13
Number of Data Points	226

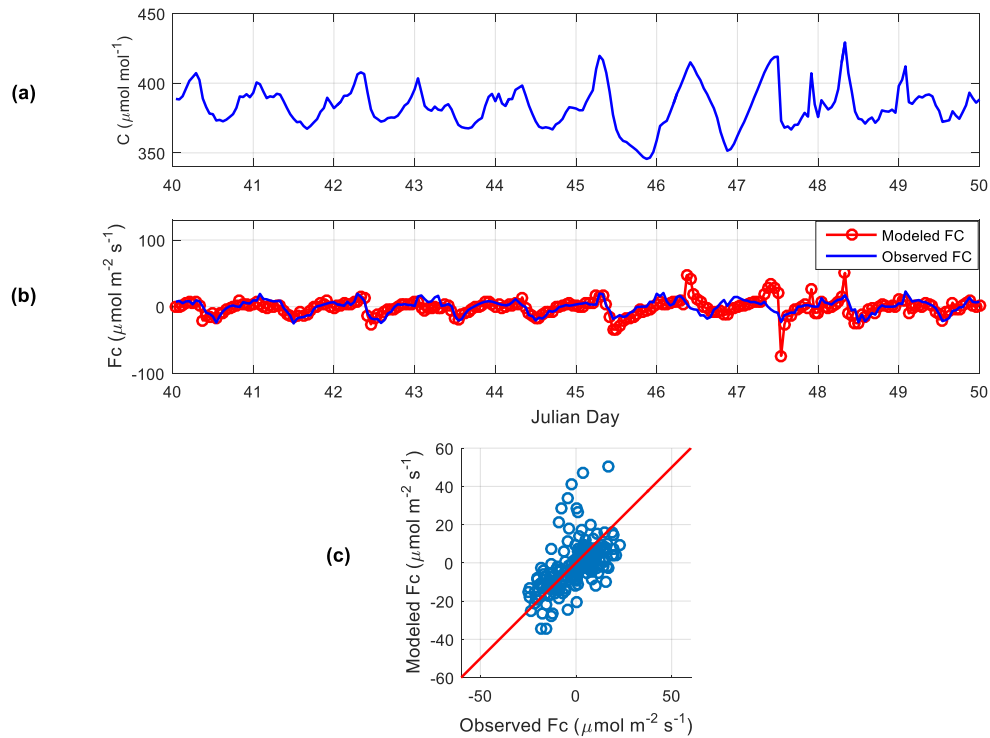


Figure 4.2.8 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 40-50, 2003.

Test period 4 (day 40 to 50, 2003) shows good agreement between modeled and observed fluxes till day 46 (Figure 4.2.8 a, b). The spurious spikes in CO₂ concentration data (> 400 to 429 $\mu\text{mol/mol}$) during 8 AM to 12 PM occur consistently during day 46, 47 and 48 leading to relatively large numerical errors of the calculated derivative term in (3.27) which causes large value maximum modeled flux ($71.91 \mu\text{mol m}^{-2} \text{s}^{-1}$) in day 48. Such spikes followed by large drop ($419.007 \mu\text{mol/mol}$ to $373.01 \mu\text{mol/mol}$) causes small value in minimum modeled flux ($-73.71 \mu\text{mol m}^{-2} \text{s}^{-1}$) on day 47. The scatterplot of modeled vs. observed CO₂ flux shows some spread (Figure 4.2.8 (c)) with correlation coefficient, 0.55 and regression coefficient, 0.7 for this period. The RMSE and the NRMSE of the modeled CO₂ fluxes are $7.90 \mu\text{mol m}^{-2} \text{s}^{-1}$ and 16.46 % with the CO₂ fluxes on the order of $47.99 \mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.866 and 0.941 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 30.16 W m^{-2} and 12.25 % with the sensible heat fluxes on the order of 246 W m^{-2} . The RMSE and NRMSE for this test period are 44.74 W m^{-2} and 10.99 % with the latent heat fluxes on the order of 407.12 W m^{-2} .

Test Period 5: Day 56-70, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.9 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 55-70, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.932	Correlation Coefficient	0.951
RMSE (W m^{-2})	28.77	RMSE (W m^{-2})	51.43
NRMSE	0.1093	NRMSE	0.1133
Max HOBS (W m^{-2})	212.02	Max EOBS (W m^{-2})	439.32
Min HOBS (W m^{-2})	-51.26	Min EOBS (W m^{-2})	-14.74
Max HMEP (W m^{-2})	189.2	Max EMEP (W m^{-2})	487.91
Min HMEP (W m^{-2})	-10.64	Min EMEP (W m^{-2})	-26.26

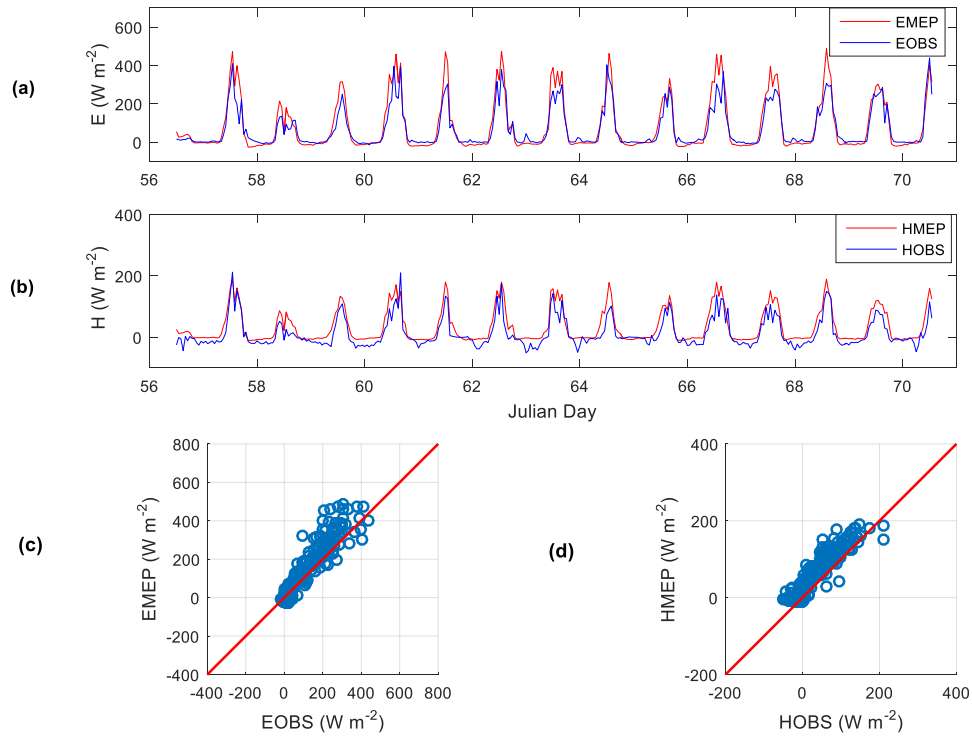


Figure 4.2.9 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 56-70, 2003.

Table 4.2.10 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 55-70, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	7.57
NRMSE	0.1267
Correlation Coefficient	0.72
Regression Coefficient	0.54
Max Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	33.84
Min Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-32.69
Max Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	29.19
Min Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-30.52
Number of Data Points	338

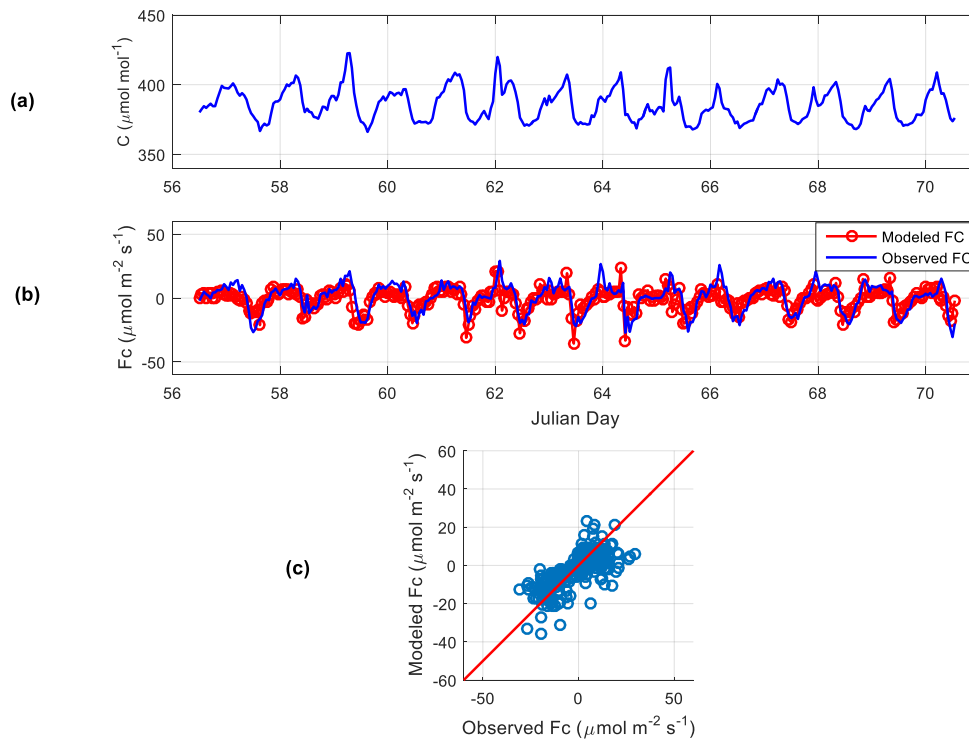


Figure 4.2.10 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 55-70, 2003.

The modeled CO₂ flux during test period 5 (day 55 to 70) well captures the diurnal variation and magnitude of the observed fluxes (Figure 4.2.10 (b)). During this period, the maximum and minimum modeled fluxes (33.84 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and -32.69 $\mu\text{mol m}^{-2} \text{s}^{-1}$) are comparable to maximum and minimum observed fluxes (29.19 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and -30.52 $\mu\text{mol m}^{-2} \text{s}^{-1}$) respectively. The scatterplot shows good agreement between the modeled and observed fluxes (Figure 4.2.10 (c)) with correlation coefficient, 0.72 and regression coefficient, 0.54. The RMSE and the NRMSE of the modeled CO₂ fluxes are 7.57 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and 12.67 % with the CO₂ fluxes on the order of 59.71 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.932 and 0.951 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 28.77 W m^{-2} and 10.93 % with the sensible heat fluxes on the order of 263.28 W m^{-2} . The RMSE and NRMSE for this test period are 51.43 W m^{-2} and 11.33 % with the latent heat fluxes on the order of 454.06 W m^{-2} .

Test Period 6: Day 73-87, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.11 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 73-87, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.923	Correlation Coefficient	0.925
RMSE (W m^{-2})	27.32	RMSE (W m^{-2})	57.56
NRMSE	0.0829	NRMSE	0.1002
Max HOBS (W m^{-2})	273.78	Max EOBS (W m^{-2})	561.86
Min HOBS (W m^{-2})	-55.61	Min EOBS (W m^{-2})	-12.91
Max HMEP (W m^{-2})	211.91	Max EMEP (W m^{-2})	580.99
Min HMEP (W m^{-2})	-10.41	Min EMEP (W m^{-2})	-24.39

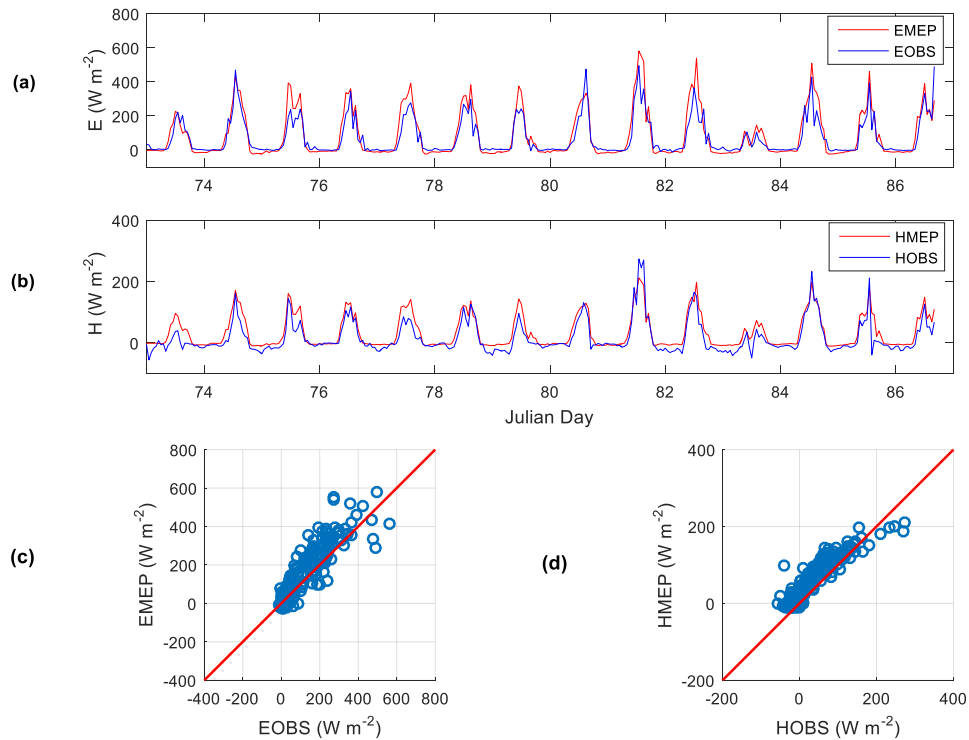


Figure 4.2.11 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 73-87, 2003.

Table 4.2.12 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 73-87, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	6.98
NRMSE	0.1475
Correlation Coefficient	0.63
Regression Coefficient	0.714
Max Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	63.67
Min Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-37.83
Max Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	19.93
Min Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-27.38
Number of Data Points	325

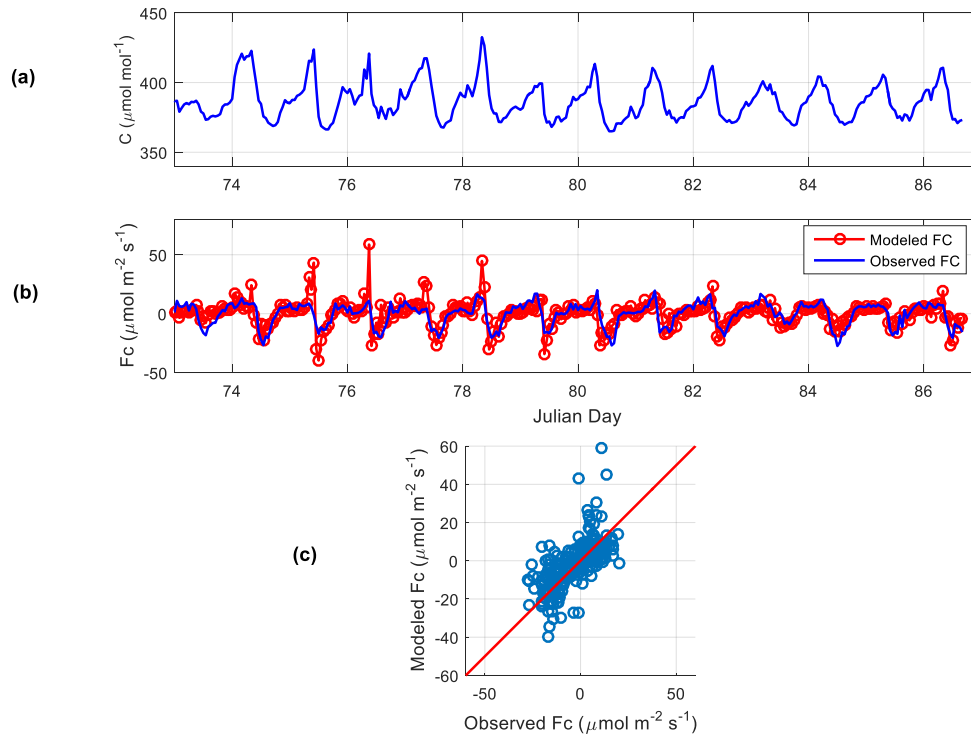


Figure 4.2.12 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 73-87, 2003.

The modeled CO₂ fluxed shows good agreement during test period 6 (day 73 to 87, 2003) except day 73 to 78 during hours 3 AM to 10 AM when the spikes in CO₂ concentration occurred ($> 410 \mu\text{mol/mol}$ to $429 \mu\text{mol/mol}$) causing spikes in modeled fluxes (Figure 4.2.12 (a), (b)). The spikes in CO₂ concentration ($416.057 \mu\text{mol/mol}$ to $432.594 \mu\text{mol/mol}$) leading to relatively large numerical errors of the calculative derivative term in (3.27) which causes large value maximum modeled flux ($63.67 \mu\text{mol m}^{-2} \text{s}^{-1}$) during day 76 (Figure 4.2.12 (a), (b)). The correlation coefficient, 0.63 and regression coefficient, 0.714 during this period. The RMSE and the NRMSE of the modeled CO₂ fluxes are $6.98 \mu\text{mol m}^{-2} \text{s}^{-1}$ and 14.75 % with the CO₂ fluxes on the order of $47.31 \mu\text{mol m}^{-2} \text{s}^{-1}$ for test period 6 (day 73 to 87, 2003). The MEP energy fluxes have correlation coefficients 0.931 and 0.937 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 27.87 W m^{-2} and 8.76 % with the observed sensible heat fluxes on the order of 329.39 W m^{-2} . The RMSE and NRMSE for this test period are 60.22 W m^{-2} and 9.61 % with the observed latent heat fluxes on the order of 574.77 W m^{-2} .

Test Period 7: Day 88-140, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.13 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 88-140, 2003

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.931	Correlation Coefficient	0.937
RMSE (W m^{-2})	27.87	RMSE (W m^{-2})	60.22
NRMSE	0.0876	NRMSE	0.0961
Max HOBS (W m^{-2})	246.29	Max EOBS (W m^{-2})	594.02
Min HOBS (W m^{-2})	-71.90	Min EOBS (W m^{-2})	-32.59
Max HMEP (W m^{-2})	219.58	Max EMEP (W m^{-2})	594.72
Min HMEP (W m^{-2})	-11.12	Min EMEP (W m^{-2})	-28.23

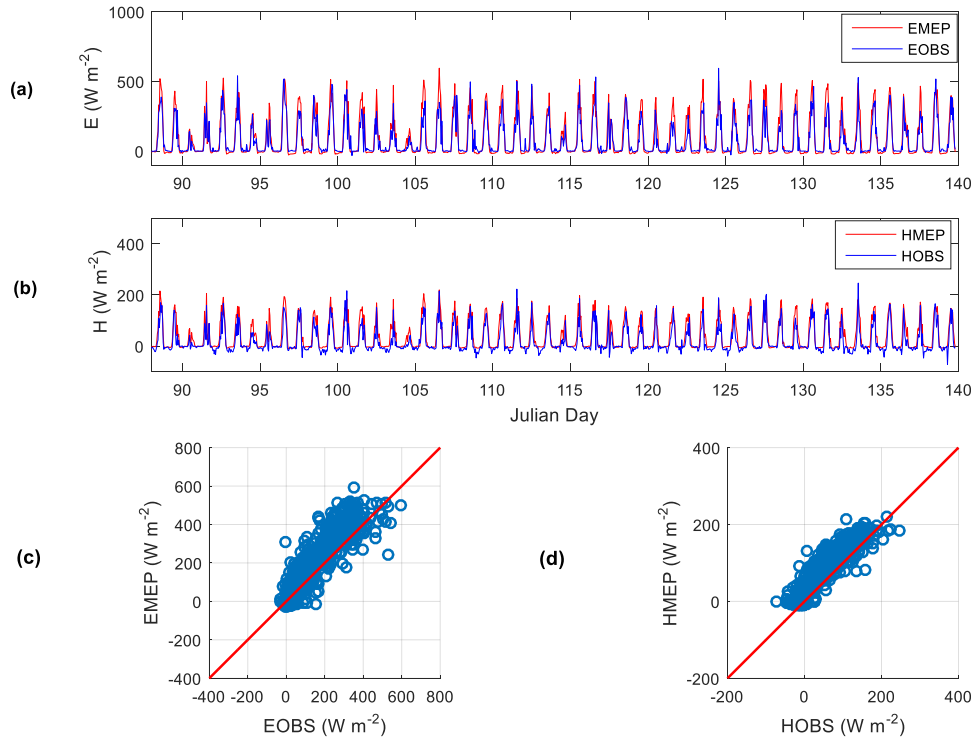


Figure 4.2.13 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 88-140, 2003.

Table 4.2.14 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 88-140, 2003

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	6.66
NRMSE	0.1023
Correlation Coefficient	0.63
Regression Coefficient	0.752
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	107.2
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-59.53
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	29.52
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-35.6
Number of Data Points	1227

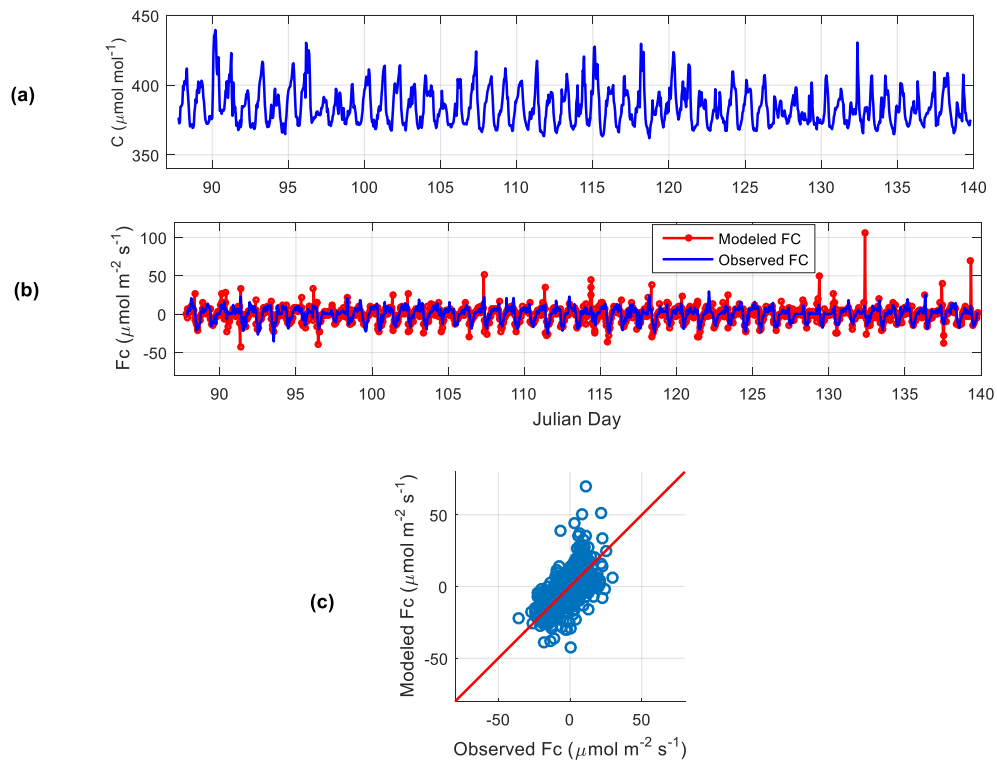


Figure 4.2.14 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 88 -140, 2003.

Test period 7 starts from day 88 to 140, 2003 and contains 1249 data points. Similar to test period 6, this period contains CO₂ concentration spikes (> 410 µmol/mol) during 2 AM to 6 AM in day 88, 90, 91, 93, 95, 96, 100, 101, 102, 107, 109, 111, 114, 115, 118, 120, 121 and 132 (Figure 4.2.14 (a)) causing spikes in modeled fluxes (Figure 4.2.14 (b)). The spikes in CO₂ concentration (388.814 µmol/mol to 430.5 µmol/mol) leading to relatively large numerical errors of the calculative derivative term in (3.27) which causes large value maximum modeled flux (107.2 µmol m⁻² s⁻¹) in day 132. Such spikes followed by large drop (392.987 µmol/mol to 378.02 µmol/mol) causes small value in minimum modeled flux (-59.5333 µmol m⁻² s⁻¹) in day 91. The correlation coefficient, 0.63 and regression coefficient, 0.752 during this period. The RMSE and the NRMSE of the modeled CO₂ flux are 6.66 µmolm⁻²s⁻¹ and 10.23 % with the CO₂ fluxes on the order of 65.12 µmol m⁻² s⁻¹. The MEP energy fluxes have correlation coefficients 0.931 and 0.937 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 27.87 W m⁻² and 8.76 % with the sensible heat fluxes on the order of 318.19 W m⁻². The RMSE and NRMSE for this test period are 60.22 W m⁻² and 9.61 % with the latent heat fluxes on the order of 626.61 W m⁻².

Test Period 8: Day 153-170, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.15 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 153-170, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.939	Correlation Coefficient	0.936
RMSE (W m^{-2})	23.08	RMSE (W m^{-2})	49.28
NRMSE	0.0935	NRMSE	0.0943
Max HOBS (W m^{-2})	206.28	Max EOBS (W m^{-2})	515.28
Min HOBS (W m^{-2})	-40.52	Min EOBS (W m^{-2})	-7.35
Max HMEP (W m^{-2})	184.24	Max EMEP (W m^{-2})	519.24
Min HMEP (W m^{-2})	-8.47	Min EMEP (W m^{-2})	-20.32

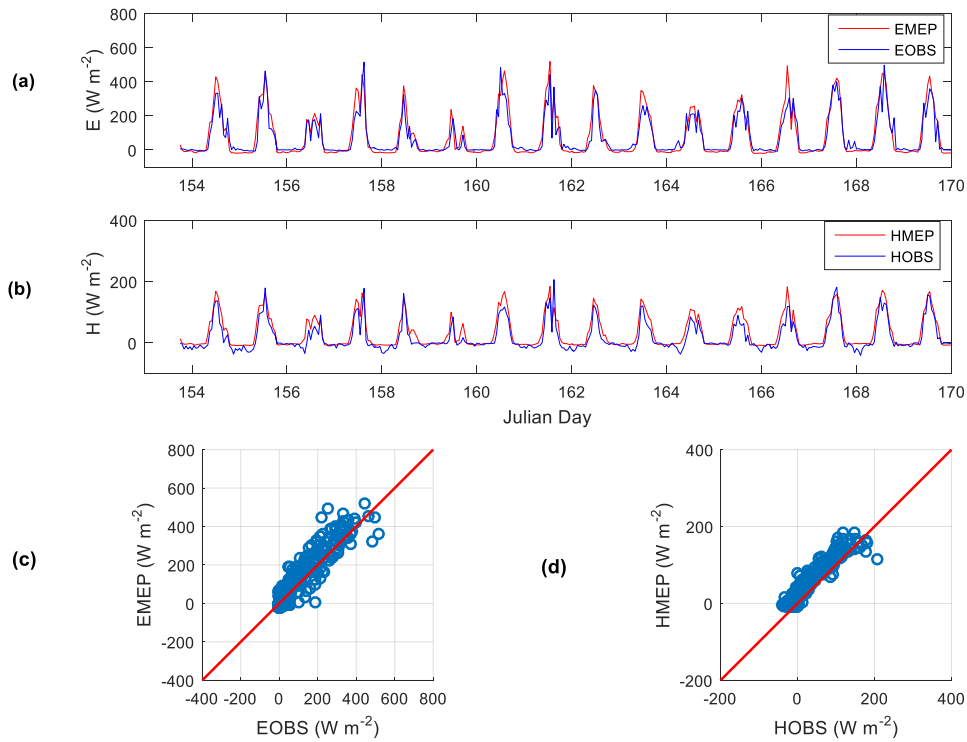


Figure 4.2.15 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 153-170, 2003.

Table 4.2.16 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Day Brazil. 153-170, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	6.50
NRMSE	0.1353
Correlation Coefficient	0.633
Regression Coefficient	0.7192
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	59.59
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-40.33
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	27.31
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-20.734
Number of Data Points	392

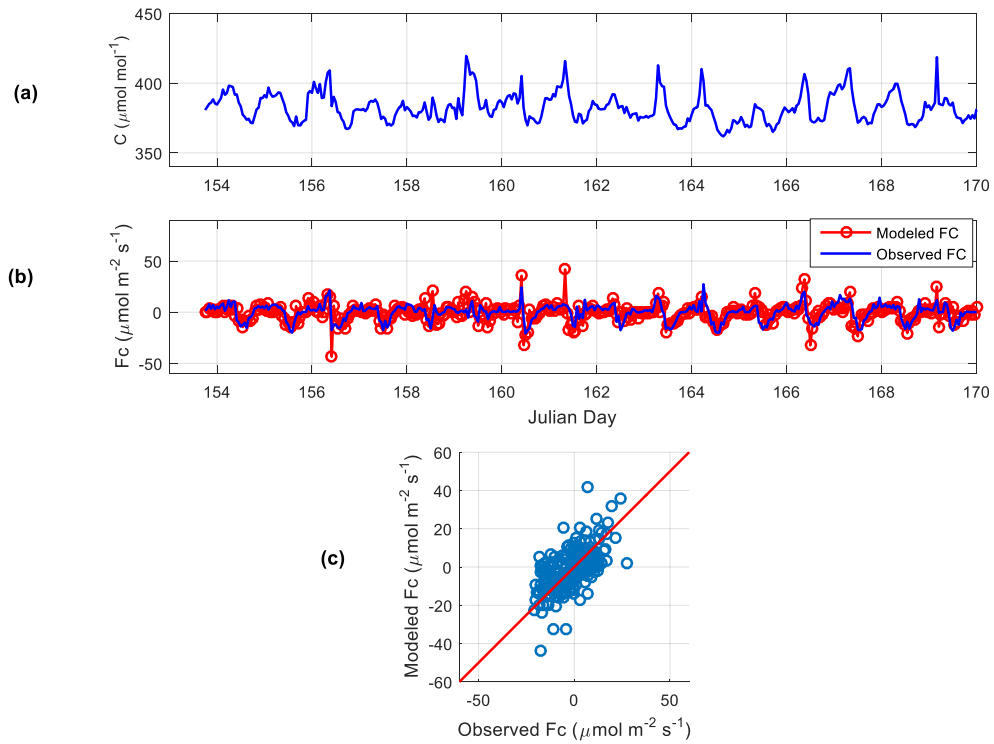


Figure 4.2.16 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 153 -170, 2003.

