THE ROLE OF AFRICA IN TERRESTRIAL CARBON EXCHANGE AND ATMOSPHERIC CO2: REDUCING REGIONAL AND GLOBAL CARBON CYCLE UNCERTAINTY

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NOAA Project Goal: Climate

NOAA Programs: Climate and ecosystems; Climate observations and analysis

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1. Long-term Research Objectives and Specific Plans to Achieve Them:

Much uncertainty remains in our understanding of the ways in which atmospheric, terrestrial and oceanic carbon reservoirs interact, and the controls, magnitude and location of fluxes that determine atmospheric CO_2 mixing ratio and terrestrial and oceanic sequestration. Analysis of the rate of increase of atmospheric [CO_2] suggests that carbon uptake by terrestrial ecosystems offsets fossil fuel emissions by 1.5-2.0 Gt per year. Several studies suggest that a significant proportion of that sink lies in northern deciduous and boreal ecosystems, but the range of estimates by different techniques is large and research also indicates a strong tropical sink. Furthermore, inverse estimates of the role of tropical regions in global carbon exchange may be underestimated because of the paucity of real data and because deep convection in the tropics may mask the tropical signal in the existing network of [CO_2] measurements. With expanded research in neo-tropical regions during the last few years, the weakest link in our current understanding of the global carbon cycle, and concomitant potential for greatest return on research effort, is in the old-world tropics, particularly in Africa. With joint funding from the US National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) this project is addressing some of these shortcomings in our understanding of the temporal and spatial dynamics of carbon exchange in Africa. The project includes both biogeochemical forward modeling, using remote sensing data and land surface models, and atmospheric inverse modeling of carbon dynamics across the African continent. Field measurements in support of the modeling activities are being carried out in Southern Africa (Kruger National Park, South Africa) and West Africa (the Gourma region of northern Mali). The field component is a directed effort to obtain vital new data and process understanding to constrain and parameterize models for regional and continental carbon cycle assessments. We are planning an additional field site in under-represented Central

Africa for the coming year, with possible site locations in Zambia or Congo-Brazzaville.

The project will provide more tightly constrained estimates of the spatial and temporal variation in carbon uptake and release from Africa. Satellite data from the AVHRR series and from MODIS and other *Terra* satellite instruments, and assimilated climate data, are being used to parameterize a land surface model (SiB3) to estimate the historical and contemporary variation in vegetation activity across the continent and predict spatially and temporally continuous fields of net carbon, water and stable isotope exchange. In parallel with this “forward modeling” of African carbon dynamics, we are preparing both regional and global inverse analyses of atmospheric [CO_2] and stable isotope concentrations. These analyses will use the existing flask measurement network augmented by new high precision [CO_2] measurements in Africa. We expect that the novel combination of forward and inverse estimates of African carbon exchange will lead to model enhancements and reductions in uncertainty, lead to improved estimates of the spatial and temporal dynamics of carbon and water exchange in Africa, and lead to an improved understanding of the impacts of climate, climate variability and land use in regional carbon dynamics and the contributions of Africa to the global carbon cycle.

Year 2 activities included deployment of continuous precision CO_2 and 13C flask measurement systems in South Africa and West Africa, intensive measurements at a savanna site in southern Africa to examine soil respiration and 13C dynamics in mixed C4-C3 ecosystems, preparation of a manuscript reviewing current knowledge of the African carbon cycle (in review), preparation of datasets and initial simulations of historical carbon cycle dynamics across the continent using the historical AVHRR data archive (1982-2002) and a land surface model, and preparation of regional data sets and atmospheric transport models for new and enhanced atmospheric inversion studies. These activities are described in more detail below.

Year 3 Work Plan

--Run long-term (1982-2002) simulations of the historical carbon cycle in Africa at high temporal and spatial resolution. Analyze resulting data fields for patterns and processes relating to the spatial and temporal variations in carbon, water and energy fluxes (April-August 2006)

--Retrieve and compile MODIS data fields for Africa for 2000-2005 period, including Vegetation Index, f_{PAR}, LAI, land use and fire (burn scar) information (April-September 2006)

--Run MODIS-based simulations of cotemporary carbon cycle in Africa (August-December)

--Install field CO_2 and flask instruments in third ACE study location (Zambia or Congo) (August-September 2006)

--Develop soil respiration and 13C fractionation model for inclusion in land surface models.

--Begin analysis of data on near surface atmospheric CO_2 concentration and flask measurements of d13C. (August 2006)

--Compare simulations using the SiB3 land surface model and site measurements of CO_2 and $^{13}C/^{18}O$ from the Kruger Park and Gourma sites (late 2006)

--Commence inverse analyses using global flask network with additional data from 2 or 3 new African field sites (early 2006)

2. Research Accomplishment/Highlights:

Major Accomplishments in Year 2

1) The African Carbon Cycle

An early activity of this project has been the compilation of a review article summarizing the current state of knowledge of carbon cycle dynamics in Africa using inventory methods, forward models (including climate and satellite-driven approaches), atmospheric inversions and land-use and biomass inventories (Williams et al., 2006, in review).

