NASA Carbon Monitoring System
Phase 1 Report

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INTRODUCTION

The Fiscal Year 2010 Congressional Appropriation directed NASA to initiate work towards a Carbon Monitoring System (CMS) and provided specific guidance. Funding was made available for pre-Phase A and pilot initiatives for the development of a carbon monitoring system. "Any pilot developed shall replicate state and national carbon and biomass inventory processes that provide statistical precision and accuracy with geospatially explicit associated attribute data for aggregation at the project, county, state and Federal level using a common dataset with complete market transparency, including extraction algorithms and correlation modeling."

The approach NASA developed in following these directions emphasizes exploitation of the satellite remote sensing resources, scientific knowledge, and end-to-end system expertise that are major strengths of the NASA Earth Science program. The approach takes into account data and expertise that are the domain or other U.S. Government agencies and anticipates close communications and/or partnerships with those agencies and their scientific and technical experts. Additionally, it lays the groundwork for CMS-related applications of future satellite sensors now in development (e.g., OCO-2) or from the Decadal Survey (e.g., Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI), Active Sensing of CO2 Emissions Over Nights, Days, and Seasons (ASCENDS), Ice, Cloud, and Land Elevation Satellite-II (ICESat-II)).

NASA's initial Carbon Monitoring System activities involved two pilot studies and a scoping effort. A brief description of each follows:

Biomass and Carbon Storage Pilot Product: A biomass and carbon storage pilot product (to be hereafter referred to as the Biomass Product) was developed. The focus is on quantifying the terrestrial vegetation aboveground carbon stock using consistent approach(es) and performing uncertainty analysis on its magnitude and spatial distribution. The initial emphasis was on production and evaluation of a U.S. biomass and carbon storage product, but a global product also will be planned.

Integrated Emission/Uptake ("Flux") Pilot Product: A global product for integrated emission/uptake (to be hereafter referred to as the Flux Product) was developed. This product was created through a combination of space-based measurements of atmospheric carbon dioxide (from Japan's Greenhouse gases Observing Satellite (GOSAT), NASA's Tropospheric Emission Spectrometer (TES), and other instruments), carbon cycle models and assimilation systems, and observationally-constrained, but model-calculated, information about the processes that couple the surface to the atmosphere.

Scoping Study: The scoping study was to map NASA's evolving observational and modeling capability and the ability of the research and applied science community to use this capability to enhance information products to meet policy and decision-making requirements. This effort will focus on streamlining the flow of information products to decision-makers from future research efforts and planned observation capabilities, allowing NASA to engage the carbon policy and decision-making community.

NASA's CMS pilot activities were carried out through a mix of directed and competed research. The directed research will be localized at NASA Centers where significant expertise on satellite data analysis and computational infrastructure can be leveraged (i.e., NASA Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), and NASA Ames Research Center (ARC)). The competed research will be selected through two mechanisms: 1) consideration of relevant proposals submitted under NASA's annual disciplinary ROSES solicitations and 2) selection of proposals submitted in response to this dedicated ROSES solicitation for Science Definition Team (SDT) members to participate in the development of the two pilot products. The primary purpose of the SDT for the pilot products was to broaden the product development leadership with respect to scientific direction and product evaluation.

The directed work at the NASA Centers emphasized the core effort involved in producing the pilot products. It is expected that the center-based efforts will involve defining, producing, evaluating, and, ultimately, archiving, and distributing the pilot products (the latter two efforts may be done through an existing NASA data center and would thus not be the responsibility of the institution(s) developing the products). The Center-based efforts will be complemented by the work of the competed Science Definition Team drawn from the broad science community to support the development and validation of the pilot products. The scoping study was led by NASA Headquarters (HQ) using a steering team of HQ and NASA Center personnel, and was carried out through a series of workshops (involving currently-funded NASA investigators as well as those from NASA's interagency partners) and directed efforts.