The 2 AM to 8 AM concentration spikes ($> 410 \mu\text{mol/mol}$) continues in test period 8 (day 155 to 170) especially, in day 159, 161 and 169 (Figure 4.2.16 (a)) causing relatively large numerical errors of the calculative derivative term in (3.27) which causes large value maximum modeled flux ($59.58 \mu\text{mol m}^{-2} \text{s}^{-1}$) in day 161 (Figure 4.2.16 b). The modeled fluxes followed observed fluxes reasonably well as shown by scatterplot (Figure 4.2.16 (c)). The correlation coefficient is 0.633 and regression coefficient is 0.7192 for this period. The RMSE and the NRMSE of the modeled CO_2 flux are $6.50 \mu\text{mol m}^{-2} \text{s}^{-1}$ and 13.25 % with the CO_2 fluxes on the order of $48.044 \mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.9387 and 0.9373 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 29.43 W m^{-2} and 11.59 % with the observed sensible heat fluxes on the order of 246.8 W m^{-2} . The RMSE and NRMSE for this test period are 55.46 W m^{-2} and 8.92 % with the observed latent heat fluxes on the order of 522.63 W m^{-2} .

. Test Period 9: Day 310-348, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.17 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 310-348, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9387	Correlation Coefficient	0.9373
RMSE (W m^{-2})	29.43	RMSE (W m^{-2})	55.46
NRMSE	0.1159	NRMSE	0.0892
Max HOBS (W m^{-2})	193.17	Max EOBS (W m^{-2})	581.38
Min HOBS (W m^{-2})	-60.66	Min EOBS (W m^{-2})	-28.94
Max HMEP (W m^{-2})	189.56	Max EMEP (W m^{-2})	537.09
Min HMEP (W m^{-2})	-10.76	Min EMEP (W m^{-2})	-40.58

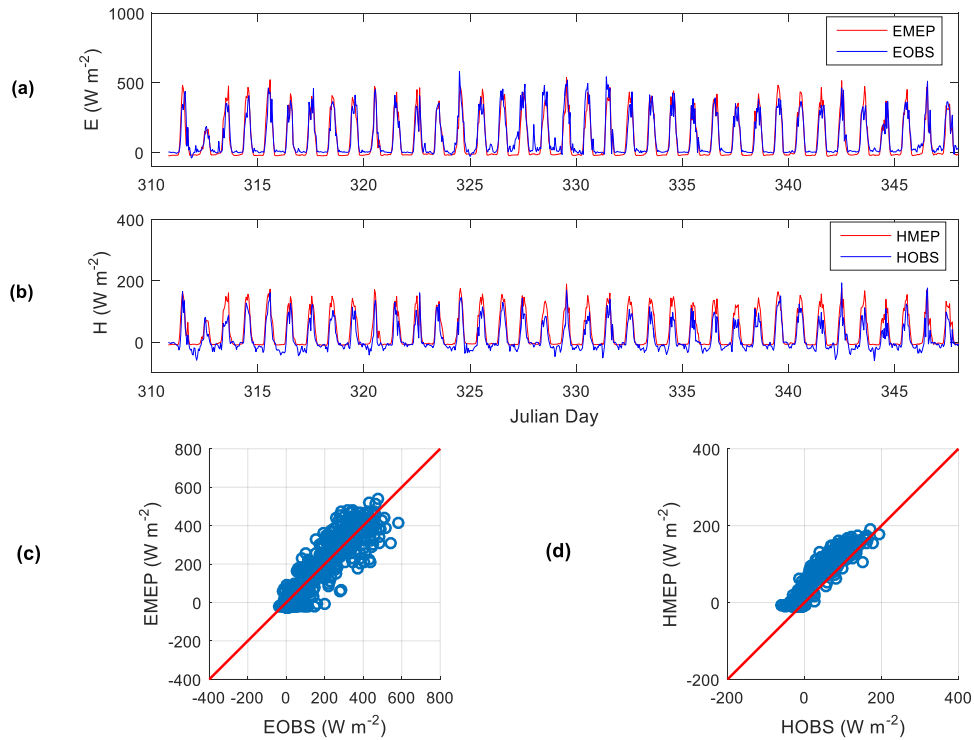


Figure 4.2.17 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 310-348, 2003.

Table 4.2.18 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 310-348, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	8.75
NRMSE	0.1525
Correlation Coefficient	0.5121
Regression Coefficient	0.4536
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	60.01
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-62.438
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	23.446
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-33.889
Number of Data Points	891

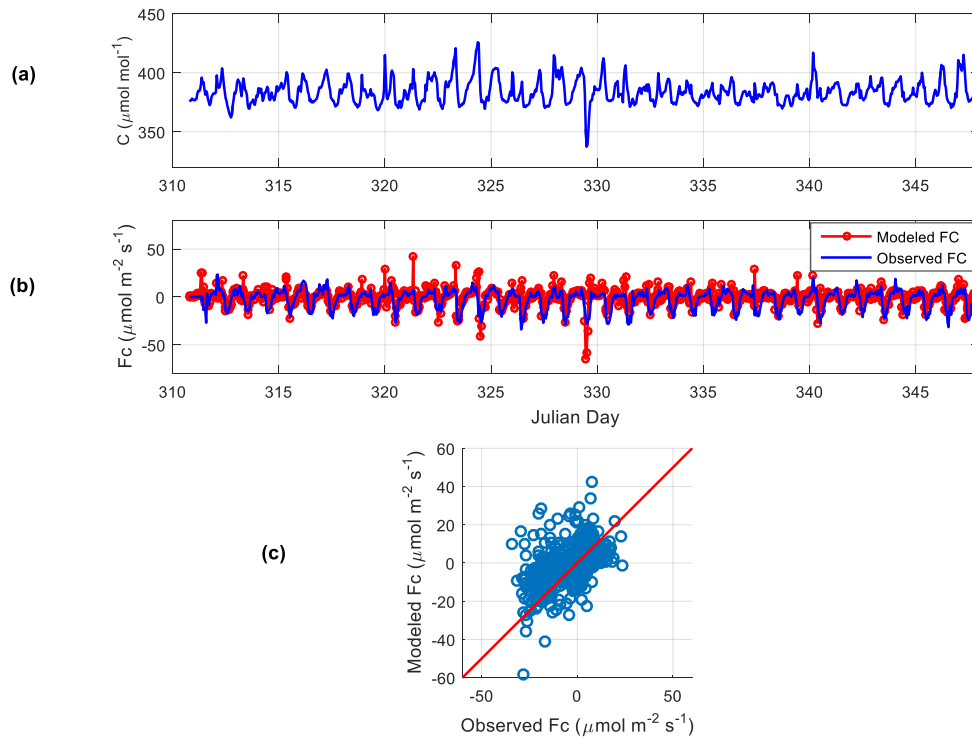


Figure 4.2.18 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 310 -348, 2003.

Test period 9 is during dry season (July to December) in Amazon basin from day 348 to 365, 2003. This period contains 910 data points. This period has a sharp drop of CO₂ concentration in day 329 (Figure 4.2.18 (a)) causes smaller value in modeled flux (-62.438 $\mu\text{mol m}^{-2} \text{s}^{-1}$) (Figure 4.2.18 (b)). The correlation coefficient is 0.5121 and regression coefficient is 0.4536 during this period. The RMSE and the NRMSE of the modeled CO₂ flux are 8.75 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and 15.25 % respectively, with the CO₂ fluxes on the order of 57.335 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.9387 and 0.9373 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 29.43 W m^{-2} and 11.59 % with the observed sensible heat fluxes on the order of 253.83 W m^{-2} . The RMSE and NRMSE for this test period are 55.46 W m^{-2} and 8.92 % with the observed latent heat fluxes on the order of 610.32 W m^{-2} .

Test Period 10: Day 348-365, 2003, Santarem KM 67 Primary Forest, Brazil

Table 4.2.19 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Santarem Primary Forest, Brazil. Day 348-365, 2003.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9297	Correlation Coefficient	0.942
RMSE (W m^{-2})	32.792	RMSE (W m^{-2})	52.492
NRMSE	0.1193	NRMSE	0.0981
Max HOBS (W m^{-2})	199.56	Max EOBS (W m^{-2})	524.403
Min HOBS (W m^{-2})	-75.41	Min EOBS (W m^{-2})	-10.422
Max HMEP (W m^{-2})	184.76	Max EMEP (W m^{-2})	535.843
Min HMEP (W m^{-2})	-9.338	Min EMEP (W m^{-2})	-23.633

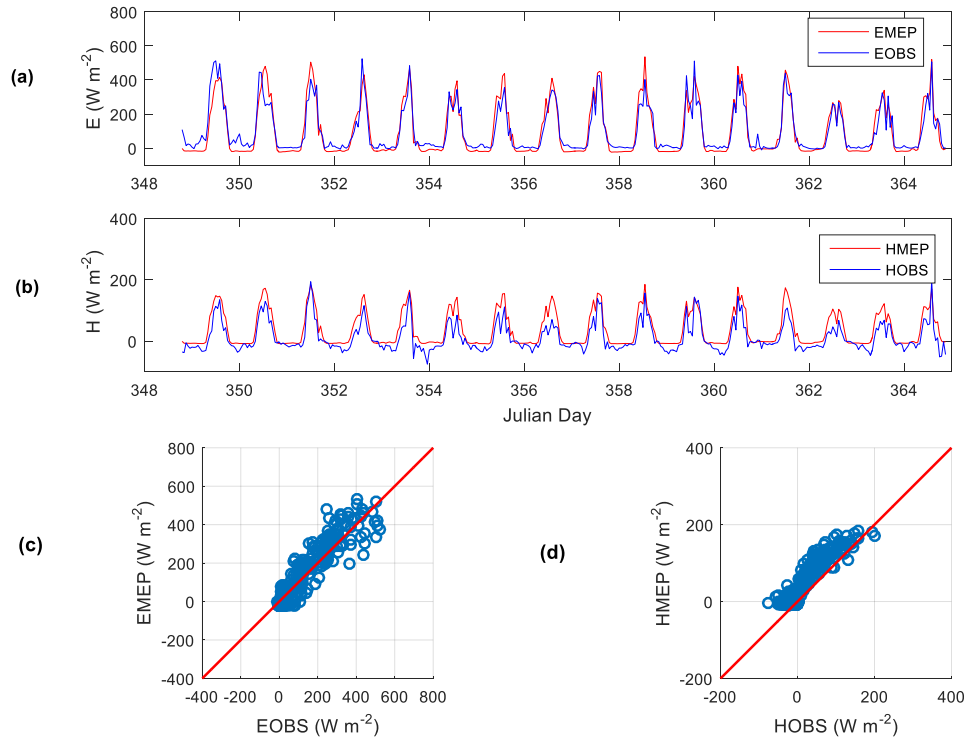


Figure 4.2.19 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Santarem Primary Forest, Brazil. Day 310-348, 2003.

Table 4.2.20 Result summary for modeled vs. observed CO₂ fluxes at Santarem Primary Forest, Brazil. Day 348-365, 2003.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	7.97
NRMSE	0.1521
Correlation Coefficient	0.5847
Regression Coefficient	0.4277
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	28.715
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-25.899
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	23.938
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-28.448
Number of Data Points	384

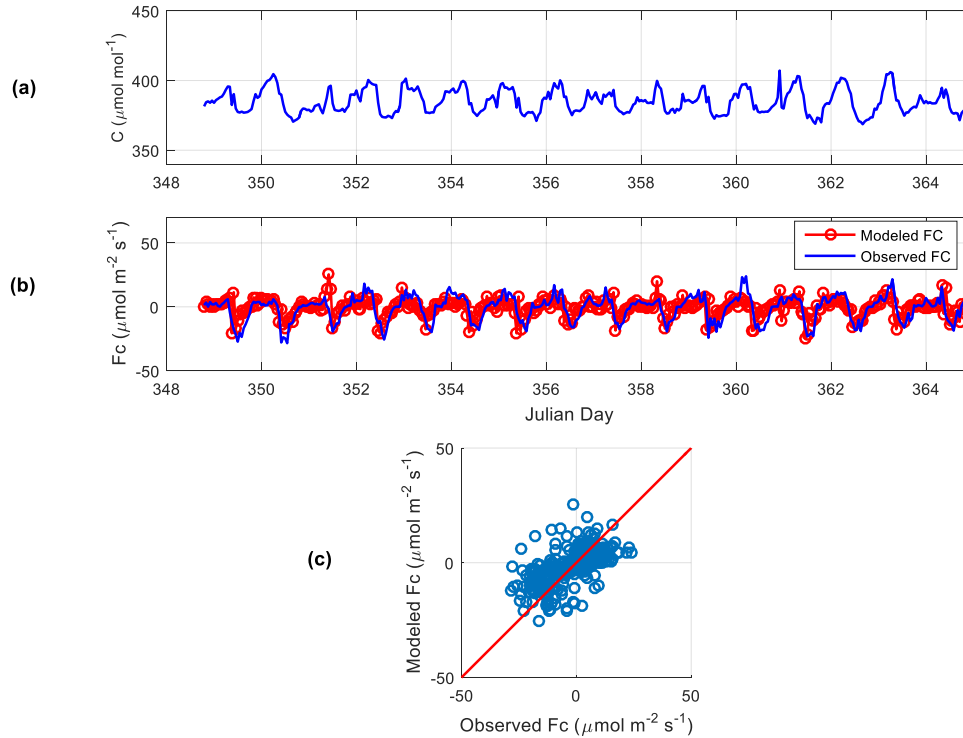


Figure 4.2.20 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Santarem Primary Forest, Brazil. Day 348-365, 2003.

Test period 10 is the final period of this case study; it contains during dry season (July to December) in Amazon basin from day 348 to 365, 2003. The modeled fluxes show good agreement with observation (Figure 4.2.20 (b)). Due to less spikes in CO₂ concentration data during this period the magnitude of maximum and minimum modeled flux ($28.715 \mu\text{mol m}^{-2} \text{s}^{-1}$ and $-25.89 \mu\text{mol m}^{-2} \text{s}^{-1}$) are comparable to maximum and minimum observed flux ($23.938 \mu\text{mol m}^{-2} \text{s}^{-1}$ and $-28.448 \mu\text{mol m}^{-2} \text{s}^{-1}$) respectively. The correlation coefficient is 0.5847 and regression coefficient is 0.4277 for this period. The RMSE and the NRMSE of the modeled CO₂ flux is $7.97 \mu\text{molm}^{-2}\text{s}^{-1}$ and 15.21 % with the CO₂ fluxes on the order of $57.335 \mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.9297 and 0.942 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 32.792 W m^{-2} and 11.93 % with the observed sensible heat fluxes on the order of 274.966 W m^{-2} . The RMSE and NRMSE for this test period are 52.492 W m^{-2} and 9.81 % with the observed latent heat fluxes on the order of 534.825 W m^{-2} .

4.2.2 Site 2

The Cedar Bridge site (39.84°N, 74.38°W) is located in the upland forests of the New Jersey Pine Barrens, the largest continuous forested landscape on the Northeastern coastal plain. Upland forests occupy 650,000 ha Pine Barrens and can be divided into three dominant stand types, Oak/Pine (19.1%), Pine/Oak (13.1%), and Pitch Pine/Scrub oak (14.3%). This is a mixed forest with canopy height 5.7 m (pine) and 0.4 m (oak) respectively in the year 2005. The height of eddy covariance tower is 16 m. The cool temperate climate has mean annual temperature 11.04 °C (with mean monthly temperatures of 0.3 °C in January and 23.8 °C in June) and mean annual precipitation is 1123 mm (S.D. 82 mm).

The model uses half-hourly time-series data of CO_2 concentration ($\mu\text{mol mol}^{-1}$), canopy surface temperature T_s (°C) and net radiation R_n (W m^{-2}). Downward CO_2 flux (FC) as well as latent (E) and sensible (H) heat flux from the atmosphere to canopy surface are defined as negative. Ground heat flux (G) is defined negative from the surface into the soil layer. Due to dense canopy cover at this site the observed ground heat flux is very small. The MEP model as in (B8) – (B10) of appendix B is used to estimate H, which is used in parameterization of diffusion coefficient of CO_2 , D_c . The distance above the canopy surface z is measured by the difference of mean canopy height (4 m) and height of CO_2 measurement (16 m) is 12 m. Scattered missing data are filled using linear interpolation when the time interval between missing data are not very large

(< 3 hours). The dataset is re-grouped into multiple no-gap time series to avoid larger gaps (> 3hrs) of the time-series records.

The comparison of modeled CO₂ flux using equation (3.27) with the observed eddy-covariance flux is characterized by the root-mean-square error (RMSE), the normalized root-mean-square error (NRMSE defined as the RMSE divided by the magnitude of the observed fluxes), correlation coefficient (covariance of the observed and modeled CO₂ fluxes divided by the product of their standard deviations) and regression coefficient (covariance of the observed and modeled CO₂ fluxes divided by the variance of observed CO₂ fluxes). The maximum and minimum observed flux over the test period and maximum and minimum model flux over test period are reported. As the MEP modeled sensible heat flux is used in the parameterization of eddy diffusivity of CO₂, the MEP modeled energy fluxes are compared with observed energy fluxes from eddy covariance measurements. This includes: root-mean-square error (RMSE), normalized root-mean-square error (NRMSE), correlation coefficient, maximum and minimum flux of the observed and MEP modeled heat fluxes over the test period. The results are shown in figures and tables followed by summary tables.

Test Period 1: Day 160-170, 2006, Cedar Bridge, New Jersey

Table 4.2.21 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Cedar Bridge, New Jersey. Day 160-170, 2006

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9704	Correlation Coefficient	0.9378
RMSE (W m^{-2})	48.2402	RMSE (W m^{-2})	61.887
NRMSE	0.08907	NRMSE	0.1017
Max HOBS (W m^{-2})	457.36	Max EOBS (W m^{-2})	533.305
Min HOBS (W m^{-2})	-84.275	Min EOBS (W m^{-2})	-75.384
Max HMEP (W m^{-2})	269.42	Max EMEP (W m^{-2})	550.609
Min HMEP (W m^{-2})	-40.127	Min EMEP (W m^{-2})	-52.673

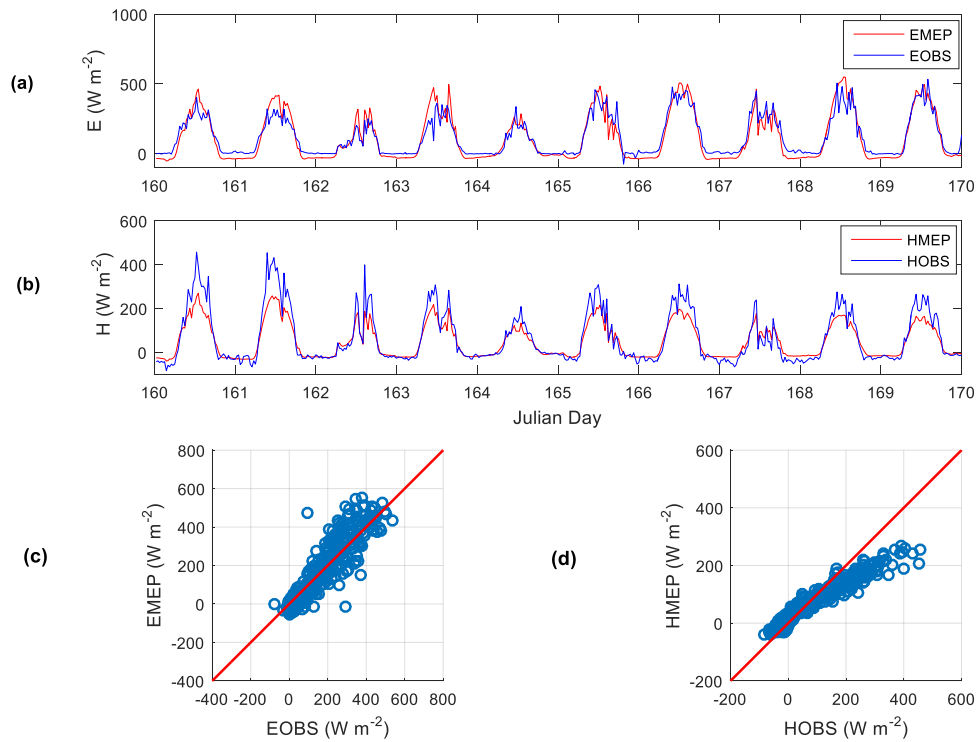


Figure 4.2.21 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Cedar Bridge, New Jersey. Day 160-170, 2006.

Table 4.2.22 Result summary for modeled vs. observed CO₂ fluxes at Cedar Bridge, New Jersey. Day 160-170, 2006.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	5.293
NRMSE	0.1494
Correlation Coefficient	0.801
Regression Coefficient	0.8247
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	27.502
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-23.191
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	11.754
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-23.67
Number of Data Points	480

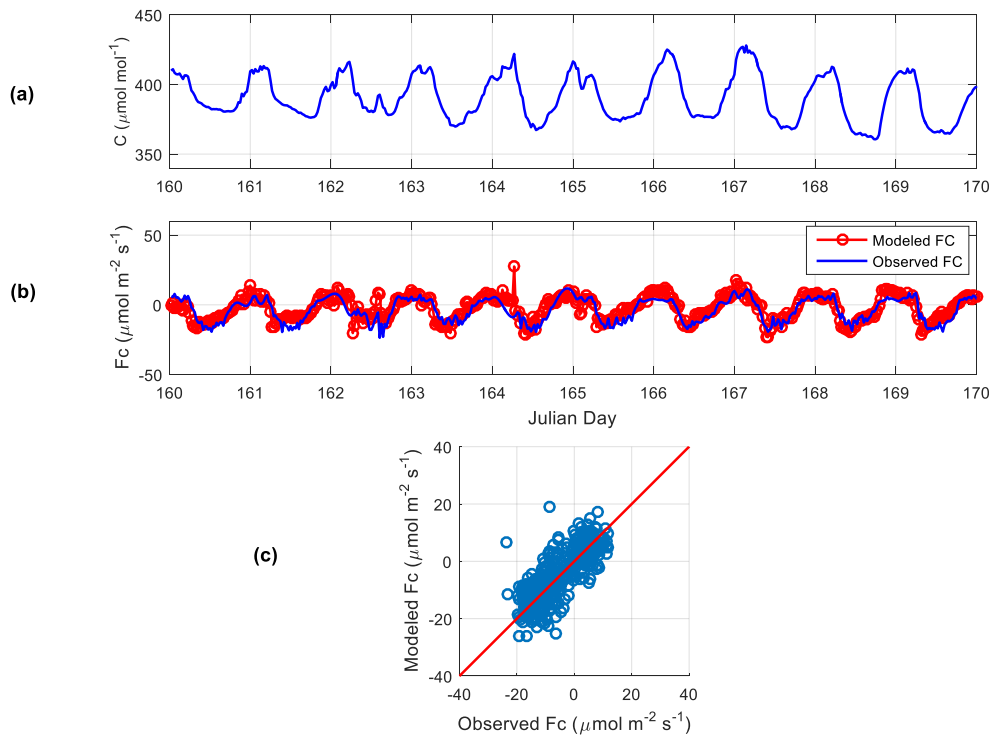


Figure 4.2.22 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Cedar Bridge, New Jersey. Day 160-170, 2006.

The modeled CO₂ fluxes using equation (3.27) well capture the diurnal variation and magnitude of the observed fluxes (Figure 4.2.22 (b)) during test period 1 (day 160 to 170, 2006). The RMSE and the NRMSE of the modeled CO₂ fluxes are 5.293 $\mu\text{mol m}^{-2}\text{s}^{-1}$ and 14.94 % respectively, with the CO₂ fluxes on the order of 35.424 $\mu\text{mol m}^{-2}\text{s}^{-1}$. The scatterplot of modeled vs. observed fluxes show great consistency along the 1:1 line (Figure 4.2.22 (c)) with correlation coefficient, 0.801 and regression coefficient, 0.8247. The magnitudes of modeled fluxes are comparable to the observed fluxes except for day 162 and 164 (Figure 4.2.22 (b)) when the observed nighttime (3 AM to 6:30 AM) CO₂ fluxes (-2.29 $\mu\text{mol m}^{-2}\text{s}^{-1}$ to - 8.65 $\mu\text{mol m}^{-2}\text{s}^{-1}$) were erroneous (negative CO₂ fluxes indicate photosynthesis). Corresponding modeled CO₂ fluxes (5.3 $\mu\text{mol m}^{-2}\text{s}^{-1}$ to 27.5 $\mu\text{mol m}^{-2}\text{s}^{-1}$) is consistent with observed CO₂ concentrations (412.11 $\mu\text{mol/mol}$ to 421.897 $\mu\text{mol/mol}$) which higher than average daytime CO₂ concentration (≈ 380 $\mu\text{mol/mol}$) for that period. The MEP energy fluxes have correlation coefficients 0.9704 and 0.9378 for sensible heat (H) and latent heat (E) fluxes, respectively. The RMSE and NRMSE for this test period are 48.24 W m^{-2} and 8.9 % with the sensible heat fluxes on the order of 541.635 W m^{-2} . The RMSE and NRMSE for this test period are 61.89 W m^{-2} and 10.17 % with the latent heat fluxes on the order of 608.69 W m^{-2} .

Test Period 2: Day 187-192, 2006, Cedar Bridge, New Jersey

Table 4.2.23 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Cedar Bridge, New Jersey. Day 187-192, 2006.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9548	Correlation Coefficient	0.9077
RMSE (W m^{-2})	24.086	RMSE (W m^{-2})	73.811
NRMSE	0.07159	NRMSE	0.0959
Max HOBS (W m^{-2})	289.94	Max EOBS (W m^{-2})	681.91
Min HOBS (W m^{-2})	-46.51	Min EOBS (W m^{-2})	-87.757
Max HMEP (W m^{-2})	197.31	Max EMEP (W m^{-2})	490.624
Min HMEP (W m^{-2})	-22.61	Min EMEP (W m^{-2})	-37.831

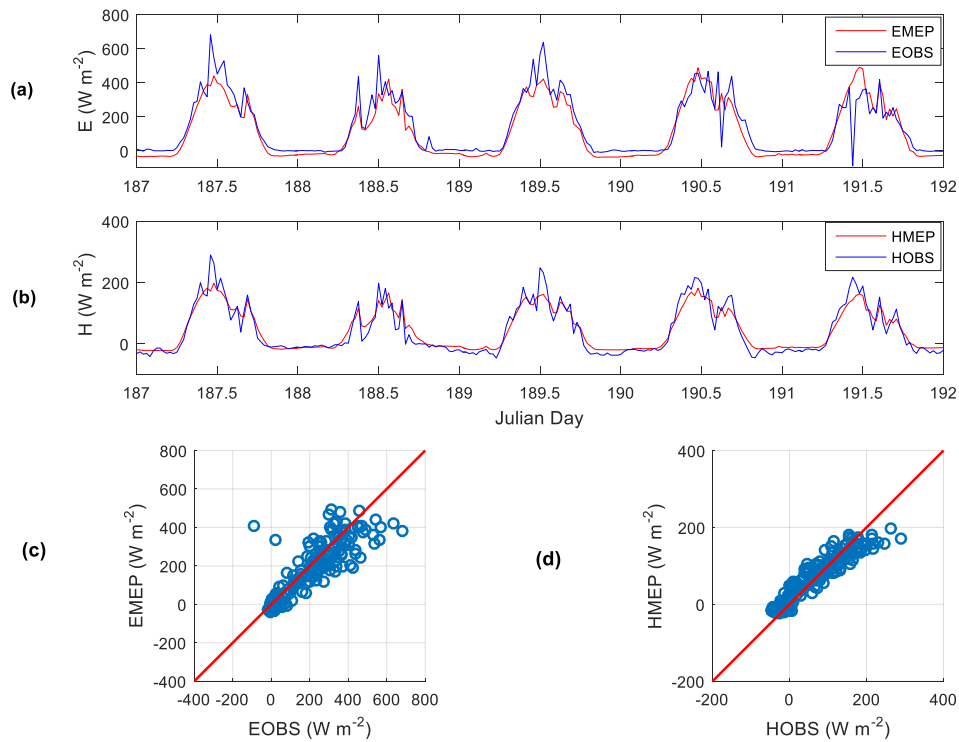


Figure 4.2.23 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Cedar Bridge, New Jersey. Day 187-192, 2006.

Table 4.2.24 Result summary for modeled vs. observed CO₂ fluxes at Cedar Bridge, New Jersey. Day 187-192, 2006.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	6.331
NRMSE	0.1759
Correlation Coefficient	0.7299
Regression Coefficient	0.7305
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	22.968
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-24.21
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	10.057
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-25.939
Number of Data Points	287

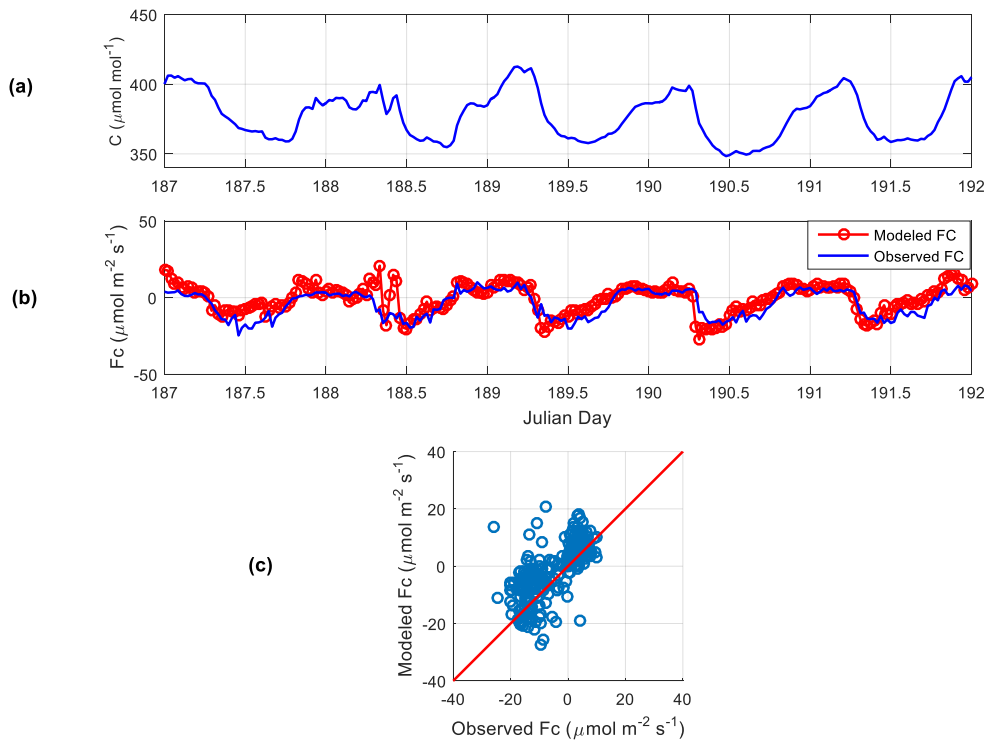


Figure 4.2.24 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Cedar Bridge, New Jersey. Day 187-192, 2006.