With low fossil emissions (0.2 Pg C yr^{-1}) and productivity that largely compensates respiration (each ~ 10 Pg C yr^{-1}), land use (0.4 Pg C yr^{-1}) is Africa's primary net carbon release, much of it through burning of forests (Figure 1). Savanna fire emissions, though large (1.5 Pg C yr^{-1}), primarily represent a short-term dry season source rapidly offset by ensuing regrowth. Nonetheless, climate-induced variability in productivity and savanna fire emissions contribute to Africa being a major source of inter-annual variability in global atmospheric carbon dioxide. The sparse observation network in and around the African continent means that Africa is one of the weakest links in our understanding of the global carbon cycle and the location of the so called “missing sink” (Figure 2). Continent-wide observations of carbon stocks, fluxes, and atmospheric concentrations are key priorities to improve our understanding of the carbon dynamics of Africa and the world. For this reason, the field components of the ACE project are intended to provide new data-streams that will reduce uncertainty in atmospheric inversions and improve our mechanistic understanding CO2 dynamics in African ecosystems, and how the mixed C3 and C4 savannas imprint on the stable isotopic signature of CO_2 sources and sinks in the continent.

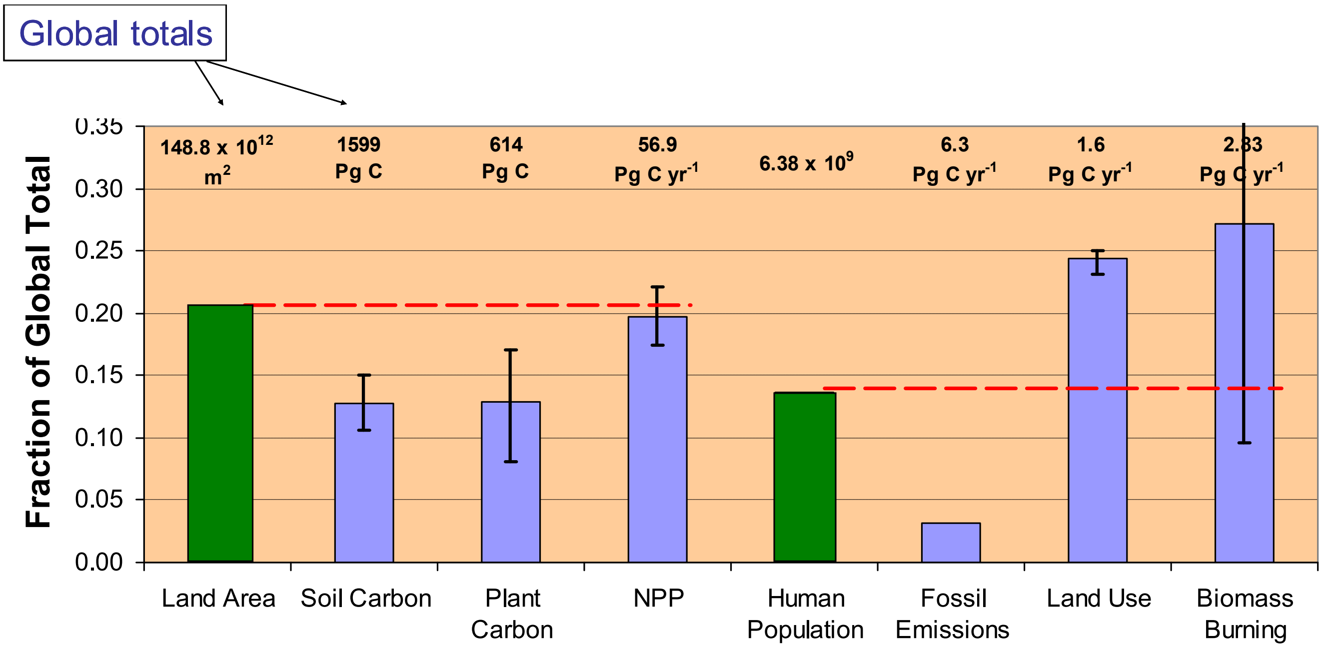


Figure 1. Carbon statistics for Africa expressed as fraction of global totals ('error bars' show range of published estimates). Land area and human population are shown as reference for Africa's fractional contribution to global carbon stocks and fluxes.

