Using Satellite Observations of PBL Depth to Improve Estimates of CO_2 Sources and Sinks

Abstract

The depth of the planetary boundary layer (PBL) is essential to understanding not only the weather and climate through surface ventilation by clouds and air quality near the surface, but also to studies of the carbon budget. The response of surface concentration of carbon dioxide (CO_2) to net ecosystem exchange (NEE) is linearly related to PBL depth and an error in depth relates directly to an error in CO_2 concentration. The rectifier effect, the correlation between PBL depth and NEE, is a leading cause of uncertainty in atmospheric CO_2 inversions (Denning et al., 1995; 1996; 1999; Gurney et al., 2003). The goal of this research is to optimize a parameterization of boundary layer top entrainment in order to obtain better model estimates of PBL depth and carbon fluxes. This will be achieved by assimilating surface observations of temperature and humidity and observations of PBL depth from CALIPSO satellite data using the Maximum Likelihood Ensemble Filter (MLEF). In addition, respiration and photosynthesis biases in the model will be estimated by assimilating CO_2 observations from the in-situ tower network. Evaluation of the model will be performed against weather, AmeriFlux data, and aircraft measurements of CO_2.

Errors in the depth of the modeled planetary boundary layer produce errors in CO_2 concentration due to a mixing of surface carbon fluxes throughout its volume. Deeper boundary layers dilute the effects of carbon assimilation more so than do shallow boundary layers because of the greater volume of air involved. In order to simulate accurate surface CO_2 concentrations, it is essential to first precisely establish the PBL depth. In reality, this is difficult to do because the processes that control the growth of the boundary layer are often too fine-scale to be resolved by regional-scale models. As part of previous work, a boundary layer top entrainment parameterization, based on the ratio of the negative hat flux at the top of the boundary layer to that at the surface, was included in the Regional Atmospheric Modeling System (RAMS) (Pielke, 1974; Tripoli and Cotton, 1982; Pielke et al., 1992; Cotton et al., 2003) in an effort to incorporate the effects of entrainment on boundary layer growth. This proposal aims to optimize the tunable parameter within this parameterization by data assimilation to better predict the PBL depth. Since the goal of this work is to improve carbon source and sink estimates, biases in the modeled assimilation and respiration will also be assessed through data assimilation to improve modeled surface fluxes.

In RAMS, the vertical eddy diffusivities for momentum, heat, and turbulent kinetic energy (TKE) are inversely proportional to the vertical gradient of potential temperature through an equation for the turbulent length scale for stable conditions by André et al. (1978). In a strongly stable layer, such as is found in the capping inversion above the boundary layer, the eddy diffusivities become small and vertical mixing is inhibited so that the inversion acts as a material surface. In the physical world, overshooting thermals penetrate the inversion and drive mixing between the boundary layer and free troposphere. The insertion of energy and mass into the PBL associated with these thermals grow the PBL (Sullivan et al., 1998) and thus affect surface CO_2 concentrations.

In order to include the effects of these thermals, an entrainment parameterization has been included in RAMS. The parameterization is based upon the assumption that the heat flux at the top of the boundary layer (z_i) is negatively proportional to the heat flux at the surface (s) and can be found in almost any boundary layer text (e.g. Stull 1988) and takes the form

$$\overline{w'\theta_v'}\,|_{zi} = -\alpha \overline{w'\theta_v'}\,|_{s}. \quad (1)$$

Here w' is the eddy vertical velocity, θ_v' is the eddy virtual potential temperature and the overbars indicate the average. However, the proportionality constant, α, has been debated in the literature (e.g. Betts, 1973; Carson, 1973; Deardorff, 1974; Rayment and Readings, 1974; Willis and Deardorff, 1974; Stull, 1976; Sullivan et al., 1998) varying anywhere from zero to one with most published values ranging from 0.1 to 0.3 and the most common value being 0.2. This is the tunable parameter that this research hopes to ascertain for regional scale modeling over the continental United States. In an idealized study comparing simulations both without the entrainment parameterization and including the parameterization with an α equal to 0.2, the results in Figure one are achieved. The PBL is not only deeper, but also warmer with a weaker capping inversion when the parameterization is included. Both of these effects have implications for carbon budget studies.