During Test period 2 (day 187 to 192, 2006) modeled fluxes show good agreement with observation except day 188 (10AM to 10:30 AM) (Figure 4.2.24 (b)) due to sudden spike in concentration (381.921 to 392.006 $\mu\text{mol/mol}$) (Figure 4.2.24 (a)). The correlation coefficient, 0.7299 and regression coefficient, 0.7305 during this period. The scatterplot shows good agreement except few outliers (Figure 4.2.24 (c)). The RMSE and the NRMSE of the modeled CO_2 fluxes are $6.331 \mu\text{mol m}^{-2} \text{s}^{-1}$ and 17.59% with the CO_2 fluxes on the order of $35.996 \mu\text{mol m}^{-2} \text{s}^{-1}$ for this period. The MEP energy fluxes have correlation coefficients 0.9548 and 0.9077 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 24.086 W m^{-2} and 7.159 % with the sensible heat fluxes on the order of 336.45 W m^{-2} . The RMSE and NRMSE for this test period are 73.811 W m^{-2} and 9.59 % with the latent heat fluxes on the order of 769.667 W m^{-2} .

Test Period 3: Day 194-202, 2006, Cedar Bridge, New Jersey

Table 4.2.25 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Cedar Bridge, New Jersey. Day 194-202, 2006.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9514	Correlation Coefficient	0.929
RMSE (W m^{-2})	50.01	RMSE (W m^{-2})	82.65
NRMSE	0.10801	NRMSE	0.1167
Max HOBS (W m^{-2})	410.898	Max EOBS (W m^{-2})	665.72
Min HOBS (W m^{-2})	-52.087	Min EOBS (W m^{-2})	-42.69
Max HMEP (W m^{-2})	204.11	Max EMEP (W m^{-2})	569.402
Min HMEP (W m^{-2})	-22.76	Min EMEP (W m^{-2})	-44.67

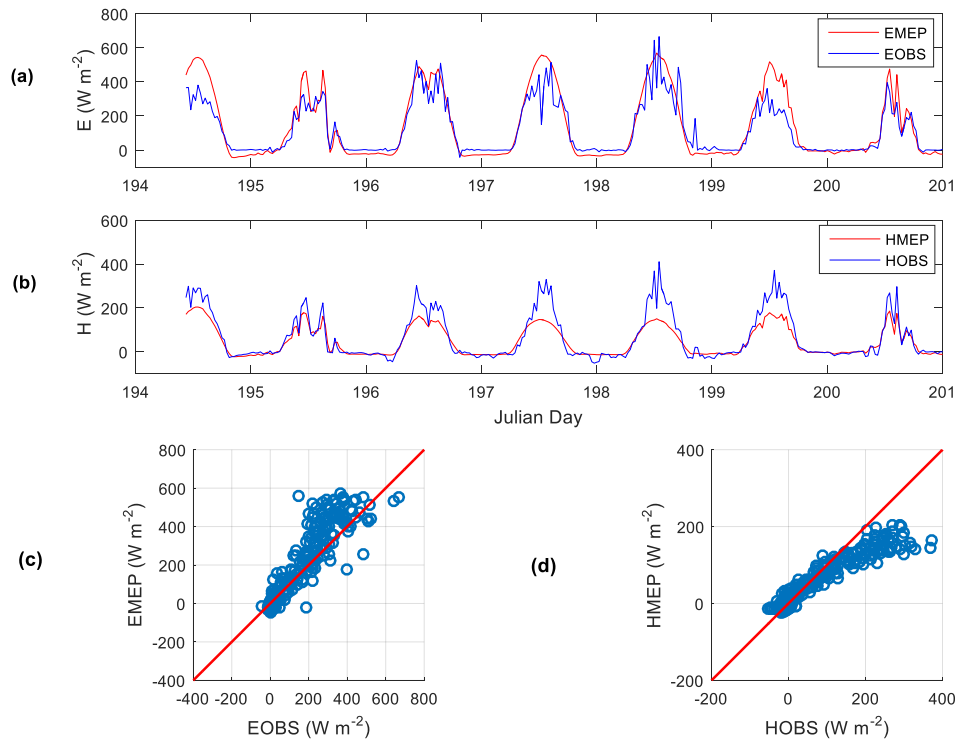


Figure 4.2.25 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Cedar Bridge, New Jersey. Day 194-202, 2006.

Table 4.2.26 Result summary for modeled vs. observed CO₂ fluxes at Cedar Bridge, New Jersey. Day 194-202, 2006.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	7.572
NRMSE	0.1895
Correlation Coefficient	0.661
Regression Coefficient	0.816
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	39.81
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-30.616
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	16.944
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-23.01
Number of Data Points	343

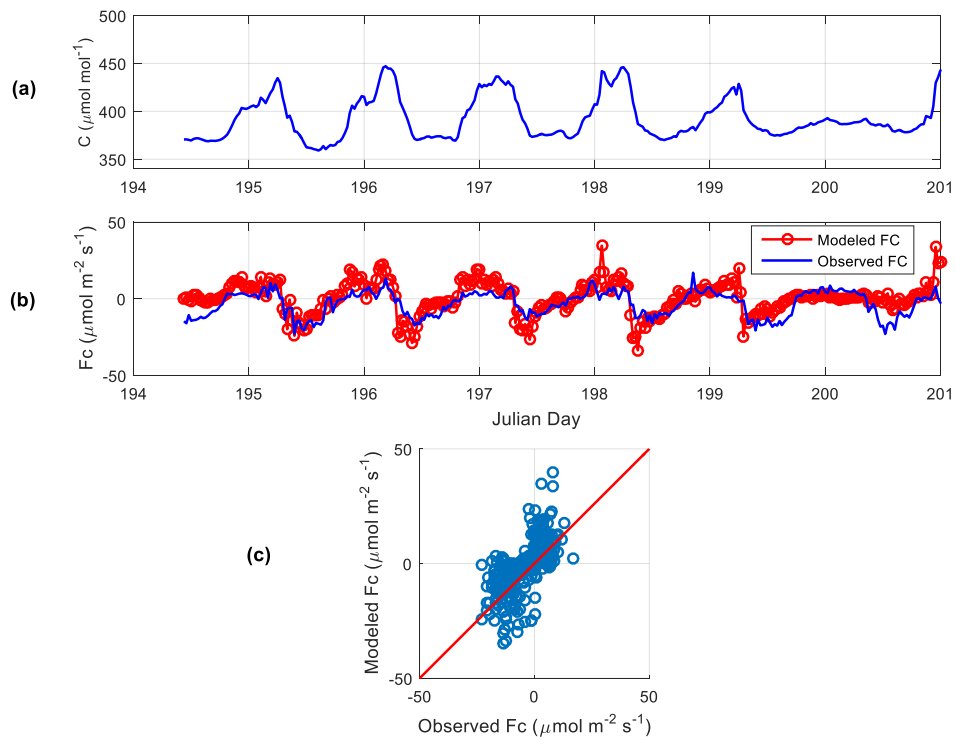


Figure 4.2.26 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Cedar Bridge, New Jersey. Day 194-202, 2006.

Test period 3 starts from day 194 to 202, 2006. During this period modeled fluxes well capture the diurnal variation and magnitude of the observed fluxes (Figure 4.2.26 (b)) with the correlation coefficient, 0.661 and regression coefficient, 0.816. The spurious spikes in CO₂ concentration data (> 400 to 465.156 $\mu\text{mol/mol}$ during 1:30 AM to 3:30 AM occur consistently during this period especially during day 201 leading to relatively large numerical errors of the calculated derivative term in (3.27) which causes large value maximum modeled flux (39.80983 $\mu\text{mol m}^{-2} \text{s}^{-1}$). The RMSE and the NRMSE of the modeled CO₂ fluxes during this period is 7.572 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and 18.95 % respectively, with the CO₂ fluxes on the order of 39.954 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.9514 and 0.929 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 50.01 W m^{-2} and 10.801 % with the sensible heat fluxes on the order of 462.985 W m^{-2} . The RMSE and NRMSE for this test period are 82.65 W m^{-2} and 11.67 % with the latent heat fluxes on the order of 708.41 W m^{-2} .

Test Period 4: Day 223-228, 2006, Cedar Bridge, New Jersey

Table 4.2.27 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Cedar Bridge, New Jersey. Day 223-228, 2006.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9694	Correlation Coefficient	0.9248
RMSE (W m^{-2})	57.467	RMSE (W m^{-2})	75.851
NRMSE	0.1199	NRMSE	0.1308
Max HOBS (W m^{-2})	429.48	Max EOBS (W m^{-2})	567.41
Min HOBS (W m^{-2})	-49.77	Min EOBS (W m^{-2})	-12.415
Max HMEP (W m^{-2})	222.262	Max EMEP (W m^{-2})	506.15
Min HMEP (W m^{-2})	-26.302	Min EMEP (W m^{-2})	-46.935

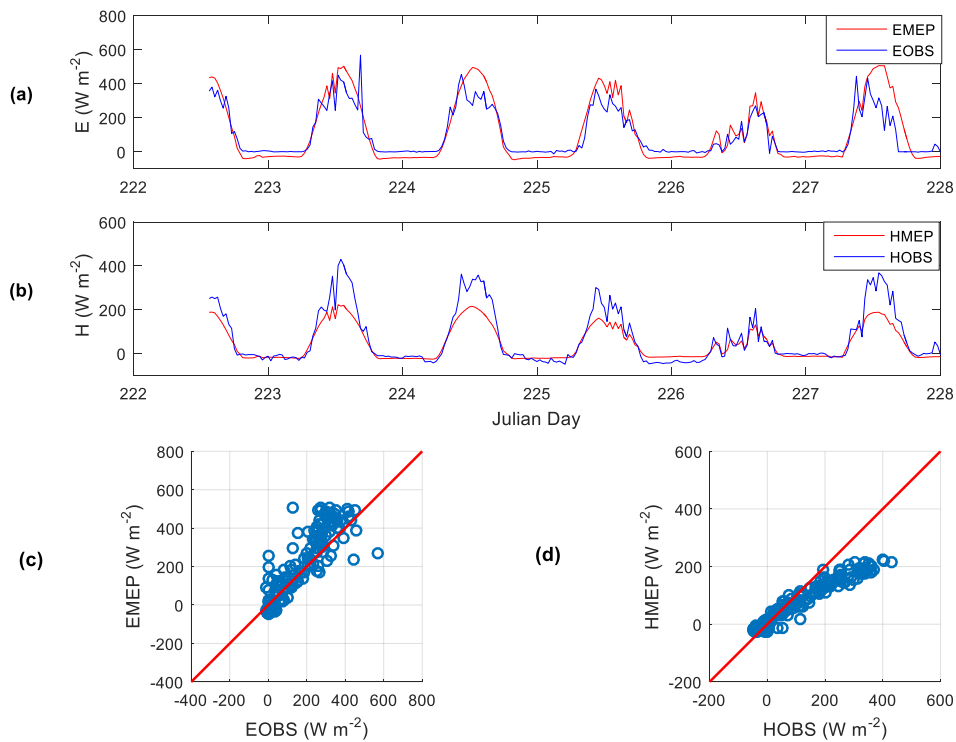


Figure 4.2.27 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Cedar Bridge, New Jersey. Day 223-228, 2006.

Table 4.2.28 Result summary for modeled vs. observed CO₂ fluxes at Cedar Bridge, New Jersey. Day 223-228, 2006.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	5.293
NRMSE	0.2027
Correlation Coefficient	0.571
Regression Coefficient	0.7703
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	33.74
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-38.81
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	8.244
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-17.868
Number of Data Points	345

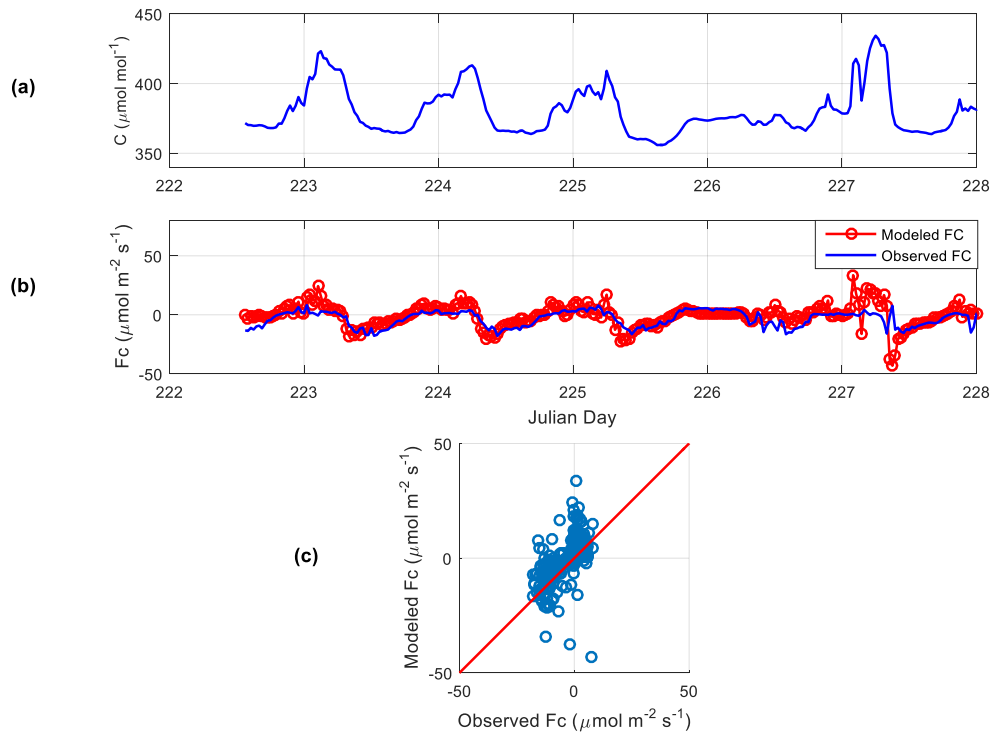


Figure 4.2.28 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Cedar Bridge, New Jersey. Day 223-228, 2006.

Test period 4 (day 223 to 228, 2006) shows reasonable agreement between modeled and observed fluxes (Figure 4.2.28 (a), (b)) except the spikes in CO₂ concentration data (> 400 to 435 $\mu\text{mol}/\text{mol}$) during 2 AM to 8 AM day 227 leading to relatively large numerical errors of the calculated derivative term in (3.27) which causes large value maximum modeled flux ($33.74 \mu\text{mol m}^{-2} \text{s}^{-1}$). The scatterplot of modeled vs. observed CO₂ flux shows some spread (Figure 4.2.28 (c)) with correlation coefficient, 0.571 and regression coefficient, 0.7703 for this period. The RMSE and the NRMSE of the modeled CO₂ fluxes are $5.293 \mu\text{molm}^{-2}\text{s}^{-1}$ and 20.27 % with the CO₂ fluxes on the order of $26.112 \mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.9694 and 0.9248 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 57.467 W m^{-2} and 11.99 % with the sensible heat fluxes on the order of 479.25 W m^{-2} . RMSE and NRMSE for this test period are 75.851 W m^{-2} and 13.08 % with the latent heat fluxes on the order of 579.825 W m^{-2} .

Test Period 5: Day 232-236, 2006, Cedar Bridge, New Jersey

Table 4.2.29 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Cedar Bridge, New Jersey. Day 232-236, 2006.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.948	Correlation Coefficient	0.92554
RMSE (W m^{-2})	67.963	RMSE (W m^{-2})	80.65
NRMSE	0.1235	NRMSE	0.1906
Max HOBS (W m^{-2})	498.01	Max EOBS (W m^{-2})	382.78
Min HOBS (W m^{-2})	-52.36	Min EOBS (W m^{-2})	-40.415
Max HMEP (W m^{-2})	197.51	Max EMEP (W m^{-2})	573.49
Min HMEP (W m^{-2})	-20.44	Min EMEP (W m^{-2})	-45.257

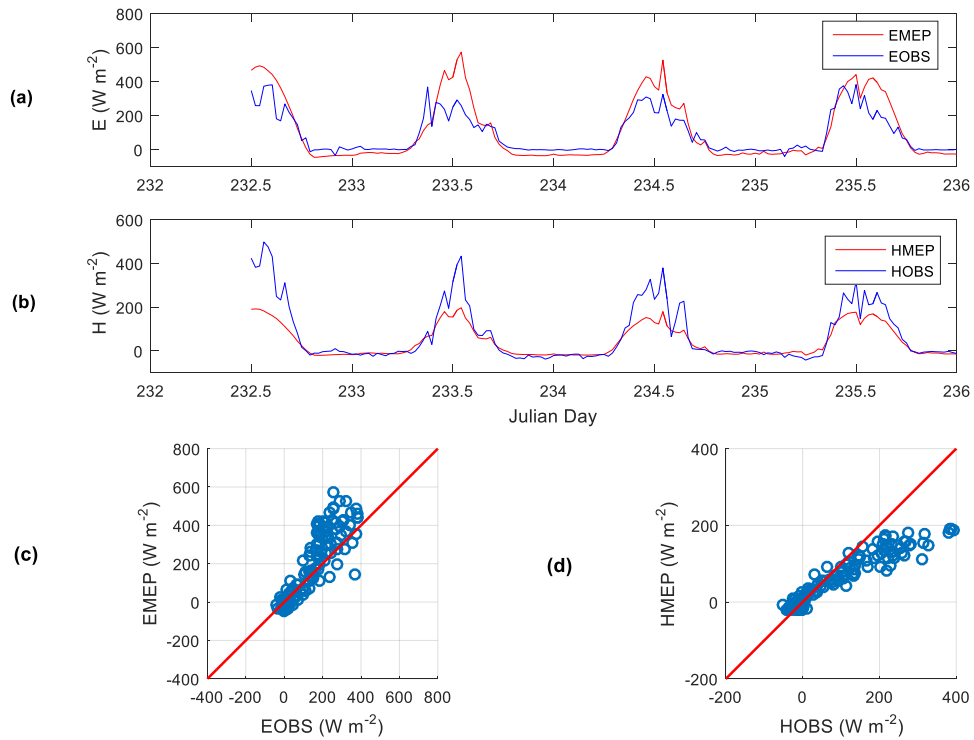


Figure 4.2.29 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Cedar Bridge, New Jersey. Day 232-236, 2006.

Table 4.2.30 Result summary for modeled vs. observed CO₂ fluxes at Cedar Bridge, New Jersey. Day 232-236, 2006.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	5.75
NRMSE	0.19501
Correlation Coefficient	0.6594
Regression Coefficient	0.9473
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	25.579
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-30.041
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	9.471
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-20.015
Number of Data Points	220

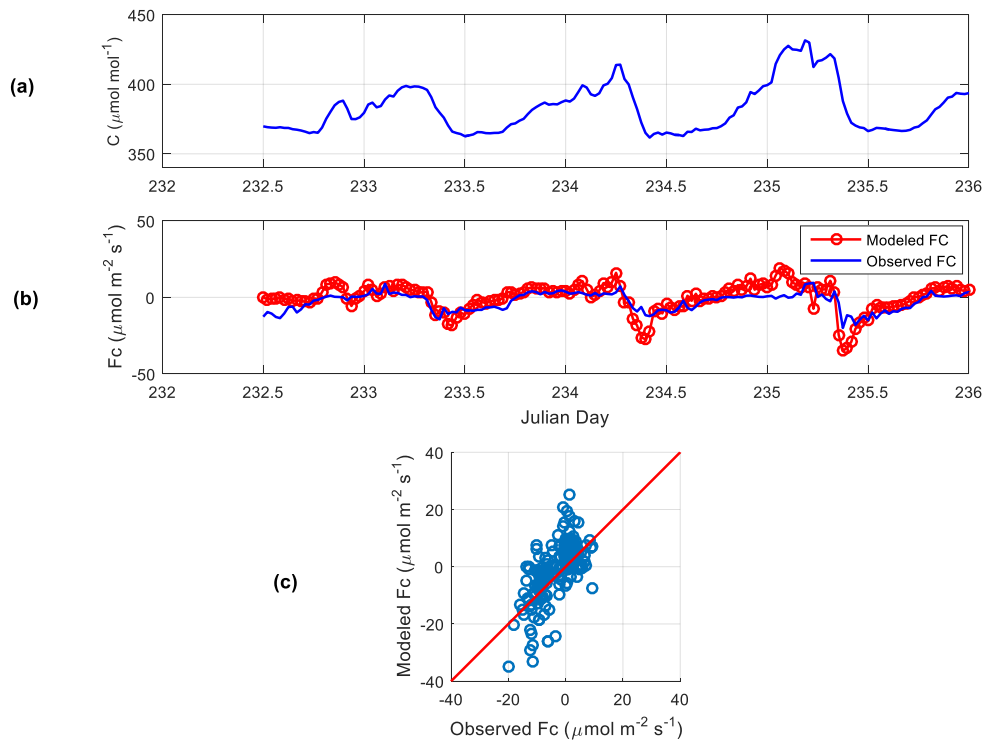


Figure 4.2.30 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Cedar Bridge, New Jersey. Day 232-236, 2006.

The modeled CO₂ flux during test period 5 (day 232 to 237) shows reasonable agreement with the observed fluxes (Figure 4.2.30 (b)). Similar to test period 3 and 4 nighttime CO₂ concentration spikes ($> 420 \mu\text{mol/mol}$) causes large values of the nighttime modeled fluxes during this time period especially day 235 (Figure 4.2.30 (a)). The scatterplot shows reasonable agreement between the modeled and observed fluxes (Figure 4.2.30 (c)) with correlation coefficient, 0.6594 and regression coefficient, 0.9473. The RMSE and the NRMSE of the modeled CO₂ fluxes are $5.75 \mu\text{molm}^{-2}\text{s}^{-1}$ and 19.501 % with the CO₂ fluxes on the order of $29.486 \mu\text{mol m}^{-2} \text{s}^{-1}$. The MEP energy fluxes have correlation coefficients 0.948 and 0.92554 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 67.963 W m^{-2} and 12.35 % with the sensible heat fluxes on the order of 550.37 W m^{-2} . The RMSE and NRMSE for this test period are 80.65 W m^{-2} and 19.06 % with the latent heat fluxes on the order of 423.195 W m^{-2} .

Test Period 6: Day 249-255, 2006, Cedar Bridge, New Jersey

Table 4.2.31 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Cedar Bridge, New Jersey. Day 249-255, 2006.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.938	Correlation Coefficient	0.9498
RMSE (W m^{-2})	43.95	RMSE (W m^{-2})	47.96
NRMSE	0.07019	NRMSE	0.07698
Max HOBS (W m^{-2})	578.68	Max EOBS (W m^{-2})	583.52
Min HOBS (W m^{-2})	-47.444	Min EOBS (W m^{-2})	-40.362
Max HMEP (W m^{-2})	229.2	Max EMEP (W m^{-2})	453.523
Min HMEP (W m^{-2})	-31.334	Min EMEP (W m^{-2})	-40.788

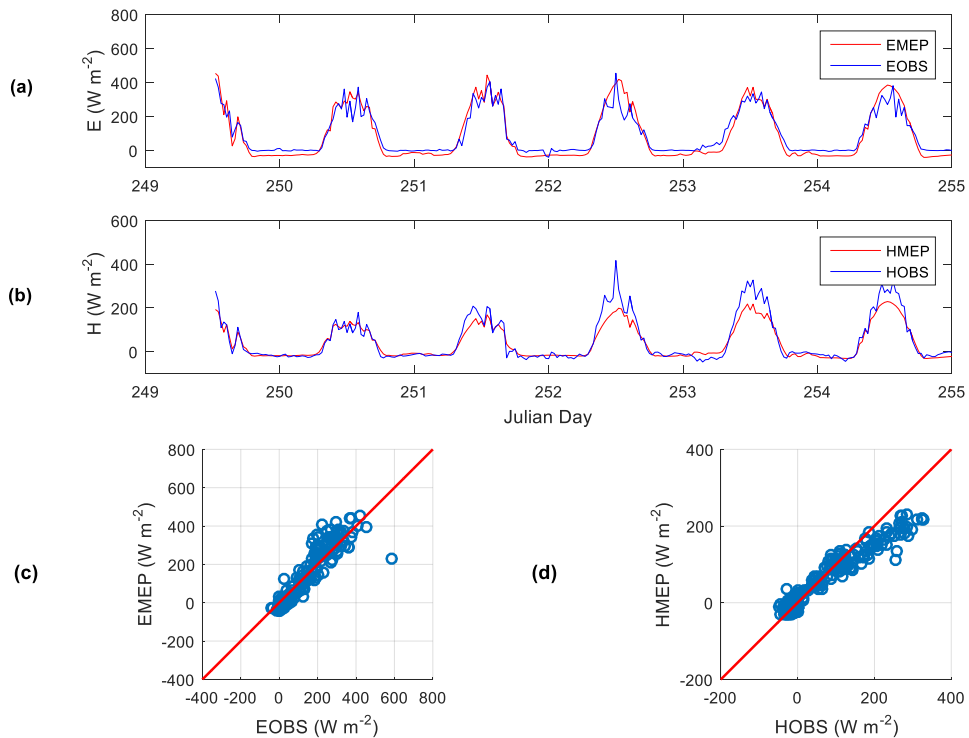


Figure 4.2.31 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Cedar Bridge, New Jersey. Day 249-255, 2006.

Table 4.2.32 Result summary for modeled vs. observed CO₂ fluxes at Cedar Bridge, New Jersey. Day 250-256, 2006.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	8.054
NRMSE	0.1336
Correlation Coefficient	0.547
Regression Coefficient	0.556
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	25.20
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-23.362
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	16.131
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-44.17
Number of Data Points	283

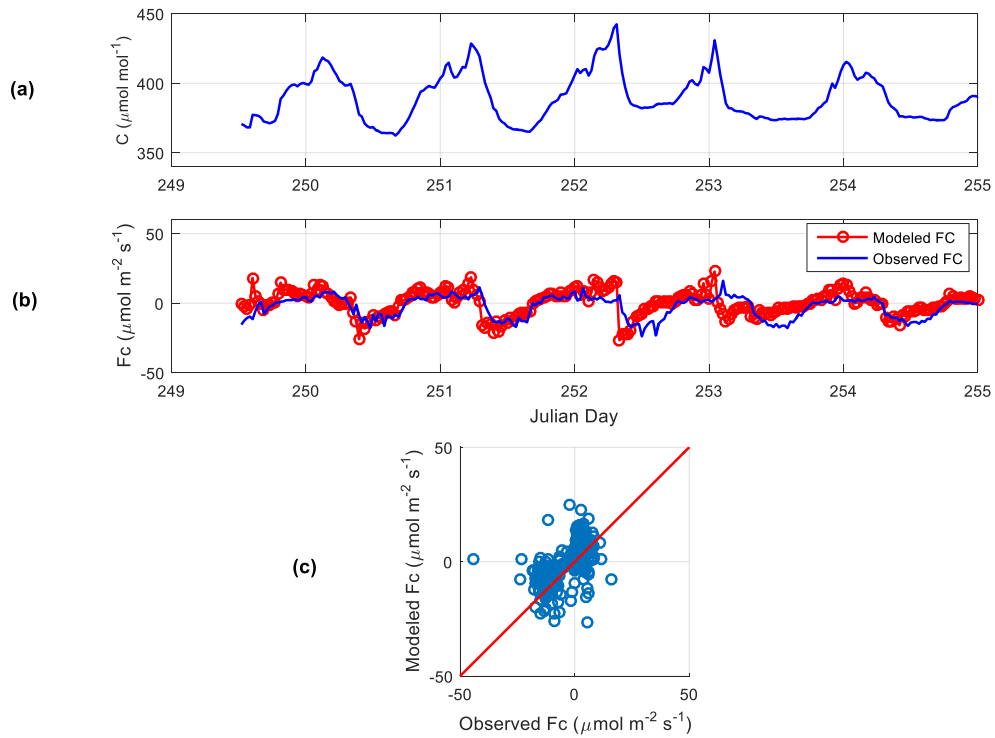


Figure 4.2.32 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of modeled vs. observed CO₂ fluxes at Cedar Bridge, New Jersey. Day 250-256, 2006.

The modeled CO₂ fluxes show reasonable agreement with observed fluxes (Figure 4.2.32 (b)) during test period 6 (day 250 to 255, 2006). The scatterplot of modeled vs. observed CO₂ flux shows some spread (Figure 4.2.32 (c)) with the correlation coefficient, 0.547 and regression coefficient, 0.556 during this period. The RMSE and the NRMSE of the modeled CO₂ fluxes are 8.054 $\mu\text{mol m}^{-2}\text{s}^{-1}$ and 13.36 % with the CO₂ fluxes on the order of 60.301 $\mu\text{mol m}^{-2}\text{s}^{-1}$. The sudden CO₂ concentration drop during day 252 (2:30 AM) causes relatively large numerical errors of the calculated derivative term in (3.27). The MEP energy fluxes have correlation coefficients 0.938 and 0.9498 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 43.95 W m^{-2} and 7.019 % with the observed sensible heat fluxes on the order of 626.124 W m^{-2} . The RMSE and NRMSE for this test period are 47.96 W m^{-2} and 7.698 % with the observed latent heat fluxes on the order of 623.882 W m^{-2} .