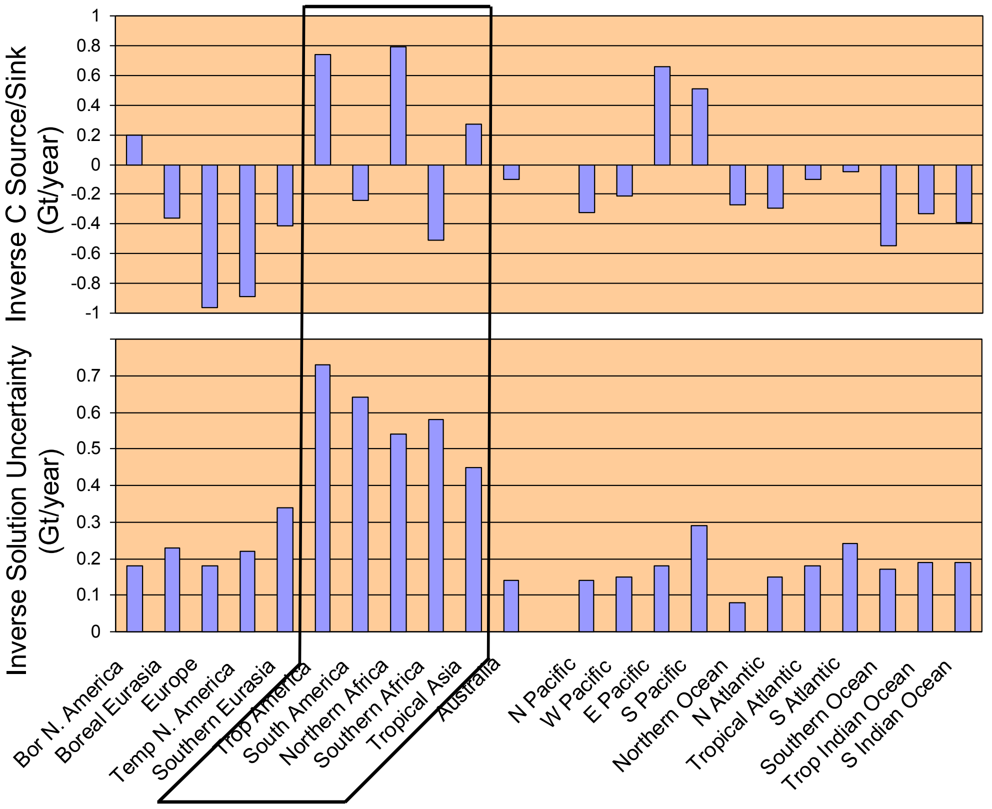


Figure 2. Inverse analysis results showing high levels of uncertainty for Africa and tropical terrestrial regions. (Data from TRANSCOM-2; Gurney et al., 2004).

2) CO_2 dynamics in tropical savannas

The intensive field site in the Kruger National Park, South Africa, was established in 2000 with initial funding from NASA Terrestrial Ecology and EOS Validation Program as a validation site with emphasis on carbon and water fluxes in tropical savannas. The site has become a primary research site for the ACE project because of the challenges savanna systems, with mixed tree-grass vegetation, present to biogeochemical models and remote sensing of vegetation function. The long-term flux measurements at the site will contribute to testing and improvement of land surface models in savannas through better understanding of the partitioning of energy and water between the tree and grass strata, the response of these water-limited systems to rainfall, particularly rainfall pulses, and functional differences between two of the most important savanna types of southern Africa. With the new funding under ACE the site is also contributing new very precise CO2 concentration ($[CO_2]$) measurements for atmospheric inversions, and measurements of atmospheric and soil 13C and soil respiration processes to better understand ^{13}C fractionation during photosynthetic uptake and respiratory release of CO_2 to the atmosphere.

Savanna systems are water limited systems and thus pulse-driven systems (because rainfall events are always discrete events, with most annual rainfall falling during only a few hours of the year). These pulse events excite physical, physiological, phenological responses in the vegetation and soil that can be complex in terms of the response time, lag dynamics, and decay characteristics (Figure 3). These pulse responses can be extremely important to the carbon and water dynamics of the system, but are often poorly represented (or not represented) by biogeochemical and biophysical models of ecosystem processes. The study of the long-term and pulse response patterns of carbon and water dynamics in these tropical savannas provides important background understanding for modeling these ecosystems that, in their different forms, occupy more than 50% of the African land surface

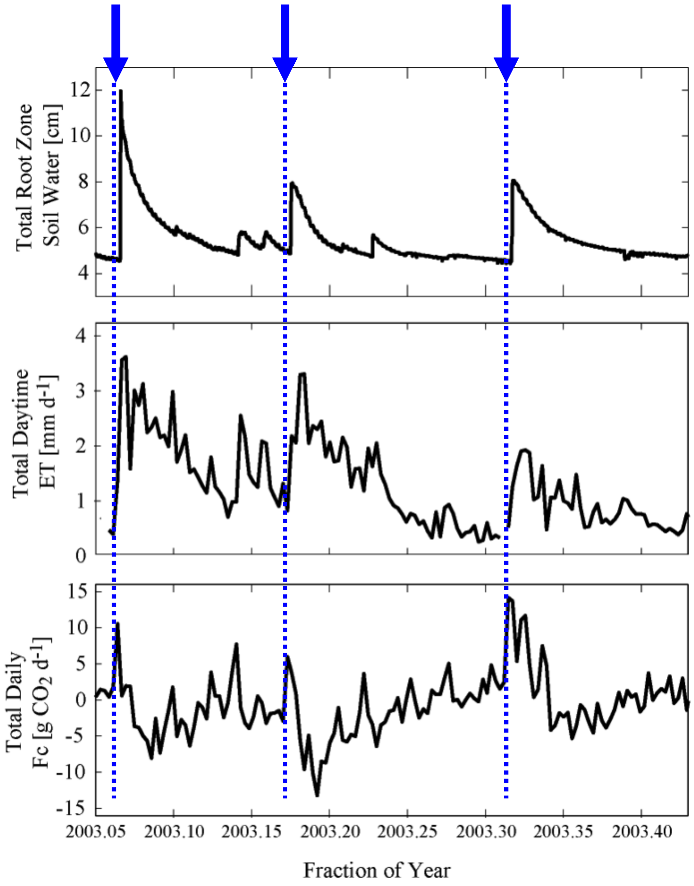


Figure 3. Pulse dynamics in tropical savannas. Measurements at the Kruger Park intensive research site during 2003 show the complex and non-linear response of savanna vegetation to rainfall events that depend not only on soil moisture, but also on phenological status and structural characteristics of the vegetation that impose lags and changing sensitivity to rainfall events through the growing season.

3) Modeling African Carbon Dynamics using Satellite Data

We plan analysis of both historical and contemporary carbon cycle dynamics across the continent using the long-term AVHRR dataset and more recent MODIS data. A study of the historical carbon dynamics of the continent has been initiated using the AVHRR archive and climate re-analyses to parameterize and run the land surface model SiB3 (Simple Biosphere Model, version 3; Figure 4-5. We are examining the spatial and temporal variability of net carbon exchange over the past 2 decades to analyze the impacts of climate variability, drought and land use on the NPP and vegetation activity in the region. In preparing the historical simulations using AVHRR datasets we have found that the seasonality of the moist tropics appears to be exaggerated (see, for example, simulations for a Congo basin site in Figure 4). Using temporally corresponding data on aerosol optical depth from MODIS, we determined that the AVHRR NDVI seasonality is negatively correlated with optical depth, with optical depth over the equator peaking during the dry seasons savanna fires to the north (December) and south (July) of the equator (Figure 6). We anticipate needing to correct the AVHRR record for the moist tropics to reduce the aerosol effect whilst retaining real inter-annual variability that may occur in the region relating to variable rainfall.

