A US Carbon Data Assimilation Program Workshop Report

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Summary

Observations have not been assembled to study the carbon cycle as an integrated whole. Observing and understanding a single reservoir (land, atmosphere or oceans) does not translate to understanding that reservoir in concordance within the coupled system. In order to understand the patterns and variability of sources and sinks of carbon dioxide, it is necessary to integrate together data about the land, atmosphere, oceans, and fossil fuels. Data assimilation is a family of techniques for improving estimates of geophysical quantities combining models and observations. Data assimilation is particularly valuable in bringing disparate observations to bear on a common problem. In order to bring data assimilation into carbon science, we proposed a focused program involving assimilation model development, reanalysis of key phenomena such as the carbon system response to El Nino, education and training of a new generation of carbon cycle modeling in assimilation techniques, and the creation of a data clearinghouse and prototype data assimilation teams. In the longer term, we suggest the incorporation of carbon assimilation into the mission of an operational forecast center, and the routine production of carbon cycle data products.

Introduction

Observations have not been assembled to study the carbon cycle as an integrated whole. Observing and understanding a single reservoir (land, atmosphere or oceans) does not translate to understanding that reservoir in concordance within the coupled system. In order to understand the patterns and variability of sources and sinks of carbon dioxide, it is necessary to integrate together data about the land, atmosphere, oceans, and fossil fuels. Analyzing the carbon system as a whole requires unprecedented integration of information, far exceeding today's modeling and data analysis techniques.

Data assimilation is a family of techniques for improving estimates of geophysical quantities combining models and observations. Although best known as a tool in weather forecasting, data assimilation is also used in analysis of complex data sets, and in estimation of parameters in models. Data assimilation is particularly valuable in bringing disparate observations to bear on a common problem to achieve the best analysis, consistent with all the available information. Data assimilation techniques can play a major role in carbon cycle science, producing robust & consistent estimates of contemporary sources and sinks by integrating together atmospheric, terrestrial and oceanic data together into a common analysis framework. The goal of the data assimilation program is to characterize the variability of CO_2 sources and sinks, aid in confirming the mechanisms causing sources and sinks, and, ultimately, increase the credibility of prediction of the carbon system.

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Currently, we observe many aspects of the carbon system, including atmospheric CO_2 concentrations and fluxes, ocean pCO_2, forest vegetation and soil carbon inventories, and fossil fuel production and use. We also observe a number of variables helpful in understanding the carbon system, including satellite measurements of land vegetation and ocean color, atmospheric constituents such as the O_2/N_2 ratio and carbon monoxide that tell us something about CO_2, and controls over carbon cycling such as temperature, rainfall, ocean circulation and solar radiation. Physical oceanographic data can provide information that can be useful in information useful in extrapolating pCO_2 and CO_2 fluxes. None of these measurement sets alone tells us everything we need to know about the carbon cycle, so we need the capability to integrate many types of information together to seek answers consistent with multiple types of observations. For prediction, we must know the environmental controls over air-sea gas exchange, photosynthesis, respiration and wildfire on land and this requires information on carbon fluxes and pools with information on multiple controls.

With the increasing amount and sophistication of both models and data describing the carbon cycle, the need for better integration is vital. As the cost of carbon observing systems increases, the needs for simulating the benefits of new observations, such as expanded CO_2 flux networks on land, satellite observatories of the atmosphere, or shipborne measurements, steadily increases. For satellite observations of atmospheric trace gases, the measurement requires knowledge of temperature, water vapor, aerosols and clouds, and is best made in an integrative assimilation model. Because of the interactions and tradeoffs in space-based estimates of trace gases, it is important to model the estimation and assimilation as a part of instrument and algorithm development. Estimates of carbon sources and sinks using space based data will use assimilation techniques, but before that, the design of space-based systems will benefit from observing system simulations.

