Statement of Work

Introduction

Past observational constraints on carbon cycling using top down methods have been limited to the continental scale (~ $10^7 – 10^8$ km^2), and using bottom up methods to the scale of a local forest (~ 1 km^2). There is a strong need for measurements of regional ($10^2 – 10^6$ km^2) carbon exchanges that can be related to underlying biome types, coherent climate forcings, and land-use and disturbance patterns to facilitate mechanistic understanding of flux drivers (Running, 2008). Promising approaches to obtain regional CO_2 fluxes focus on adapting atmospheric data-assimilation techniques to make use of the wealth of information in both remote sensing products and new continuous atmospheric CO_2 measurements made on the continents (Denning et al., 2005; Peters et al., 2005; 2007).

An important contribution to this community effort has been NOAA's CarbonTracker (CT) product, which uses global CO_2 observations to optimize fluxes predicted by various submodels, including a remote-sensing driven land-flux product. The CT atmospheric model has a high resolution nest over North America where available observations are also more dense, and can estimate fluxes on weekly and 1 degree resolution. Nonetheless, large uncertainties remain in these estimates, large gaps remain in the U.S. observing network, and major challenges remain in optimally filling in these gaps and in making the best use of available observations. Because of the lack of very-tall communication towers and the prevalence of complex terrain and meteorology, both of these challenges are amplified in the Mountain West (comprised by states of ID, MT, WY, UT, CO, AZ, and NM).

Mountain forests play a significant role in the global carbon cycle (Schimel et al., 2002). A number of studies have identified temperate northern hemisphere terrestrial ecosystems (Tans et al., 1990; Ciais et al., 1995) and forests in particular (Wofsy et al., 1993; Thornton et al., 2002; Schimel et al., 2002) as significant sinks for anthropogenic CO_2 but estimated fluxes vary greatly (Stephens et al., 2007). Because most level ground at temperate latitudes has been converted for agriculture or other uses, the majority of these forests are located in complex terrain and at higher elevations. Figure 1 shows output from the Biome-BGC model (Melillo et al., 1995) showing estimated U.S. net ecosystem exchange (NEE) and net primary productivity (NPP) for

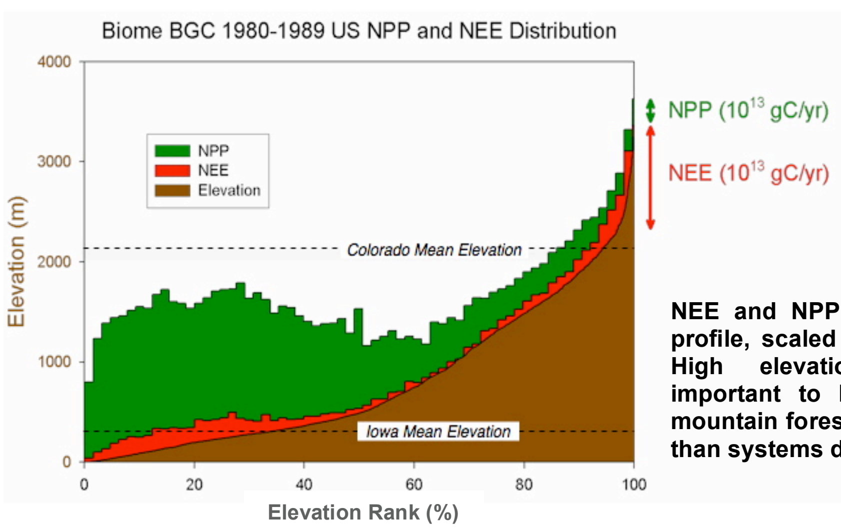


Figure 1. Plant productivity (NPP), net carbon uptake (NEE), and elevation for the coterminous U.S over the decade of the 1980s, as predicted by Biome BGC (Melillo et al., 1995). The brown region shows elevation as a function of cumulative area, so that around 30% of the coterminous U.S. is above 1000 m elevation. Model-estimated NEE and NPP are shown on top of the elevation profile, scaled differently as indicated on the right. High elevation areas are disproportionately important to NEE because of the abundance of mountain forests, which store relatively more carbon than systems dominated by herbaceous vegetation.

the 1980s plotted over elevation as a function of elevation rank. This model predicts that 40% of coterminous U.S. net carbon uptake occurred in mountainous terrain over this period. Further, while the preponderance of NPP occurs at low elevations, dominance of forest vegetation and promotion of soil carbon storage at low temperatures can lead to significantly more NEE per unit NPP in the mountains. This figure also illustrates that using NPP as a predictor of NEE, as is often done, can be misleading.

Mountain and subalpine forests of the Western U.S. have been shown to be significant sinks for atmospheric CO_2 (Anthoni et al., 1999; Sacks et al. 2006). A host of human and natural mechanisms may be important factors in determining the balance of carbon in mountain forests, including 1) regrowth from past logging or other disturbances, 2) ongoing logging and other disturbances, 3) fire suppression, 4) seasonal and long-term temperature anomalies, 5) seasonal and long-term precipitation anomalies, 6) changes in precipitation type, 7) insect outbreaks, and 8) CO_2 fertilization. The complexity of influences on carbon in the Mountain West are highlighted by recent studies in the Front Range of Colorado, showing 1) that longer growing seasons are actually correlated with less annual carbon uptake, possibly because of a decrease in available snow-melt water during the late spring and early summer photosynthetic period (Sacks et al., 2006), 2) that reduced snowfall leads to significantly reduced annual soil respiration, as a result of colder wintertime soil temperatures (Monson et al., 2006), and 3) that widespread beetle-kill results in significantly reduced ecosystem respiration reflecting the large decrease in heterotrophic respiration combined with only modest increases in litter and woody debris (see Figure 7 below).