4.2.3 Site 3

Delta Junction 1920 Control site (63.89°N, 145.74°W) is located near Delta Junction, just to the north of the Alaska Range in interior Alaska. This evergreen needle leaf forest has a canopy overstory consisted of homogeneous stands of black spruce with a mean canopy height of 4 m with a sparse understory consisted primarily of shrubs. The site extended from the 9.5 m high eddy covariance tower for more than 1 km to the south, west, and north, with the shortest fetch to the east (approximately 200 m). The continental climate characterized by large daily and annual temperature ranges, low humidity, and relatively low precipitation. The mean annual temperature is -2.3 °C with mean annual Rainfall, 304 mm and mean annual Snowfall, 940 mm.

The model uses half-hourly time-series data of CO_2 concentration ($\mu\text{mol mol}^{-1}$), canopy surface temperature T_s (°C) and net radiation R_n (W m^{-2}) Downward CO_2 flux (FC) as well as latent (E) and sensible (H) heat flux from the atmosphere to canopy surface are defined as negative. Ground heat flux (G) is defined negative from the surface into the soil layer. Due to dense canopy cover at this site the observed ground heat flux is very small. The MEP model as in (B8) – (B10) of appendix B is used to estimate H, which is used in parameterization of diffusion coefficient of CO_2 , D_c . The distance above the canopy surface z is measured by the difference of mean canopy height (4 m) and height of CO_2 measurement (9.5 m) is 5.5 m. Scattered missing data are filled using linear interpolation when the time interval between missing data are not very large

(< 3 hours). The dataset is re-grouped into multiple no-gap time series to avoid larger gaps (> 3hrs) of the time-series records.

The comparison of modeled CO₂ flux using equation (3.27) with the observed eddy-covariance flux is characterized by the root-mean-square error (RMSE), the normalized root-mean-square error (NRMSE defined as the RMSE divided by the magnitude of the observed fluxes), correlation coefficient (covariance of the observed and modeled CO₂ fluxes divided by the product of their standard deviations) and regression coefficient (covariance of the observed and modeled CO₂ fluxes divided by the variance of observed CO₂ fluxes). The maximum and minimum observed flux over the test period and maximum and minimum model flux over test period are reported. As the MEP modeled sensible heat flux is used in the parameterization of eddy diffusivity of CO₂, the MEP modeled energy fluxes are compared with observed energy fluxes from eddy covariance measurements. This includes: root-mean-square error (RMSE), normalized root-mean-square error (NRMSE), correlation coefficient, maximum and minimum flux of the observed and MEP modeled heat fluxes over the test period. The results are shown in figures and tables followed by summary tables.

Test Period 1: Day 233-238, 2006, Delta Junction 1920-Control, Alaska

Table 4.2.33 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Delta Junction 1920-Control, Alaska. Day 233-238, 2004.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9440	Correlation Coefficient	0.9479
RMSE (W m^{-2})	21.6844	RMSE (W m^{-2})	65.9230
NRMSE	0.08998	NRMSE	0.5134
Max HOBS (W m^{-2})	206.074	Max EOBS (W m^{-2})	120.488
Min HOBS (W m^{-2})	-34.93	Min EOBS (W m^{-2})	-7.92
Max HMEP (W m^{-2})	171.28	Max EMEP (W m^{-2})	268.38
Min HMEP (W m^{-2})	-19.537	Min EMEP (W m^{-2})	-28.30

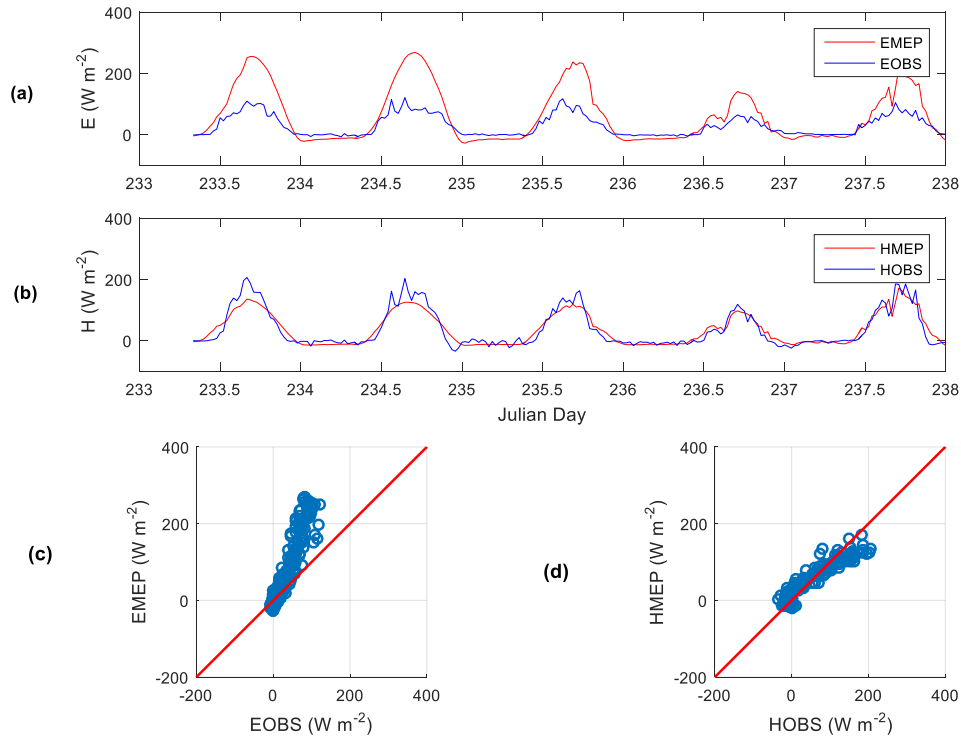


Figure 4.2.33 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Delta Junction 1920-Control, Alaska. Day 233-238, 2004.

Table 4.2.34 Result summary for modeled vs. observed CO₂ fluxes at Delta Junction 1920-Control, Alaska. Day 233-238, 2004.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	2.886
NRMSE	0.15352
Correlation Coefficient	0.6795
Regression Coefficient	0.6532
Max Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	9.7029
Min Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-13.38
Max Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	6.085
Min Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-12.7162
Number of Data Points	226

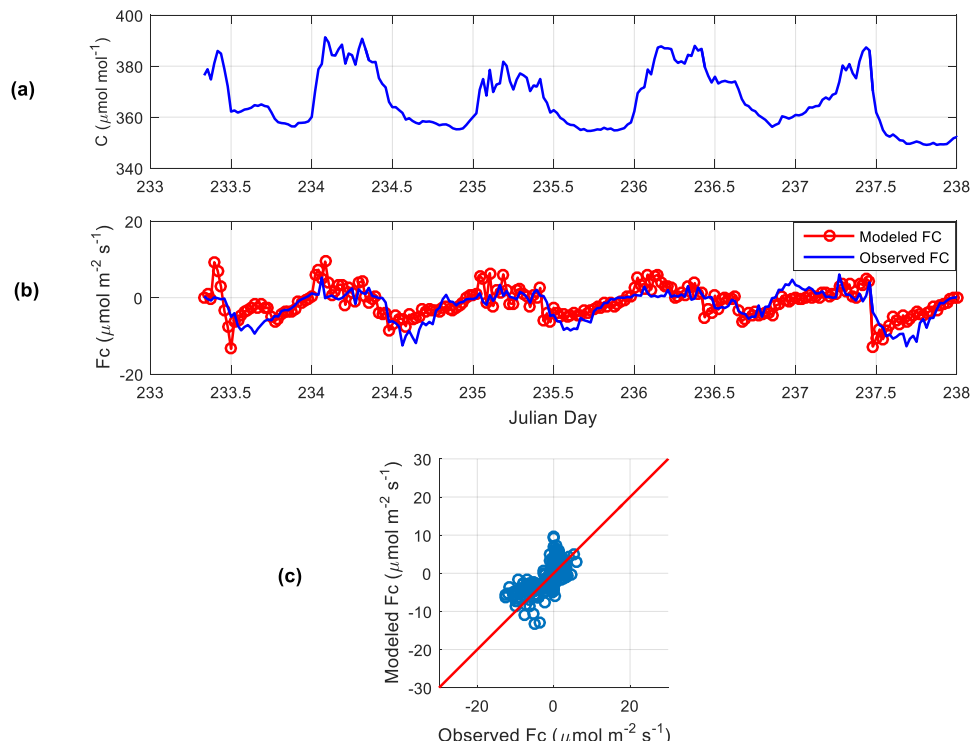


Figure 4.2.34 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Delta Junction 1920-Control, Alaska. Day 233-238, 2004.

The modeled CO₂ fluxes using equation (3.27) capture the diurnal variation and magnitude of the observed fluxes reasonably well (Figure 4.2.34 (b)) during test period 1 (day 233 to 238, 2004). The RMSE and the NRMSE of the modeled CO₂ fluxes are 2.886 $\mu\text{mol m}^{-2}\text{s}^{-1}$ and 15.352 % respectively, with the CO₂ fluxes on the order of 18.8012 $\mu\text{mol m}^{-2}\text{s}^{-1}$. The scatterplot of modeled vs. observed fluxes show good agreement (Figure 4.2.34 (c)) with correlation coefficient 0.6795 and regression coefficient, 0.6532 respectively. The maximum and minimum observed CO₂ fluxes are comparable to maximum and minimum modeled fluxes (Table 4.2.34). The MEP energy fluxes have correlation coefficients 0.944 and 0.9479 for sensible heat (H) and latent heat (E) fluxes, respectively. The RMSE and NRMSE for this test period are 21.6844 W m^{-2} and 8.998 % with the sensible heat fluxes on the order of 190.817 W m^{-2} . The RMSE and NRMSE for this test period are 65.923 W m^{-2} and 51.34 % with the latent heat fluxes on the order of 128.408 W m^{-2} . The MEP model as in (B8) – (B10) of appendix B was used to calculate the energy fluxes as ground heat flux ≈ 0 for forested area. Due to sparse understory in this site, ground heat flux may not be zero which cannot be verified as ground heat flux were measured for only once at 12.30 AM day 235 when observed ground heat, latent heat and sensible heat fluxes were -13.6469 W m^{-2} , -2.525 W m^{-2} and -15.873 W m^{-2} respectively.

Test Period 2: Day 247-252, 2006, Delta Junction 1920-Control, Alaska

Table 4.2.35 Result summary for MEP modeled vs. observed sensible and latent heat fluxes at Delta Junction 1920-Control, Alaska. Day 247-252, 2004.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics	
Correlation Coefficient	0.9269	Correlation Coefficient	0.7734
RMSE (W m^{-2})	30.344	RMSE (W m^{-2})	63.85
NRMSE	0.1105	NRMSE	0.4751
Max HOBS (W m^{-2})	254.1	Max EOBS (W m^{-2})	131.25
Min HOBS (W m^{-2})	-20.463	Min EOBS (W m^{-2})	-3.151
Max HMEP (W m^{-2})	209.29	Max EMEP (W m^{-2})	228.18
Min HMEP (W m^{-2})	-32.248	Min EMEP (W m^{-2})	-22.775

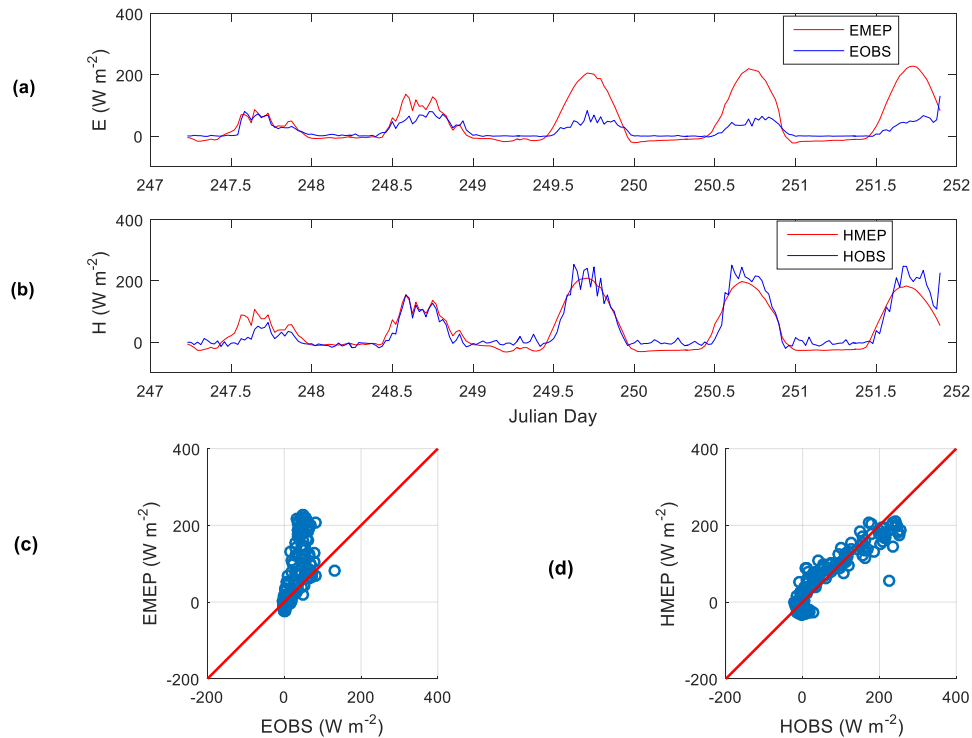


Figure 4.2.35: (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) Scatter plot of EMEP vs. EOBS, (d) Scatter plot of HMEP vs. HOBS at Delta Junction 1920-Control, Alaska. Day 247-252, 2004.

Table 4.2.36 Result summary for modeled vs. observed CO₂ fluxes at Delta Junction 1920-Control, Alaska. Day 247-252, 2004.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	2.454
NRMSE	0.1531
Correlation Coefficient	0.524
Regression Coefficient	0.9164
Max Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	7.007
Min Modeled FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-9.581
Max Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	6.021
Min Observed FC ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	-10.0138
Number of Data Points	225

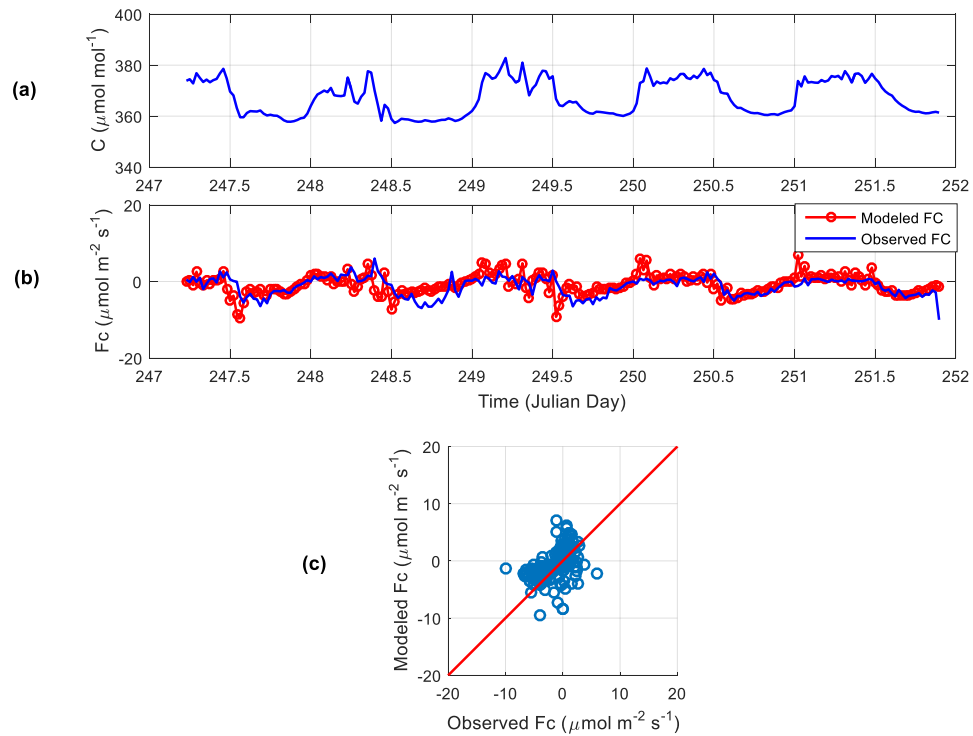


Figure 4.2.36: (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Delta Junction 1920-Control, Alaska. Day 247-252, 2004.

Modeled CO₂ fluxes show reasonable agreement with observed fluxes during test period 2 (day 247 to 252, 2004) (Figure 4.2.36 (b), (c)) with correlation coefficient, 0.524 and regression coefficient, 0.9164. The RMSE and the NRMSE of the modeled CO₂ fluxes are 2.454 $\mu\text{mol m}^{-2}\text{s}^{-1}$ and 15.31% with the CO₂ fluxes on the order of 16.0348 $\mu\text{mol m}^{-2}\text{s}^{-1}$. Similar to test period 1, the maximum and minimum observed CO₂ fluxes are comparable to maximum and minimum modeled fluxes (Table 4.2.36). The MEP energy fluxes have correlation coefficients 0.9269 and 0.7734 for sensible heat (H) and latent heat (E) fluxes respectively. The RMSE and NRMSE for this test period are 30.344 W m^{-2} and 11.05 % with the sensible heat fluxes on the order of 274.563 W m^{-2} . The RMSE and NRMSE for this test period are 63.85 W m^{-2} and 47.51 % with the latent heat fluxes on the order of 134.401 W m^{-2} . The large error in latent heat fluxes are due to similar causes as test period 1 (day 233 to 238, 2004) described in previous section.

4.2.4 Site 4

Lucky hills site (31.74°N, 110.052°W) is located on the USDA-ARS Walnut Gulch Experimental Watershed in south-eastern Arizona. The study site has a temperate semi- arid climate with mean annual temperature 17.6 °C and mean annual precipitation 320 mm. About 60% average fall during the months of July–September as part of the North American Monsoon (Adams and Comrie, 1997). The open shrubland, dominated by a diverse stand of desert shrub species with shrub heights range from 0.3 to 1 m. Most of the ground between the shrub canopies consists of bare and rocky soil (39% bare-soil cover of which 47% is composed of rock) with very small amounts of herbs and grasses. About 10% of the surface is covered with plant litter, and the canopy coverage is 51%. The eddy covariance system is located in an area with a fetch of >1 km in all directions with tower height 6.5 m (3.1 before Julian day 150, 2008).

The model uses half-hourly time-series data of CO_2 concentration ($\mu\text{mol mol}^{-1}$), canopy surface temperature T_s (°C) and net radiation R_n (W m^{-2}) Downward CO_2 flux (FC) as well as latent (E) and sensible (H) heat flux from the atmosphere to canopy surface are defined as negative. Ground heat flux (G) is defined negative from the surface into the soil layer. Due to considerable percentage of bare-soil cover at this site the observed ground heat flux is substantial. The MEP model as in (B1) – (B7) of appendix B is used to estimate H, which is used in parameterization of diffusion coefficient of CO_2 , D_c . The distance above the canopy surface z is measured by the difference of mean canopy height and height of CO_2 measurement is 4.3 m. Scattered

missing data are filled using linear interpolation when the time interval between missing data are not very large (< 3 hours). The dataset is re-grouped into multiple no-gap time series to avoid larger gaps (> 3 hrs) of the time-series records.

The comparison of modeled CO₂ flux using equation (3.27) with the observed eddy-covariance flux is characterized by the root-mean-square error (RMSE), the normalized root-mean-square error (NRMSE defined as the RMSE divided by the magnitude of the observed fluxes), correlation coefficient (covariance of the observed and modeled CO₂ fluxes divided by the product of their standard deviations) and regression coefficient (covariance of the observed and modeled CO₂ fluxes divided by the variance of observed CO₂ fluxes). The maximum and minimum observed flux over the test period and maximum and minimum model flux over test period are reported. As the MEP modeled sensible heat flux is used in the parameterization of eddy diffusivity of CO₂, the MEP modeled energy fluxes are compared with observed energy fluxes from eddy covariance measurements. This includes: root-mean-square error (RMSE), normalized root-mean-square error (NRMSE), correlation coefficient, maximum and minimum flux of the observed and MEP modeled heat fluxes over the test period. The results are shown in figures and tables followed by summary tables.

Test Period 1: Day 229-238, 2006, Walnut Gulch Lucky Hills, Arizona

Table 4.2.37 Result summary for MEP modeled vs. observed sensible, latent and ground heat fluxes at Walnut Gulch Lucky Hills, Arizona. Day 229-238, 2008.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics		Ground Heat Flux (G) Statistics	
Correlation Coefficient	0.9519	Correlation Coefficient	0.8967	Correlation Coefficient	0.9542
RMSE (W m ⁻²)	27.018	RMSE (W m ⁻²)	44.462	RMSE (W m ⁻²)	41.931
NRMSE	0.07344	NRMSE	0.1121	NRMSE	0.1372
Max HOBS (W m ⁻²)	291.231	Max EOBS (W m ⁻²)	362.232	Max GOBS (W m ⁻²)	198.061
Min HOBS (W m ⁻²)	-76.64	Min EOBS (W m ⁻²)	-34.23	Min GOBS (W m ⁻²)	-107.56
Max HMEP (W m ⁻²)	233.54	Max EMEP (W m ⁻²)	310.59	Max GMEP (W m ⁻²)	227.23
Min HMEP (W m ⁻²)	-22.17	Min EMEP (W m ⁻²)	-25.96	Min GMEP (W m ⁻²)	-60.68

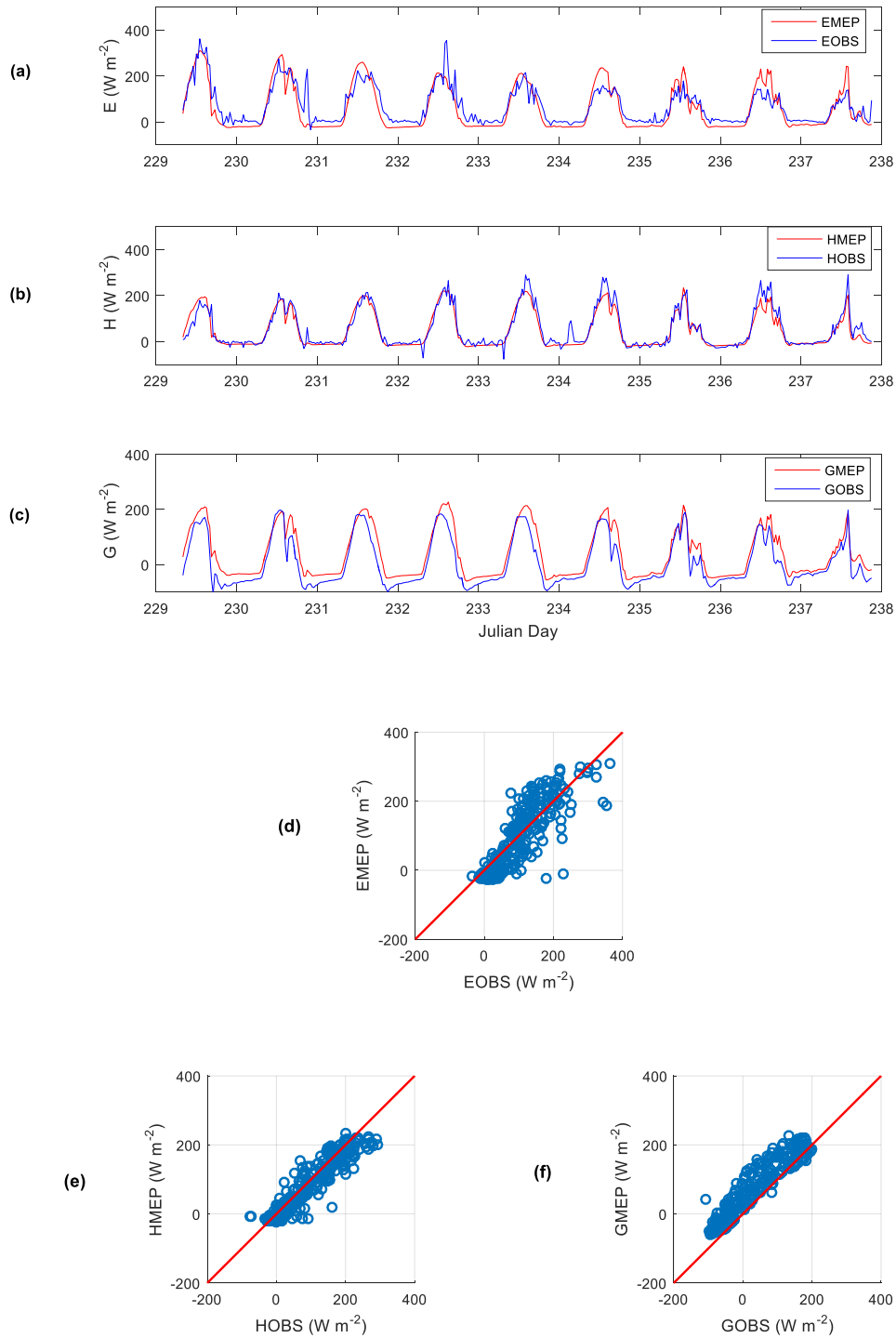


Figure 4.2.37 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) MEP model ground heat fluxes (GMEP) vs. observed ground heat fluxes (GOBS) (d) Scatter plot of EMEP vs. EOBS, (e) Scatter plot of HMEP vs. HOBS (f) Scatter plot of GMEP vs. GOBS at Walnut Gulch Lucky Hills, Arizona. Day 229-238, 2008.

Table 4.2.38 Result summary for modeled vs. observed CO₂ fluxes at Walnut Gulch Lucky Hills, Arizona. Day 229-238, 2008

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	2.584
NRMSE	0.1624
Correlation Coefficient	0.6388
Regression Coefficient	0.6451
Max Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	14.18
Min Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-12.472
Max Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	5.71
Min Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-10.206
Number of Data Points	410

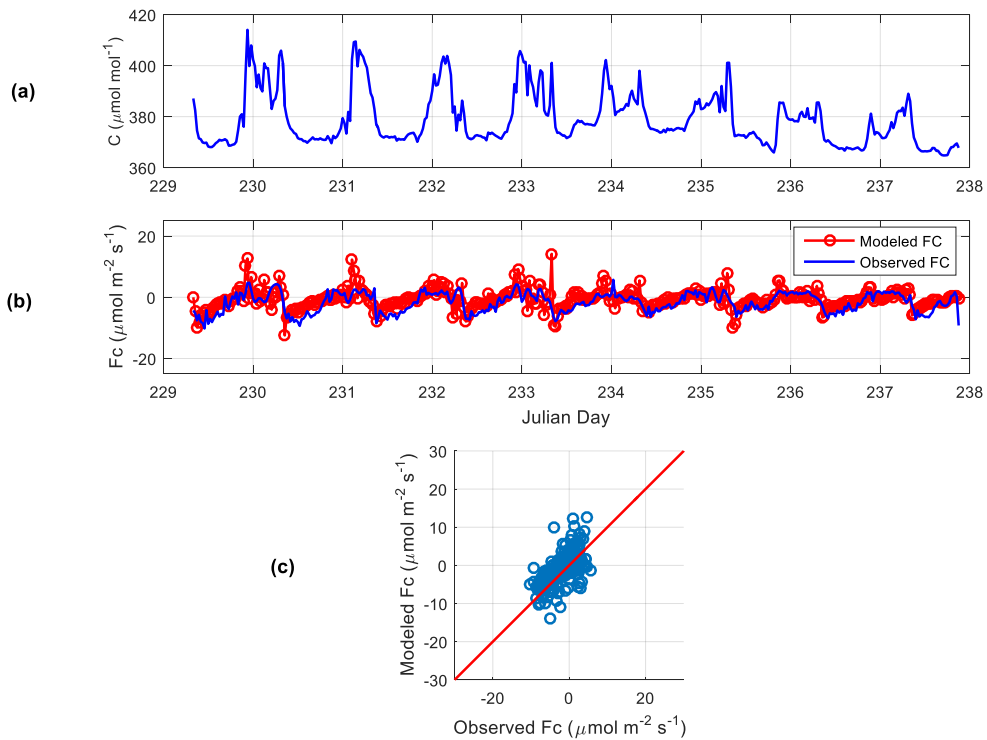


Figure 4.2.38 (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Walnut Gulch Lucky Hills, Arizona. Day 229-238, 2008.

The modeled CO₂ fluxes using equation (3.27) capture the diurnal variation and magnitude of the observed fluxes (Figure 4.2.38 (b)) reasonably well during test period 1 (day 229 to 238, 2008). The RMSE and the NRMSE of the modeled CO₂ fluxes are 2.584 $\mu\text{mol m}^{-2}\text{s}^{-1}$ and 16.24 % respectively, with the CO₂ fluxes on the order of 15.916 $\mu\text{mol m}^{-2}\text{s}^{-1}$. The scatterplot of modeled vs. observed fluxes shows agreement along 1:1 line (Figure 4.2.38 (c)). The correlation coefficient was 0.6388 and regression coefficient was 0.6451 during this period. The magnitudes of modeled fluxes are comparable to the observed fluxes except for a small number of points where spikes in CO₂ concentration data (> 400 $\mu\text{mol/mol}$) resulted from linear interpolation of the missing CO₂ concentration data causing relatively large numerical errors of the calculated derivative term in (3.27) associated with large value of modeled fluxes. The correlation coefficients are 0.9519, 0.8967 and 0.9542, MEP model sensible heat (H), latent heat (E) and ground heat fluxes (G), respectively. The RMSE and NRMSE for this test period are 27.018 W m^{-2} and 7.344 % with the sensible heat fluxes on the order of 367.871 W m^{-2} . The RMSE and NRMSE for this test period are 44.462 W m^{-2} and 11.21 % with the latent heat fluxes on the order of 396.462 W m^{-2} . The RMSE and NRMSE for this test period are 41.931 W m^{-2} and 13.72 % with the ground heat fluxes on the order of 305.621 W m^{-2} .