A hierarchy of carbon data assimilation models are needed as integration tools for the Carbon Cycle Science Program. These models will integrate process models for the land, atmosphere and oceans, observations of physics, biology and fossil carbon, and advanced mathematical techniques. Products from the program will include improved and consistent estimates of:

- The distribution of carbon in the land, atmosphere and ocean reservoirs (*state estimation*),
- The distribution of air-sea and land-atmosphere CO_2 exchange (*flux estimation*)
- Estimates of parameters controlling carbon cycle processes (*parameter estimation*).

These products and the models that produce them form the basis for several important activities. They will lead to:

- robust & consistent estimates of contemporary sources and sinks
- measurement & verification of fossil & biofuels emissions and sequestration
- Design and assessment of new observing systems
- Development of improved predictive capabilities for the carbon system.

Current status and capabilities

Observational data streams

Existing observations of the carbon system are made through a number of research networks, operational programs and process studies. Key data sets include the global flask network, defining surface CO_2 concentrations, along with concentrations of a number of other trace species, the global FLUXNET program, which measures CO_2 fluxes on land using the eddy covariance technique, and marine surveys and time series of pCO_2, DIC and other marine constituents. Land vegetation is regularly inventoried by forest and agricultural management agencies in many regions-some measurements are made of soils and these data are increasingly being used to define land carbon stocks. Intensive field programs in terrestrial and oceanic areas provide a wealth of data on carbon cycle processes and controls, and are a major resource for process model development and evaluation. In addition to these direct carbon cycle measurements, satellite observations of land and ocean surfaces provide information about the variability of phytoplankton and vegetation activity, and meteorological and physical oceanographic data provide information on controls over fluxes. Changing land use is a key control over the terrestrial carbon cycle and high/moderate resolution satellite imagery is improving knowledge of land cover and land cover change.

While substantial data resources exist for the carbon cycle, we face two major challenges. First, biogeochemical processes are highly variable in time and space, although the scales vary between the land, ocean and atmosphere. However, in all of these domains, the carbon system is undersampled relative to variability.

- Data are limiting and thus it is important use existing data efficiently and strategically add measurements.

Data describing the carbon system are collected by a mix of nations, scientific disciplines, and agencies. Most carbon observations become available long after collection, and are held in a variety of venues and formats. Many of the data are not routinely made available to the scientific community at all, and access can be difficult. There are existing databases of micrometeorological, meteorological and biological data (for example at the ORNL DAAC and CVDIAC).

- A more integrated system is needed to provide carbon data, together with agreements to provide access in a timely fashion. If routine analyses of the carbon system are done daily, seasonally or annually, timely data access must be provided.
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Many of the key data for carbon assimilation are collected by site-based process studies funded through research programs. Some of these projects are part of networks such as AmeriFlux of the LTER program, some are not. However, few of the research-oriented programs provide resources allowing PIs to provide data in real or near real-time. The European CarboEuroFlux program is experimenting with real-time transmission of flux data to allow raw data to be automatically archived across a network and is implementing software to do initial data processing and QA/QC. Fluxnet is already experimenting with near-realtime modeling of flux sites. Resources to do this are modest compared to investment in networks and should have large scientific payoff.

- Resources to provide timely data and automate some analysis and QA/QC functions is required for research and process study sites to function efficiently in an integrated observation and analysis system such as is envisioned here.

Component process and coupled carbon system models

Process modeling of the carbon cycle has advanced significantly. Ocean biogeochemical models have been developed and are increasingly being tested and developed using oceanographic process data, time series measurements and ocean color observations. Land surface physical models are at an advanced stage of development and are being coupled to land carbon (vegetation and soils) models in a number of groups. Longer-term controls over the carbon cycle such as natural disturbance and land use are being added to models as global land cover and land cover change data improve. Several experiments have been done using coupled carbon-climate models.

Data assimilation schemes for a number of specific processes have been developed. Ocean carbon data have been used in assimilation schemes to estimate oceanic carbon fluxes. Several groups are beginning to assimilate CO_2 flux observations into terrestrial process models, and ideas are emerging as to how to assimilate multiple process observations simultaneously. Important developments are occurring in related fields. Hydrology is somewhat ahead of biogeochemistry in adopting data assimilation and techniques exist for assimilating soil moisture and temperature that can be applied in terrestrial biogeochemical models, since water and temperature are controls over carbon processes.