The semi-arid ecosystems of the Western and Southwestern U.S. are also capable of surprising carbon fluxes. Although carbon fluxes in semi-arid ecosystems are not well-understood, there are reports of large annual uptake (50-130 gC m^{-2} yr^{-1}, Hastings et al. 2005; Jasoni et al. 2005) or release (130-140 gC m^{-2} yr^{-1}, Emmerich, 2003) of carbon in these regions. Despite the relatively small organic carbon pools and low rates of NPP, semi-arid regions are thought to be taking up a large amount of anthropogenic CO_2 as woody plants expand onto historical grasslands in response to large-scale fire suppression. Pacala et al. (2001) estimated that 0.13 petagrams of carbon per year were taken up by woody encroachment in the U.S. during the 1980s. This sink constituted 22-43% of the total U.S. sink in their estimate and is thought to be associated primarily with ecosystems of the Southwest such as juniper woodland, mesquite savanna, and oak savanna. Recent modeling has suggested that the climate in this region may transition to a permanent drought (Seager et al., 2007), which would likely have a large impact on this potentially important carbon sink.

While it has been recognized for some time that the Rocky Mountains and the semi-arid Southwest represent significant potential net CO_2 sinks in the U.S. and are highly sensitive to land-use practices and climate change, the original North American Carbon Program (NACP) plans for new continuous CO_2 observing sites (Wofsy and Harriss, 2002) and more recent plans have omitted these regions (Figure 2). The bias towards Central and Eastern U.S. CO_2 observations has persisted despite the argument that because of potentially enhanced sensitivity to climate change, drought, and other disturbances western forests may need more intense carbon flux observations, not less. Through recent and ongoing NCAR-university collaborative efforts, we have deployed a network of low-cost accurate CO_2 measurement systems in a regional atmospheric continuous CO_2 network in the Rocky Mountains (Rocky RACCOON, http://raccoon.ucar.edu). Subsets of RACCOON data have been included in the CT (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker) and GlobalView (http://www.esrl.noaa.gov/

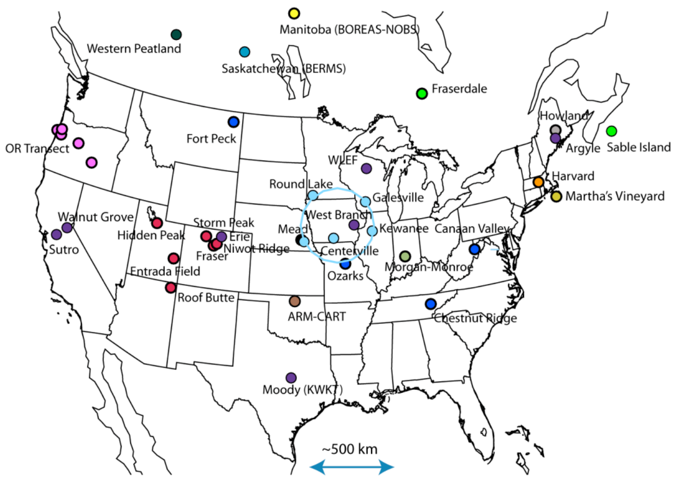


Figure 2. Map of existing North American continuous well-calibrated CO_2 measurements. Colors denote measuring group, with Rocky RACCOON sites in Red. Courtesy of N. Miles (http://www.amerifluxco2.psu.edu).

gmd/ccgg/globalview) products, and we are developing mountain CO_2 modeling tools and data filtering techniques to optimize the utility of our measurements in resolving regional carbon fluxes and their drivers on monthly to interannual time scales.

Relevance to NOAA Climate Program Office Goals

This proposal will address NOAA's Climate Mission Goal to understand climate variability, and specifically the Global Carbon Cycle (GCC) Program's goal to improve our ability to predict the fate of anthropogenic CO_2, through a combination of focused observations and modeling. In direct response to the 2009 GCC solicitation we aim to improve our ability to resolve carbon sources and sinks seasonally and at regional scales in the Mountain West (**Optimal Carbon Observing Networks**) and to understand key processes that control the sources and sinks of carbon in terrestrial systems (**Causes of Variability in Sources and Sinks**). In addition to enhancing NOAA's mission we will also enhance a high-profile NOAA product by contributing data to and researching potential improvements to CarbonTracker.

We will accomplish this by maintaining an existing network of accurate CO_2 instruments across the Central Rocky Mountains and Southwest, making the data available in near real-time to the scientific community, and using these measurements in data-based analyses and as input to the CT data assimilation system to estimate fluxes and their influence from drought, fire, and insect outbreaks. Our approach is highly efficient in its capitalization of existing efforts, as it integrates key carbon parameter studies into the ongoing Rocky RACCOON observational program and new data and network simulations into the ongoing CT modeling program. Together, these efforts will reduce uncertainties in North American uptake of anthropogenic CO_2, characterize important processes regulating carbon fluxes in mountain forests and semi-arid ecosystems, and help to plan future observations to detect carbon flux variability in the Mountain West. Our research will address the following:

Research Questions

Q1) How can we optimally measure regional spatial-scale and monthly to interannual time-scale carbon fluxes and their drivers across the U.S. Mountain West?

Q2) What are the monthly to interannual fluxes of CO_2 between the atmosphere and regions of the U.S. Central Rocky Mountains and Southwest, and how do these fluxes contribute to the North American carbon balance and interannual variability?

Q3) How are the key climate and disturbance drivers of drought, fire, and insect outbreak influencing regional carbon fluxes in mountain ecosystems?

Approach

Proper investigation of these questions requires fusion of top-down diagnostic approaches with bottom-up ecosystem modeling. As such, we propose to use our network of CO_2 observations to improve region-specific flux estimates in the CT system (see below in Flux Analysis Tools). Data from two of our sites have been included in the 2007 and 2008 CT releases and continuing these observations will further support this effort. In addition, we will investigate the impact and value of these two sites using branched CT runs and observing system simulation experiments (OSSEs), and we will do the same for our other sites so that they may be considered for inclusion in future CT releases. The ability of atmospheric models to ingest continental CO_2 data, in particular in complex terrain, is not well known. To minimize the effect of terrain-influenced CO_2 transport and model-data mismatch on retrieved carbon budgets, we propose to conduct additional branched CT runs to explore the impact of assimilating the data at different times of day and model levels. Finally, we will perform additional OSSEs to investigate the potential contribution of new Mountain West observing sites in CT.