This document summarizes the results of CMS-Phase 1 activities. The report is based on the written contributions from participating investigators from the Science Definition Team, Pilot Projects, and Scoping Studies.

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SCIENCE DEFINITION TEAM (SDT) ASSESSMENT & RECOMMENDATIONS

2.1 Assessment of Phase 1 Activities

- The initial work on the pilot projects provided a mechanism for NASA scientists, both within NASA and through NASA-funded projects, to demonstrate and prove the ability to pull together science and technology from across the agency to answer a focused set of science questions. It allowed NASA to formulate how a CMS multi-disciplinary project could be done and to demonstrate the science and technology capabilities currently in place at NASA.
- While each Phase 1 pilot has some shortcomings, the pilot projects completed some short-term goals laid out at the start of the program. For the Flux pilot, this includes making a first-order assessment of how carbon flux can be measured and modeled in a more comprehensive and complete CMS.
- While a number of approaches are being used to assess the errors associated with the Pilot project, there still needs to be an assessment of the errors present in these data using observations that were produced independently of the data used to generate this product, as well as a cross-comparison with other national scale products.
- Both local and regional products completed with 30-50% accuracy, which is good considering the input data, but not the state of the art achieved on smaller scales.
- Creation of error maps along with biomass maps is a very positive step.
- The use of purely empirical methods for biomass estimation has been expedient in producing useful products.
- Gridded flux estimates upscaled from FLUXNET observations are useful for evaluating the CMS Integrated Flux Product – The upscaling of FLUXNET observations to regional, continental, and global scales provides alternative and independent gridded flux estimates (EC-MOD). EC-MOD can be used to evaluate the CMS Integrated Flux Product in terms of magnitude, spatial patterns, and interannual variability.
- EC-MOD has been used to assess the magnitude, patterns, and interannual variability of global ecosystem carbon and water fluxes as well water use efficiency. Results show that extreme climate events (e.g., drought) and disturbances (e.g., fires) are the dominant sources of the interannual variability of global land-atmosphere carbon fluxes. The severe extended droughts, particularly the 2005 drought, substantially reduced annual GPP, and also reduced net carbon uptake.
- Different global flux products have been compared during the CMS Phase 1, including the bottom-up products, top-down products, and FLUXNET-derived

products. There are large differences among these global products in terms of magnitude and spatiotemporal patterns.

- Different products are at different readiness levels for users. The Biomass product is generally more ready to be communicated to users than the atmospheric flux data.
- Just as the CMS products are diverse, the policy communities are also very diverse. Each Federal, State and local agency and organization has different needs, which range from regulatory requirements to scientific explorations. To be successful, CMS will need to build relationships with each of these communities to show policy relevance for the program.
- CMS science directly relates to the "social cost of carbon" (SCC), a measure required under a presidential Executive Order for use in regulatory impact analysis and developed by the US Interagency Working Group on the Social Cost of Carbon, February 2010.
- The SCC pivots on a "climate sensitivity parameter" established by the Intergovernmental Panel on Climate Change, and this parameter can be directly informed by CMS science.
- "Value of information" techniques can be used to demonstrate the economic value of CMS science in some applications.

2.2 Recommendations for Phase 2:

- For the Flux activity, effort should be put towards finer scale assessment of fluxes that could be used to improve our full understanding of specific carbon cycle processes on atmospheric carbon levels. This could include, for example, a look at areas of abrupt disturbance (e.g. hurricane damage or forest fire) to elicit a "signal" of that disturbance in the atmospheric carbon record.
- Develop a coherent vision for the design of an integrated CMS, with clear linkages to other national efforts focused on carbon monitoring (e.g., FIA, USGS, NOAA)..
- Supplement error maps with detailed error budgets for each estimation approach. Consider error budgets as a principal building block for future CMS systems, and therefore as a principal product of this CMS.
- Include a suite of mission types (e.g. lidar, hyperspectral, InSAR) in CMS design.
- Refine the modeling approach for land-atmosphere fluxes to focus on (i) the evaluation and/or calibration of key spatial input data including photosynthetically active radiation and land cover; (ii) the optimization of key model parameters using Fluxnet observations and state-of-the-art data assimilation (or model-data fusion) techniques, and (iii) the assessment of uncertainties associated with the flux products.
- Evaluate and/or calibrate key spatial input data used as input to the land models as they can lead to significant biases in flux estimates..
- Add full representation of disturbance regime and disturbance effects in flux estimations.