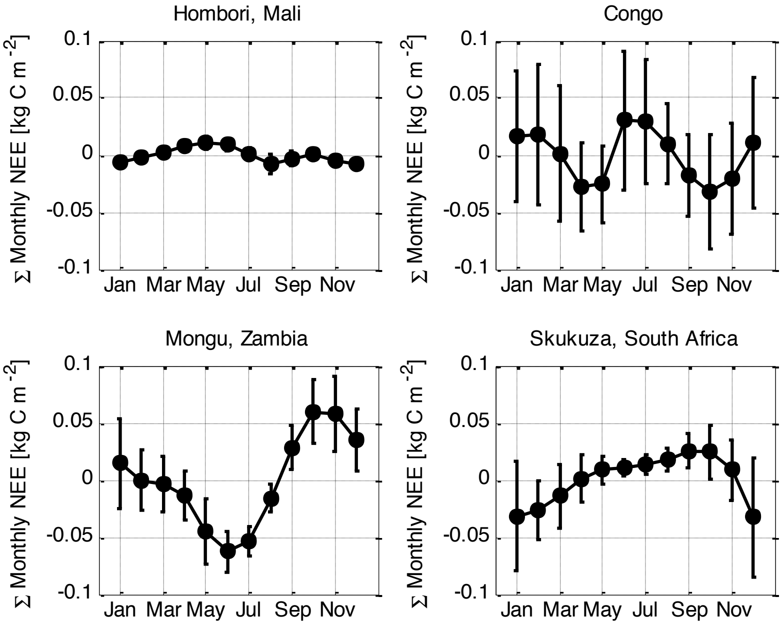


Figure 4. Monthly net ecosystem exchange (NEE) for 4 sample sites in Africa estimated using the Simple Biosphere Model (SiB3) and the long-term (1983-2000) AVHRR dataset. Climate data for the period were obtained from NCEP climate re-analysis fields. Hombori and Skukuza are active ACE field sites for measurement of ecosystem fluxes by eddy covariance and atmospheric CO_2 using the ACE Precision CO_2 and flask sampling system. A third measurement site is planned for either Mongu or a moist tropical (Congo basin) site to be established in the near future by Afriflux collaborators.

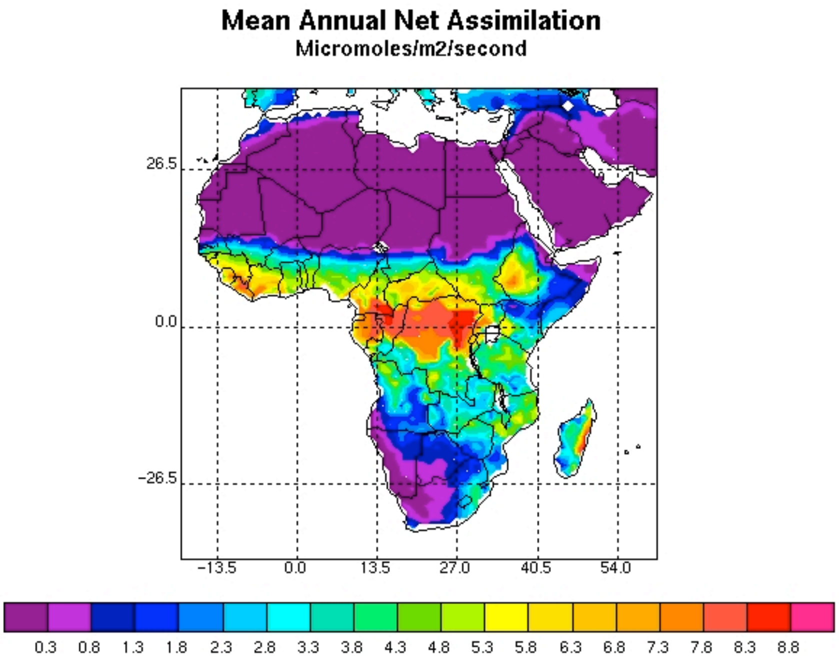


Figure 5. Annual average net assimilation rate (1983-2000) estimated using the SiB3 model, NCEP climate re-analyses and the long-term AVHRR data set.