We will also perform data-based analyses of our measurements. As an independent flux-estimation approach, we will calculate monthly regional upwind flux estimates for all of our sites using the boundary-layer (BL) budgeting methodology of Bakwin et al. (2004). We will use the FLEXPART model to estimate mixing heights for the flux calculations, and to estimate the corresponding region of influence for these fluxes so that they can be compared to CT and independent results. Both CT and BL budgeting require measurements that are regionally representative. We will analyze our data using hourly CO_2 variability, wind speed and direction, and local vertical CO_2 gradients to assess their regional representativeness (see Figure 4 below). We will also compare the observed diurnal cycles to CT predictions, with a focus on hour-to-hour variability and trends to assess model representativeness and to ensure that CT is ingesting our data at the optimal time and model height.

To understand the contributions of drought, fire, and insect outbreak on carbon exchange in the Mountain West, we will analyze the regional-scale weekly to interannual fluxes derived from CT and the monthly to interannual fluxes derived from BL budgets. We will compare interannual precipitation, temperature, and drought index anomalies to the most robust estimates of regional flux to explore the effect of drought. We will run alternative fire flux maps forward with CT transport and FLEXPART influence functions to predict fire signals at our sites and investigate whether during strong events observed signals can be used to assess the accuracy of the fire products. Finally, we will make use of our observations in valley locations to make data-based estimates of trends in nighttime ecosystem respiration and daytime NEE in response to insect outbreaks, and we will examine the CT and BL budget flux estimates for regional-scale evidence of these impacts.

These approaches require precise and accurate continuous CO_2 observations of well-mixed boundary-layer air or descending free-tropospheric air across the region. To be useful, our regional CO_2 measurements must be comparable across the network and to networks operated by other laboratories to within 0.2 ppm or better (LSCOP, 2002). We will ensure this by maintaining and verifying comparability relative to the WMO CO_2 scale at this level (Stephens et al., 2006).

Observations

Instrumentation (Q1)

Making accurate CO_2 measurements requires careful attention to gas handling, numerous automated quality control diagnostics, and a suite of reference cylinders closely linked to the WMO CO_2 calibration scale. Our approach builds on those of Zhao et al. (1997) and Trivett and Köhler (1999), but with considerable changes (Stephens et al., 2006). The Autonomous Inexpensive Robust CO_2 Analyzer (AIRCOA) requires less than $10,000 in components, can be rapidly assembled and tested, and runs autonomously for months at a time. We place a high priority on data management and on automated data retrieval, processing, and diagnostic error checking. We make calibrated CO_2 measurements available to the public in near real-time (http://raccoon.ucar.edu) to facilitate our quality control efforts and to enable collaborators who are interested in using recent data.

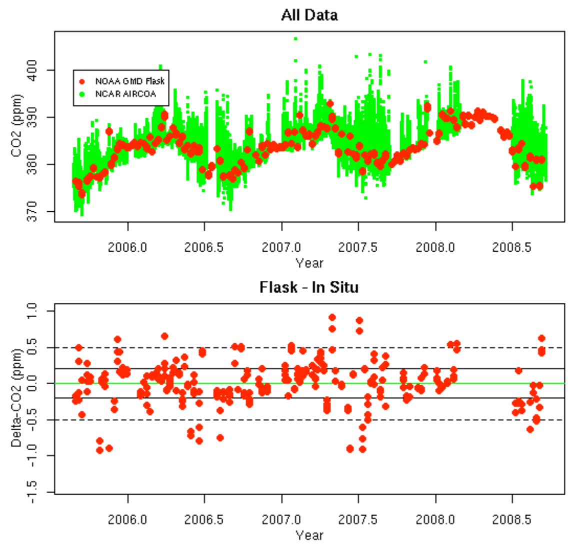


Figure 3. Results from comparisons to NOAA GMD flask samples at Niwot Ridge. See text for mean offsets and variability.

We sample air from one of three inlet lines on a tower and calibrate our measurements using a suite of four calibration gases. A fifth calibrated high-pressure cylinder is analyzed three times a day as a surveillance check on instrument performance. All of our reference gases are rigorously tied to the WMO CO_2 Calibration Scale with the use of the NCAR CO_2 and O_2 Calibration Facility (http://www.eol.ucar.edu/~stephens/CALFAC). AIRCOA is based on a LiCor LI-820 single-cell infrared gas analyzer (IRGA), which dramatically lowers the cost relative to more stable analyzers but increases the short-term noise and instrument drift rate. We overcome the short-term noise with signal averaging and instrument drift with frequent calibrations. Additional potential sources of CO_2 measurement bias that we address with automated diagnostics include: incomplete flushing of the sample cell and dead volumes, incomplete drying of the sample air, IRGA sensitivity to pressure broadening, IRGA sensitivity to temperature, leaks to ambient air, leaks of calibration gas through solenoid valves, and modification of CO_2 concentrations by the drying system or plastic components.

After averaging for 100 seconds, we report values with a measurement precision of +/- 0.1 ppm. We evaluate measurement accuracy in several different ways. Laboratory comparison tests show unit-to-unit biases are 0.05 ppm or smaller (Stephens et al., 2006). Measurements of long-term surveillance cylinders are generally within 0.1 ppm of laboratory assigned values. Figure 3 shows results from comparisons between our AIRCOA unit and flask measurements made by NOAA GMD at Niwot Ridge. For 347 individual comparisons, the NOAA network flasks have a mean offset and standard deviation relative to our measurements of 0.07 ppm +/- 0.21 ppm. Collectively these results give us confidence in the accuracy and comparability of our AIRCOA measurements to a level of 0.2 ppm. Further details, schematics, and photographs of the AIRCOA system are available online at http://raccoon.ucar.edu and in Stephens et al., 2006. Atmospheric CO_2 measurements of this quality will be useful to a wide variety of independent researchers focused on the North American Carbon Program.