- Conduct uncertainty assessment of the biomass and flux pilot products, A comprehensive, quantitative analysis of the uncertainties associated with biomass and flux estimates is essential for the development and evaluation and use of these products..
- Extend the data period of the CMS Integrated Flux Product –The data period of the bottom-up fluxes should be extended to at least 2000-2012 so that the data can be used to examine the interannual variability of carbon fluxes, particularly the impacts of severe extended droughts and disturbances.
- In Phase 2, CMS should benefit from more communication between known user communities and the CMS Science Team by holding regular meetings, briefings, telecons, and by writing articles, web pages and newsletter articles to let as many people as possible know about the work we are doing and its potential utility to meet their needs for carbon monitoring information.
- CMS needs to design communication strategies to continually reach out beyond the known user community, and bring the needs of these new potential users to the attention of CMS scientists.
- CMS directly links to the federal social cost of carbon. The interagency working group leading the estimation of the social cost of carbon has stated the need for improvements in the key parameter, climate sensitivity. CMS projects directly or indirectly related to this parameter should be linked to the next round of the interagency working group's efforts.
- Global forest carbon measurements remain critical for assessing "leakage" and distinguishing it from measurement error.

PILOT PROJECTS

3.1 Biomass- local (R. Dubayah et al.)

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Introduction
The Biomass Pilot Project is focused on quantifying terrestrial vegetation carbon stocks for the U.S. as well as globally. There are two approaches being implemented. The first is a continental (top-down) approach using remote sensing data products to produce a U.S. biomass map at moderate scales (250 m to 1 km). The second is a local scale (bottom-up) approach that utilizes fine-scale lidar and other remote sensing data to map biomass at 30 m resolution wall-to-wall for select U.S. counties. The objectives of this local scale work are to: (1) develop remote sensing protocols that fuse available remotely sensed observations with existing and new field data; (2) provide accurate validation test areas for the continental-scale biomass work, and: (3) demonstrate efficacy for prognostic ecosystem modeling.