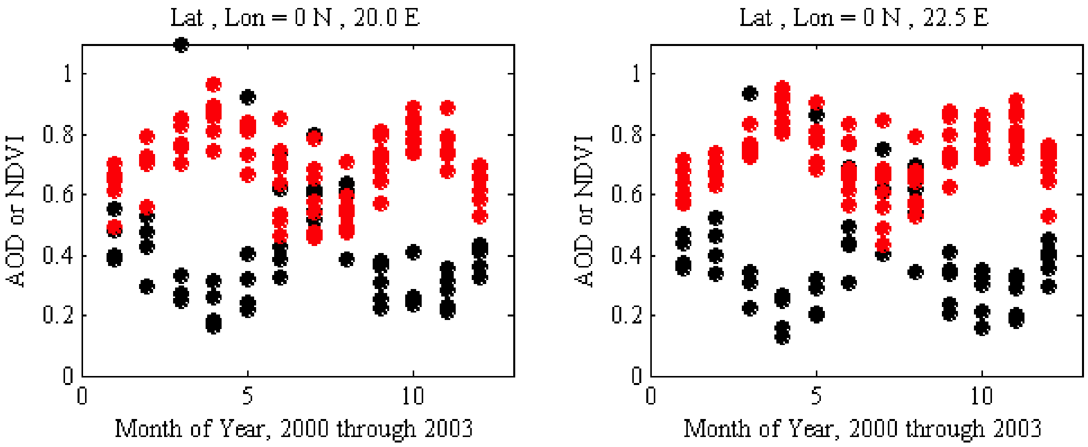
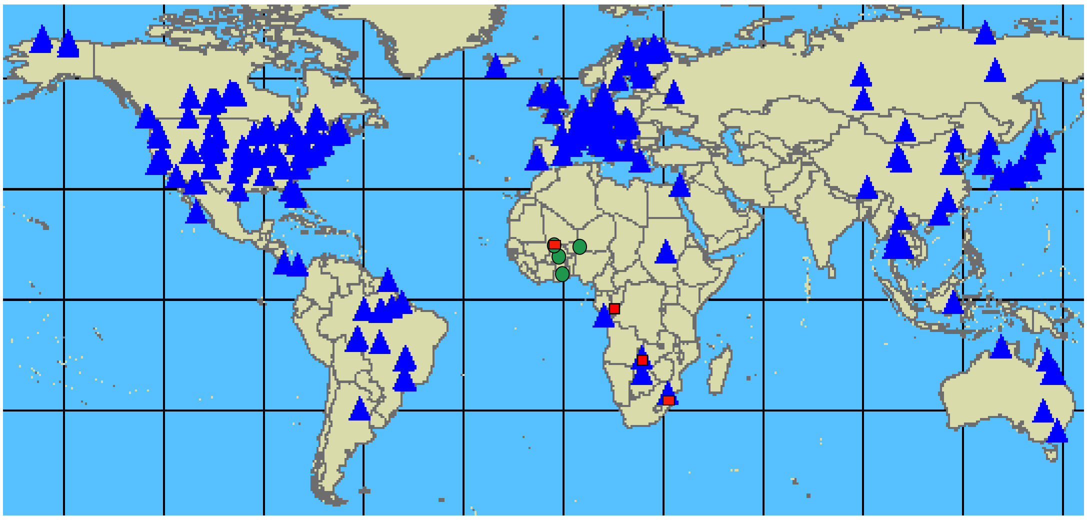


Figure 6. Monthly average AVHRR NDVI (red) and MODIS aerosol optical depth (black) in the moist tropics of Africa. Data are shown for two sites on the equator and for years with overlapping AVHRR and MODIS data availability (2000-2003). Note the strong seasonality in AVHRR NDVI that is negatively correlated with aerosol optical depth.

4) Precision CO_2 for Atmospheric Inversions

Precision CO_2 systems will provide continuous very precise measurements of atmospheric carbon dioxide concentration ([CO_2]) that will be used to infer CO_2 drawdown in both regional and global atmospheric inversions. The systems are designed to measure [CO_2] with a precision of 0.2 ppm, and with continuous (48 averages per day) and long-term data collection. The system includes a gas-analyzer with a pump and valve system to draw air from above the canopy for sample measurements and automatic zero and span calibration at 2-4 hour intervals. For instrument stability and precision the systems are thermally insulated and the sample air is dried prior to measurements. Two systems have been installed alongside eddy flux measurement



Global distribution of existing Fluxnet sites (▲)
New continuous precision CO_2 measurements (🟥) in South Africa and Mali supported by ACE.
New and planned African sites (🟢), including sites in Mali, Ghana, Burkina Faso, and Niger.

Figure 7. Representation of Africa in the global network of eddy flux sites, and continuous precision CO_2 measurements and flask sampling sites installed (South Africa and Mali) and planned (Zambia and/or Congo-Brazzaville) under the ACE project.

systems in Africa. The first at our research site in South Africa (Kruger National Park) and the second at a new eddy covariance site in the Gourma region of northern Mali (Figure 7-8). Measurements in West Africa have been made possible through a developing collaboration between the ACE project and the African Monsoon Multidisciplinary Analysis (AMMA) and in particular with collaborators Eric Mougin (CESBIO, Toulouse, France) and Colin Lloyd (CEH, Wallingord, UK). We are currently constructing a third instrument system for deployment at an eddy flux site operated by collaborators in Zambia and/or Congo (Figure 7).