Observing Sites (Q1)

We installed AIRCOA units for ongoing measurements at three sites in August and September of 2005 (Figure 2). The first of these sites (**NWR**) is at 11,560 feet elevation near tree-line on Niwot Ridge, just west of Ward, Colorado. Niwot Ridge is a Long-Term Ecological Research site and there is an AmeriFlux tower run by the University of Colorado 3 miles east and 1,500 feet lower on the ridge. The AIRCOA unit is located at a site where NOAA GMD has collected weekly flask samples for measurement of CO_2 and other species for over 40 years. This allows us to make the ongoing intercomparison shown in Figure 3. Our second site (**SPL**) is at the Desert Research Institute's Storm Peak Laboratory at 10,500 feet on Mt. Werner near Steamboat Springs, Colorado. This mountain-top observatory has a long history of measurements related to cloud physics, cloud-aerosol chemistry, and air quality. In contrast to these high-alpine sampling sites, we chose a third site (**FEF**) at 9,000 feet in the Fraser Experimental Forest at the bottom of the St. Louis Creek Valley near Fraser, Colorado. Atmospheric CO_2 at this site is heavily influenced by the local forest, but its location relative to nocturnal drainage flows will allow us to investigate respiration rates at a scale much larger than typically attempted.

We added a fourth site (**HDP**) in April of 2006 at 10,994 feet elevation on Hidden Peak near Snowbird, Utah. This mountain-top site generally experiences regionally well-mixed or free-tropospheric air, but with influences from Salt Lake City during boundary-layer growth and venting periods. We installed a fifth AIRCOA site at 9,783 feet elevation on Roof Butte in Northern Arizona (**RBA**) within the Navajo Nation. This peak is the tallest of the Chuska Mountains, which rise over 4,000 feet above the surrounding plateau, and typically samples well-mixed boundary-layer air that has passed over the semi-arid ecosystems of Arizona, southern Utah, and New Mexico. We installed our sixth site at the University of Utah's Entrada Field Station (**EFS**) in Southeastern Utah (http://entrada.utah.edu/). This field station has recently been established and is being used for a number of research and teaching objectives. The site is located at 4,180 feet elevation in a canyon on the Dolores River. We installed sampling lines at 3 locations (river level, 40 m, and 80 m higher in elevation) to sample vertical profiles of CO_2 within the canyon. Local vegetation is relatively sparse and during afternoon well-mixed conditions the highest inlet provides CO_2 observations representative of a large region.

We propose to continue measurements at these 6 sites for the additional 3-year duration of this project. In future years, based on the results of the network optimization research proposed here, we may pursue support for additional sites in New Mexico, Nevada, Wyoming, Montana, and Idaho to further extend our Rocky Mountain network. Gloor et al. (2001) demonstrated that the typical region of influence or "concentration footprint" for a continental well-mixed boundary-layer observing site is on the order of 10^6 km^2 which shows that our existing network provides overlapping information on carbon fluxes for much of the Central Rocky Mountains and Southwest. Furthermore, Figure 2 (and Fig. 6 below) shows the important contribution our sites have made and will make to CT and other modeling efforts in NACP. The low maintenance demands of our observing network means that we can provide these six high-accuracy continuous CO_2 records to the community at a very low cost.

Our research goals require auxiliary meteorological measurements. Five of our sites (NWR, FEF, SPL, HDP, and EFS) are co-located with meteorological and environmental observations that aid in their interpretation. However the HDP observations are only maintained during winter and the EFS observations are only made at valley-bottom. For the sites and times

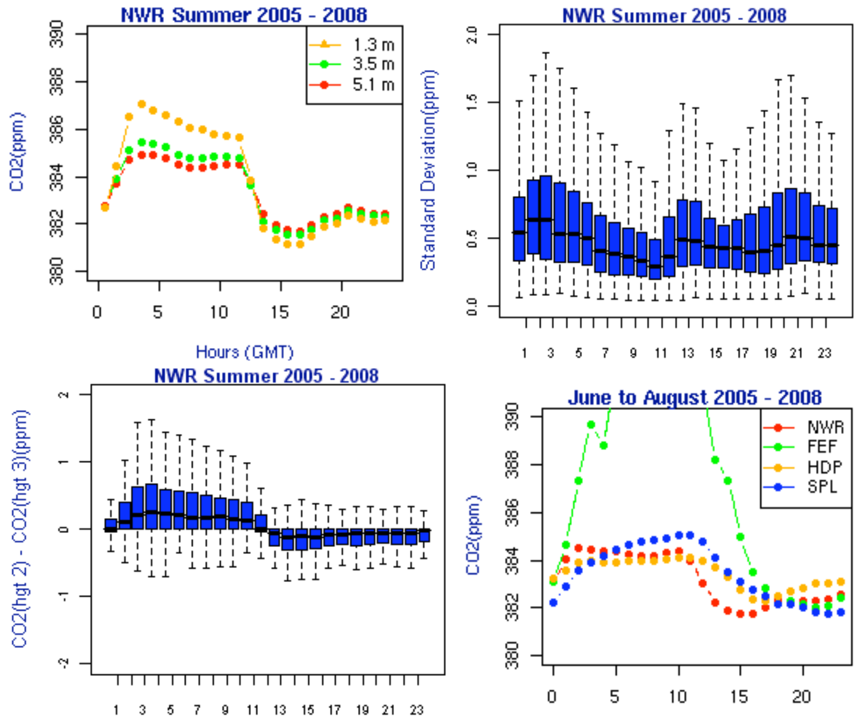


Figure 4. Summertime RACCOON data averaged over the months June-August. a) Calibrated CO_2 values from three heights at NWR b) Boxplot of the distribution of hourly standard deviations at NWR. c) Boxplot showing the distribution of 3.5 m to 5.1 m vertical gradients at NWR. d) Diurnal cycles from four sites after applying filters discussed in text.

without co-located meteorological observations, we have had to use nearby observing sites to estimate local conditions. We have acquired and will soon deploy a full meteorological system to measure air temperature, relative humidity, wind speed and direction, photosynthetically active radiation (PAR), and precipitation at RBA, and are proposing to acquire and install two additional meteorological systems: at HDP for year-round observations, and at EFS for observations co-located with our highest inlet.