The other variables to be optimized through data assimilation are the biases of plant photosynthesis, β_{GPP}, and plant respiration, β_{RESP}. Errors are inherent in all atmospheric and land-ecosystem models due to the complexity of the subject. Some errors are stochastic and can be neglected in the average, but others are persistent because of a missing process, incorrect empirical constant, etc. and should be taken into account (Zupanski et al., 2007). Photosynthesis and respiration are calculated by the third version of the Simple Biosphere model (SiB3) initially developed by Sellers et al. (1986) coupled to RAMS (termed SiB-RAMS), informed by Terra Moderate Resolution Imaging Spectroradiometer (MODIS) data as to the condition of surface vegetation, and can be assumed to contain biases that should be corrected to accurately model surface carbon fluxes. The net ecosystem exchange (NEE) or the net surface flux of carbon can be assumed to take the form of the product of the respiration bias and respiration minus the photosynthesis bias times the gross primary production (GPP) (Zupanski et al., 2007) or:

$$NEE(x,y,t) = \beta_{RESP}(x,y)R(x,y,t) - \beta_{GPP}(x,y)G(x,y,t) \qquad (2)$$

Respiration and GPP are represented by R and G respectively and are functions of x and y grid coordinates as well as of time, t. The biases are assumed to vary only with space.

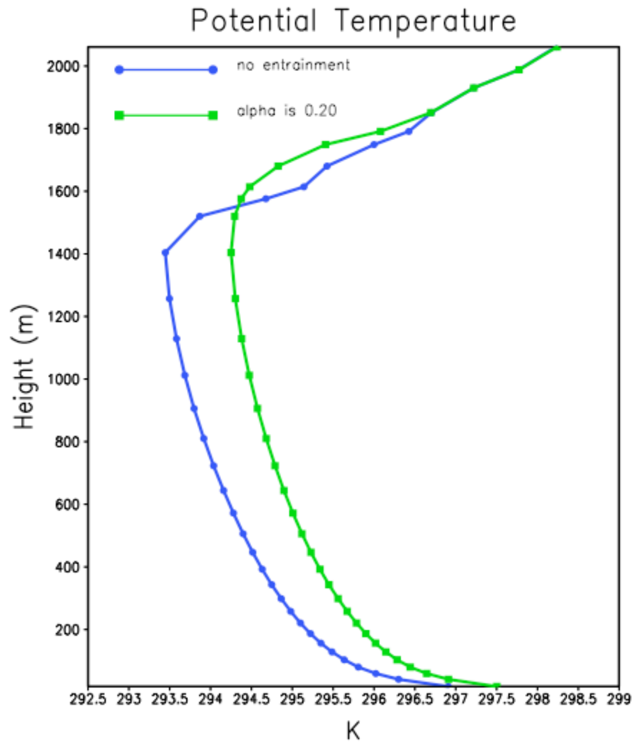

Figure 1 Profile of potential temperature for simulations both including and neglecting entrainment at 12 pm LT

The data assimilation technique to be used is the Maximum Likelihood Ensemble Filter (MLEF) described by Zupanski (2005) and by Zupanski and Zupanski (2006). The MLEF technique seeks to minimize a cost function dependent upon a general nonlinear observation operator without using any perturbed observations (Zupanski et al., 2007). In order to optimize the entrainment parameterization's α, ground-based temperature and relative humidity as well as PBL depth data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite will be assimilated. Weather observations will be used for evaluation purposes. In addition, the photosynthesis and respiration biases will be optimized using CO_2 concentration data from the in-situ tower network and will be evaluated against aircraft and AmeriFlux CO_2 observations.

The CALIPSO satellite was launched in April 2006 to examine the vertical structure of thin clouds and aerosol layers from space with an expected lifetime of three years within the A-train constellation of satellites (Vaughan et al., 2004). The backscatter from the lidar instrument on CALIPSO can be use to identify aerosol layers in the atmosphere (Figure 2). Aerosols originate at the surface and are vertically well-mixed by turbulent eddies within the boundary layer. The free tropospheric air, detached from the surface due to stability in the capping inversion, is relatively clear. This condition makes it possible to determine the depth of the PBL as the level above the ground, at which the backscatter signal decreases by a specified, pre-determined amount (Melfi et al., 1985; Palm et al., 1998).