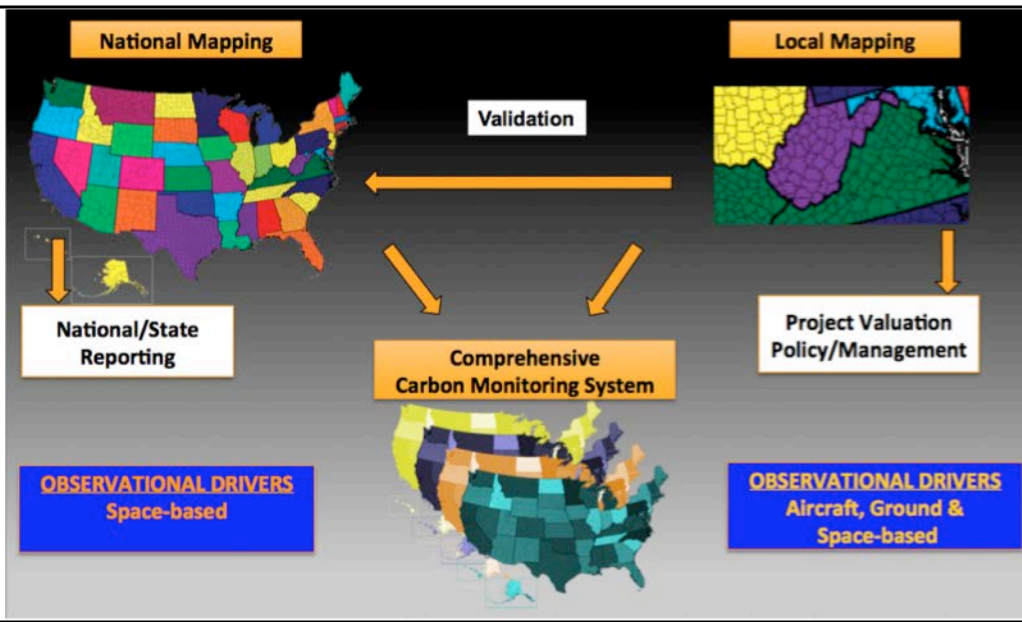


Figure 3.1.a. Nested scales of observation are fundamental to a comprehensive CMS which requires both top-down and bottom-up analysis. Local mapping is critical for project valuation, policy and management activities.

Methodological Approaches
Our approach (Fig. 3.1.b.) combines new field data collection with existing, wall-to-wall lidar mapping of each county, along with existing radar and optical data. The field data were

used with allometry to provide field biomass estimates. The remote sensing data were then used with a subset of these field data in two ways. The first was to drive empirical estimation models. These included machine learning methods (such as random forests) as well as traditional statistical models. The second method uses these data to initialize an ecosystem model (the Ecosystem Demography model) to make estimates of aboveground carbon and flux.

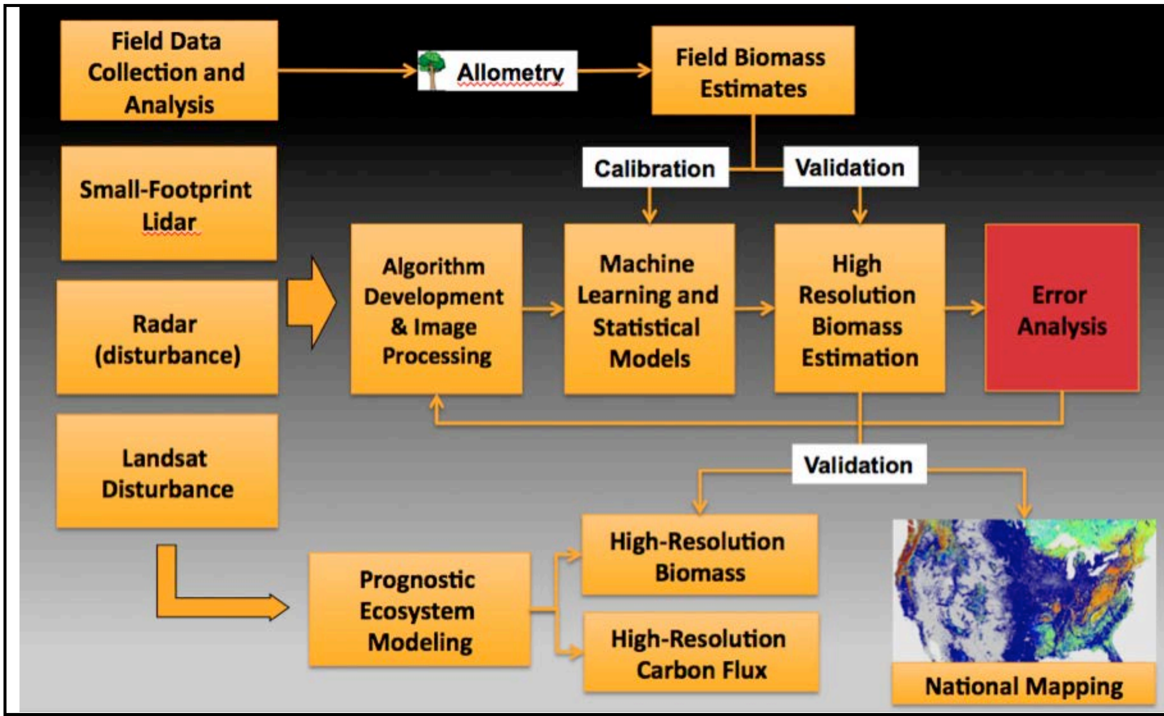


Figure 3.1.b. Overall methodological flow of local-scale CMS activities and the relationship to national mapping efforts.