Representativeness of Observations and Models (Q1)

Complex terrain induces complex atmospheric flows and it has long been recognized that mountain-top observations can reflect both local and regional influences. For most of our research goals, we require regionally-representative measurements in order to constrain fluxes over a broad area and to allow comparison to and use by models that are unable to represent local-scale circulations. In mountain regions, valley inversions and upslope flows can hinder regional observations, while high winds and vigorous convection can enhance them. The CarboEurope community recently produced a set of recommendations (CarboEurope, 2005) for flagging mountain CO_2 observations as locally or regionally influenced using wind speed, CO_2 variability, or model back-trajectories. We have implemented their recommendations using CO_2 variability and are working towards implementing their recommendations using wind speed. In addition, because our AIRCOA systems have multiple inlets, we have been able to develop an additional criterion for flagging locally influenced data based on observed vertical CO_2 gradients.

Figure 4b shows the distributions of hourly standard deviations for the 5.1 m inlet at NWR during the months of June, July, and August. This figure illustrates that in the late evening (500-1100 GMT) and mid-day (1400-1800 GMT) 75% of hourly standard deviations are below 0.7 ppm. This low variability suggests that these periods are usually representative of large well-mixed air masses. Figure 4a illustrates that we are able to detect systematic afternoon 3.5 m to 5.1 m vertical gradients at this high-altitude tundra site of 0.05 ppm, and Figure 4c shows the distribution of these differences. Figure 4d shows the results of screening data at four of our sites for hourly standard deviations less than 1.0 ppm and hourly-average vertical gradients less than 0.5 ppm. This preliminary filter rejects approximately 10% of hours at the non-valley sites and the resulting correspondence between the different locations, even with our valley site during afternoon, suggests the filter is doing a decent job of removing local influences and the filtered data are representative of concentrations over large regions. We will compare these diurnal cycles in concentrations and variability to those predicted by CT to evaluate the representativeness of both our observations and the model.

Flux Analysis Tools

Continuous atmospheric CO_2 data over continents reveal large and systematic variations containing extensive information about carbon fluxes on various time and space scales (Hurwitz, et al. 2004). Consequently they are amenable to analysis on several different fronts.

Boundary-layer Budgeting (Q2)

A number of recent studies (Bakwin et al., 2004; Helliker et al., 2004; Styles et al., 2007) have demonstrated that continuous observations of CO_2 concentration over the continents contain quantitative information about fluxes on regional scales, and that these fluxes can be estimated with simple BL budgeting techniques. We will make use of these techniques, comparing our mid-afternoon CO_2 observations to marine background and free-troposphere measurements (NOAA GMD, Stephens et al., 2007), in order to infer regional-scale monthly-mean fluxes upwind of all of our sites. Figure 5 shows monthly-mean afternoon CO_2 concentrations derived at our existing sites after filtering the data for strong local influences, and a proxy for free-troposphere concentrations constructed by interpolating NOAA GMD measurements from Mauna Loa, Hawaii and Cold Bay, Alaska. The differences between the continental and marine BL sites reveal clear signals of regional carbon exchange with maximum uptake signals in spring as expected for this region, and the agreement among the continental records lends confidence to their ability to capture spatially integrated fluxes.

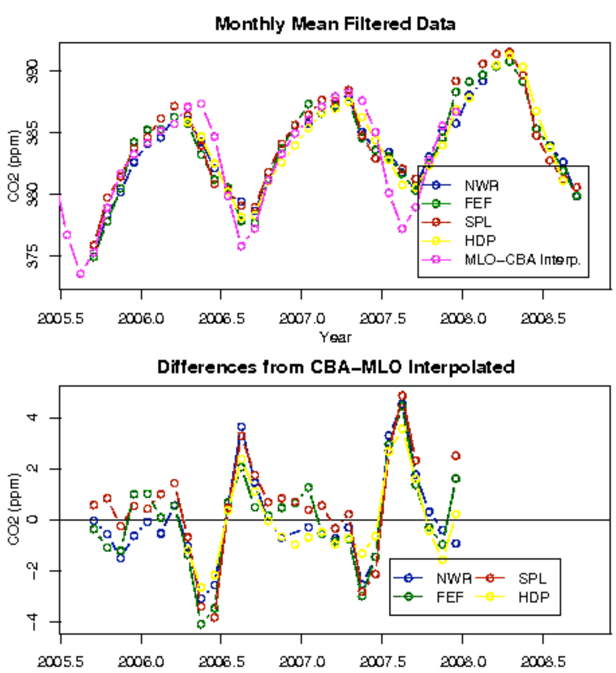


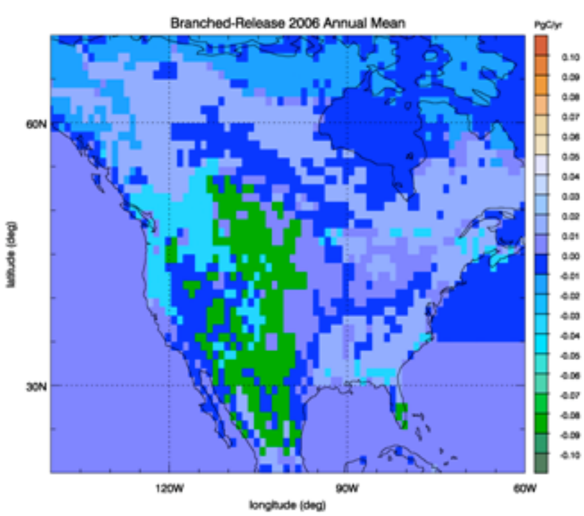
Figure 5. Monthly mean filtered CO_2 concentrations at 4 sites and differences from marine boundary layer concentrations interpolated to the same latitude.

BL budget techniques must rely on model estimates of atmospheric mixing depths in order to convert concentration differences to monthly flux estimates, and on model estimates of upwind influence regions for comparison to independent flux estimates or driver maps. We propose to use atmospheric mixing depths from the WRF mesoscale model and particle influence functions generated from the FLEXPART LaGrangian particle dispersion model. This combined FLEXPART-WRF model has already been adapted to the region for a prior field project. The FLEXPART model (Stohl et al., 2005) has been used extensively by the atmospheric chemistry community for transport and dispersion modeling of atmospheric trace gases. FLEXPART was originally designed for use in the Austrian Alps and thus contains additional parameterizations for terrain-induced convection and grid cell boundary layer depth variability. We will use FLEXPART for generating observation influence functions using winds from the nested 36 km / 12 km resolution NCAR WRF model. Daily 0 Z forecast output is available in near real time and archived on the NCAR Mass Storage System. Additionally, we will use NOAA/NCEP North American Regional Reanalysis meteorology (32 km) to look for significant forecast differences.