Observational operators

While carbon cycle component models are relatively mature, most carbon models have not been developed for use in assimilation systems. A number of changes will be required in order to provide component and coupled carbon models for carbon cycle assimilation systems. In order to assimilate and integrate a wide range of different observations, the models must include state state variables and parameters related to the observations. Because existing models were developed for a range of more specific applications, few or none include the full range of processes required to link to the full array of available observations. Examples of a missing process (in many models) include wildfire, emerging as a significant contributor to interannual CO_2 variability and longterm ecosystem structure. Examples of a related missing state variable includes tree diameter, the primary variable measured in most forest inventories and flux sites. Missing processes result in model error. Missing variables mean that model output cannot be compared directly to observations. “Observation operators” are often required that relate the model prognostic variable (eg total wood biomass/unit area) to the measured variable (mean diameter/unit area). Observational operators can be as simple as a linear regression, or as complex as a full radiative transfer scheme. While observational operators are not well-developed, models of terrestrial and marine radiative transfer, together with other component models, provide a strong basis for developing such operational operators to couple process models to assimilation systems.

<u>Assimilation systems</u>.

The state of the art in data assimilation is relatively mature, and experience gained in ocean, chemical and meteorological data assimilation will provide a head start for the carbon program. There are two classes of solution methods applied to problems of estimating states or parameters from spatially or temporally distributed observations for large scale nonlinear systems: 4-D variational (4Dvar) and Ensemble Kalman Filter methods (EnKF). The large scale here refers to the number of degrees of freedom in the states or parameters. Both classes of methods assume that the measure of error is minimized subject to the constraints of observations, the equations describing the model physics and biology and prior information about the states and parameters. The primary differences between the the 4DVar and EnKF methods lie in how they deal with the mean and covariance of the error. This is necessarily a technical matter and both methods have advantages and disadvantages. The EnKF produces an estimate of the uncertainty of the solution directly, but does not exactly minimize the cost function. 4DVar estimates the solution exactly, but can only produce an estimate of the full uncertainty if additional calculations are done (computing the Hessian matrix of the cost function). There are other limitations and advantages of each method and research is needed to determine the applicability of specific assimilation techniques for the carbon problem. An initial system, developed for the NCAR-CSU Advanced Study Institute on Carbon Data Assimilation and Observing System Design, made successful use of the variational approach to retrieve fluxes from concentrations.

The carbon problem presents challenges that will require the development of new theory and methodology. Carbon sinks are the result of longterm processes such as forest regrowth and carbon dioxide fertilization, but occur through carbon fluxes that are highly variable in time on daily and seasonal scales. As a result, inferring fluxes on short time scales is only a partial solution to the problem and carbon assimilation will ultimately have to use models that couple time scales ranging from minutes to decades. This is analogous to using coupled atmosphere-ocean models in seasonal-to-interannual forecasting, in which anaomalies such as the El Nino arise from a coupling of “fast”: atmospheric and slower oceanic processes. Assimilation of observations pertaining to these diverse physical time scales into coupled models is at the scientific frontier for meteorological models and the carbon problem poses physical and mathematical challenges of the same order. Estimation of fluxes from concentrations and transport is the first challenge for carbon data assimilation and represents a relatively small extrapolation from existing practice. Carbon cycle “reanalsysis”, the diagnosis of processes and mechanisms and parameter estimation for key carbon cycle processes using assimilation, is a challenging but crucial activity that must be fostered.

Research gaps, challenges, and opportunities

The carbon science community is poised to develop carbon data assimilation systems. Several key gaps exist that must be filled to realize this promise.