Two counties in Maryland, U.S. were chosen as the focus areas of our research. Field data included both existing measurements that were part of the U.S. Forest Service Inventory and Analysis network (FIA) as well as 300 new variable radius plots. These plots were distributed using a model-based stratified sampling approach based on land cover class and lidar height class (Fig. 3.1.c and Fig. 3.1.d). The existing lidar data were obtained in 2005 at a point density of about 1 point per square meter. Height percentiles and other metrics were calculated from these. Additionally, ALOS/PALSAR radar data and Landsat time since disturbance products were included as predictive variables.

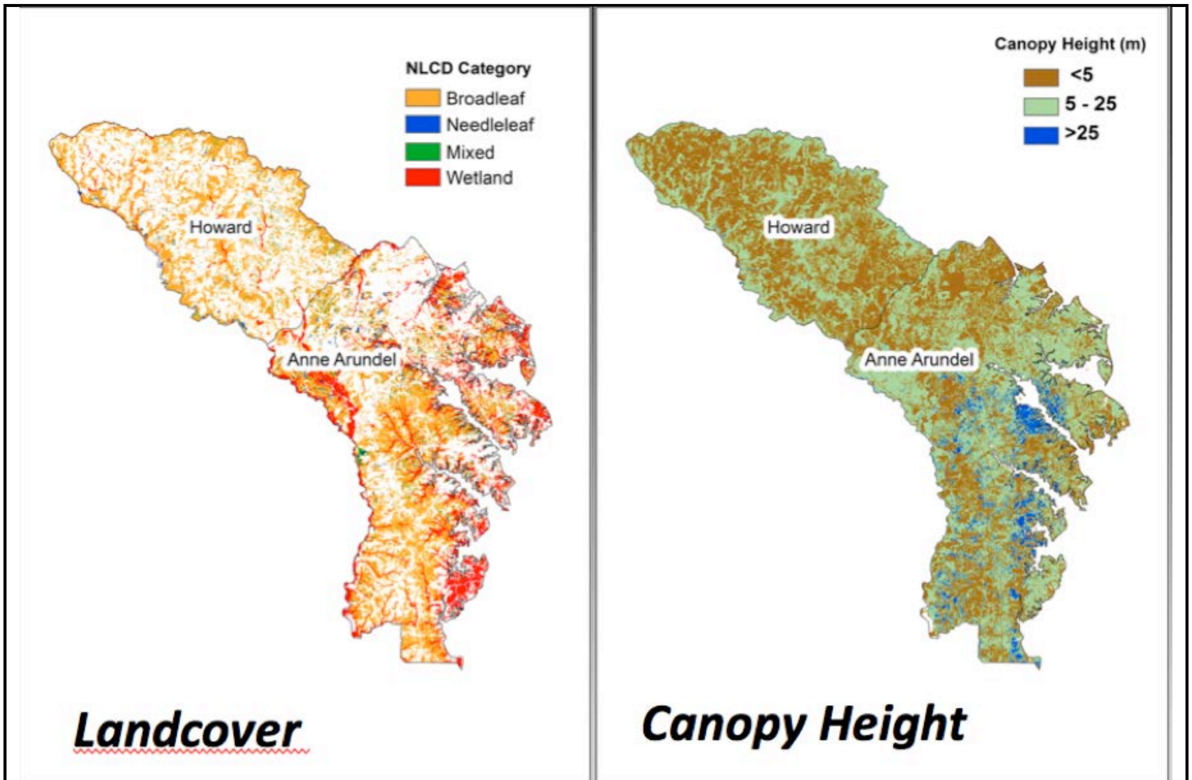


Figure 3.1.c. Field plots were placed into each county according to model-based stratification based on NLCD landcover classes (left) and height classes (right). About 60 new plots were placed in each landcover stratum, and distributed equally between height classes in that stratum (see Fig 3.1.d.).