Test Period 2: Day 245-249, 2006, Walnut Gulch Lucky Hills, Arizona

Table 4.2.39 Result summary for MEP modeled vs. observed sensible, latent and ground heat fluxes at Walnut Gulch Lucky Hills, Arizona. Day 245-249, 2008.

Sensible Heat Flux (H) Statistics		Latent Heat Flux (E) Statistics		Ground Heat Flux (G) Statistics	
Correlation Coefficient	0.9548	Correlation Coefficient	0.8943	Correlation Coefficient	0.9531
RMSE (W m ⁻²)	27.6134	RMSE (W m ⁻²)	43.652	RMSE (W m ⁻²)	41.129
NRMSE	0.0662	NRMSE	0.1635	NRMSE	0.1237
Max OBS (W m ⁻²)	325.302	Max EOBS (W m ⁻²)	229.055	Max GOBS (W m ⁻²)	233.89
Min OBS (W m ⁻²)	-92.059	Min EOBS (W m ⁻²)	-37.972	Min GOBS (W m ⁻²)	-98.569
Max MEP (W m ⁻²)	265.7305	Max EMEP (W m ⁻²)	274.869	Max GMEP (W m ⁻²)	261.693
Min HMEP (W m ⁻²)	-24.8721	Min EMEP (W m ⁻²)	-25.314	Min GMEP (W m ⁻²)	-64.556

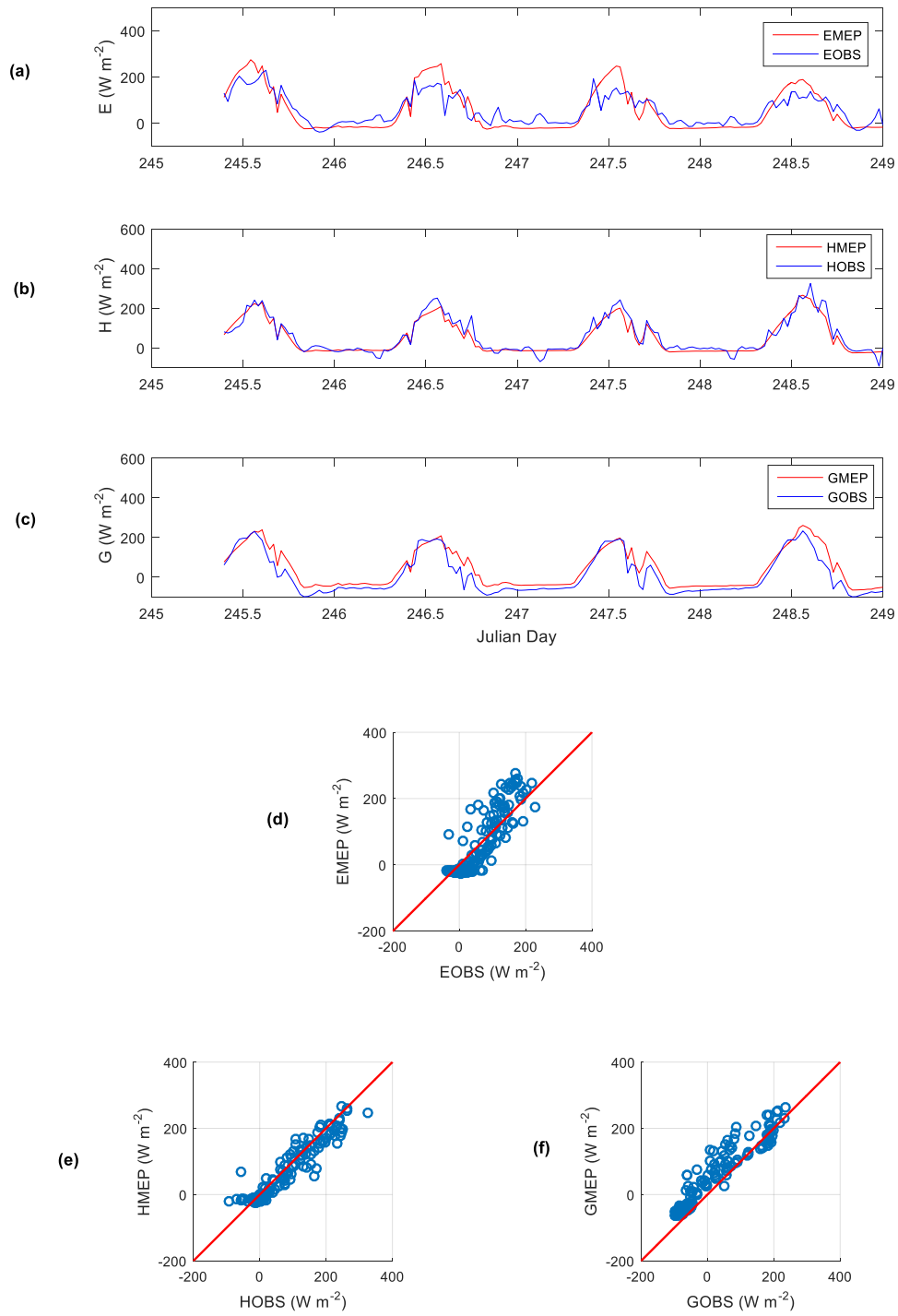


Figure 4.2.39 (a) MEP model latent heat fluxes (EMEP) vs. observed latent heat fluxes (EOBS) (b) MEP model sensible heat fluxes (HMEP) vs. observed sensible heat fluxes (HOBS) (c) MEP model ground heat fluxes (GMEP) vs. observed ground heat fluxes (GOBS) (d) Scatter plot of EMEP vs. EOBS, (e) Scatter plot of HMEP vs. HOBS (f) Scatter plot of GMEP vs. GOBS at Walnut Gulch Lucky Hills, Arizona. Day 245-249, 2008.

Table 4.2.40 Result summary for modeled vs. observed CO₂ fluxes at Walnut Gulch Lucky Hills, Arizona. Day 245-249, 2008.

CO ₂ Flux (FC) Statistics	
RMSE ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	2.8484
NRMSE	0.1696
Correlation Coefficient	0.5450
Regression Coefficient	0.5175
Max Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	8.1220
Min Modeled FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-10.9087
Max Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	8.1206
Min Observed FC ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-8.679
Number of Data Points	192

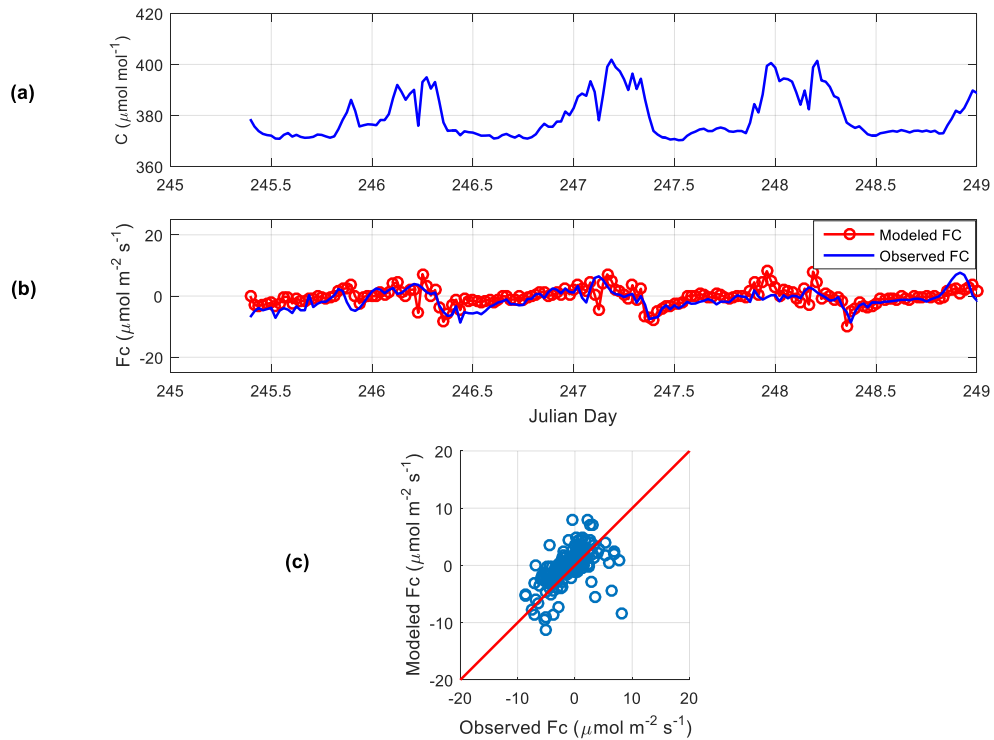


Figure 4.2.40: (a) CO₂ profile, (b) Observed vs. modeled CO₂ fluxes, (c) Scatterplot of observed vs. modeled CO₂ fluxes at Walnut Gulch Lucky Hills, Arizona. Day 245-249, 2008.

Similar to test period 1, the modeled CO₂ fluxes followed observed CO₂ fluxes consistently (Figure 4.2.40 (b)) during test period 2 (day 245 to 249, 2008). The scatter plot (Figure 4.2.40 (c)) shows reasonable agreement with correlation coefficient, 0.6388 and regression coefficient, 0.6451. The RMSE and the NRMSE of the modeled CO₂ fluxes are 2.584 $\mu\text{mol m}^{-2}\text{s}^{-1}$ and 16.24 % with the CO₂ fluxes on the order of 15.916 $\mu\text{mol m}^{-2}\text{s}^{-1}$ for this period. The correlation coefficients are 0.9548, 0.8943 and 0.9531, MEP model sensible heat (H), latent heat (E) and ground heat fluxes (G), respectively. The RMSE and NRMSE for this test period are 27.6134 W m^{-2} and 6.62 % with the sensible heat fluxes on the order of 417.361 W m^{-2} . The RMSE and NRMSE for this test period are 43.6516 W m^{-2} and 16.35% with the latent heat fluxes on the order of 267.0273 W m^{-2} . The RMSE and NRMSE for this test period are 41.1285 W m^{-2} and 12.37 % with the ground heat fluxes on the order of 332.458 W m^{-2} .

4.3 Result Summary

Result for sensible, latent and CO₂ fluxes for the four study sites are summarized in this section. Result summary for Santarem Primary Forest site in the Brazilian amazon during test period 1 to test period 10 in 2003 are presented in Tables 4.3.1, 4.3.2, 4.3.3 and 4.3.4; Summary of results for 6 test periods in 2006 at Cedar bridge site in New Jersey Pine barrens are presented in tables 4.3.5, 4.3.6 and 4.3.7; Summary of results for 2 test periods in 2004 at Delta Junction 1920 Control site north of the Alaska Range in interior Alaska are presented in tables 4.3.8 to 4.3.10; Finally summary of results for 2 test periods in 2008 in Lucky Hills site, Walnut Gulch Experimental Watershed in south-eastern Arizona are presented in tables 4.3.11, 4.3.12, 4.3.13 and 4.3.14. Table 4.3.15, 4.3.16, and 4.3.17 present the sensible heat flux, latent heat flux and CO₂ flux statistics averaged over testing periods for respective study sites. Due to large gaps in data only two test periods are available for Delta Junction and Lucky Hills site. The Santarem Primary forest results contain both dry (July to December) and wet seasons (January to June) in southern hemisphere while for the Cedar Bridge, Delta Junction and Lucky Hills sites results are available only during growing seasons (June-September) in northern hemisphere.

The observed vs. MEP modeled sensible heat fluxes show consistently high correlation coefficients for all the test periods for all four sites with the averaged over test periods 0.92485, 0.955333, 0.93545 and 0.95335 for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky Hills respectively demonstrating the

MEP sensible modeled fluxes are capable of capturing the diurnal variation and magnitude of observed sensible heat fluxes. The NRMSE for above sites are 10.207 %, 9.7043 %, 10.024 % and 6.982 % for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky Hills sites respectively. The lower (more accurate) value of NRMSE for Lucky hills site is due to using the partition of all the energy fluxes (H, E, G) in MEP model, while G is not used for Santarem Primary Forest, Cedar Bridge, Delta Junction due to forested land cover. The RMSE of MEP model sensible heat flux is about 28 W m^{-2} for all the sites except cedar bridge (48.6 W m^{-2}) due to high standard deviation in observed sensible heat data ($107.1591 \text{ W m}^{-2}$) in cedar bridge site. The mean absolute error (MAE) defined as the average of absolute differences between observed and modeled H fluxes averaged of the periods are $21.28012 \text{ W m}^{-2}$, $28.99298 \text{ W m}^{-2}$, $19.68319 \text{ W m}^{-2}$ and $18.95338 \text{ W m}^{-2}$ for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky Hills site respectively. The RMSE – MAE shows there are some variability with in the errors for all the four sites although large errors are less likely to occur as the difference between RMSE and MAE is not significantly large during the test periods in the study sites. The magnitude of maximum modeled sensible heat fluxes are well comparable to observed sensible heat fluxes in all the stations except Cedar Bridge site where maximum observed sensible heat fluxes are consistently high ($> 400 \text{ W m}^{-2}$) for most test periods. The modeled sensible heat fluxes during nighttime have large numerical differences with observed fluxes negative which is due to eddy covariance method tends to underestimate night time fluxes by 10-30% [Goulden et al., 1996; Twine et al., 2000]. However it has insignificant effect over CO_2 flux estimation using proposed method due to eddy-diffusivity parameter according to Equation (3.13)

has much reduced sensitivity to the uncertainty in model parameters due to its one third power dependence of H.

The observed vs. MEP modeled latent heat fluxes show consistently high correlation coefficients for all the test periods for all four sites with the averaged over test periods 0.93934, 0.929107, 0.86065 and 0.8955 for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky Hills respectively. The NRMSE for above sites are 11.32 %, 11.88 %, 49.424 % and 13.78 % respectively for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky Hills site. Relatively large error in Delta Junction site is due to The MEP model as in (B8) – (B10) of appendix B was used to calculate the energy fluxes as ground heat flux ≈ 0 for forested area. Due to sparse understory in this site, ground heat flux may not be zero which cannot be verified as ground heat flux were measured for only once (12.30 AM day 235) during two test periods when observed ground heat was not zero. Also, latent heat fluxes are not used in computing CO₂ fluxes in proposed method.

The CO₂ flux modeled using proposed method show consistent agreement for all four test sites with average correlation coefficient in the test periods are 0.6122, 0.662, 0.602 and 0.592 for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky Hills site respectively with average regression coefficient (observed flux is regressor) 0.593, 0.774, 0.785 and 0.58 respectively for above sites. The average NRMSE during the testing periods are 14.339 %, 17.4352%, 15.331 % and 16.6 % for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky Hills sites

respectively implying modeling errors are limited as for forest sites, the relative uncertainty of eddy-covariance fluxes, defined as the standard deviation of the random errors around hourly mean fluxes, may reach 50% [Vickers et al., 2010]. The average RMSE over all the test periods are $7.4596 \mu\text{molm}^{-2}\text{s}^{-1}$, $6.382167 \mu\text{molm}^{-2}\text{s}^{-1}$, $2.67 \mu\text{molm}^{-2}\text{s}^{-1}$ and $2.7162 \mu\text{molm}^{-2}\text{s}^{-1}$ with the CO_2 fluxes with the order of $52.9245 \mu\text{molm}^{-2}\text{s}^{-1}$, $37.87883 \mu\text{molm}^{-2}\text{s}^{-1}$, $17.418 \mu\text{molm}^{-2}\text{s}^{-1}$ and $16.3578 \mu\text{molm}^{-2}\text{s}^{-1}$ for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky hills sites respectively. The standard deviation of CO_2 concentration data varies significantly between the test periods for the forested sites due to spikes in CO_2 concentration data (see Tables 4.3.4, 4.3.5, 4.3.7, 4.3.10 and 4.3.14). Due to presence of outliers in CO_2 concentration time series, the mean absolute error (MAE) defined as the average of absolute differences between observed and modeled CO_2 fluxes is calculated for the study sites which is much lower than corresponding RMSE values. The average MAE are $5.316628 \mu\text{molm}^{-2}\text{s}^{-1}$, $4.525786 \mu\text{molm}^{-2}\text{s}^{-1}$, $1.9216 \mu\text{molm}^{-2}\text{s}^{-1}$ and $1.959426 \mu\text{molm}^{-2}\text{s}^{-1}$ for Santarem Primary Forest, Cedar Bridge, Delta Junction 1920 Control and Lucky hills sites respectively. The magnitudes of the observed fluxes are well captured by modeled fluxes for all the sites except for a small number of points where spikes in CO_2 concentration data ($> 400 \mu\text{mol/mol}$) resulted from linear interpolation of the missing CO_2 concentration data causing relatively large numerical errors of the calculated derivative term in (3.27) associated with large value of modeled fluxes during nighttime. Another reason for the differences in magnitude between modeled and observed fluxes during nighttime is eddy covariance method tends to underestimate night time fluxes by 10-30% [Goulden et al., 1996; Twine et al., 2000].

Table 4.3.1 Summary of results for sensible heat fluxes at Santarem Primary Forest, Brazil, 2003

Sensible Heat Flux (H)	Test Period 1	Test Period 2	Test Period 3	Test Period 4	Test Period 5	Test Period 6	Test Period 7	Test Period 8	Test Period 9	Test Period 10
Correlation Coefficient	0.94	0.92	0.94	0.87	0.93	0.92	0.93	0.94	0.94	0.93
RMSE (W m^{-2})	27.62	27.94	26.21	30.16	28.77	27.32	27.87	23.08	29.43	32.79
MAE (W m^{-2})	20.96	20.35	20.35	23.05	22.58	20.38	19.74	17.01	22.53	25.85
NRMSE	0.1209	0.0819	0.0869	0.1225	0.1093	0.0829	0.0876	0.0935	0.1159	0.1193
RMSE-MAE (W m^{-2})	6.66	7.59	5.86	7.11	6.19	6.94	8.13	6.07	6.90	6.94
SD HOBS (W m^{-2})	56.02	62.29	53.65	42.42	47.87	52.70	49.21	46.16	45.83	46.88
Max HOBS (W m^{-2})	189.28	298.95	239.50	165.77	212.02	273.78	246.29	206.28	193.17	199.56
Min HOBS (W m^{-2})	-39.07	-42.33	-62.09	-80.38	-51.26	-55.61	-71.90	-40.52	-60.66	-75.41
Max MEP (W m^{-2})	201.35	188.98	187.96	173.99	189.20	211.91	219.58	184.24	189.56	184.76
Min HMEP (W m^{-2})	-13.12	-11.01	-10.57	-9.33	-10.64	-10.41	-11.12	-8.47	-10.76	-9.34

Table 4.3.2 Summary of results for latent heat fluxes at Santarem Primary Forest, Brazil, 2003

Latent Heat Flux (E) Statistics LBA	Test Period 1	Test Period 2	Test Period 3	Test Period 4	Test Period 5	Test Period 6	Test Period 7	Test Period 8	Test Period 9	Test Period 10
Correlation Coefficient	0.94	0.95	0.94	0.94	0.95	0.93	0.94	0.94	0.94	0.94
RMSE (W m^{-2})	65.64	62.85	55.30	44.74	51.43	57.56	60.22	49.28	55.46	52.49
MAE (W m^{-2})	46.87	45.04	38.67	29.83	32.62	37.31	38.28	32.86	40.37	39.30
RMSE- MAE (W m^{-2})	18.77	17.81	16.63	14.91	18.81	20.25	21.94	16.42	15.09	13.19
NRMSE	0.1585	0.1341	0.1381	0.1099	0.1133	0.1002	0.0961	0.0943	0.0892	0.0981
SD EOBS (W m^{-2})	127.43	107.84	104.88	98.91	104.89	110.52	119.15	113.20	141.94	133.77
Max EOBS (W m^{-2})	404.83	459.99	382.65	382.65	439.32	561.86	594.02	515.28	581.38	524.40
Min EOBS (W m^{-2})	-9.20	-8.74	-17.81	-24.47	-14.74	-12.91	-32.59	-7.35	-28.94	-10.42
Max EMEP (W m^{-2})	552.50	533.57	499.75	464.48	487.91	580.99	594.72	519.24	537.09	535.84
Min EMEP (W m^{-2})	-33.74	-29.17	-27.72	-24.95	-26.26	-24.39	-28.23	-20.32	-40.58	-23.63

Table 4.3.3 Summary of results for CO₂ fluxes at Santarem Primary Forest, Brazil, Test period 1-5, 2003

CO ₂ Flux (FC) Statistics	Test Period 1	Test Period 2	Test Period 3	Test Period 4	Test Period 5
RMSE (μmolm ⁻² s ⁻¹)	6.36	8.39	7.52	7.90	7.57
MAE (μmolm ⁻² s ⁻¹)	4.48	5.84	5.61	5.92	5.59
RMSE -MAE (μmolm ⁻² s ⁻¹)	1.88	2.54	1.91	1.98	1.98
NRMSE	0.1285	0.1981	0.1263	0.1646	0.1267
Correlation Coefficient	0.73	0.42	0.71	0.55	0.72
Regression Coefficient	0.66	0.40	0.56	0.70	0.54
Max Modeled FC (μmolm ⁻² s ⁻¹)	44.30	59.71	23.26	71.91	33.84
Min Modeled FC (μmolm ⁻² s ⁻¹)	-35.49	-27.97	-39.43	-73.71	-32.69
Max Observed FC (μmolm ⁻² s ⁻¹)	23.76	17.01	32.35	22.86	29.19
Min Observed FC (μmolm ⁻² s ⁻¹)	-25.77	-25.33	-27.13	-25.13	-30.52
SD Observed FC (μmolm ⁻² s ⁻¹)	9.72	9.36	10.54	10.33	11.05
Max Observed CO ₂ (μmol/mol)	407.99	470.65	418.44	429.24	422.67
Min Observed CO ₂ (μmol/mol)	367.88	350.48	367.27	345.65	366.12
SD Observed CO ₂ (μmol/mol)	10.35	15.72	10.29	14.79	11.66
Mean Observed CO ₂ (μmol/mol)	382.97	382.52	384.02	383.20	385.82
No. of Data Points	168	189	248	226	338

Table 4.3.4 Summary of results for CO₂ fluxes at Santarem Primary Forest, Brazil, Test period 6-10, 2003

CO ₂ Flux (FC) Statistics	Test Period 6	Test Period 7	Test Period 8	Test Period 9	Test Period 10
RMSE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	6.98	6.66	6.50	8.75	7.97
MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	4.83	4.83	4.55	5.88	5.63
RMSE -MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	2.15	1.83	1.95	2.87	2.34
NRMSE	0.1475	0.1023	0.1353	0.1525	0.1521
Correlation Coefficient	0.63	0.63	0.63	0.51	0.58
Regression Coefficient	0.71	0.75	0.72	0.45	0.43
Max Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	63.67	107.20	59.59	60.01	28.72
Min Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-37.83	-59.53	-40.33	-62.44	-25.90
Max Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	19.93	29.52	27.31	23.45	23.94
Min Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-27.38	-35.60	-20.73	-33.89	-28.45
SD Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	9.88	9.00	7.99	10.03	9.82
Max Observed CO ₂ ($\mu\text{mol/mol}$)	432.59	439.58	419.47	425.91	407.13
Min Observed CO ₂ ($\mu\text{mol/mol}$)	365.04	361.94	361.82	337.28	368.64
SD Observed CO ₂ ($\mu\text{mol/mol}$)	13.30	13.16	10.30	9.94	8.48
Mean Observed CO ₂ ($\mu\text{mol/mol}$)	386.32	384.49	382.43	383.81	385.03
No. of Data Points	325	1227	392	891	384

Table 4.3.5 Summary of sensible heat fluxes at Cedar Bridge, New Jersey, 2006

Sensible Heat Flux Statistics	Test Period 1	Test Period 2	Test Period 3	Test Period 4	Test Period 5	Test Period 6
Correlation Coefficient	0.970	0.955	0.951	0.969	0.948	0.938
RMSE (W m^{-2})	48.240	24.086	50.010	57.467	67.963	43.950
MAE (W m^{-2})	31.095	17.451	29.420	35.836	37.165	22.990
RMSE-MAE (W m^{-2})	17.145	6.635	20.590	21.631	30.798	20.960
NRMSE	0.0891	0.0716	0.1080	0.1199	0.1235	0.0702
SD HOBS (W m^{-2})	117.673	75.348	104.144	121.697	121.071	103.023
Max OBS (W m^{-2})	457.360	289.940	410.898	429.480	498.010	578.680
Min HOBS (W m^{-2})	-84.275	-46.510	-52.087	-49.770	-52.360	-47.444
Max MEP (W m^{-2})	269.420	197.310	204.110	222.262	197.510	229.200
Min MEP (W m^{-2})	-40.127	-22.610	-22.760	-26.302	-20.440	-31.334

Table 4.3.6 Summary of Latent Heat Fluxes at Cedar Bridge, New Jersey. 2006

Latent Heat Flux Statistics	Test Period 1	Test Period 2	Test Period 3	Test Period 4	Test Period 5	Test Period 6
Correlation Coefficient	0.938	0.908	0.929	0.925	0.926	0.950
RMSE (W m^{-2})	61.887	73.811	82.650	75.851	80.650	47.960
MAE (W m^{-2})	45.961	48.986	54.139	54.457	53.980	35.450
RMSE-MAE (W m^{-2})	15.926	24.825	28.511	21.394	26.670	12.510
NRMSE	0.1017	0.0959	0.1167	0.1308	0.1906	0.0770
SD EOBS (W m^{-2})	141.155	163.694	150.397	134.463	113.870	122.277
Max EOBS (W m^{-2})	533.305	681.910	665.720	567.410	382.780	583.520
Min EOBS (W m^{-2})	-75.384	-87.757	-42.690	-12.415	-40.415	-40.362
Max EMEP (W m^{-2})	550.609	490.624	569.402	506.150	573.490	453.523
Min EMEP (W m^{-2})	-52.673	-37.831	-44.670	-46.935	-45.257	-40.788

Table 4.3.7 Summary of CO₂ Fluxes at Cedar Bridge, New Jersey. 2006

CO ₂ Flux (FC) Statistics	Test Period 1	Test Period 2	Test Period 3	Test Period 4	Test Period 5	Test Period 6
RMSE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	5.29	6.33	7.57	5.29	5.75	8.05
MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	3.93	4.47	5.64	3.72	4.10	5.30
RMSE-MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	1.36	1.86	1.93	1.58	1.65	2.76
NRMSE	0.1494	0.1759	0.1895	0.2027	0.1950	0.1336
Correlation Coefficient	0.80	0.73	0.66	0.57	0.66	0.55
Regression Coefficient	0.82	0.73	0.82	0.77	0.95	0.56
Max Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	27.50	22.97	39.81	33.74	25.58	25.20
Min Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-23.19	-24.21	-30.62	-38.81	-30.04	-23.36
Max Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	11.75	10.06	16.94	8.24	9.47	16.13
Min Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-23.67	-25.94	-23.01	-17.87	-20.02	-44.17
SD Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	8.44	8.79	8.31	6.61	6.01	8.08
Max Observed CO ₂ ($\mu\text{mol/mol}$)	427.96	420.43	465.16	434.36	431.54	442.38
Min Observed CO ₂ ($\mu\text{mol/mol}$)	360.61	348.40	359.04	355.90	360.55	362.33
SD Observed CO ₂ ($\mu\text{mol/mol}$)	16.18	18.13	23.09	16.64	17.26	16.73
Mean Observed CO ₂ ($\mu\text{mol/mol}$)	390.56	378.80	393.62	380.17	382.84	388.84
No. of Data Points	480	287	343	345	220	283

Table 4.3.8 Summary of sensible heat fluxes at Delta Junction, Alaska. 2004

Sensible Heat Flux Statistics	Test Period 1	Test Period 2
Correlation Coefficient	0.944	0.9269
RMSE(W m ⁻²)	21.6844	30.344
MAE (W m ⁻²)	16.08	23.29
RMSE-MAE (W m ⁻²)	5.61	7.05
NRMSE	0.08998	0.1105
SD HOBS (W m ⁻²)	61.69	79.78
Max HOBS (W m ⁻²)	206.074	254.1
Min HOBS (W m ⁻²)	-34.93	-20.463
Max HMEP (W m ⁻²)	171.28	209.29
Min HMEP (W m ⁻²)	-19.537	-32.248

Table 4.3.9 Summary of latent heat fluxes at Delta Junction, Alaska. 2004

Latent Heat Flux Statistics	Test Period 1	Test Period 2
Correlation Coefficient	0.9479	0.7734
RMSE (W m ⁻²)	65.923	63.85
MAE (W m ⁻²)	44.04	39.90
RMSE-MAE (W m ⁻²)	21.88	23.95
NRMSE	0.5134	0.4751
SD EOBS (W m ⁻²)	34.60	25.56
Max EOBS (W m ⁻²)	120.488	131.25
Min EOBS (W m ⁻²)	-7.92	-3.151
Max EMEP (W m ⁻²)	268.38	228.18
Min EMEP (W m ⁻²)	-28.3	-22.775

Table 4.3.10 Summary of CO₂ fluxes at Delta Junction, Alaska. 2004

CO ₂ Flux (FC) Statistics	Test Period 1	Test Period 2
RMSE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	2.886	2.454
MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	2.20	1.64
RMSE-MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	0.69	0.81
NRMSE	0.15352	0.1531
Correlation Coefficient	0.6795	0.524
Regression Coefficient	0.6532	0.9164
Max Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	9.7029	7.007
Min Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-13.38	-9.581
Max Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	6.085	6.021
Min Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-12.7162	-10.014
SD Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	3.88	2.45
Max Observed CO ₂ ($\mu\text{mol/mol}$)	391.33	382.81
Min Observed CO ₂ ($\mu\text{mol/mol}$)	349.12	357.33
SD Observed CO ₂ ($\mu\text{mol/mol}$)	11.54	6.86
Mean Observed CO ₂ ($\mu\text{mol/mol}$)	366.64	367.38
No. of Data Points	226	225