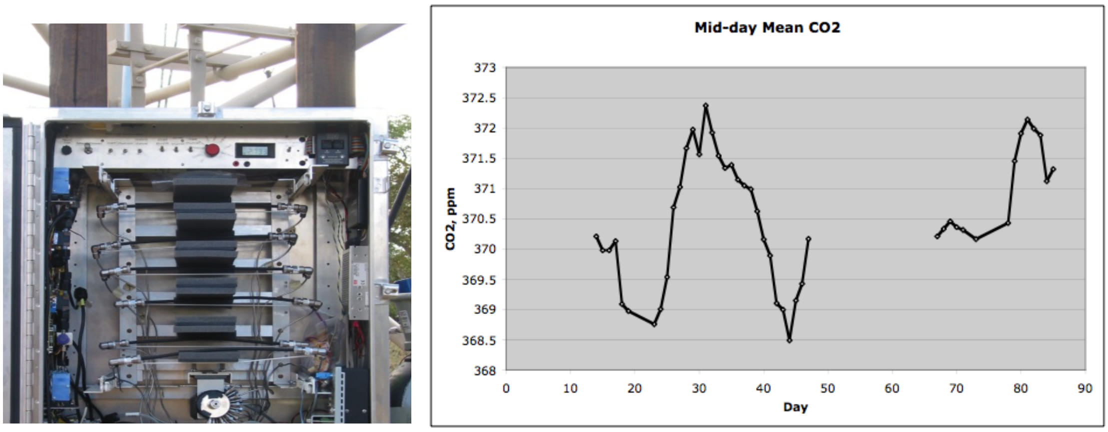


Figure 8. Precision carbon dioxide and flask sampling system (left) and midday atmospheric CO_2 concentration measurements (right) at the Skukuza eddy flux site in the Kruger National Park, South Africa. The system uses automatic calibration with WMO-traceable standards and a temperature controlled infrared gas analyzer to measure CO_2 concentration to an absolute precision of ~0.2 ppm.

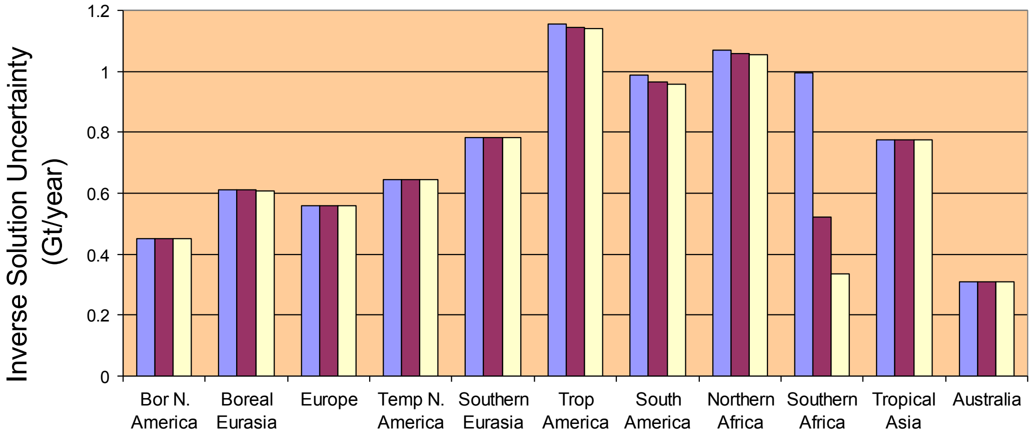


Figure 9. Effect of precision CO_2 sites in Southern Africa on atmospheric inversion uncertainty for Africa and other terrestrial regions (Blue: using existing flask network; Maroon: anticipated effect of adding a precision CO2 site in South Africa; white: adding a precision CO2 site in Zambia). Atmospheric inversion uncertainty arises from lack of CO2 observations and uncertainty in simulated atmospheric transport: the response of African inversions to additional sites indicates that inversions for Africa are especially data-limited, with relatively low transport uncertainty.

5) Global atmospheric inversions

The impact of the new CO_2 data-streams for atmospheric inversions for Africa can be estimated in advance using the existing flask network measurements and atmospheric transport model, and synthetic CO_2 data from each prospective site. For the two southern Africa sites (Skukuza and Mongu) the impact on inversions for the southern Africa region is dramatic (Figure 9). The southern Africa stations have little impact on northern Africa inversions, but inversions for northern Africa will be improved through input of data from the Mali site. We have also developed new bioclimate-based inversion basis regions for Africa (Figure 10). These regions are being used in new simulations of atmospheric transport using the PCTM atmospheric tracer transport model to derive new transport vectors for atmospheric inversions. The new transport vectors and basis regions will facilitate more spatially resolved inversions for regions that are internally self-consistent (unlike previous inversions that separate Africa into two climatically and biologically diverse regions at the equator). With new CO_2 data-streams from northern and southern Africa and from a third site in (or near) the Congo basin, we anticipate dramatic improvements in future atmospheric inversion results.

Figure 10. Bioclimate defined basis regions for new atmospheric inversion studies in Africa.

6) Regional Inversions

Terrestrial CO2 measurements respond to local and regional vegetation activity and carry the imprint of carbon fluxes occurring in regions on the order of 10^4 km^2 or more. Several methods have been examined to use the diurnal and seasonal changes in near-surface CO2 concentration to infer regional growth and respiration signals. One of the most promising involves soling the mass budget of the planetary boundary layer using estimates of the degree of mixing between the PBL and free troposphere, In this project we are using the atmospheric tracer transport model to define the PBL turnover time which will allow us to use our precision CO2 measurements to estimate regional fluxes. Initial investigations of this method (prior to availability of sufficient CO2 measurements) have focused on the utility of the transport model (PCTM) to estimate PBL turnover times and net fluxes for the region (Figure 11). As longer time-series of measurements become available from our African precision CO2 sites, regional inversions will provide an independent assessment of terrestrial exchange rates at intermediate scales that can be compared to the global inversions and the forward model estimates based on MODIS vegetation measurements.