1. More interaction is required between biogeochemical modelers, measurement and assimilation system experts, mandating a program of workshops, institutes and research exchanges
2. Component and coupled carbon cycle models must be developed from existing carbon process models, taking into account the requirements of the assimilation systems, and goals (state, flux or parameter estimation)
3. A central clearinghouse for carbon cycle data is needed to enable the development of increasingly integrative assimilation models.
4. Observational operators must be developed to link models and observables in assimilation systems
5. Many assimilation approaches require the development of tangent linear and adjoint models from the underlying process models. Biogeochemical modelers generally lack experience and expertise in these mathematical techniques and support will be required for these powerful tools to be regularly employed.
6. Evaluation of measurement bias. Measurement biases, from representativeness, instrumental, algorithmic or sampling error creates analysis and modeling errors. Assimilation models that will integrate multiple data types will be more vulnerable to bias than inverse models that have largely relied on data from surface concentration networks. The space/time variations in biases from different measurements must be defined as well as possible before use in assimilation systems.

7. Land and ocean biogeochemistry is regulated by longterm processes (eg., ocean circulation and gas exchange, disturbance and recovery of land vegetation) varying over periods much longer than those of most observational records. Assimilation techniques for the carbon system must be developed to account for this "background" in order to provide mechanistic understanding of the present-day variability of fluxes and storage.
8. Basic atmospheric mixing processes, especially PBL mixing and unresolved convection have a major impact on CO_2 distributions and must be understood to estimate surface fluxes from atmospheric observations. Additional analysis, partnership with physical meteorologists and possibly new field studies are required to improve models of these processes for coupled surface-atmosphere assimilation systems.
9. Fossil fuel emissions have generally been defined in carbon cycle studies from data sets with low spatial and temporal resolution. Techniques using atmospheric tracers of fossil fuel combustion and improved socio-economic data are needed to understand fossil emissions in new higher resolution assimilation schemes. These techniques can also help to quantify biomass burning fluxes.

Pilot studies

Participants in the workshop suggested a series of pilot studies that could serve to bring the disparate communities together, provide early scientific payoff and proof of concept and serve as a testbed for increasingly capable assimilation systems. Specific projects could include:

1. Analysis of carbon sources and sinks during the 1997-1998 El Nino. This unusually severe ENSO was coincident with the largest increase in the growth rate of atmospheric CO_2 yet recorded. Diagnosing the controls

over sources and sinks during this period will be test of our understanding. Evidence suggests effects of atmospheric CO_2 from oceanic processes and terrestrial sources, possibly dominated by biomass burning. Explaining the atmospheric CO_2 anomaly will requiring diagnosing ocean state and fluxes, ENSO impacts on land climate, and climate effects on ecosystem metabolism and combustion. Within the 1997-1998 ENSO project, there is scope for high-resolution basin-scale ocean modeling, and global coupled land-atmosphere-ocean modeling, including land use and wildfire components.

2. A North American Carbon Program pilot process analysis. Significant uncertainties exist in interpreting planned North American airborne and tall tower concentration measurements in terms of surface fluxes. PBL mixing, the “rectifier” effect, the representativeness of point samples (tall towers, aircraft profiles) of model grid cells and the use of chemical combustion tracers should be addressed using extant data before new experiments are deployed. Additional data might be obtained opportunistically by adding carbon cycle measurements to already planned experiments led by other disciplines (eg hydrometeorology). This study would require the development of regional coupled land-atmosphere assimilation modelsv, and would provide early tests of such models.
3. Single column time series studies at land and ocean time series sites. Assimilation of multiple constraints on carbon cycle models could be done at longterm measurement sites such as AmeriFlux sites and HOTS/BATS. These 1-D assimilation studies would be a testbed for two aspects of carbon data assimilation. First, they would serve to evaluate the observational operators and information and content for multiple data types (eddy fluxes, satellite visible and microwave radiances, biomass inventories, pCO_2). Second, they require that fast and slow timescales (forest stand development, nutrient upwelling) be coupled and provide a

test of the capabilities of the assimilation approach to reolve multiple time scales.