Table 4.3.11 Summary of sensible heat fluxes at Lucky Hills, Arizona. 2008

Sensible Heat Flux (H)	Test Period 1	Test Period 2
Correlation Coefficient	0.9519	0.9548
RMSE(W m ⁻²)	27.018	27.6134
MAE (W m ⁻²)	18.23	19.68
RMSE-MAE (W m ⁻²)	8.79	7.94
NRMSE	0.07344	0.0662
SD HOBS (W m ⁻²)	83.45	87.90
Max HOBS (W m ⁻²)	291.231	325.302
Min HOBS (W m ⁻²)	-76.64	-92.059
Max HMEP (W m ⁻²)	233.54	265.731
Min HMEP (W m ⁻²)	-22.17	-24.872

Table 4.3.12 Summary of latent heat fluxes at Lucky Hills, Arizona. 2008

Latent Heat Flux (E) Statistics	Test Period 1	Test Period 2
Correlation Coefficient	0.8967	0.8943
RMSE (W m ⁻²)	44.462	43.652
MAE (W m ⁻²)	33.94	34.74
RMSE-MAE (W m ⁻²)	10.52	8.91
NRMSE	0.1121	0.1635
SD EOBS (W m ⁻²)	80.23	63.51
Max EOBS (W m ⁻²)	362.232	229.055
Min EOBS (W m ⁻²)	-34.23	-37.972
Max EMEP (W m ⁻²)	310.59	274.869
Min EMEP (W m ⁻²)	-25.96	-25.314

Table 4.3.13 Summary of ground heat fluxes at Lucky Hills, Arizona. 2008

Ground Heat Flux (G)	Test Period 1	Test Period 2
Correlation Coefficient	0.9542	0.9531
RMSE(W m ⁻²)	41.931	41.129
MAE (W m ⁻²)	33.86	32.31
RMSE-MAE (W m ⁻²)	8.07	8.82
NRMSE	0.1372	0.1237
SD GOBS (W m ⁻²)	85.42	96.58
Max GOBS (W m ⁻²)	198.061	233.89
Min GOBS (W m ⁻²)	-107.56	-98.569
Max GMEP (W m ⁻²)	227.23	261.693
Min GMEP (W m ⁻²)	-60.68	-64.556

Table 4.3.14 Summary of CO₂ fluxes at Lucky Hills, Arizona. 2008

CO ₂ Flux (FC) Statistics	Test Period 1	Test Period 2
RMSE (μmolm ⁻² s ⁻¹)	2.584	2.8484
MAE (μmolm ⁻² s ⁻¹)	1.94	1.98
RMSE-MAE (μmolm ⁻² s ⁻¹)	0.65	0.86
NRMSE	0.1624	0.1696
Correlation Coefficient	0.6388	0.545
Regression Coefficient	0.6451	0.5175
Max Modeled FC (μmolm ⁻² s ⁻¹)	14.18	8.122
Min Modeled FC (μmolm ⁻² s ⁻¹)	-12.472	-10.909
Max Observed FC (μmolm ⁻² s ⁻¹)	5.71	8.1206
Min Observed FC (μmolm ⁻² s ⁻¹)	-10.206	-8.679
SD Observed FC (μmolm ⁻² s ⁻¹)	3.19	3.05
Max Observed CO ₂ (μmol/mol)	414.04	401.85
Min Observed CO ₂ (μmol/mol)	364.78	368.37
SD Observed CO ₂ (μmol/mol)	10.39	8.56
Mean Observed CO ₂ (μmol/mol)	378.94	379.99
No. of Data Points	410	192

Table 4.3.15 Summary results of sensible heat fluxes Averaged over test periods at Santarem Primary Forest, Brazil (2003), Cedar Bridge, New Jersey (2006), Delta Junction Control 1920, Alaska (2004) and Lucky Hills, Arizona (2008)

Sensible Heat (H) Flux Statistics Averaged over Test Periods	Santarem Primary Forest	Cedar Bridge	Delta Junction Control	Lucky Hills
Correlation Coefficient	0.92485	0.955333	0.93545	0.95335
RMSE(W m ⁻²)	28.1192	48.61937	26.0142	27.3157
MAE (W m ⁻²)	21.28012	28.99298	19.68319	18.95338
RMSE-MAE (W m ⁻²)	6.839081	19.62639	6.331009	8.362317
NRMSE	0.10207	0.097043	0.10024	0.06982
SD HOBS (W m ⁻²)	50.30345	107.1591	70.73488	85.67629
Max HOBS (W m ⁻²)	222.46	444.0613	230.087	308.2665
Min HOBS (W m ⁻²)	-57.923	-55.4077	-27.6965	-84.3495
Max HMEP (W m ⁻²)	193.153	219.9687	190.285	249.6353
Min HMEP (W m ⁻²)	-10.4768	-27.2622	-25.8925	-23.5211

Table 4.3.16 Summary results of latent heat fluxes averaged over test periods at Santarem Primary Forest, Brazil (2003), Cedar Bridge, New Jersey (2006), Delta Junction Control 1920, Alaska (2004) and Lucky Hills, Arizona (2008)

Latent Heat Flux (E) Statistics Averaged over Test Periods	Santarem Primary Forest	Cedar Bridge	Delta Junction Control	Lucky Hills
Correlation Coefficient	0.93934	0.929107	0.86065	0.8955
RMSE(W m ⁻²)	55.4972	70.46817	64.8865	44.057
MAE (W m ⁻²)	38.11576	48.82894	41.97213	34.34375
RMSE-MAE (W m ⁻²)	17.38144	21.63923	22.91437	9.71325
NRMSE	0.11318	0.11878	0.49425	0.1378
SD EOBS (W m ⁻²)	116.255	137.6426	30.08306	71.86805
Max EOBS (W m ⁻²)	484.6378	569.1075	125.869	295.6435
Min EOBS (W m ⁻²)	-16.7171	-49.8372	-5.5355	-36.101
Max EMEP (W m ⁻²)	530.6089	523.9663	248.28	292.7295
Min EMEP (W m ⁻²)	-27.8993	-44.6923	-25.5375	-25.637

Table 4.3.17 Summary results of CO₂ fluxes averaged over test periods at Santarem Primary Forest, Brazil (2003), Cedar Bridge, New Jersey (2006), Delta Junction Control 1920, Alaska (2004) and Lucky Hills, Arizona (2008)

CO ₂ Flux (FC) Statistics Averaged over Test Periods	Santarem Primary Forest	Cedar Bridge	Delta Junction Control	Lucky Hills
RMSE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	7.4596	6.382167	2.67	2.7162
MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	5.316628	4.525786	1.9216	1.959426
RMSE-MAE ($\mu\text{molm}^{-2}\text{s}^{-1}$)	2.142972	1.85638	0.7484	0.756774
NRMSE	0.14339	0.174352	0.15331	0.166
Correlation Coefficient	0.61218	0.66155	0.60175	0.5919
Regression Coefficient	0.59225	0.774133	0.7848	0.5813
Max Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	55.2205	29.13317	8.35495	11.151
Min Modeled FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-43.5316	-28.3717	-11.4805	-11.6904
Max Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	24.9311	12.10017	6.053	6.9153
Min Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	-27.9934	-25.7787	-11.365	-9.4425
SD Observed FC ($\mu\text{molm}^{-2}\text{s}^{-1}$)	9.771482	7.708425	3.166953	3.122375
Max Observed CO ₂ ($\mu\text{mol/mol}$)	427.3673	436.9707	387.0725	407.945
Min Observed CO ₂ ($\mu\text{mol/mol}$)	359.213	357.8033	353.2235	366.579
SD Observed CO ₂ ($\mu\text{mol/mol}$)	11.79853	18.00399	9.203402	9.473647
Mean Observed CO ₂ ($\mu\text{mol/mol}$)	384.0605	385.8048	367.0096	379.4666
Total Data Points	4388	1958	451	602

CHAPTER 5

CONCLUSION AND FUTURE RESEARCH

This proof-of-concept study demonstrates the feasibility of predicting surface CO₂ fluxes using a single level near-surface CO₂ concentration data. The proposed new method for estimating CO₂ fluxes is parameter parsimonious capturing the dynamics of CO₂ fluxes at sub-daily time scales. The parameterization of eddy-diffusivity based on the similarity theory of boundary layer turbulence combined with the MEP model of surface heat fluxes facilitates its application to monitoring and modeling CO₂ at regional to global scales using remote sensing only observations. Due to rapid improvement in satellite remote sensing technology in recent years, global CO₂ concentration data are becoming more abundant with improved spatial and temporal resolutions. This novel model of CO₂ fluxes allows direct analysis of carbon cycle in response to global climate change characterized by solar radiation, air temperature, and atmospheric water vapor in the context of coupled water-energy-carbon cycles. More independent tests of the proposed model are anticipated to further evaluate its performance and explore more applications in the study of regional and global carbon budgets. On-going work is on assessing the usefulness of the proposed model in assessing regional and global CO₂ fluxes only using remote sensing data. The proposed model may also be used for estimating other GHGS fluxes such as methane (CH₄), Water vapor flux. The field scale tests confirm that the proposed model is a promising modeling tool for the study of regional and global GHGS budget since:

1. CO₂ fluxes are derived using near-surface CO₂ concentration time-series to avoid concentration gradient data subject to relatively large measurement errors of remote sensing observation. Use of single level CO₂ data facilitates the estimation of CO₂ fluxes using remote sensing data as accurate measurement of CO₂ concentration at two levels separated by a short distance (on the order of 10⁰ – 10¹ meter) required by bulk transfer models is difficult, if possible at all, from remote platforms.

2. The reduced sensitivity of the modeled fluxes to model parameters (i.e. eddy diffusivity), due to the one-sixth power dependence on sensible heat flux, could substantially reduce the uncertainties of the current estimates of regional and global carbon budget.

3. The parameterization of eddy-diffusivity using the MEP model of surface heat fluxes directly links the change of carbon fluxes in response to climate change characterized by radiative forcing, surface temperature warming and greenhouse gas (water vapor) increase as the sensible heat flux is expressed analytically as a function of the three climatic variables.

The uncertainty in eddy-covariance measurements of CO₂ fluxes is largely caused by intermittent turbulence, low wind velocity conditions, temperature inversions, inhomogeneous landscapes, and other random measurement errors [Aubinet, 2008; Baldocchi, 2003; Hollinger and Richardson, 2005; Post et al., 2015; Vickers et al., 2010]. For forest sites, the relative uncertainty of eddy-covariance fluxes, defined as the standard

deviation of the random errors around hourly mean fluxes, may reach 50% [Vickers *et al.*, 2010]. The errors of the modeled fluxes for both sites are no more than 16%, implying that the modeling errors are limited. The modeled CO₂ fluxes have reduced sensitivity to the measurement error of CO₂ concentration at single level compared to that of the corresponding bulk gradient. The sensitivity of the modeled CO₂ fluxes to the model parameters (i.e. eddy-diffusivity) is also reduced due to its one-sixth power dependence on sensible heat flux. While the uncertainty of the sensible heat flux is 20% [Vickers *et al.*, 2010], the corresponding uncertainties of the eddy-diffusivity and the modeled fluxes are only 6% and 3%, respectively. The model is expected to perform well under all-sky conditions due also to the one-sixth power dependence of the eddy-diffusivity on sensible heat flux as well as net radiation, implying much reduced sensitivity of the modeled CO₂ fluxes to the uncertainties of net radiation using the MEP model of heat fluxes. In fact, eddy-diffusivity parameterized according to Eq. (3.13) well characterizes the diurnal variability of turbulent mixing intensity of the surface layer even using the climatology of diurnal variations of net radiation and surface temperature.

This proof-of-concept study justifies the proposed model as a practical solution for monitoring and modeling global GHGS budget over remote areas and oceans where ground observations of GHGS fluxes are limited or non-existent. Due to rapid improvement in remote sensing technology in recent years, global CO₂ concentration data are available from satellites and other resources with improved spatial and temporal resolutions. Data from NASA Orbiting Carbon Observatory (OCO-2) to be launched in 2014 combined with this model could produce improved regional and global distributions

of carbon fluxes than existing ones [Marland et al., 2009] for identification CO₂ of sinks and sources. The new parameterization of eddy-diffusivity as in Eq (3.13) allows direct analysis of carbon cycle and budget in response to global climate change characterized by solar radiation, warming trend of temperature, atmospheric water vapor in the context of water-energy carbon cycle. More independent tests of the proposed model are anticipated to further evaluate its usefulness and explore more applications in monitoring and modeling regional and global carbon cycle and budget.

We have demonstrated the usefulness and potential of the proposed gradient independent model of CO₂ fluxes for the study of regional and global GHGS budget. The parsimony of model input makes it ideal for estimating fluxes of GHGS including CO₂ and methane given limited data availability and space-time coverage and resolution. Further field scale tests of the proposed model at daily and longer time scales are underway. One focus of the on-going research is to investigate its application to producing regional and global distributions of carbon fluxes for identifying sinks and sources of carbon and re-evaluating the regional and global carbon budget at monthly and annual time scales.

APPENDIX A

FRACTIONAL INTEGRAL AND DERIVATIVE

As a generalization of integration of integer order, the integral of a function of non-integer order $0 < \alpha < 1$ is defined as (Miller and Ross, 1993),

$$\frac{d^{-\alpha} f(t)}{dt^{-\alpha}} = \frac{1}{\Gamma(\alpha)} \int_0^t \frac{f(s)}{(t-s)^{1-\alpha}} ds, \quad (A1)$$

The minus sign in front of α on the left hand side stands for integration operation. This definition is referred as Reimann-Liouville fractional integral of order α in mathematical literature.

The fractional derivative $f(t)$ of order $0 < \alpha < 1$ can be defined accordingly

$$\frac{d^{\alpha} f(t)}{dt^{\alpha}} = \frac{1}{\Gamma(1-\alpha)} \frac{d}{dt} \int_0^t \frac{f(s)}{(t-s)^{\alpha}} ds, \quad (A2)$$

when $f(0) = 0$, (A2) is equivalent to

$$\frac{d^{\alpha} f(t)}{dt^{\alpha}} = \frac{1}{\Gamma(1-\alpha)} \int_0^t \frac{\dot{f}(s)}{(t-s)^{\alpha}} ds, \quad (A3)$$

For example, fractional integral/derivative of a liner function $f(t) = t$, are shown to be based on (A2) and (A3)

$$\frac{d^{-\alpha}f(t)}{dt^{-\alpha}} = \frac{t^{1+\alpha}}{\Gamma(2+\alpha)} , \quad (A4)$$

$$\frac{d^{\alpha}f(t)}{dt^{\alpha}} = \frac{t^{1-\alpha}}{\Gamma(2-\alpha)} , \quad (A5)$$

Where, the prime symbol (\prime) stands for derivative and Γ stands for gamma function.

As $\alpha \rightarrow 0$ and 1, the results are given by ordinary calculus.

APPENDIX B

MEP MODEL OF HEAT FLUXES

The Maximum Entropy Production (MEP) model (Wang and Bras, 2011) predicts the surface heat fluxes by partitioning land surface net radiation flux into the surface turbulent and conductive heat fluxes

$$E + H + G = R_n \quad (\text{B1})$$

Where, E (W m^{-2}) is the latent heat flux, H (W m^{-2}) is the sensible heat flux, G (W m^{-2}) is the ground heat flux and R_n (W m^{-2}) is the net radiation. Following the MEP formalism, the surface heat fluxes are expressed as

$$G = \frac{B(\sigma) I_s}{\sigma I_0} H |H|^{-\frac{1}{6}} \quad (\text{B2})$$

$$E = B(\sigma) H \quad (\text{B3})$$

$$B(\sigma) = 6 \left(\sqrt{1 + \frac{11}{36} \sigma} - 1 \right) \quad (\text{B4})$$

$$\sigma = \frac{\lambda^2 q_s}{c_p R_v T_s^2} \quad (\text{B5})$$

Where, I_s ($\text{W m}^{-2} \text{K}^{-1} \text{s}^{1/2}$) is the thermal inertia of soil varying with moisture content (e.g., Verhoef, 2004). A convenient method for estimating I_s is based on an

analytic solution of diffusion equation (Wang et al., 2010). I_0 ($\text{W m}^{-2} \text{K}^{-1} \text{s}^{1/2}$) is the “apparent thermal inertia of the air” parameterized based on Monin-Obukhov Similarity Theory (MOST) (Wang and Bras, 2009). T_s is the temperature at soil skin (or canopy) surface (K), λ is the latent heat of vaporization of liquid water ($2.5 \times 10^6 \text{ J kg}^{-1} \text{K}^{-1}$), c_p is the specific heat of air at constant pressure ($10^3 \text{ J kg}^{-1} \text{K}^{-1}$) and R_v is the gas constant of water vapor ($461 \text{ J kg}^{-1} \text{K}^{-1}$). q_s is the specific humidity at ground (or canopy) surface (kg kg^{-1}). q_s may be directly measured or estimated from meteorological and/or hydrological variables. The most convenient method to compute q_s from relative humidity (RH) and surface temperature (T_s) using Clausius-Clapeyron equation according to (B6).

$$q_s(T_s) = 0.62 \left(\frac{e_0}{P_s} \right) \exp \left[\frac{\lambda}{R_v} \left(\frac{1}{T_0} - \frac{1}{T_s} \right) \right] \quad (\text{B6})$$

Alternately q_s may be derived from surface temperature (T_s) and surface soil water potential (ψ_s) if the retention curve is known given by (B7) (Edelfsen and Anderson, 1943, p.141).

$$q_s(T_s, \psi_s) = \frac{e_0}{P_s} \exp \left[\frac{\lambda}{R_v} \left(\frac{1}{T_0} - \frac{1}{T_s} \right) \right] \exp \left(\frac{g \psi_s}{R_v T_s} \right) \quad (\text{B7})$$

Where, e_0 is the saturation vapor pressure at (an arbitrary reference temperature T_0 , P_s is the surface atmospheric pressure (10^5 Pa) and g is the gravitational constant (9.81 m s^{-2}).

At $T_0 = 273\text{K}$, $e_0 = 611 \text{ Pa}$.

Over land surfaces covered with close canopy $I_s \cong 0$. The surface heat fluxes are expressed using (B1) - (B3) reduces to

$$G = 0 \quad (B8)$$

$$H = \frac{R_n}{1+B(\sigma)} \quad (B9)$$

$$E = \frac{R_n}{1+B^{-1}(\sigma)} \quad (B10)$$

Where, $B(\sigma)$ and σ are given by (B4) and (B5) respectively except T_s and q_s represent leaf temperature and specific humidity at leaf surface (Wang and Bras, 2011).

APPENDIX C

MATLAB CODES

The procedures to computer F_c using HOD method consist of the following steps, which are illustrated by Figure 5.

- 1) Load CO₂ concentration, CO₂ flux, net radiation, and canopy surface temperature data from **.csv file**.
- 2) Find a period with most available data and fill the missing points using **linear interpolation**.
- 3) Compute H in terms of R_n and T_s using **MEP model**.
- 4) Compute D_c in terms of H and z using Eq. (2).
- 5) Compute F_c in terms of D_c and C using Eq. (3).
- 6) Compare the modeled F_c to the observed F_c .

The procedures to run the numerical model are as follows (MATLAB codes are included below)

- 1) Run **readme.m** to upload **input data** (*Santarem_KM67_Pramary_2003.csv*) in **MATLAB**.
- 2) Run the **Interpolation.m** to fill the missing data points, if any, using linear interpolation.
- 3) Run **MEP.m** to calculate H , variable MEP_H, using input data of R_n and T_s , saved in file **MEP_40_50.mat**.
- 4) Run the **HOD.m** to calculate D_c according to Eq. (2) followed by F_c according to Eq. (3), and plot the results in Figure 1. The input data and model output are shown in Appendix D.

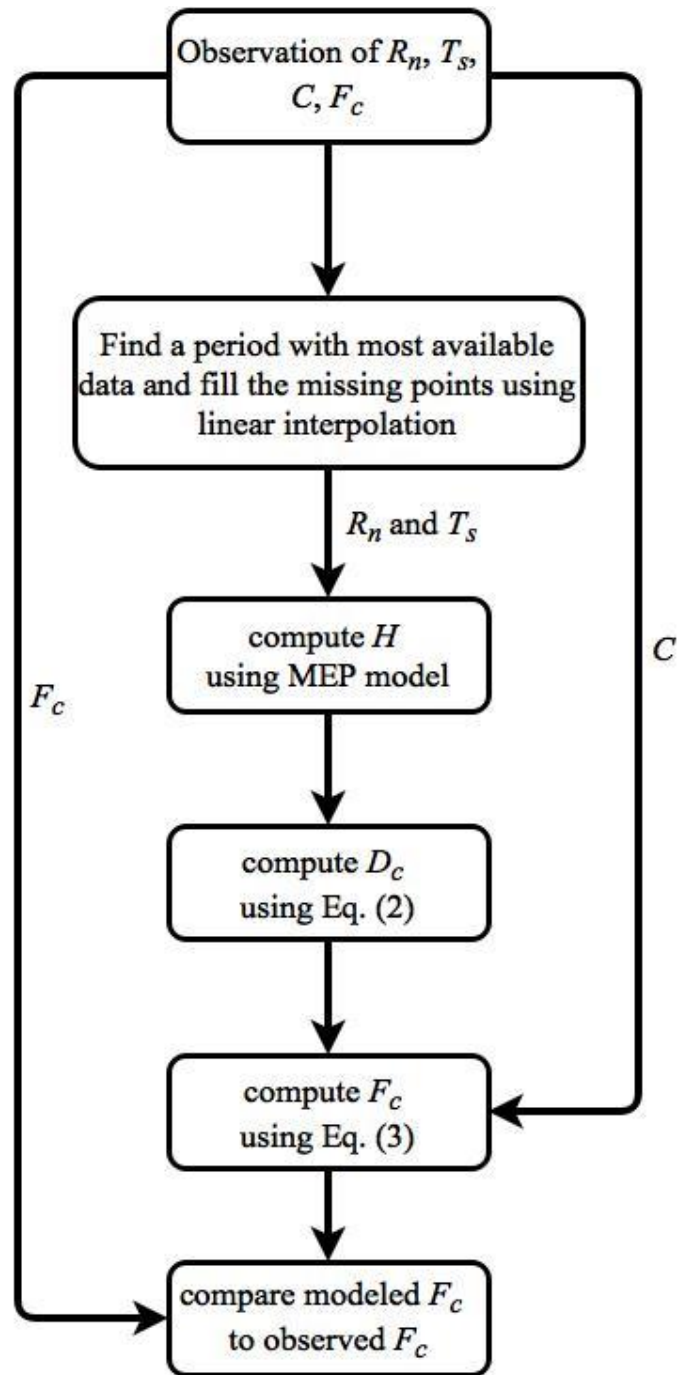


Figure 5 : Flow Chart of Proposed Model

Code 1: readdata.m

(Reads data from *.csv* file to *.mat* file).

```
clc
clear
filename = 'Santarem_KM67_Pramary_2003.csv';
Rn = xlsread(filename,'BJ2:BJ8761'); %Rn Net Radiation
RH = xlsread(filename,'AO2:AO8761'); %Relative humidity of air
Ts = xlsread(filename,'BW2:BW8761'); % Air temperature at 0.61m
P = xlsread(filename,'BE2:BE8761');%Pressure Kpa
CO2 = xlsread(filename,'T2:T8761');% CO2 concentration
LE = xlsread(filename,'AV2:AV8761'); % Latent Heat Flux
H = xlsread(filename,'AU2:AU8761'); % Sensible Heat Flux
FC = xlsread(filename,'AW2:AW8761'); %CO2 Flux
WS = xlsread(filename,'BF2:BF8761'); % Wind Speed
TA = xlsread(filename,'BP2:BP8761'); % Air temperature
UST = xlsread(filename,'BK2:BK8761');
save('Santarem_KM67_Pramary_2003.mat','Rn',
    'RH','Ts','P','CO2','LE','H','FC','WS','TA','UST');
N = length(Rn);
X = 1:N;
figure(1); plot(X, Rn);
figure(2); plot(X, RH);
figure(3); plot(X, Ts);
figure(4); plot(X, P);
figure(5); plot(X, CO2);
figure(6); plot(X, LE);
figure(7); plot(X, H);
figure(8); plot(X, FC);
figure(9); plot(X, WS);
figure(10); plot(X, TA);
figure(12); plot(X, UST);
```

Code 2: Interpolation.m

(Finds a period with most available data and fill the missing points using linear interpolation)

```
clear
clc
close all
load('Santarem_KM67_Pramary_2003.mat','Rn',
    'RH','Ts','P','CO2','LE','H','FC','WS','TA','UST');
N = length(Rn);
X = 1:N;
figure(1); plot(X, Rn);
figure(2); plot(X, RH);
figure(3); plot(X, Ts);
figure(4); plot(X, P);
figure(5); plot(X, CO2);
figure(6); plot(X, LE);
figure(7); plot(X, H);
figure(8); plot(X, FC);
figure(9); plot(X, WS);
figure(10); plot(X, TA);
figure(12); plot(X, UST);
Rn1 = Rn;
RH1 = RH;
Ts1 = Ts;
P1 = P;
CO21 = CO2;
LE1 = LE;
H1 = H;
FC1 = FC;
WS1 = WS;
TA1 = TA;
UST1 = UST;
N = length(Rn);
X = (1:N)./24;
Rn1(Rn == -9999) = NaN;
RH1(RH == -9999) = NaN;
Ts1(Ts == -9999) = NaN;
P1(P == -9999) = NaN;
CO21(CO2 == -9999) = NaN;
LE1(LE == -9999) = NaN;
H1(H == -9999) = NaN;
```



```

FC1(FC == -9999) = NaN;
WS1(WS == -9999) = NaN;
TA1(TA == -9999) = NaN;
UST1(UST == -9999) = NaN;
figure(1); plot(X, Rn1);
figure(2); plot(X, RH1);
figure(3); plot(X, Ts1);
figure(4); plot(X, P1);
figure(5); plot(X, CO21);
figure(6); plot(X, LE1);
figure(7); plot(X, H1);
figure(8); plot(X, FC1);
xlabel('Julian Day');
ylabel('CO2 Flux (umol/(m2s))');
figure(9); plot(X, WS1);
figure(10); plot(X, TA1);
figure(12); plot(X, UST1);
T1 = 960;
T2 = 1200;
X1 = T1:T2;
X = 1:length(X1);
Rn2 = Rn1(X1);
RH2 = RH1(X1);
Ts2 = Ts1(X1);
P2 = P1(X1);
CO22 = CO21(X1);
LE2 = LE1(X1);
H2 = H1(X1);
FC2 = FC1(X1);
WS2 = WS1(X1);
TA2 = TA1(X1);
UST2 = UST1(X1);
Rn3 = Rn2;
RH3 = RH2;
Ts3 = Ts2;
P3 = P2;
CO23 = CO22;
LE3 = LE2;
H3 = H2;
FC3 = FC2;
WS3 = WS2;
TA3 = TA2;
UST3 = UST2;
Rn4 = find(~isnan(Rn3));
Rn5 = interp1(Rn4, Rn3(Rn4),X,'spline');
RH4 = find(~isnan(RH3));

```

```

RH5 = interp1(RH4, RH3(RH4),X,'spline');
Ts4 = find(~isnan(Ts3));
Ts5 = interp1(Ts4, Ts3(Ts4),X,'spline');
P4 = find(~isnan(P3));
P5 = interp1(P4, P3(P4),X,'spline');
CO24 = find(~isnan(CO23));
CO25 = interp1(CO24, CO23(CO24),X,'spline');
LE4 = find(~isnan(LE3));
LE5 = interp1(LE4, LE3(LE4),X,'spline');
H4 = find(~isnan(H3));
H5 = interp1(H4, H3(H4),X,'spline');
FC4 = find(~isnan(FC3));
FC5 = interp1(FC4, FC3(FC4),X,'spline');
WS4 = find(~isnan(WS3));
WS5 = interp1(WS4, WS3(WS4),X,'spline');
TA4 = find(~isnan(TA3));
TA5 = interp1(TA4, TA3(TA4),X,'spline');
UST4 = find(~isnan(UST3));
UST5 = interp1(UST4, UST3(UST4),X,'spline');
save('Santarem_KM67_Pramary_2003_40_50.mat','Rn5','RH5','Ts5','P5','CO25','LE5','H
5','FC5','WS5','TA5','UST5');
X = (X+T1)./24;
figure(1); plot(X, Rn5);
figure(2); plot(X, RH5);
figure(4); plot(X, P5);
figure(5); plot(X, CO25);
figure(6); plot(X, LE5);
figure(7); plot(X, H5);
figure(8); plot(X, FC5);
figure(9); plot(X, WS5);
figure(10); plot(X, TA5);
figure(12); plot(X, UST5);
figure(3); plot(X, Ts5);

```

Code 3: *MEP.m*

(Calculates H in terms of R_n and T_s using MEP model)

```
clear
clc
close all
load('Santarem_KM67_Pramary_2003_40_50.mat','Rn5','RH5','Ts5','P5','CO25','LE5','H5',
',FC5','WS5','TA5','UST5');
Rn = Rn5';
RH = RH5';
Ts = Ts5';
P = P5';
CO2 = CO25';
LE = LE5';
H = H5';
FC = FC5';
WS = WS5';
TA = TA5';
UST = UST5';
esT0 = 6.11;
Lv = 2.5E6;
Rv = 461;
T0 = 273;
Rd = 287;
KA = T0 + TA;
KS = T0 + Ts;
Length = length(Rn);
I0 = zeros(Length,1);
Julian = ((1:Length)+960)./24;
RH = 1;
P = 100;
e = RH .* esT0 .* exp(Lv ./ Rv .* (1./T0 - 1./KA)); % water vapor pressure
rhov = e .* 100 ./ (Rv .* KA); % water vapor density
rhod = (1000 .* P - e .* 100) ./ (Rd .* KA);
rho = rhov + rhod;
qa = rhov ./ rho;
qs = qa;
alpha = 1;
beta = 5;
gamma2 = 9;
kappa = 0.41;
cp = 1000;
g = 9.81;
sigma = Lv .^ 2 ./ cp ./ Rv .* qs ./ KS .^2;
B = 6 .* (sqrt(1+11./36.* sigma)-1);
```

```

EMEP = B .* Rn./(1+B);
HMEP = Rn ./ (1+B);
figure(1);
subplot(2,1,1)
plot(Julian, EMEP,'r-', Julian, LE,'b-');
axis([40,50,-100,500])
legend('EMEP','EOBS');
title('MEP VS OBS, 2003')
xlabel('Julian Day');
ylabel('E (W m-2)');
subplot(2,1,2)
plot(Julian, HMEP,'r-', Julian, H,'b-');
axis([40,50,-100,300])
legend('HMEP','HOBS');
xlabel('Julian Day');
ylabel('H (W m-2)');
save('MEP_40_50.mat', 'HMEP');