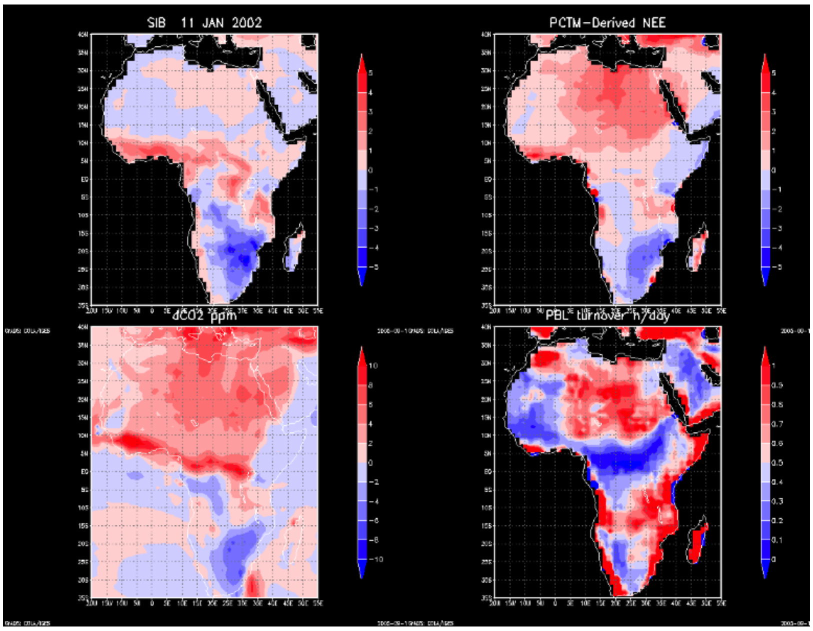


Figure 11. Regional Carbon Flux Estimation using a PBL-budget approach with near-surface [CO2] and atmospheric transport. This figure shows a snapshot (11 January 2002) of an annual simulation. The regional inversion method was described by investigator Berry and collaborators (Betts, Helliker, and Berry, 2004, Coupling between CO2, water vapor, temperature and radon and their fluxes in an idealized equilibrium boundary layer over land. JGR, 109, D18103).

7) Respiration and ^{13}C Dynamics in Savannas

Tropical savannas are unique in the mixture of plant functional types (trees and grasses) that utilize contrasting photosynthetic pathways (C3 and C4, respectively). In many African savannas, the C4 grasses dominate net primary production, but the relative productivity of the trees and grasses depends largely on tree cover. The fractionation of ^{13}C in savanna productivity reflects the relative importance of trees and grasses, but the temporal and spatial dynamics of d^{13}C in photosynthetic and respiratory fluxes is complex. To improve our ability to simulate ^{13}C dynamics in forward models, and our understanding of ^{13}C variability for atmospheric inversions, we have deployed instruments and sampling systems at our intensive savanna research site in South Africa to explore patterns of d^{13}C in soil carbon and respiration.

One of the main goals of the soil and respiration measurements is to narrow uncertainty in the isotopic signal associated with biosphere/atmosphere exchange in Africa. We are focusing efforts in Kruger National Park because it is representative of the savanna biome. Because of the mix between C3 and C4 species in savannas across Africa, it is currently difficult to predict or model temporal or spatial variation in biosphere/atmosphere d^{13}C exchange. Soils in particular represent an important area of uncertainty because of uneven mixing of C3 and C4 biomass spatially across savannas and because of temporal lags between carbon input from litter fall and decomposition from soils. The problem is compounded further by vertical variation in soil ^{13}C associated with root inputs, progressive enrichment during decomposition and the Suess effect.

Our initial results illustrate two key points. First, vegetation cover (interspace vs. canopy samples) results in only a two per mill differences in the d^{13}C signal in soil respiration. Second, the subsurface profiles of d^{13}C suggest that roots from C3 vegetation may be exploiting interspace zones given the increase in C3 SOM signal at 20-25 cm and this use of the interspaces by tree species may help explain some of the similarity in fluxes from these two settings. There are some significant differences between d13C of soil surface fluxes with respect to season (Figure 12), with a strongly enriched signal from the interspace locations immediately following the onset of October rains. This pulse of enriched d^{13}C may result from decomposition of surface soils that are dominated by a C4 signal.