CarbonTracker Data Assimilation (Q2)

The CT team encourages collaboration from the community in the form of data contributions and model experimentation, and the CT system's transparency and modularity greatly facilitate such interactions. The CT system is described in detail online (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker) and in Peters et al., 2007. Briefly, CT uses an Ensemble Kalman Filter (EKF) data assimilation technique to optimize surface CO_2 fluxes run through the TM5 transport model against observed atmospheric CO_2 mole fractions. The initial CO_2 fluxes come from a collection of submodels representing biosphere/fire, ocean, and fossil-fuel fluxes. In the optimization, the fossil-fuel fluxes are fixed while the other components are adjusted using weekly and regional scaling parameters. On land, there are up to 19 different scalable ecosystems within 11 global geographic divisions for a total of 124 globally distinct ecoregions corresponding to 124 scaling factors.

Data from our NWR and SPL sites have been included in the 2007 and 2008 CT runs. Figure 6a illustrates the impact the inclusion of these sites had on the 2007b release of CT. Including the RACCOON data reduced annual-mean uptake for both the Temperate North American region and the Temperate Grass and Shrub ecoregion by 0.1 PgC/yr, and significantly shifted the predicted uptake from west to east. Without these data, the CT system is more heavily influenced by the prior guess of the CASA submodel in these undersampled regions. We will rigorously assess CT model outputs in other tests (below), but our initial goal is to obtain estimates of the monthly and interannual fluxes of CO_2 in the Central Rocky Mountains and Southwest, using output from CT runs incorporating data from these and possibly other RACCOON sites. We will compare these flux estimates to our BL budgets and other regional flux estimates and use them to test hypotheses about the sensitivity of regional carbon fluxes to trends in drought, fire, and insect



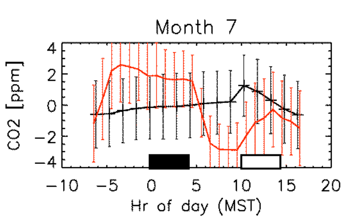


Figure 6. a) Differences between 2006 annual mean fluxes retrieved by CT for a run with NWR and SPL data and a run without (without – with, PgC/yr/ecoregion). b) Comparison between observed (red) and modeled (black) diurnal cycles at NWR. Continuous data is ingested from 0-4 MST, while flask data is ingested fom 11-14 MST. Courtesy of John Miller.

outbreaks.

Ecosystem modeling (Q3)

To further understand the sensitivity of regional carbon fluxes to climate factors, we intend to employ a regionally-optimized ecosystem model, SIPNET (Sacks et al., 2006). For studies of drought and insect outbreak, we will use the SIPNET ecosystem model in conjunction with the estimated regional fluxes from CT and BL budgeting to diagnose the causes of flux variability. In addition, at our valley sampling locations undergoing bark beetle disturbance, the model will be used to assert and test model definitions of insect outbreak impacts on forest carbon cycling. The goal in using SIPNET is to evaluate how well alternate formulations of drought and disturbance can simulate the observed fluxes and concentrations and in turn understand which carbon cycling mechanisms are most likely to be impacted by widespread insect outbreak and drought in the Central Rocky Mountains.

The SIPNET ecosystem model has been extensively parameterized and tested at the Niwot Ridge Ameriflux site, a high altitude forest site in the Rocky Mountains (Sacks et al., 2006). The model has shown good simulation ability for CO_2 and H_2O fluxes from hourly to interannual timescales at Niwot Ridge (Sacks et al., 2007; Zobitz et al. 2007). SIPNET is designed for spatial runs over a grid. The domain of the model will be approximately 1000 km x 1000 km, encompassing the CO_2 observing sites and upwind regions at a 250 m resolution and run on an hourly time step. A variety of input data sets are needed for the ecosystem model. Climate data from in situ observing stations, reanalysis, and statistical downscaling are currently being combined to create a terrain-corrected surface meteorology forcing dataset. Key climate variables needed by SIPNET are air temperature, vapor pressure deficit (VPD), PAR, precipitation, soil temperature, and soil moisture.

Network and Model Optimization tools

The following work will be done in collaboration with NOAA ESRL GMD staff (see support letter in appendix).

CarbonTracker Branch Runs (Q1)

Branch runs similar to that illustrated in Figure 6a will be run at NOAA ESRL to compare the CT surface biosphere fluxes with and without the inclusion of data from several combinations of existing RACCOON sites. This will build on the past branch runs to include more recent years and to explore the potential inclusion of more of our existing sites. CT is presently ingesting nighttime RACCOON data at the corresponding above-sea-level model altitude. However, because of smoothed model topography, this leads to a mismatch of several thousand feet between observation and model height above ground. Figure 6b illustrates that this can result in important features of the diurnal cycle being misrepresented and possible bias in the retrieved fluxes. We will also use branched runs, and the knowledge gained from our data-based representativeness analyses, to explore the impact of ingesting RACCOON data into CT at different times of day and at different model levels. We will compare retrieved fluxes and their interannual variability between the branched runs to assess the performance of the ecosystem flux submodel and whether including the RACCOON data significantly alters our ability to detect relationships to climate forcing variables such as drought and fire. We plan to conduct 2 branched runs per year with the assistance of NOAA ESRL.

CarbonTracker Observing System Simulation Experiments (Q1)

To assess the value of existing and potential Mountain West CO_2 observations to CT in terms of flux detection ablitity, we will also conduct simple OSSEs. These experiments will follow the design of OSSEs already performed by the CT team. First, a hypothetical flux of interest (e.g. a 0.1 Pg/yr drought-induced flux over several months in the Southwest) will be specified over a region in the Mountain West or Southwest and run forward through CT. The predicted CO_2 field will then be sampled at various locations and specific combinations of these pseudo-data records will be used in the CT framework to attempt to retrieve the specified flux field. An alternative to testing based on environmentally plausible flux scenarios would be to run OSSEs for the seven Mountain West states to determine where observations are needed to detect state-specific fluxes. We have identified several potential future RACCOON locations and these OSSEs will be used to help identify which of these sites improve CT's ability to detect regional fluxes. OSSEs run fairly quickly and we plan to conduct 5-10 OSSEs per year with the assistance of NOAA ESRL.