At each plot, prisms were used to identify trees within and outside of the plot (hence the plots had variable radius). This resulted in about 7-10 trees for inclusion and for which species and dbh were noted. Jenkins equations were then used to obtain allometric aboveground biomass and carbon. The USFS additionally created 20 new FIA-style plots and another 20 variable radius plots for comparison. These were in addition to the existing FIA plot network in the county (which is quite limited).

Figure 3.1.d. Each 30 m grid cell over each county was classified into one of the strata described in Fig. 3.1.c. A set of 300 points was randomly selected (60 in each landcover class) and sampled for biomass. Because of the suburban nature of the counties points could fall outside of forest areas, such as backyards, road medians, and agricultural lands.

Remote sensing data sets

Small-footprint lidar

The primary remote sensing data set was the small footprint lidar acquired by each county. These data were flown about 5 years earlier and are part of continuing efforts by the state for providing up-to date floodplain mapping. These data were obtained wall-to-wall at a point density of about 1 point/m^2. The first and last return data were then used to derive various lidar percentile height metrics. These percentiles were aggregated using a 2m x 2 m forest/non-forest cover map for each 30 m pixel in the counties (Fig. 3.1.e).

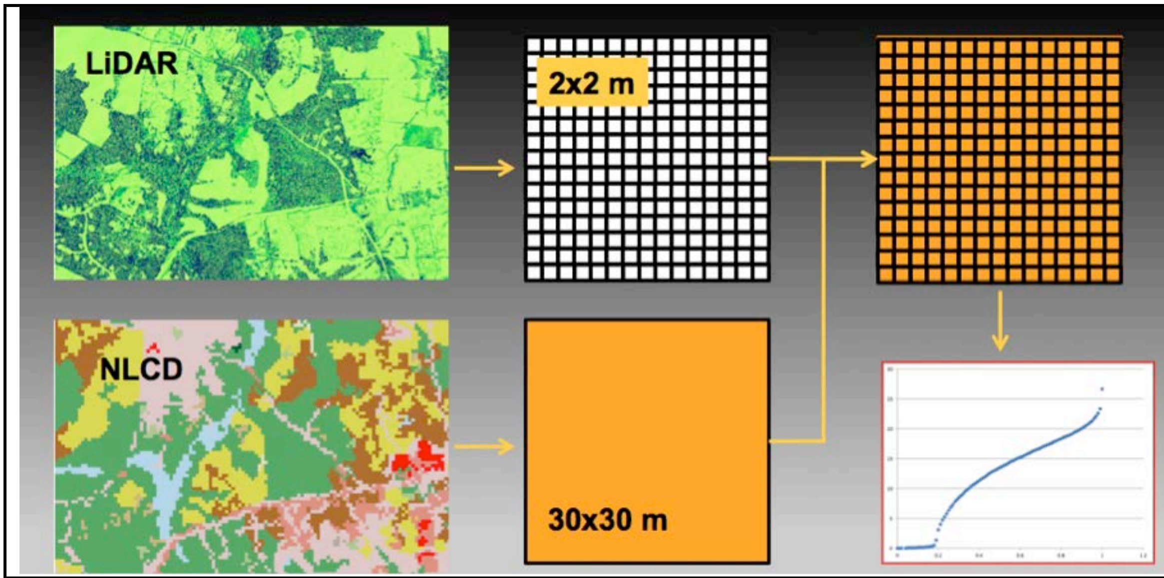


Figure 3.1.e. Lidar height metrics were derived using the first and last return data and a 2m x 2m forest/non-forest map. Heights for forested areas within each 2m pixel were then aggregated to create a percentile height distribution within each 30 m pixel, from which height metrics were derived.