```

Code 4: *HOD.m*

(Calculates D_c in terms of H and z , then calculate F_c in terms of D_c and C)

```
clear
clc
close all
load('Santarem_KM67_Pramary_2003_40_50.mat','Rn5','RH5','Ts5','P5','CO25','LE5','H5',
',FC5','WS5','TA5','UST5');
load('MEP_40_50.mat','HMEP');
Rn = Rn5';
RH = RH5';
Ts = Ts5';
P = P5';
CO2 = CO25';
LE = LE5';
H = HMEP;
FC = FC5';
WS = WS5';
TA = TA5';
UST = UST5';
Length = length(H);
N = Length;
t = (((1:N))+960)./24;
rho = 1.2;
CO2MolMass = 44.01;
AirMolMass = 28.97;
CO2New = 1E-6 * CO2MolMass * rho / AirMolMass * CO2;
CO2FluxOBS = FC .* CO2MolMass*1E-9;
zb = 19;
kappa = 0.41;
cp = 1000;
T0 = 300; % temperature
g = 9.81;
alpha = 1;
beta = 5;
gamma2 = 9;
H13 = abs(H.^(1/3));
Dc3 = zeros(N,1);
Fc3 = zeros(N,1);
Dk = zeros(N,1);
for i = 1:N
    if H(i)>0 % Unstable
        Value_Under_Sqrt = gamma2*kappa*g*H(i)*zb/(2*rho*cp*T0);
        u_star = (Value_Under_Sqrt)^(1/3);
        Ck = sqrt(3)/alpha;
```

```

    Value_Under_Sqrt_New = gamma2*kappa*g/(2*rho*cp*T0);
else    %Stable
    Value_Under_Sqrt = -2*beta*kappa*g*H(i)*zb/(rho*cp*T0);
    u_star = (Value_Under_Sqrt)^(1/3);
    Ck = 2/(1+2*alpha);
    Value_Under_Sqrt_New = -2*beta*kappa*g/(rho*cp*T0);
end
Dc3(i) = Ck*kappa*zb*u_star;
Dk(i) = abs(Ck*kappa*(Value_Under_Sqrt_New)^(1/3));
end
for i = 1:N
    if Dc3(i) == 0
        Dc3(i) = 1;
    end
    if Dk(i) == 0
        Dk(i) = 1;
    end
end
dt = 60*60;%half-hourly data
for n = 1:N
    a = 0; %a = summation of total
    b1 = 0;
    b2 = 0;
    for i = 1:n-1
        b1 = sum(Dc3(i:(n-1))); % b1 = sumation of Dc(i+1) to Dc(N)
        b2 = sum(Dc3(i+1:(n-1))); % b2 = sumation of Dc(i) to Dc(N)
        bb1 = sqrt(b1);
        bb2 = sqrt(b2);
        bb = bb1 - bb2;
        a = a + (CO2New(i+1)-CO2New(i))/Dc3(i)*bb;
    end
    Fc3(n) = 2*Dc3(n)/sqrt(pi*dt)*a;
end
Fc3u = Fc3 .* 1E9 ./ CO2MolMass;
Fc2 = zeros(N,1);
for n = 1:N
    a = 0;
    c2 = 0;
    c1 = 0;
    for i = 1:n-1
        c1 = CO2New(i+1)-CO2New(i);
        c2 = sqrt(n-i)-sqrt(n-i-1);
        a = a + c1*c2;
    end
    Fc2(n) = 2*sqrt(Dc3(n)/pi/dt)*a;
end

```

```

Fc2u = Fc2 .* 1E9 ./ CO2MolMass;
Fc4 = zeros(N,1);
for n = 1:N
    a = 0; %a = summation of total
    b1 = 0;
    b2 = 0;
    for i = 1:n-1
        b1 = sum(H13(i:(n-1))); % b1 = sumation of Dc(i+1) to Dc(N)
        b2 = sum(H13(i+1:(n-1))); % b2 = sumation of Dc(i) to Dc(N)
        bb1 = sqrt(b1);
        bb2 = sqrt(b2);
        bb = bb1 - bb2;
        a = a + (CO2New(i+1)-CO2New(i))/H13(i)*bb;
    end
    Fc4(n) = 2*sqrt(Dk(n)*zb^(4/3)*H13(n)^2)/sqrt(pi*dt)*a;
end
Fc4u = Fc4 .* 1E9 ./ CO2MolMass; %Unit change to mumol/(m^2s)
min2 = min(min(FC),min(Fc2u));
max2 = max(max(FC),max(Fc2u));
min3 = min(min(FC),min(Fc3u));
max3 = max(max(FC),max(Fc3u));
Corrcoef2 = corrcoef(Fc2u,FC);
Corrcoef3 = corrcoef(Fc3u,FC);
P2 = polyfit(FC, Fc2u,1);
slope2 = P2(1);
P3 = polyfit(FC, Fc3u,1);
slope3 = P3(1);
Number = find(Fc4u>-1.5E-6 & Fc4u<1E-6);
Errors = Fc4u(Number) - FC(Number);
SquareEs = Errors.^2;
RMSE = sqrt(mean(SquareEs))
RelativeE=abs(Errors./FC(Number));
RMSRE = sqrt(mean(RelativeE.^2)) %Relative rooted mean square error
NRMSE = RMSE/(max(FC)-min(FC))
P4 = polyfit(FC(Number), Fc4u(Number),1);
subplot('position',[0.15 0.75 0.7 0.2]);
plot(t,CO2,'-b','LineWidth',1.5);
axis([40,50,340,440])
ylabel('C (\mumol mol^{-1})','FontSize',11);
grid on
title('(a)','FontSize',12);
subplot('position',[0.15 0.5 0.7 0.2]);
plot(t, Fc4u,'-or',t, FC,'b','LineWidth',1.5,'MarkerSize',6);
AX = legend('Eq (3)','Obs');
LEG = findobj(AX,'type','text');
xlabel('Time (Julian Day)','FontSize',11);

```

```

ylabel('Fc (\mumol m^{-2} s^{-1})','FontSize',11);
set(LEG,'FontSize',15)
axis([40,50,-80,60]);
grid on
title('(b)','FontSize',12);
subplot('position',[0.325 0.07 0.35 0.35]);
scatter(FC, Fc4u,'LineWidth',1.5);hold on;
plot(-80:1:80,-80:1:80,'r','LineWidth',1.5);hold off
xlabel('Observed Fc (\mumol m^{-2} s^{-1})','FontSize',11);
ylabel('Modeled Fc (\mumol m^{-2} s^{-1})','FontSize',11);
grid on;
title('(c)','FontSize',12);
axis([-40,40,-40,40])
axis('square');

```


Appendix D: Input Data and Model Output

Table D1: Input data and model output at the Santarem Forest site shown in Figure 4.2.8

Julian Day	C ($\mu\text{mol mol}^{-1}$)	Observed F_c ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	R_n (W m^{-2})	T_s ($^{\circ}\text{C}$)	H_{MEP} (W m^{-2})	Modeled F_c ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
40.96	388.70	7.397	-27.226	25.266	-8.643	0.000
41.00	388.32	8.717	-26.710	25.005	-8.464	-0.347
41.04	390.61	5.168	-22.482	24.837	-7.087	1.828
41.08	396.12	7.959	-27.071	24.355	-8.478	5.923
41.13	401.62	8.314	-16.861	24.150	-5.266	6.542
41.17	404.34	3.557	-8.044	24.058	-2.501	4.663
41.21	407.21	9.495	-15.779	23.928	-4.884	6.719
41.25	402.27	7.975	86.886	24.169	26.713	0.756
41.29	388.97	0.311	219.046	25.331	67.203	-21.116
41.33	382.84	-8.994	178.414	25.730	55.631	-14.293
41.38	378.15	-10.737	242.561	25.884	76.208	-16.428
41.42	377.77	-14.550	327.747	26.052	103.919	-10.603
41.46	373.22	-23.904	434.599	26.972	139.897	-18.442
41.50	373.65	-14.207	470.378	27.698	151.524	-10.382
41.54	372.61	-6.893	333.215	26.993	104.599	-9.802
41.58	373.81	-2.359	124.015	24.974	37.840	-3.920
41.63	375.73	0.618	100.708	23.679	31.232	-1.119
41.67	377.78	1.789	21.606	24.055	6.551	0.346
41.71	382.30	0.306	-6.033	24.293	-1.833	2.253
41.75	390.49	-0.375	-15.624	24.373	-4.765	9.067
41.79	390.03	6.893	-17.223	24.874	-5.282	3.277
41.83	392.09	5.415	-18.822	24.503	-5.766	4.326
41.88	389.89	4.717	-17.842	24.679	-5.448	0.858
41.92	393.10	9.751	-14.078	24.670	-4.334	3.847
41.96	400.53	9.007	-10.932	24.132	-3.350	7.628
42.00	399.24	19.225	-17.739	23.854	-5.484	3.700
42.04	394.04	11.554	-25.474	23.669	-7.936	-1.085
42.08	389.26	11.084	-19.853	23.531	-6.211	-2.698
42.13	390.56	9.305	-22.019	23.319	-6.932	0.814
42.17	390.04	7.986	-20.214	23.245	-6.392	0.039
42.21	392.41	8.360	-14.181	23.189	-4.491	2.132

42.25	391.80	8.951	54.455	23.411	17.168	1.396
42.29	387.24	-1.438	125.928	23.788	39.399	-6.511
42.33	382.30	-7.330	220.452	24.295	68.654	-11.415
42.38	377.77	-13.252	302.446	24.762	94.024	-14.192
42.42	374.57	-25.128	495.259	26.117	157.556	-15.898
42.46	372.00	-17.766	399.292	26.343	126.817	-13.700
42.50	372.38	-16.116	293.165	26.439	92.181	-7.676
42.54	369.21	-15.542	354.533	27.150	112.643	-13.853
42.58	367.27	-13.100	274.499	27.514	87.799	-12.013
42.63	369.20	-12.821	308.277	27.939	98.302	-5.513
42.67	371.82	-3.565	92.360	27.602	29.808	-1.095
42.71	374.25	0.608	6.756	27.336	2.186	0.465
42.75	379.43	1.616	-31.767	26.745	-10.207	5.911
42.79	382.14	3.244	-32.901	26.125	-10.407	4.026
42.83	389.55	4.756	-32.746	25.378	-10.238	8.756
42.88	385.97	6.189	-20.576	25.470	-6.469	0.645
42.92	382.06	6.710	-9.850	25.657	-3.087	-1.482
42.96	384.35	3.472	-10.984	25.378	-3.417	1.681
43.00	386.60	2.549	-12.170	25.061	-3.744	2.609
43.04	390.92	1.217	-23.258	24.819	-7.051	5.956
43.08	391.04	7.446	-29.704	24.670	-8.933	3.338
43.13	392.83	2.744	-31.613	24.503	-9.561	4.324
43.17	398.84	6.750	-15.162	24.188	-4.627	6.664
43.21	406.36	19.433	-5.518	23.891	-1.703	7.278
43.25	407.80	14.827	47.290	23.836	14.679	16.045
43.29	406.55	8.956	136.662	23.973	41.974	12.896
43.33	393.20	-9.225	231.192	24.816	69.986	-13.145
43.38	381.23	-17.480	493.276	26.053	151.307	-27.010
43.42	375.89	-18.706	399.005	26.785	124.632	-17.771
43.46	374.23	-18.546	394.595	27.174	120.102	-12.419
43.50	372.40	-24.425	535.310	27.623	169.391	-13.495
43.54	373.06	-20.118	651.192	28.436	212.021	-8.416
43.58	374.93	-10.318	528.763	29.295	175.594	-3.320
43.63	375.39	-7.464	333.927	29.340	112.545	-3.270
43.67	375.24	-0.368	217.014	29.451	73.140	-3.384
43.71	376.71	3.664	-7.375	28.793	-2.484	-0.107
43.75	380.02	2.822	-35.327	27.708	-11.636	3.505
43.79	383.88	3.830	-29.963	27.027	-9.524	4.089
43.83	385.74	2.639	-23.775	26.651	-7.408	3.187
43.88	390.10	2.378	-12.429	26.144	-3.839	4.579
43.92	395.56	0.930	-13.976	25.583	-4.312	7.196

43.96	403.48	15.411	-6.911	25.005	-2.124	8.239
44.00	393.73	16.900	-11.346	23.725	-3.530	-2.482
44.04	383.69	11.386	-7.272	23.282	-2.291	-5.524
44.08	381.25	6.846	-5.673	22.839	-1.817	-3.075
44.13	380.21	8.035	-4.848	22.894	-1.555	-2.171
44.17	383.20	14.015	-2.888	22.968	-0.924	0.579
44.21	381.01	16.392	-5.054	22.526	-1.634	-1.873
44.25	380.46	1.131	5.261	22.351	1.717	-1.805
44.29	383.67	2.072	42.342	22.293	13.798	3.843
44.33	384.91	4.101	48.376	22.427	15.611	2.006
44.38	381.15	0.723	125.686	22.521	40.163	-6.280
44.42	375.11	-13.793	323.060	23.239	100.281	-16.380
44.46	370.09	-20.684	549.369	25.106	170.288	-19.927
44.50	368.45	-18.741	280.668	25.659	87.840	-11.406
44.54	367.84	-10.558	284.175	24.876	86.088	-9.554
44.58	367.58	-4.746	176.385	24.898	53.796	-7.058
44.63	368.33	-1.639	79.528	24.496	24.111	-3.729
44.67	371.40	1.081	45.283	24.149	13.645	0.581
44.71	373.55	3.691	4.900	24.432	1.476	0.713
44.75	375.00	5.924	-23.364	24.503	-7.075	1.607
44.79	383.67	7.512	-16.195	24.188	-4.954	6.947
44.83	390.14	8.189	-8.510	23.836	-2.636	6.664
44.88	392.34	7.686	-3.507	23.780	-1.092	3.976
44.92	387.06	6.030	-2.115	23.669	-0.661	-0.465
44.96	392.38	4.228	-2.424	23.503	-0.761	4.189
45.00	385.45	2.822	-2.991	23.060	-0.952	-2.065
45.04	383.62	2.168	-3.868	22.802	-1.240	-0.980
45.08	388.56	2.871	-4.075	22.636	-1.317	3.333
45.13	388.56	6.543	-5.570	22.820	-1.789	1.725
45.17	395.24	11.305	-5.622	22.820	-1.804	6.129
45.21	396.75	6.645	-3.095	22.857	-0.994	3.510
45.25	398.32	1.963	65.657	22.931	21.036	14.127
45.29	391.40	-0.516	171.957	23.086	54.152	-2.271
45.33	383.91	-13.020	199.190	23.516	62.860	-9.503
45.38	378.06	-14.165	269.645	24.074	84.607	-13.278
45.42	372.64	-20.684	457.283	25.227	141.876	-18.290
45.46	368.80	-16.339	425.617	25.871	132.865	-16.476
45.50	367.79	-17.927	327.774	26.241	102.634	-11.115
45.54	368.36	-13.608	337.678	26.752	106.499	-7.490
45.58	367.85	-6.268	232.203	26.870	73.078	-7.078
45.63	366.79	-7.575	193.056	26.952	61.035	-7.545

45.67	370.38	-5.428	192.231	27.450	60.765	0.332
45.71	371.79	-0.410	12.688	27.365	4.022	-0.152
45.75	374.36	0.660	-24.964	27.037	-7.848	1.973
45.79	379.20	2.479	-13.875	26.650	-4.387	3.776
45.83	382.76	1.548	-26.357	26.388	-8.377	5.540
45.88	382.35	2.151	-29.193	26.181	-9.318	2.334
45.92	381.80	3.353	-31.154	25.928	-9.959	1.351
45.96	380.54	4.176	-24.758	25.676	-7.927	0.078
46.00	380.59	4.757	-30.689	25.024	-9.863	0.610
46.04	386.22	6.054	-23.778	24.503	-7.591	5.289
46.08	390.75	3.340	-20.425	24.002	-6.430	6.166
46.13	394.92	3.194	-9.284	23.669	-2.889	5.434
46.17	410.19	2.996	-14.339	23.540	-4.477	17.487
46.21	419.60	19.725	-10.883	23.374	-3.422	14.931
46.25	416.60	18.625	45.648	23.411	14.359	16.215
46.29	407.39	0.990	120.697	23.557	37.852	2.701
46.33	393.71	-5.451	218.235	24.351	68.302	-14.786
46.38	377.28	-18.374	394.845	25.416	123.554	-35.053
46.42	366.74	-15.799	536.176	26.804	170.647	-35.500
46.46	361.32	-12.598	560.833	27.346	179.858	-28.847
46.50	358.60	-15.503	509.253	28.003	163.008	-22.731
46.54	357.74	-14.163	487.127	26.960	151.728	-17.671
46.58	355.66	-8.938	496.000	27.742	159.802	-18.947
46.63	353.83	-7.091	345.746	28.360	111.865	-16.369
46.67	351.91	-0.589	141.332	28.212	45.254	-12.512
46.71	349.36	-0.133	-6.138	28.010	-1.958	-3.628
46.75	346.93	0.157	-25.017	27.859	-8.132	-7.734
46.79	345.65	0.151	-14.752	27.726	-4.795	-5.577
46.83	346.55	7.538	-15.784	27.291	-5.116	-4.006
46.88	350.66	6.340	-10.265	26.482	-3.243	-0.571
46.92	359.01	19.499	-8.098	25.322	-2.491	3.992
46.96	369.29	15.579	-4.384	24.225	-1.342	6.564
47.00	371.44	20.634	-3.250	23.780	-1.007	3.738
47.04	372.99	7.903	-3.972	23.411	-1.250	3.491
47.08	379.01	2.003	-4.384	23.171	-1.391	6.435
47.13	385.34	4.218	-3.456	23.134	-1.098	7.144
47.17	392.33	14.551	-2.218	23.152	-0.704	7.556
47.21	397.53	16.245	-4.591	23.078	-1.462	10.038
47.25	403.50	11.177	0.103	23.171	0.033	4.146
47.29	409.78	3.862	39.409	23.030	12.493	47.518
47.33	414.95	-2.185	133.290	23.368	41.668	41.266

47.38	411.24	-3.956	108.324	23.944	33.400	18.390
47.42	406.12	-4.578	207.726	23.850	63.806	11.172
47.46	402.15	-13.225	270.400	24.602	82.954	7.731
47.50	396.27	-12.852	291.859	25.359	89.958	-0.266
47.54	392.15	-18.026	371.660	25.680	113.483	-2.318
47.58	386.92	-15.555	359.384	26.059	109.982	-7.227
47.63	382.01	-4.523	131.848	25.916	40.525	-7.396
47.67	375.06	-0.917	15.011	24.847	4.565	-7.066
47.71	364.99	5.447	0.516	23.460	0.161	-5.169
47.75	357.77	10.168	-4.746	23.208	-1.503	-12.312
47.79	351.51	1.065	-6.087	23.115	-1.938	-11.385
47.83	352.68	8.380	-2.682	23.152	-0.854	-4.900
47.88	356.52	14.454	-2.682	23.115	-0.854	-2.141
47.92	362.15	14.629	-2.373	23.078	-0.757	0.361
47.96	367.45	11.994	-1.702	22.894	-0.546	1.549
48.00	372.15	9.638	-1.805	22.636	-0.583	2.489
48.04	377.79	8.876	-2.992	22.443	-0.972	4.513
48.08	383.55	6.796	-3.817	22.268	-1.246	5.685
48.13	389.73	7.103	-3.559	22.305	-1.162	6.525
48.17	395.41	5.467	-5.004	22.360	-1.631	8.062
48.21	401.47	3.493	-2.992	22.342	-0.976	7.401
48.25	407.48	7.309	13.206	22.323	4.317	19.795
48.29	412.37	0.410	63.966	22.256	20.814	28.729
48.33	416.53	-4.309	199.173	22.630	63.666	34.097
48.38	418.69	-7.633	281.093	23.462	88.343	28.943
48.42	419.01	-8.984	358.702	24.361	112.827	23.976
48.46	373.01	-22.812	361.620	25.162	115.967	-71.578
48.50	368.07	-12.575	248.131	25.603	80.616	-26.616
48.54	368.98	-10.973	204.077	25.380	64.740	-13.197
48.58	366.72	-8.736	185.351	25.608	59.804	-14.554
48.63	370.04	-9.223	156.411	25.130	47.721	-4.311
48.67	370.20	0.078	74.388	25.154	22.884	-4.567
48.71	374.69	0.223	-6.190	24.795	-1.873	0.725
48.75	378.73	1.967	-14.135	24.893	-4.322	3.498
48.79	376.01	2.395	-26.774	25.005	-8.280	-1.688
48.83	407.07	0.726	-23.679	24.002	-7.296	26.322
48.88	384.83	0.095	-24.246	24.392	-7.463	-9.122
48.92	375.72	0.294	-30.179	24.503	-9.383	-8.915
48.96	387.78	12.764	-27.961	23.790	-8.666	7.823
49.00	384.38	6.486	-25.794	23.669	-8.031	-0.694
49.04	381.10	5.053	-24.195	23.595	-7.583	-2.451

49.08	382.78	3.170	-22.131	23.632	-6.958	0.703
49.13	386.81	7.542	-12.742	23.521	-4.043	3.036
49.17	395.76	10.539	-7.222	23.226	-2.295	7.076
49.21	414.69	11.117	-5.262	22.950	-1.676	15.640
49.25	429.24	17.214	42.251	22.968	13.510	50.996
49.29	407.23	8.515	142.024	23.547	44.368	-8.766
49.33	394.20	-5.524	225.702	24.481	70.060	-13.625
49.38	379.66	-4.010	202.848	24.148	62.553	-24.459
49.42	374.49	-23.528	605.039	24.976	187.219	-25.446
49.46	373.90	-12.213	472.146	25.424	145.076	-12.064
49.50	370.96	-21.837	565.111	26.035	170.223	-15.489
49.54	373.84	-16.643	523.428	26.753	159.343	-3.769
49.58	375.38	-9.367	448.986	26.983	134.599	-2.250
49.63	371.56	-12.013	306.857	26.915	91.893	-10.027
49.67	374.15	-2.445	58.245	26.769	17.654	-0.658
49.71	380.45	1.982	-15.735	25.747	-4.679	3.341
49.75	379.84	0.051	-28.014	25.975	-8.385	0.784
49.79	379.55	0.038	-23.422	26.200	-7.073	0.276
49.83	381.00	-0.077	-13.723	26.294	-4.161	1.250
49.88	378.77	0.621	-11.144	26.388	-3.411	-1.149
49.92	398.00	5.042	-5.881	24.968	-1.765	11.791
49.96	402.42	4.065	-8.925	24.708	-2.681	9.502
50.00	412.05	22.864	-3.302	23.817	-1.019	9.474
50.04	386.36	15.392	-3.044	23.189	-0.964	-10.165
50.08	385.15	7.767	-3.663	23.078	-1.166	-2.609
50.13	388.19	9.001	-6.088	23.097	-1.937	1.134
50.17	390.50	9.946	-6.913	22.987	-2.206	2.093
50.21	389.71	7.172	-5.314	23.041	-1.694	0.547
50.25	391.39	6.639	41.480	23.208	13.150	5.357
50.29	391.92	4.109	47.774	23.307	14.985	3.992
50.33	390.55	1.630	96.993	23.590	30.049	1.528
50.38	384.03	-2.308	106.177	24.037	32.267	-7.976
50.42	380.13	-10.853	329.210	23.925	100.821	-11.862
50.46	372.24	-21.604	416.645	24.694	134.230	-21.722
50.50	372.81	-20.038	408.664	25.565	122.573	-8.618
50.54	373.37	-16.842	391.949	25.306	117.238	-5.858
50.58	379.85	-6.157	217.825	24.376	65.691	6.115
50.63	376.66	-5.400	190.223	24.533	57.349	-4.913
50.67	374.41	-1.027	54.276	24.930	16.170	-4.173
50.71	379.14	-0.730	-6.552	24.944	-1.938	1.415
50.75	384.10	6.510	-13.982	25.098	-4.152	4.999

50.79	393.18	13.897	-14.085	24.355	-4.273	9.287
50.83	389.23	7.182	-15.323	23.762	-4.752	1.224
50.88	386.01	6.462	-19.606	23.595	-6.125	-0.581
50.92	388.24	7.367	-13.466	23.558	-4.221	2.445
50.96	389.74	6.555	-8.152	23.577	-2.555	2.303

Table D2: Input data and model output at the Cedar Bridge New Jersey site shown in Figure 4.2.22

Julian Day	C ($\mu\text{mol mol}^{-1}$)	Observed F_c ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	R_n (W m^{-2})	T_s ($^{\circ}\text{C}$)	H_{MEP} (W m^{-2})	Modeled F_c ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
160.98	409.85	5.972	-61.520	14.140	-27.052	0.000
161.00	410.94	5.608	-60.760	13.810	-27.001	1.228
161.02	408.33	7.833	-62.950	13.580	-28.215	-2.466
161.04	407.36	5.189	-65.710	13.440	-29.691	-1.972
161.06	407.18	5.364	-67.260	13.220	-30.557	-1.298
161.08	407.82	3.902	-71.400	13.160	-32.514	-0.226
161.10	405.72	2.303	-92.800	13.260	-42.463	-3.234
161.13	403.82	3.525	-89.000	13.430	-41.027	-3.872
161.15	406.48	6.617	-69.880	12.920	-32.156	0.897
161.17	406.49	3.980	-71.500	12.820	-33.218	-0.482
161.19	405.64	6.328	-62.450	12.730	-29.286	-1.501
161.21	400.71	3.317	-42.700	13.200	-20.410	-5.848
161.23	395.65	-1.881	16.140	13.930	7.852	-8.608
161.25	394.07	-3.291	107.400	14.590	52.285	-13.524
161.27	391.87	-5.329	197.800	15.170	98.028	-15.348
161.29	389.10	-10.508	253.600	15.540	128.848	-17.308
161.31	387.38	-12.687	279.800	15.550	145.261	-16.041
161.33	386.91	-13.029	276.400	15.820	144.361	-13.009
161.35	386.39	-12.019	402.800	16.150	210.188	-13.674
161.38	385.17	-18.035	432.900	16.460	224.024	-14.574
161.40	384.44	-15.347	518.200	16.850	268.151	-14.322
161.42	383.78	-15.438	409.000	17.170	211.829	-12.563
161.44	383.82	-17.817	560.600	17.210	291.411	-11.974
161.46	383.04	-16.729	590.000	17.790	308.252	-13.139
161.48	382.13	-19.326	689.500	18.410	360.496	-14.209
161.50	382.28	-15.467	733.000	18.400	383.954	-11.871
161.52	382.20	-15.709	584.000	18.220	304.438	-10.527
161.54	382.29	-12.845	572.100	18.330	299.432	-9.629
161.56	381.94	-14.802	500.200	18.880	261.733	-9.677
161.58	382.02	-12.655	486.500	18.880	257.862	-8.652
161.60	381.42	-12.487	433.700	19.000	233.234	-9.462
161.63	380.57	-15.026	467.100	19.100	249.641	-10.570
161.65	380.47	-10.021	360.500	19.290	195.773	-8.519
161.67	380.72	-7.188	249.100	18.970	135.566	-6.585

161.69	380.81	-4.954	238.200	19.330	129.962	-6.320
161.71	380.62	-3.695	124.300	19.320	67.420	-5.348
161.73	380.72	-1.336	86.300	19.430	46.873	-4.335
161.75	381.00	-0.025	7.850	19.070	4.251	-1.733
161.77	382.18	1.065	-42.360	18.200	-22.482	-0.545
161.79	383.85	1.573	-58.540	17.280	-30.722	0.152
161.81	387.24	1.460	-63.660	15.900	-33.096	2.759
161.83	386.92	0.947	-63.340	15.570	-32.913	-0.242
161.85	393.33	0.252	-59.010	14.800	-30.347	6.753
161.88	391.48	-0.406	-57.380	14.480	-29.405	0.161
161.90	394.01	-0.808	-58.000	13.730	-29.839	3.469
161.92	394.85	-0.734	-64.420	14.020	-33.424	2.557
161.94	401.63	0.034	-65.620	13.020	-34.222	9.454
161.96	409.38	1.715	-67.280	12.330	-36.059	13.685
161.98	410.32	4.227	-66.400	11.550	-36.508	8.306
162.00	407.79	6.278	-63.390	11.460	-35.877	3.101
162.02	410.98	6.275	-66.710	10.740	-38.065	7.796
162.04	409.28	3.697	-69.000	10.980	-39.765	3.160
162.06	409.30	1.511	-67.530	10.460	-38.965	3.631
162.08	412.97	0.539	-65.730	9.560	-37.902	7.651
162.10	410.52	0.803	-64.290	9.730	-37.385	1.894
162.13	413.16	2.322	-62.950	9.090	-36.524	6.060
162.15	411.55	5.115	-65.600	9.050	-38.135	2.215
162.17	411.76	7.019	-64.950	8.760	-37.736	3.113
162.19	410.23	2.465	-58.090	8.840	-33.799	0.980
162.21	403.25	0.557	-34.390	9.800	-20.003	-5.324
162.23	395.40	-2.129	23.590	11.330	13.671	-12.280
162.25	391.89	-8.291	102.400	12.220	59.762	-17.296
162.27	389.65	-7.602	188.000	12.800	110.605	-15.759
162.29	388.74	-9.770	275.600	13.040	163.917	-13.147
162.31	387.70	-10.821	352.800	13.440	210.386	-12.683
162.33	386.73	-11.880	432.100	13.990	257.096	-12.387
162.35	385.70	-19.529	499.000	14.570	294.600	-12.460
162.38	385.16	-12.414	569.100	15.220	334.408	-11.420
162.40	384.98	-14.705	617.900	15.860	359.470	-10.153
162.42	384.93	-15.547	655.200	16.350	377.911	-9.191
162.44	384.08	-18.360	635.100	17.220	359.216	-10.308
162.46	383.62	-15.204	669.400	17.500	377.020	-9.826
162.48	382.48	-18.167	652.700	18.230	362.360	-11.187
162.50	382.11	-16.016	659.700	18.700	363.314	-9.911
162.52	381.52	-16.968	469.000	18.690	256.490	-9.029