Ongoing and Planned CarbonTracker Developments (Q1, Q2 and Q3)

In addition to the work described above to incorporate RACCOON data in CT and conduct OSSEs for network design, there are other improvements planned by the CT team that will greatly benefit our research goals, while not requiring any additional work to be proposed here. We mention them briefly because we will play an active role in helping to assess the impact of these improvements on flux retrievals in the Mountain West. These planned improvements and their specific impact in this region include:

1) Incorporation of OCO satellite column CO_2 data for improved spatial coverage.
2) Incorporation of high-resolution fossil-fuel emission maps not scaled by population to improve retrievals where low populations, but high power plant emissions exist.
3) Using hourly biosphere submodel fluxes rather than a monthly-mean version of CASA to reduce errors associated with the highly variable spring transition.
4) Alternative scaling schemes other than of gross fluxes to allow small fluxes to be adjusted where they add up to a big part of the annual-mean (e.g. winter respiration, woody encroachment).
5) Using new high-resolution fire fluxes instead of fluxes with monthly resolution to improve capturing signals of large episodic fires.

Long-term CarbonTracker Objectives (Q1, Q2 and Q3)

While CT has many advantages and great potential, because it is still quite new and limited by the availability of specific components, observational data, and computing resources, there are a number of areas of promising work on improvements to the optimization code and submodels. Limitations that are most likely to hamper regional flux analyses in the Mountain West will be explored by examining the branch and OSSE output from the RACCOON runs. With successful analysis, we intend to investigate the feasibility of porting the CT code and running it at UW. This represents a long-term goal and is not specifically proposed here because of limited ESRL resources for training new CT users. Pending availability of these resources in the future, Desai and the Ph.D. student will spend time at NOAA to learn the CT codebase and modeling framework. The ported CT could then be used to run additional OSSEs and branch runs and also to investigate improvements of the inversion core.

One of these improvements that we hope to consider is the role of ecoregion specification in CT. Currently, there exists a limitation of scaling entire temperate North American ecoregions together in CT. This choice was made because the available observations do not generally support further dividing into smaller regions. However, for our area of interest, this means that if a drought in the Mountain West leads to a model-data offset at our RACCOON sites, this offset can only be resolved by scaling, for example, coniferous forest fluxes over the entire U.S. Model modifications to ecoregion locations and number could be investigated. The simplest step would be to divide the U.S. temperate region into separate eastern and western forest ecoregions. We could then examine the impact of scaling these ecoregions separately from the rest of the country, and determine specifically whether the correspondence between retrieved interannual variability and key climate drivers improves. It is known that similar ecosystem types can have very different climate adaptations between ecoregions. We expect that CT may be better able to capture some of the unique effects of long-term drought and fire in this configuration, especially after incorporation of the RACCOON data and better estimates of fire and fossil-fuel fluxes.

To conduct research on the CT code, we would employ an advanced Ph.D. student who has prior mesoscale modeling experience. This would minimize the need for significant support from the limited CT staff at NOAA ESRL. Computation would be performed across idle processing time on distributed sets of computing clusters at the University of Wisconsin provided by via the Grid Laboratory of Wisconsin (GLOW) network infrastructure, which is ideally suited to the ensemble assimilation framework of CT.

Causes of Variability in Observed Sources and Sinks

Most of the work described above is focused on quantifying carbon sources and sinks in the western U.S. and understanding uncertainties due to measurement availability and model assimilation methodology. Once estimates of regional fluxes in the Mountain West have been quantified from CT and BL budgets, they can be analyzed for their spatial and temporal variability and the relationship of this variability to climate and land use forcing. While there are clearly many potential causes of flux variability in this region, we focus on three pertinent changes ongoing in the Mountain West that we believe will be significant controlling factors on carbon fluxes in the region and are ones that are most likely to be directly sensed by the atmospheric CO_2 network, particularly the RACCOON sites.

Drought (Q3)

The timing and length of late summer drought typical to the Central Rocky Mountains and Southwest is a strong control on the net annual fluxes of CO_2 in this region (Sacks et al., 2006). Prior analysis at the Niwot Ridge Ameriflux site has shown that the timing of this drought is correlated with the timing of snowmelt. Thus, the nature and frequency of this drought is likely to change under a warming winter and spring climate, potentially leading to a larger scale state of permanent drought. Analysis of trends in this drought will be conducted with CT optimized flux time series for the Southwest and compared to independent flux estimates in the region along with regional drought indices such as the Palmer Drought Severity Index, Standardized Precipitation Index, and the Water Supply Index. These comparisons will be used to assess how well CT captures the dynamics of drought impacts on carbon cycling and if not, what mechanisms are lacking in CT (i.e., those noted in the prior section). CT has been successfully used to observe and diagnose the large scale North American drought in 2002

(Peters et al., 2007) and thus shows promise in revealing drought effects on regional carbon cycling. We hypothesize that the RACCOON data will improve the interannual variability of CT CO_2 fluxes in the Mountain West, when compared against independent estimates of regional flux and its drought sensitivity (as assessed from ecological and flux tower studies).

We will also investigate and compare MODIS snow cover estimates to the Colorado Snowpack Telemetry snow monitoring sites (http://www.wcc.nrcs.usda.gov/snow). If accurate enough, we will correlate the timing of snow melt to key climate variables to allow for improved model prediction of snowmelt processes and how they, in turn, relate to the observed variability in regional carbon flux. These data could be used as a forcing to the SIPNET ecosystem model and then to test the sensitivity of fluxes to changes in precipitation amount and timing. We have optimized SIPNET at the Niwot Ridge Ameriflux site and thus believe that the model is well-tuned to drought sensitivity. These sensitivities can then be used to estimate what drought signals may be expected in the RACCOON data that may not have previously been identified with the CT assimilation due to lack of model mechanisms in the CT CASA biosphere model (e.g., snowmelt timing).