Landsat time since disturbance

Disturbance is one of the one most important factors affecting biomass dynamics. Knowing the time since disturbance provides important information on successional state (and therefore sequestration potential, especially in carbon models) and also for biomass loss from forest patches disturbed after lidar data collection. A 30-year time series of Landsat data were used to create the disturbance mosaic shown in Fig. 3.1.f.

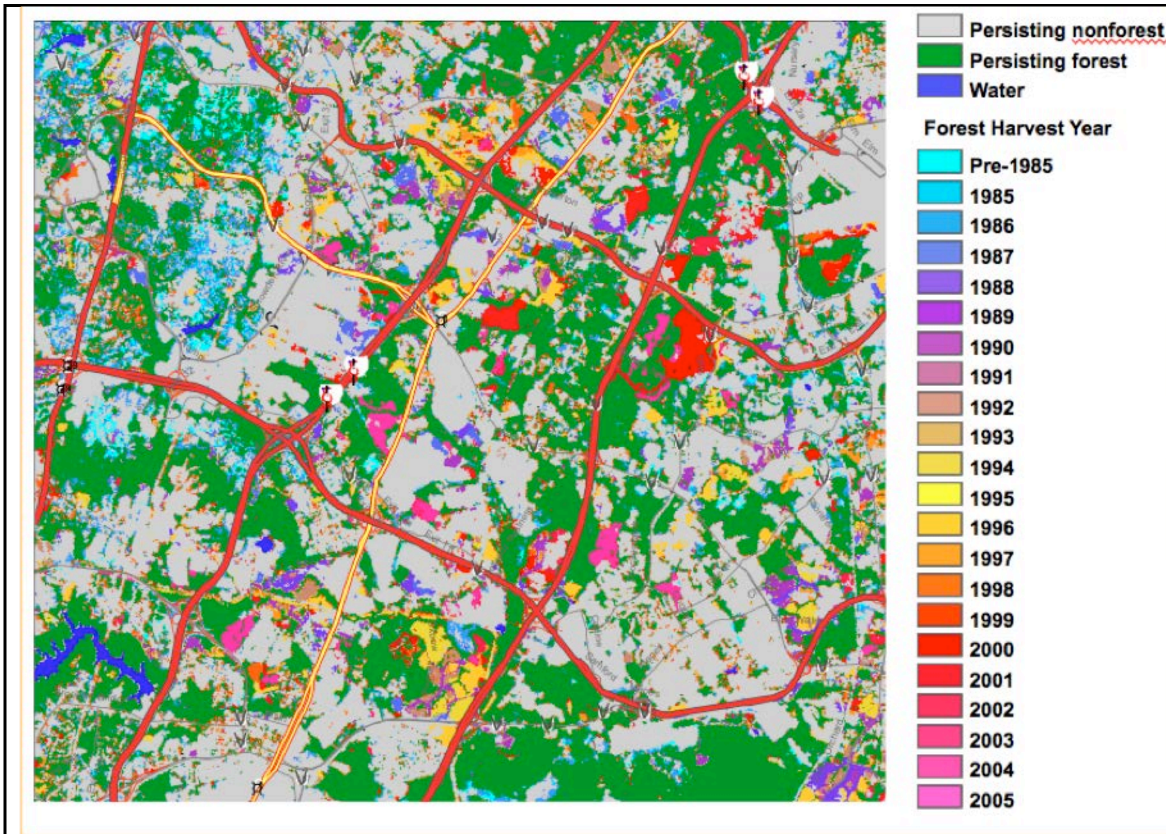


Figure 3.1.f. Landsat time since disturbance for a portion of Howard County in the I-95 Corridor. Because of the suburban nature of the area, much of the forest is fragmented and shows the effects of expansion. Such time-series are critical to any CMS.

Radar data

Radar provides all-weather, wide-area coverage and potentially useful information on ecosystem structure and biomass, especially for lower biomass areas. We processed PALSAR data from the ALOS platform for 5 dates in 2010. These data were geocoded, calibrated and mosaicked to produce a resulting set of images at 30 m resolution matching our baseline grid mapping for the counties (Fig. 3.1.g).