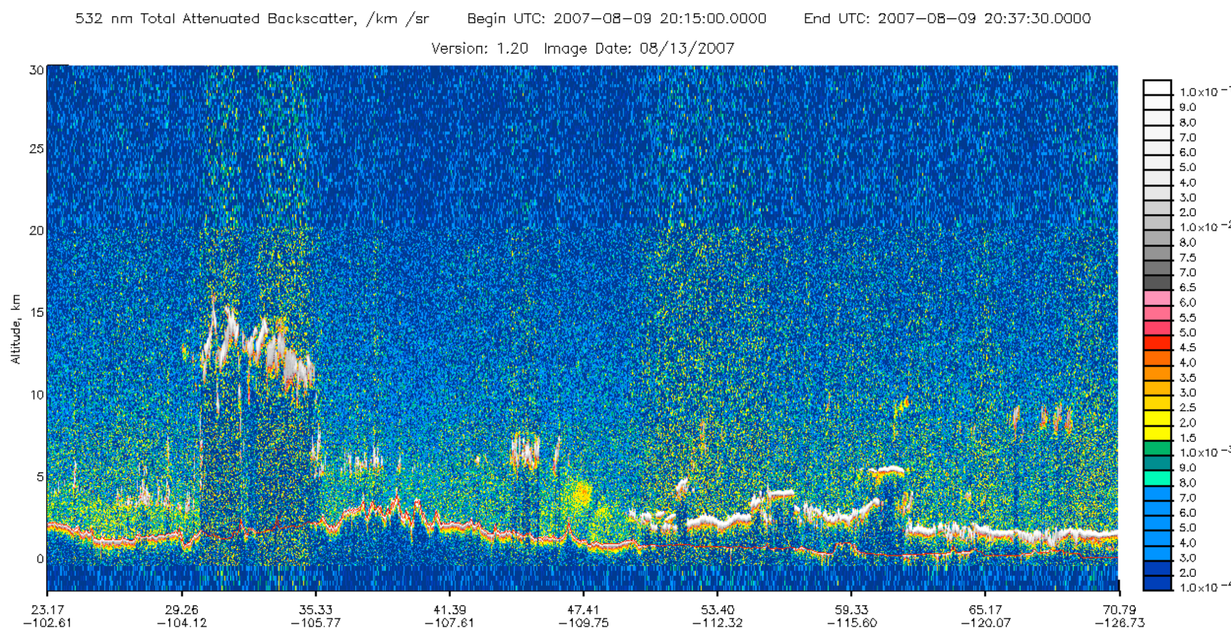

Figure 2 Backscatter retrieval from the CALIPSO satellite

Many of the ground-based data measurements are obtained by the National Oceanic and Atmospheric Administration (NOAA). The National Climatic Data Center (NCDC) archives hourly observations of temperature, relative humidity, and wind velocity. The Earth System Research Laboratory Global Monitoring Division (ESRL/GMD) tall tower network provides measurements of CO_2 and related gases in the continental boundary layer as part of the North American Carbon Program. The Carbon Cycle Greenhouse Gases Group (CCGG) has developed an automated system for obtaining air samples from aircraft, which can then be analyzed for atmospheric trace gases such as CO_2, CH_4, CO, and N_2O. This system has been in use in northern Colorado since 1992 aboard small aircraft and is currently being adapted to a wider range of aircraft. AmeriFlux is a network of flux towers in the Americas that provides observations of ecosystem level exchanges of CO_2, water, energy, and momentum and is part of the larger global network, FLUXNET (Hargrove et al., 2003).

Knowledge of the depth of the planetary boundary layer is essential to carbon budget studies as well as studies sensitive to vertical mixing at the surface. This research seeks to better simulate boundary layer dynamics by optimizing a parameterization that replicates the effects of entrainment at the boundary layer top. As this will affect CO_2 concentrations, biases of modeled photosynthesis and respiration will also be optimized to correct for inherent model errors. Data from the CALIPSO satellite, MODIS, and ground-based measurements of temperature, relative humidity, and CO_2 concentration will be used to improve our estimates of the tunable parameters. One of the goals of the Science Mission Directorate is to “Study planet Earth from space to advance scientific understanding and meet societal needs.” Using information form the

CALIPSO satellite, a stronger understanding of the carbon cycle can be achieved and lead to a better comprehension of anthropogenic climate change.

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