Insect Outbreak (Q3)

Mountain pine bark beetles are a re-occuring pest that is a major mortality factor for lodgepole pines in western North America (Kurz et al., 2008; Raffa et al., 2008). The current infestation in the Rocky Mountains has been exceptionally virulent and a warming climate has been at least partially implicated as the cause. Our RACCOON observations at FEF have occurred while the trees in the St. Louis creek drainage have experienced widespread mortality. Our CO_2 measurements at the base of this valley show large increases in CO_2 at night as the valley drainage flow pools respiration from a large area. Figure 7 shows that this nocturnal build-up has decreased over the past three years, suggesting a decrease in ecosystem respiration in response to the insect outbreak. This decrease indicates that the reduction in autotrophic respiration is greater than any short-term increase in litter fall, and will be a valuable test of models predicting the impact of the recent outbreaks on regional scale carbon fluxes.

The SIPNET ecosystem model is currently being modified to include a module to simulate the effect of beetle disturbance in the Mountain West. We will analyze wind and soil temperature measurements that are available from a network of sites in the valley to account for the variable strength of the nighttime drainage flow, as well as for the impact of shifts in the surface energy budget on trends in this flow. Conversely, the SIPNET model, driven by local meteorology in the valley, and remotely sensed maps of vegetation indices, will be used to account for the impact of variations in soil temperature and moisture on predicted respiration fluxes. We will

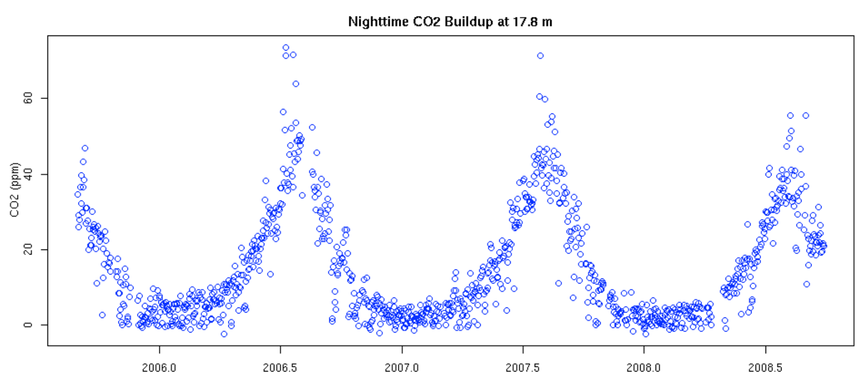


Figure 7. Nighttime CO_2 buildup measured at the FEF site, plotted as the difference between CO_2 averaged from 23-05 and from 11-16 MST.

perform qualitative comparisons between the SIPNET predictions and drainage-normalized CO_2 signals, and we will also invert the CO_2 concentations based on a simple model of valley drainage flow to estimate fluxes for quantitative comparisons. The comparisons will be used to tune model disturbance parameters (e.g. litter, coarse woody debris, and stag turnover rates).

Finally, model respiration and photosynthetic rates will be analyzed to estimate the effect that beetle disturbace has on carbon biogeochemistry, and how increasing rates of insect outbreak under global warming may alter the dynamics of carbon cycling in the Mountain West. The FEF data analysis and ecosystem modeling will be used in combination with examination of trends in regional CT and BL budgeting fluxes to estimate the effect that bark beetle damage has on regional carbon respiration and photosynthetic fluxes. They will also be used to make suggestions for how to incorporate disturbance processes into a CT data assimilation framework.

Fire (Q3)

The long term (century scale) fate of biosphere stored carbon in the U.S. Mountain West is primarily a function of the frequency and severity of forest fires. In CT, fire emissions are represented as monthly mean fluxes from the Global Fire Emissions Database v2 (GFED), which has a spatial resolution of 1x1 degree. Fire needs to be specified in CT so as to be able to identify the biosphere carbon flux signal in atmospheric CO_2. However, fires tend to be episodic in time and correlation exists in spatial scale and severity. Both of these effects lead to unique signatures in the atmospheric CO_2 concentrations that would not be captured in the monthly mean coarse resolution fire flux framework of CT. The CT optimization is likely doing a poor job of fully capturing the influence of fire on continental atmospheric CO_2.

Recently, a high space (1 km^2) and time (daily) resolution fire flux map for the contiguous U.S. has been produced at NCAR (Wiedinmyer and Neff, 2007). This fire flux map, scaled to 1x1 degree and monthly means, will be compared directly to the CT GFED fire flux map. If significant differences are present, we will consider doing a branch run of CT with the alternate fire flux replacing the western U.S. portion of the CT fire flux map. CT modeled CO_2 concentrations will then be compared to RACCOON data to assess if these fire fluxes improved the model-observed difference of concentration and how estimates of regional biosphere flux in CT may have changed.

FLEXPART will also be used with the RACCOON data and the fire CO_2 flux map to directly investigate the presence of fire influenced CO_2 in RACCOON data. These signals will then be filtered and subset to assess the ability of the RACCOON data to detect and quantify CO_2 emissions from fires as they occur, and to be used to validate the previously described fire flux maps. Fires will also be incorporated into disturbance rate parameters in the SIPNET model to estimate how the long-term fate of biospheric carbon is changing in the Mountain West due to changing fire frequency caused by land management.

Deliverables

1) A publicly available near real-time atmospheric CO_2 data set, containing concentrations measured continuously for 4.5-6.5 years at 6 sites in the Central Rocky Mountains and Southwest, with accuracy of 0.2 ppm or better and in a format amenable to use by NACP and community investigators.

2) Regional-scale monthly and annual flux estimates for the Central Rocky Mountains and Southwest over this time period determined from CarbonTracker and boundary-layer budgeting techniques.

3) Network analysis of the value of adding existing and potential new Mountain West observation sites to the CT framework.

4) An assessment of the contribution of drought, fire, and insect outbreak drivers to variations in the uptake of anthropogenic CO_2 in the Mountain West, and implications for future trends in fluxes and how to optimally observe them.

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