162.54	380.33	-12.960	390.700	19.010	210.420	-9.933
162.56	379.50	-17.440	577.400	19.750	307.842	-11.239
162.58	379.74	-11.304	526.400	20.220	280.989	-8.417
162.60	378.72	-12.557	547.000	20.630	289.185	-10.612
162.63	378.12	-9.895	483.100	21.150	254.282	-9.782
162.65	377.18	-8.733	422.900	21.500	220.967	-10.186
162.67	376.92	-5.972	342.300	21.710	178.718	-8.492
162.69	376.35	-5.599	265.200	21.820	137.831	-8.222
162.71	376.15	-2.373	148.700	21.750	76.679	-6.287
162.73	376.41	-1.199	56.800	21.250	28.927	-3.876
162.75	376.59	-1.137	53.780	21.350	27.380	-3.579
162.77	377.50	1.482	-21.530	20.970	-10.789	-1.157
162.79	380.09	2.861	-53.120	19.350	-26.006	1.277
162.81	384.77	3.006	-62.310	17.960	-30.320	4.548
162.83	390.14	3.210	-57.960	17.340	-28.378	6.936
162.85	392.87	3.674	-50.810	16.350	-24.857	5.601
162.88	396.27	4.323	-49.780	15.840	-24.342	6.751
162.90	398.27	5.084	-53.900	15.350	-26.348	6.149
162.92	395.09	5.884	-53.310	15.510	-26.148	0.349
162.94	395.69	6.650	-52.830	15.500	-25.904	2.345
162.96	399.60	7.308	-50.050	15.040	-24.481	6.064
162.98	401.65	7.785	-51.120	14.580	-25.041	5.639
163.00	397.24	8.008	-52.100	14.580	-25.690	-1.251
163.02	399.18	7.903	-51.450	14.310	-25.260	3.200
163.04	408.30	7.397	-52.570	13.570	-25.785	12.281
163.06	411.58	6.417	-53.670	13.170	-26.329	9.761
163.08	409.80	4.889	-53.300	13.050	-26.251	4.396
163.10	408.82	2.740	-54.580	12.730	-26.929	3.476
163.13	410.40	-0.006	-54.810	12.490	-27.032	5.465
163.15	412.51	-2.938	-53.650	12.390	-26.457	6.492
163.17	415.40	-5.547	-51.410	12.200	-25.326	7.842
163.19	416.20	-7.324	-41.550	12.170	-20.463	5.912
163.21	410.94	-7.760	-13.420	13.020	-6.583	-0.553
163.23	402.86	-6.347	86.400	14.310	42.064	-15.530
163.25	394.05	-4.805	103.900	15.110	50.654	-18.350
163.27	392.12	-7.194	76.000	15.020	36.896	-9.375
163.29	393.62	-3.252	65.200	14.900	31.549	-3.076
163.31	391.36	-6.304	73.300	15.040	35.051	-7.207
163.33	388.19	-7.879	81.600	15.370	38.888	-10.035
163.35	383.17	-6.748	96.200	15.780	45.654	-15.288
163.38	383.50	-5.715	126.200	16.190	60.760	-9.090

163.40	383.22	-7.177	147.000	16.390	69.992	-8.573
163.42	380.79	-11.891	172.600	16.690	81.810	-12.350
163.44	380.31	-17.934	311.600	17.060	146.603	-11.621
163.46	381.15	-18.002	448.400	17.760	210.362	-8.654
163.48	380.13	-15.331	499.100	18.860	231.645	-11.213
163.50	380.84	-11.186	249.400	18.240	116.177	-5.953
163.52	385.31	-8.667	180.800	17.780	82.707	2.625
163.54	391.75	-5.464	94.300	16.850	43.108	8.520
163.56	392.62	-23.666	500.000	17.860	226.928	7.129
163.58	388.33	-13.519	427.900	19.590	193.411	-6.892
163.60	383.55	-22.998	289.200	19.130	131.327	-11.745
163.63	382.76	-13.715	503.000	19.990	228.340	-9.560
163.65	379.35	-15.873	420.800	20.280	189.862	-13.928
163.67	378.04	-11.344	242.200	20.110	109.252	-9.912
163.69	378.16	-7.326	260.000	20.650	118.053	-7.689
163.71	378.34	-6.190	176.800	20.800	80.079	-5.862
163.73	379.13	-2.509	88.300	20.710	39.933	-3.295
163.75	380.70	1.490	-3.442	20.030	-1.540	-0.268
163.77	383.85	4.497	-29.820	18.980	-13.115	3.403
163.79	388.08	6.060	-26.820	18.170	-11.715	4.184
163.81	390.67	5.724	-27.270	17.690	-11.883	3.978
163.83	390.56	4.361	-34.230	17.330	-14.797	1.897
163.85	391.72	5.124	-35.710	16.900	-15.395	2.528
163.88	394.03	4.156	-35.560	16.500	-15.340	3.830
163.90	395.51	5.060	-37.870	16.280	-16.343	3.659
163.92	398.34	2.816	-42.750	15.970	-18.464	5.423
163.94	403.06	4.477	-37.590	15.700	-16.211	7.772
163.96	407.43	5.813	-53.670	15.180	-23.237	10.116
163.98	409.39	2.973	-55.170	14.850	-23.960	8.261
164.00	409.85	4.227	-54.210	14.520	-23.712	6.377
164.02	411.02	3.488	-51.610	14.270	-22.823	6.415
164.04	413.04	4.934	-52.210	14.000	-23.172	7.311
164.06	413.58	7.213	-52.040	13.730	-23.350	6.038
164.08	408.41	3.104	-51.390	13.680	-23.382	-0.628
164.10	408.21	4.825	-51.170	13.740	-23.441	1.982
164.13	407.90	2.721	-51.800	13.650	-23.792	1.966
164.15	409.28	2.505	-50.990	13.380	-23.486	3.697
164.17	411.40	3.260	-47.680	13.190	-22.010	5.007
164.19	412.44	4.003	-38.060	13.130	-17.571	4.288
164.21	409.95	3.706	-13.370	13.930	-6.144	0.525
164.23	405.74	-0.259	39.160	14.710	17.992	-4.772

164.25	397.84	-3.748	114.900	15.910	52.788	-16.621
164.27	393.54	-5.705	195.000	17.020	89.321	-14.829
164.29	390.17	-9.363	274.700	17.890	125.174	-14.897
164.31	386.55	-10.413	355.500	18.970	160.790	-16.978
164.33	383.27	-8.784	438.900	20.360	196.687	-18.193
164.35	380.78	-13.649	512.300	21.230	228.935	-17.921
164.38	378.65	-13.816	574.300	21.930	256.140	-17.807
164.40	376.37	-10.611	637.400	22.950	282.514	-18.714
164.42	375.74	-9.332	691.100	23.090	309.669	-15.635
164.44	370.88	-11.310	544.200	23.860	244.197	-22.680
164.46	370.63	-14.369	597.600	24.220	268.480	-16.446
164.48	370.48	-10.889	414.600	24.280	185.841	-12.791
164.50	369.70	-7.577	382.700	24.860	170.767	-12.913
164.52	370.23	-9.390	354.600	24.860	159.212	-9.822
164.54	371.23	-14.545	401.600	24.880	171.775	-7.794
164.56	371.81	-11.307	461.900	24.950	196.977	-7.706
164.58	371.88	-14.075	323.600	24.290	135.136	-7.152
164.60	372.46	-11.575	696.700	25.800	296.759	-7.684
164.63	376.48	-10.692	543.700	25.110	227.153	1.018
164.65	379.02	-6.565	341.800	24.660	141.487	1.615
164.67	380.53	-8.419	237.200	23.740	97.513	1.291
164.69	379.86	-5.462	278.300	24.160	114.184	-2.339
164.71	379.81	-0.404	106.500	23.740	43.459	-1.636
164.73	380.59	-1.020	67.300	22.820	27.252	-0.330
164.75	380.61	-0.283	27.240	22.700	10.957	-0.757
164.77	382.27	0.895	-15.870	21.660	-6.385	0.827
164.79	384.92	2.822	-42.430	20.490	-17.154	3.333
164.81	388.37	2.850	-54.090	19.310	-22.010	4.985
164.83	391.74	2.492	-53.310	18.410	-21.812	5.798
164.85	392.97	3.732	-52.060	17.940	-21.526	4.328
164.88	398.22	4.786	-52.140	17.660	-21.744	8.570
164.90	399.73	4.076	-53.630	17.260	-22.553	6.365
164.92	402.64	3.840	-52.000	16.780	-22.022	7.584
164.94	405.31	4.350	-47.470	16.330	-20.181	7.700
164.96	405.92	5.101	-46.570	16.010	-19.836	5.931
164.98	404.50	5.588	-43.920	16.110	-18.729	3.216
165.00	403.79	5.411	-43.500	16.110	-18.617	2.785
165.02	403.06	4.600	-38.920	15.880	-16.673	2.119
165.04	404.44	3.288	-40.620	15.710	-17.408	3.898
165.06	405.43	1.613	-39.800	15.510	-17.100	3.960
165.08	412.96	-0.291	-35.280	14.750	-15.333	10.602

165.10	412.19	-2.288	-32.420	14.590	-14.047	4.988
165.13	412.11	-4.244	-30.110	14.670	-12.971	4.356
165.15	411.47	-6.022	-27.330	14.910	-11.647	3.231
165.17	411.25	-7.488	-25.730	15.190	-10.859	3.018
165.19	412.01	-8.505	-17.190	14.950	-7.305	3.256
165.21	417.78	-8.939	-0.627	14.810	-0.267	2.666
165.23	421.90	-8.654	23.710	15.210	9.956	19.167
165.25	410.47	-7.515	49.960	16.220	20.377	-7.375
165.27	402.86	-5.387	78.100	17.480	31.075	-10.429
165.29	399.73	-6.356	134.500	18.260	53.318	-7.982
165.31	392.97	-16.786	195.700	19.900	76.526	-16.280
165.33	390.60	-9.154	230.600	20.790	90.483	-11.634
165.35	382.51	-9.216	255.600	21.430	99.903	-23.089
165.38	376.80	-13.194	269.300	22.190	105.476	-23.524
165.40	375.35	-17.183	329.700	22.720	128.844	-18.208
165.42	372.87	-16.255	385.600	23.020	151.285	-19.619
165.44	369.26	-19.081	303.300	23.100	119.930	-20.245
165.46	371.61	-16.854	302.500	22.800	115.843	-9.587
165.48	370.06	-14.376	301.000	22.940	115.932	-13.713
165.50	367.26	-19.449	419.200	22.780	159.413	-18.721
165.52	367.85	-13.920	312.400	22.770	120.205	-11.383
165.54	368.87	-16.620	251.900	22.080	98.993	-8.197
165.56	368.81	-14.546	263.600	21.640	105.788	-9.019
165.58	369.84	-10.317	198.300	21.120	81.210	-5.986
165.60	371.65	-10.254	155.100	20.090	63.654	-3.051
165.63	374.06	-10.559	156.800	19.330	65.010	-0.387
165.65	378.06	-8.449	130.100	18.800	55.699	3.969
165.67	379.72	-5.413	86.400	18.330	37.615	2.183
165.69	380.20	-2.149	51.660	18.050	22.364	0.689
165.71	381.48	-1.387	28.090	17.650	11.988	1.462
165.73	382.70	0.652	7.940	17.280	3.352	1.327
165.75	384.44	3.076	-11.300	16.960	-4.765	2.036
165.77	388.12	5.290	-23.510	16.680	-9.919	5.120
165.79	392.15	7.250	-25.970	16.240	-10.945	6.289
165.81	395.28	8.915	-24.790	15.890	-10.473	6.244
165.83	397.88	10.240	-24.150	15.570	-10.237	6.240
165.85	399.73	11.184	-17.690	15.440	-7.498	5.266
165.88	402.80	11.703	-8.510	15.540	-3.604	5.150
165.90	408.88	11.754	-13.420	15.590	-5.702	9.918
165.92	409.85	11.295	-16.950	15.610	-7.214	7.210
165.94	413.02	10.283	-13.580	15.680	-5.784	7.870

165.96	416.50	8.674	-17.230	15.640	-7.339	9.465
165.98	415.37	6.427	-19.550	15.550	-8.302	5.912
166.00	411.25	4.139	-9.170	15.900	-3.866	1.407
166.02	411.54	4.051	-6.986	16.300	-2.906	2.701
166.04	401.92	5.252	-26.460	16.710	-10.972	-7.586
166.06	396.87	5.486	-42.700	16.630	-17.900	-5.989
166.08	397.02	3.561	-52.610	16.310	-22.178	-1.329
166.10	400.83	2.301	-54.620	15.970	-23.141	3.798
166.13	405.17	3.026	-56.040	15.550	-23.866	6.614
166.15	405.31	5.047	-55.000	15.200	-23.593	3.742
166.17	406.26	5.126	-51.380	14.970	-22.246	4.077
166.19	406.77	5.839	-44.370	14.740	-19.323	3.574
166.21	405.05	2.255	-22.530	14.920	-9.843	0.912
166.23	402.34	1.586	-11.660	15.260	-5.093	-0.824
166.25	396.95	-6.464	101.400	16.570	43.927	-12.360
166.27	392.71	-7.820	184.200	18.030	80.010	-11.831
166.29	388.99	-10.854	267.300	19.080	116.893	-13.250
166.31	385.85	-13.519	327.200	19.830	143.274	-13.787
166.33	382.24	-13.861	424.600	20.630	186.407	-16.882
166.35	380.19	-16.778	487.000	21.250	213.074	-15.184
166.38	378.18	-14.522	540.200	21.880	236.636	-15.431
166.40	377.07	-9.738	536.200	22.280	237.956	-13.524
166.42	376.07	-16.553	547.600	22.690	244.726	-12.910
166.44	375.15	-16.233	655.400	23.390	297.632	-13.255
166.46	374.60	-16.797	639.200	23.600	290.116	-11.924
166.48	375.23	-12.796	699.400	23.810	326.480	-8.995
166.50	374.72	-9.108	611.100	23.860	287.257	-9.803
166.52	374.53	-13.630	462.100	23.950	219.823	-8.325
166.54	373.45	-13.917	321.700	24.020	153.063	-8.932
166.56	375.10	-14.634	599.800	24.950	299.498	-4.858
166.58	376.27	-9.299	145.500	23.670	72.113	-2.547
166.60	375.18	-13.265	289.900	23.610	145.123	-6.922
166.63	376.01	-10.906	346.500	25.050	179.079	-4.026
166.65	376.51	-7.816	145.500	24.190	74.380	-2.844
166.67	376.51	-8.782	299.900	24.950	160.649	-4.267
166.69	376.94	-11.465	218.600	24.880	118.965	-3.110
166.71	377.14	-5.712	206.000	24.910	116.069	-3.161
166.73	378.09	-2.607	90.200	24.720	50.190	-1.151
166.75	379.28	-0.651	26.030	24.470	14.245	0.084
166.77	378.76	2.295	-4.263	24.090	-2.213	-0.559
166.79	379.44	3.848	-43.060	20.580	-18.571	0.081

166.81	383.22	2.523	-47.670	19.170	-20.492	3.488
166.83	386.82	2.324	-38.200	18.570	-16.455	4.459
166.85	389.82	2.688	-54.740	17.810	-23.593	5.742
166.88	389.27	3.111	-54.220	17.450	-23.542	2.300
166.90	393.00	3.533	-57.890	17.780	-25.740	6.224
166.92	398.42	3.892	-55.800	16.910	-25.118	9.333
166.94	403.21	4.125	-56.800	17.660	-28.346	10.896
166.96	406.57	4.172	-61.010	17.880	-31.587	10.748
166.98	408.57	4.004	-57.390	17.230	-29.719	9.292
167.00	411.24	3.732	-54.900	16.720	-28.423	9.782
167.02	413.91	3.499	-54.330	16.210	-28.038	10.116
167.04	414.93	3.450	-53.180	15.450	-27.488	8.551
167.06	415.80	3.530	-53.320	15.330	-27.750	7.995
167.08	418.91	3.153	-52.580	15.140	-27.326	10.165
167.10	423.06	2.589	-52.110	14.560	-26.966	12.135
167.13	425.01	2.375	-50.570	14.540	-26.218	10.713
167.15	424.08	2.975	-55.000	14.560	-28.748	7.644
167.17	422.25	4.144	-52.870	14.820	-27.688	5.232
167.19	421.70	3.837	-43.960	14.950	-23.019	4.998
167.21	419.45	1.123	-20.130	15.490	-10.486	2.050
167.23	415.75	-0.581	32.480	16.850	16.795	-0.942
167.25	411.18	-2.946	107.800	18.260	55.254	-5.845
167.27	408.40	-6.180	187.900	19.530	96.448	-4.150
167.29	401.29	-8.910	272.700	20.950	141.057	-14.726
167.31	394.74	-12.139	336.400	21.660	175.951	-18.883
167.33	390.09	-14.615	421.700	22.430	221.249	-19.258
167.35	387.94	-15.783	484.900	23.190	254.228	-15.467
167.38	383.65	-17.341	550.000	24.130	287.595	-20.454
167.40	381.11	-14.734	595.400	24.820	311.793	-18.689
167.42	378.37	-15.796	622.900	25.590	323.094	-19.394
167.44	376.81	-11.761	612.600	26.050	324.073	-17.184
167.46	376.46	-14.390	703.000	26.680	376.243	-14.563
167.48	377.52	-12.207	699.000	27.160	383.611	-9.675
167.50	377.86	-12.137	670.800	27.420	373.084	-8.995
167.52	377.83	-12.665	549.100	27.350	312.227	-8.358
167.54	377.32	-12.752	614.600	27.900	349.372	-9.445
167.56	377.46	-11.962	677.600	28.440	392.911	-8.208
167.58	376.65	-9.369	620.300	28.340	357.304	-9.589
167.60	376.76	-7.972	572.800	28.500	329.797	-7.610
167.63	376.74	-8.988	492.200	28.670	283.915	-6.987
167.65	376.69	-9.375	427.600	28.660	247.849	-6.477

167.67	376.68	-7.825	363.600	29.000	207.446	-5.825
167.69	375.93	-6.116	269.500	28.700	142.868	-6.461
167.71	376.45	-6.466	184.200	27.580	93.569	-3.806
167.73	377.63	-2.874	72.500	26.700	36.605	-1.339
167.75	378.37	-0.075	12.550	25.320	6.175	-0.549
167.77	380.40	1.500	-29.720	24.300	-14.322	1.497
167.79	385.79	1.968	-57.000	23.030	-26.915	6.625
167.81	388.34	1.666	-62.500	21.510	-29.037	5.072
167.83	392.13	1.099	-60.360	20.680	-27.949	6.742
167.85	396.63	0.772	-58.530	19.890	-27.007	8.540
167.88	396.59	1.190	-56.100	19.280	-25.757	4.659
167.90	397.75	2.859	-56.750	19.590	-26.333	5.074
167.92	403.04	5.897	-57.470	19.390	-27.060	9.741
167.94	403.89	8.878	-54.760	19.380	-26.105	6.555
167.96	407.03	9.990	-56.370	19.280	-27.128	8.697
167.98	417.69	8.167	-53.470	17.170	-25.201	17.522
168.00	422.43	5.325	-54.470	16.670	-25.601	15.259
168.02	424.87	4.686	-53.700	16.750	-25.377	13.167
168.04	426.33	7.693	-55.530	16.230	-26.390	11.866
168.06	427.00	6.473	-53.890	16.030	-25.927	10.333
168.08	422.88	8.874	-52.740	16.180	-25.652	4.281
168.10	427.96	10.908	-52.580	15.460	-25.402	11.834
168.13	422.82	11.113	-54.290	16.060	-26.196	2.652
168.15	424.27	9.903	-55.490	16.020	-26.822	6.942
168.17	422.22	7.145	-54.330	16.310	-26.246	3.657
168.19	422.82	2.906	-41.370	16.280	-19.855	4.908
168.21	421.02	2.021	-15.390	16.630	-7.305	1.875
168.23	418.23	-0.552	22.420	17.250	10.491	0.012
168.25	413.00	-0.397	81.300	18.660	37.329	-6.943
168.27	410.04	-3.939	49.210	19.230	22.338	-3.514
168.29	408.62	-7.472	105.500	19.300	47.042	-3.170
168.31	402.60	-13.048	144.400	20.380	63.353	-11.784
168.33	395.28	-14.871	268.100	21.870	116.909	-21.120
168.35	387.09	-16.480	343.200	23.470	153.123	-27.686
168.38	381.35	-19.305	426.500	24.780	192.751	-27.957
168.40	378.83	-17.713	497.600	25.620	224.221	-22.997
168.42	377.27	-16.461	639.300	27.060	290.851	-21.128
168.44	376.66	-8.592	184.900	26.190	83.718	-11.312
168.46	376.09	-14.937	335.200	26.510	149.266	-13.091
168.48	374.92	-14.133	337.500	27.060	151.771	-13.533
168.50	372.18	-10.444	260.800	26.970	114.753	-15.284

168.52	370.17	-12.947	235.100	27.020	104.278	-14.957
168.54	368.31	-17.603	423.300	27.700	187.423	-18.569
168.56	369.68	-10.776	343.200	27.860	157.851	-10.530
168.58	369.25	-12.277	370.800	27.970	170.528	-12.052
168.60	370.01	-12.894	214.600	27.700	98.285	-7.638
168.63	369.56	-13.247	427.900	28.240	194.350	-11.054
168.65	369.08	-8.204	403.600	28.800	183.953	-10.817
168.67	367.78	-6.852	325.300	28.950	146.698	-11.639
168.69	368.34	-5.627	211.200	28.460	96.370	-7.378
168.71	368.49	-6.304	196.600	28.270	90.742	-7.034
168.73	369.88	-1.862	67.340	27.720	31.044	-2.985
168.75	373.03	1.273	-21.580	26.530	-10.034	0.605
168.77	376.45	0.834	-20.260	25.340	-9.330	2.458
168.79	380.67	3.878	-42.480	24.200	-19.755	5.558
168.81	385.94	2.732	-54.530	23.050	-25.496	7.995
168.83	390.24	3.377	-51.450	22.080	-24.063	8.055
168.85	391.79	4.489	-50.940	21.720	-23.967	5.972
168.88	394.32	6.406	-53.990	21.470	-25.791	6.882
168.90	395.95	4.520	-51.760	20.920	-25.001	6.121
168.92	398.43	2.781	-49.970	20.270	-24.312	6.961
168.94	400.34	3.843	-49.140	19.620	-24.095	6.765
168.96	402.68	4.822	-48.470	19.370	-24.121	7.393
168.98	405.95	4.212	-45.210	18.830	-22.638	8.617
169.00	406.49	6.443	-40.880	18.760	-20.363	6.221
169.02	406.00	5.592	-46.680	18.720	-22.979	4.793
169.04	405.69	5.975	-40.670	18.420	-19.778	3.955
169.06	405.33	4.737	-35.830	18.360	-17.284	3.266
169.08	407.46	3.568	-40.740	18.080	-19.514	5.695
169.10	408.54	4.995	-39.730	17.630	-18.853	5.231
169.13	408.54	6.336	-40.830	17.510	-19.205	4.195
169.15	409.05	3.632	-41.330	17.340	-19.378	4.365
169.17	412.64	6.026	-36.490	16.800	-17.041	7.294
169.19	412.01	8.140	-29.470	16.650	-13.653	3.950
169.21	408.05	3.383	-10.800	17.350	-4.935	-0.120
169.23	404.47	-1.842	37.550	18.430	16.820	-3.777
169.25	400.38	-5.537	104.100	19.580	45.517	-7.217
169.27	393.64	-9.976	174.900	20.890	73.878	-14.740
169.29	386.76	-6.400	254.900	22.530	104.174	-20.071
169.31	381.99	-9.726	333.100	23.570	133.179	-20.175
169.33	378.09	-14.030	378.900	24.730	148.623	-20.056
169.35	374.79	-13.723	472.400	25.870	182.887	-20.868

169.38	372.25	-11.135	540.700	26.840	208.331	-20.239
169.40	368.81	-14.896	586.300	28.040	224.905	-22.675
169.42	366.38	-18.641	629.200	29.060	243.889	-21.956
169.44	365.44	-11.452	673.300	30.070	264.977	-19.061
169.46	364.24	-11.589	679.200	30.640	271.301	-18.587
169.48	364.29	-13.913	692.500	31.170	278.191	-15.325
169.50	364.83	-9.417	720.000	31.860	297.284	-12.975
169.52	365.15	-8.759	713.000	32.120	300.086	-11.940
169.54	363.55	-7.539	514.000	31.950	210.226	-13.747
169.56	363.92	-12.686	504.600	31.860	204.977	-10.473
169.58	364.00	-9.743	605.100	32.310	252.198	-10.787
169.60	362.61	-11.599	516.400	32.350	212.099	-12.850
169.63	362.47	-9.509	445.400	32.130	184.132	-10.533
169.65	362.92	-8.287	412.500	32.440	167.294	-8.514
169.67	362.14	-4.738	290.700	32.140	114.635	-9.133
169.69	360.70	-5.069	234.600	31.380	88.573	-10.102
169.71	360.61	-3.571	141.800	31.070	53.402	-7.157
169.73	361.30	-0.648	87.200	30.600	32.950	-4.667
169.75	363.80	1.847	26.180	29.750	9.928	-0.640
169.77	371.91	2.477	-20.280	28.350	-7.491	5.708
169.79	378.64	2.789	-46.920	26.230	-16.900	10.053
169.81	384.55	3.272	-55.230	24.800	-20.039	10.571
169.83	389.96	3.679	-54.930	23.610	-20.189	11.102
169.85	394.15	5.719	-53.400	22.620	-19.883	10.762
169.88	397.66	3.965	-50.050	22.030	-18.751	10.332
169.90	400.15	4.625	-49.270	21.570	-18.529	9.555
169.92	402.86	4.309	-46.850	20.880	-17.721	9.610
169.94	404.86	3.871	-46.020	20.400	-17.459	9.043
169.96	406.43	3.400	-45.930	20.070	-17.423	8.512
169.98	408.03	2.662	-45.210	19.840	-17.164	8.347
170.00	409.18	2.773	-44.010	19.550	-16.754	7.763
170.02	409.54	3.588	-43.200	19.250	-16.498	6.716
170.04	408.52	4.534	-43.240	19.020	-16.551	4.827
170.06	407.82	5.038	-43.980	19.090	-16.787	4.263
170.08	408.07	4.686	-46.770	19.090	-17.819	4.760
170.10	411.38	5.066	-48.080	18.950	-18.343	7.958
170.13	408.42	8.456	-48.340	18.920	-18.369	2.526
170.15	408.47	5.498	-48.160	18.970	-18.294	3.851
170.17	410.74	5.189	-43.870	18.600	-16.749	5.984
170.19	410.07	7.621	-37.020	18.630	-14.095	3.599
170.21	404.14	8.519	-21.900	19.450	-8.229	-1.961

170.23	399.12	1.865	32.150	20.480	11.992	-6.271
170.25	393.34	-9.899	105.200	21.560	39.003	-13.515
170.27	383.17	-6.238	190.400	23.270	70.671	-25.941
170.29	377.52	-10.600	231.300	24.550	87.023	-22.655
170.31	374.07	-9.391	314.400	25.530	118.604	-21.247
170.33	371.68	-15.599	409.300	26.070	155.496	-20.012
170.35	369.35	-17.566	466.500	26.820	178.307	-19.675
170.38	367.99	-16.578	509.100	27.650	195.515	-17.611
170.40	367.13	-17.353	618.300	28.300	238.097	-16.628
170.42	366.04	-16.815	597.600	28.830	234.299	-15.916
170.44	365.56	-17.765	557.000	29.320	225.263	-13.903
170.46	365.78	-15.728	569.300	29.550	236.026	-11.714
170.48	366.18	-16.904	637.700	30.060	267.026	-10.493
170.50	365.65	-12.666	659.500	30.260	270.789	-11.558
170.52	367.17	-16.171	510.600	30.100	210.280	-6.205
170.54	366.36	-19.241	574.700	30.360	243.356	-9.856
170.56	364.81	-14.423	507.500	30.430	210.488	-11.598
170.58	364.81	-12.591	503.100	30.460	211.285	-9.318
170.60	365.26	-11.474	417.000	30.080	177.183	-7.264
170.63	364.63	-11.938	453.200	30.200	190.836	-9.024
170.65	365.68	-11.039	402.200	30.420	165.274	-5.401
170.67	367.72	-9.738	286.000	29.440	111.585	-1.753
170.69	369.35	-6.713	228.600	27.980	87.384	-0.573
170.71	370.51	-6.072	136.100	26.930	51.405	-0.290
170.73	372.97	0.131	43.730	26.050	16.499	1.868
170.75	376.44	3.395	0.736	24.490	0.278	1.330
170.77	379.66	3.603	-13.680	23.500	-5.191	5.977
170.79	382.55	3.734	-21.140	22.850	-8.065	5.375
170.81	385.53	4.880	-23.850	22.370	-9.123	5.835
170.83	388.17	3.782	-30.520	22.050	-11.678	6.391
170.85	391.14	5.295	-23.450	21.730	-8.963	6.305
170.88	392.53	5.588	-15.190	21.680	-5.786	4.698
170.90	393.54	4.546	-11.630	21.680	-4.405	4.032
170.92	396.05	6.574	-22.330	21.400	-8.413	6.540
170.94	397.49	6.227	-17.890	21.160	-6.740	5.334
170.96	398.53	4.374	-21.340	21.180	-8.012	5.312
170.98	401.00	4.334	-19.530	21.030	-7.293	6.274

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