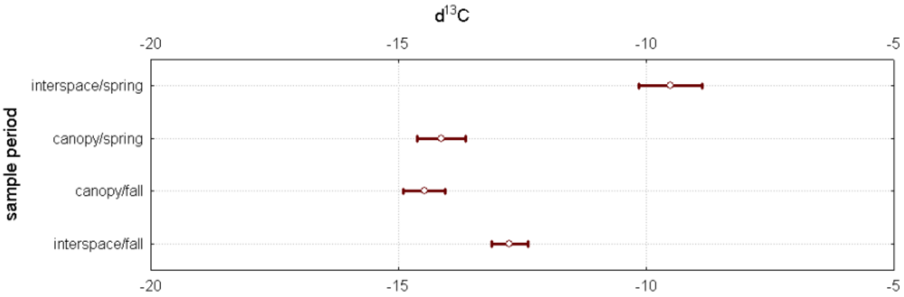


Figure 12. d^{13}C of soil CO_2 flux by season and sampling location for 2006

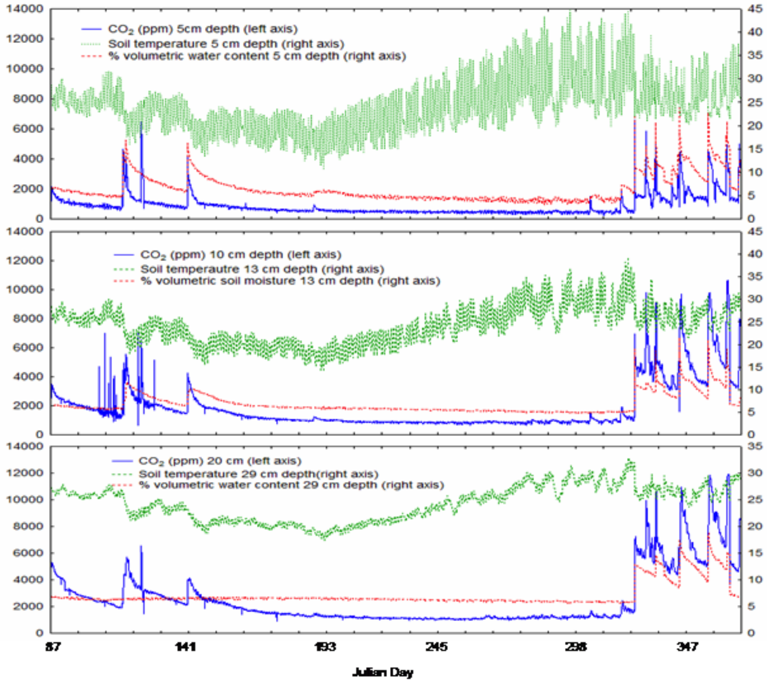


Figure 13. Soil CO_2 concentrations, water content and temperature during 2006 for an undercanopy sampling location. Note the close correspondence between soil CO_2 and water content through the year.

Soil CO_2 probes (Vaisala Instruments) have been in place in an under-canopy site in the Kruger National Park since March, 2005. The resulting record shows a period of elevated soil CO_2 concentrations at the end of the wet season in March, very little soil CO_2 production through the dry season and then a large spike in activity with the onset of rains in October of 2006 (Figure 13). Across the seasons, soils also appear to respond very quickly to rain events with CO_2 concentrations peaking just hours after the input of water to the soil. Interestingly we find that soil CO_2 concentrations increase following rains even at depths below the level of water infiltration. We do not yet know the cause of these deeper pulses of CO_2 following rain but are investigating the possibility of root respiration (plant responses to rain) and physical mechanisms including a temporary barrier to CO_2 flux related to the infiltrating water. Our fall installation of a soil CO_2 concentration profile in an interspace site should help address this question because of phenological differences between grasses and trees.

7. Outreach:

The Kruger Park Times, March 23, 2005. *What is a flux tower?* Publication in a popular South African bi-weekly newspaper for the Kruger Park area describing for the general public the local and continental aims of ACE in understanding regional and global carbon dynamics.

8. Presentations and Publications:

Hanan, N. P., Williams, C. A, Scholes, R. J, Denning, A. S, Berry, J. A, Neff, J, Privette, J., 2005 (In and) Out of Africa: estimating the carbon exchange of a continent, Seventh International Carbon Dioxide Conference (ICDC7), Broomfield, CO, September 26-30, 2005. (Invited Presentation)

Hanan, N., 2004, *Afriflux: promoting research on ecosystem function and land-atmosphere interactions in Africa*, Fluxnet Open Science Meeting, December 13-15, 2004, Florence, Italy. (Invited oral presentation)

Hanan, N., Bob Scholes, Werner Kutsch, Ian McHugh, Walter Kubheka, 2004, *Water and productivity in semi-arid savannas: examining the water-limited paradigm using whole-ecosystem flux measurements,* Kruger National Park Science Network Meeting, Skukuza, South Africa, March 29-April 2, 2004. (Oral presentation)

Hanan, N. P., Scholes, R. J., Williams, C. A. and Kutsch, W., 200x Coupled carbon, water and energy fluxes in contrasting fine- and broad-lead savannas of southern Africa. In preparation for *Journal of Arid Environments*

Kutsch, W. L., Hanan, N. P., Scholes, R. J., McHugh, I., Khubeka, W., Eckhardt, H., Williams C. A., 200x, Response of carbon fluxes to water relations in a savanna ecosystem. In preparation for *Journal of Arid Lands*

Kutsch, W., Niall Hanan, Robert Scholes, Ian McHugh, Walter Kubheka, Holger Eckhardt, 2005, *Savanna carbon and water fluxes*, Kruger National Park Annual Science Networking Meeting, Skukuza, South Africa, April 4-8, 2005 (Oral presentation).

Williams, C.A., Hanan, N.P., Scholes, R.J., 2005, Seasonal Controls on Water and Carbon Fluxes Responding to Pulse Precipitation Events in Dryland Systems: Examples from Southern African Savannas, American Geophysical Union Fall Meeting, San Francisco, December 5-9, 2005. (Oral Presentation)

Williams, C.A., Niall Hanan, Joe Berry, Robert Scholes, A. Scott Denning, Jason Neff, Jeffrey Privette, 2005, *Africa and the global carbon cycle: field networks and* *model studies of African carbon exchange*, Kruger National Park Annual Science Networking Meeting, Skukuza, South Africa, April 4-8, 2005 (Oral presentation).

Williams, C.A., Niall Hanan, Joseph Berry, Robert Scholes, A. Scott Denning, Jason Neff, Jeffrey Privette, 2005, *Africa and the global carbon cycle: field networks and model studies of African carbon exchange*, National Science Foundation US-Africa Workshop: Enhancing Collaborative Research on the Environment in Sub-Saharan Africa, Arlington, VA, January 24-26, 2005 (Poster presentation).

Williams, C. A., Hanan, N. P., Neff, J., Scholes, R. J., Berry, J. A., Denning, A. S., Baker, D., 2006, Africa and the Global Carbon Cycle, (submitted to *Global Change Biology*).

Williams, C.A., Hanan, N. P. and Scholes, R.J. Seasonal variation in environmental controls on water and carbon fluxes in savannas. In preparation for *Agricultural and Forest Meteorology*