4. Observing system design. Data assimilation models can be used to simulate the impact of new observations on analyses of carbon sources and sinks. Such studies are needed as the NACP is implemented, to assess the capabilities of satellite systems, and to locate and design new intensive studies. Observing system design studies can also help guide new oceanographic transect inventory studies. While the carbon system is too complex for optimal sampling designs, assessing the marginal return of incremental observations will be extremely useful in resource-constrained situations.

Priorities

We present priorities for support in the near-term, mid-term and long-term, to scope an overall 10-year program. Priorities are based on urgency, feasibility and scientific payoff. We note that this program includes enabling (eg educational), tool-building and research activities and deliverables.

Near-term (1-3 years)

1. Support for training, communication and collaboration. A series of workshops, and summer institutes, following on from the initial summer 2002 Institute at NCAR, along with collaborative visits should be supported to enhance interaction between the carbon measurement, modeling and assimilation communities. Curriculum development for graduate training should be initiated.
2. Prototype assimilation model development. Support is urgently needed for interdisciplinary teams to develop component and coupled prototype carbon assimilation models. Development will include model development, adjoint and tangent linear model development and coupling

to assimilation systems. 1-D (flux tower, time series) and 3- or 4-D systems should all be encouraged.

3. A data clearinghouse activity for carbon modeling should be initiated, allowing a diverse set of carbon cycle data to be accessed and used in integrated studies through a common portal. Bias and error fields should be available along with measurements. NASA's LDAS and NCAR's CDAS systems provide pathfinders for a future carbon system.
4. Early studies of the 1997-1998 El Nino effects on the carbon cycle should be initiated, building on, and possibly guiding, prototype assimilation model development. International coordination of this pilot study should be encouraged.
5. Land CO_2 concentration network. Instruments and data analytical approaches should be developed to integrate concentration and flux measurements. The existing AmeriFlux network will probvide a platform for these activities.

<u>Mid-term</u>

1. Completion and distribution of curriculum and teaching materials for data assimilation and biogeochemical modeling. By year 3 we should be reaching and to and training a new generation of students in advanced techniques for modeling.
2. Development of a multi-decadal reanalysis of carbon sources, sinks and storage in the land, atmospheric and oceanic reservoirs, including fossil and biomass burning fluxes. Such a record, updated periodically as models and data improve, will serve as a benchmark assessment of the magnitude of the major carbon cycle processes, and a foundation for prediction.
3. Development of a data assimilation capability for satellite measurements, including ongoing and planned trace gas measurements from space. Spaceborne measurements have a proven capability to constrain models of the carbon cycle, and improved sensors together with new geophysical

products (CO, CO_2, CH_4) have the potential to contribute. Realizing their potential to constrain surface sources and sinks will require a new analytical approach and intensive communication between modelers and observationalists.

4. Development of a prototype coupled-land-atmosphere-ocean carbon assimilation model or models as a basis for eventual quasi-operational use. The best constraint on the carbon cycle should come when the domains are analyzed simultaneously in a common model. Such a model would assimilate direct (eg CO_2, pCO_2, eddy fluxes) and ancillary (eg ocean color, climate) observations and return fluxes and storage of carbon.

Long-term

1. Assimilation into global coupled climate-carbon system models at process level (with initial states and parameters constrained by data). This achivement would produce a reanalysis of carbon and climate in which physical and biogeochemical variables were estimated together and consistently. This capability should become a benchmark technique for Earth System analysis and prediction.
2. Quasi-operational carbon assimilation experiments should be done, using the coupled carbon model developed in the mid-term phase of the program, meaning analyses produced and regularly updated. Seasonal-to-interannual forecasts of carbon sources and sinks can be done, assuming that human impacts will not change rapidly, but climate effects will result from variations in climate, such as accompany the El Nino cycle. Thus, these carbon forecasts would be tied to SI forecasts of weather.
3. Training in data assimilation techniques should be regularly available for biogeochemists, on a similar basis to advanced training in other fundamental techniques. This will likely include graduate training in a few

centers of excellence, curriculum materials to support programs broadly and short courses and summer institutes for intensive training.

Resource requirements

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