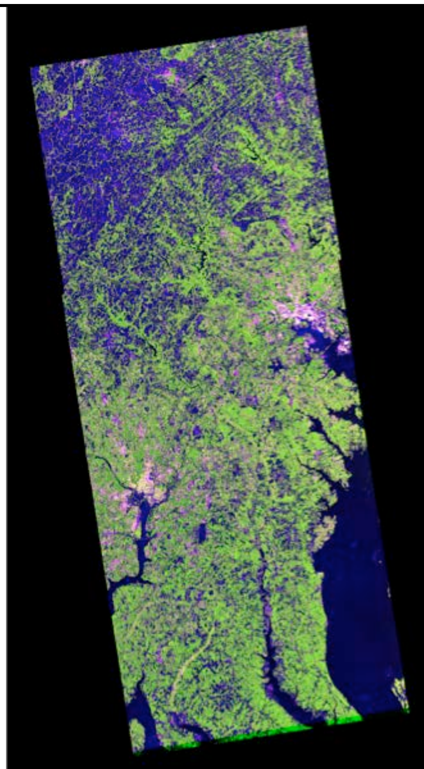


Figure 3.1.g. PALSAR radar mosaic for Maryland study areas.

Statistical approaches

We tested two statistical methods: ordinary least squares regression (OLS), and Bayesian model averaging (BMA). We employed random forest (RF) and quantile random forest machine learning algorithms (QRF). We also evaluated an experimental forest-growth model.

OLS and BMA

We had available many (over 50) predictor variables that could be used in a regression approach. Choosing a smaller number of subsets is a challenging problem, but is important for creating stable models. We limited our regression models to about four variables and employed two methods to achieve this parsimony. The first is a method called "all-possible subsets" that iteratively tries all combination of variables and chooses the ones that provide the most explanatory power and stability. A second method, called Bayesian Model Averaging, uses a Bayesian approach to pick variables.

Random forest and Quantile Random forest

Random forest is a now well-known machine learning procedure widely employed in biomass estimation. It suffers from a common problem of underestimation of high biomass values. To overcome this limitation and to provide robust error bounds, we employed a quantile random forest approach. Such an approach predicts not the median value (as in normal random forests) but a particular quantile. This allows for error bounds (say 5% and 95% quantiles) to be predicted, as well as high biomass values (large quantiles). As far as we know this is the first time such an approach has been used for biomass estimation.

Carbon Modeling Efforts

The ability to evaluate future carbon states rests firmly in the domain of physically-based ecosystem models. Such models predict not only biomass, but carbon flux now and in the future. To be effective these models require accurate initialization data, most importantly, current forest status (age and structure). In addition, information on climate and soils is also required. We used the Ecosystem Demography model (ED) for our efforts here. No ecosystem model has been run at the resolution of our county data (1 ha) over such a large area (and indeed the computation effort was equivalent to running ED globally at coarse resolution).

Climatological and soil data were obtained and processed for the counties. Then a series of experiments was performed to evaluate the effect of increasing resolution and adding successional state and structure to the models, that is going from what is basically a potential vegetation model to one that is predicting actual carbon status at the resolution required. A summary of these experiments is given in Fig. 3.1.h.

ED Version	1° Climate	0.25° Climate	1° Soil	1ha Soil	Lidar	LandSat Forest/ Non Forest Mask
Version 1.x, Abiotic/Technologial Focus: Designing repeatable, robust process for running ED at high resolution						
1.0	x		x			
1.1	x			x		
1.2		x	x			
1.3		x		x		
1.4	x			x		x
1.5	x			x	x	x
1.6		x		x	x	x

Figure 3.1.h. ED was run using a variety of input layers at varying resolutions, with V1.6 the most sophisticated.

Use of the ED model also required detailed model species allometry refinements to run at such high resolutions for the mid-Atlantic region. This required a considerable validation effort (Fig. 3.1.i).

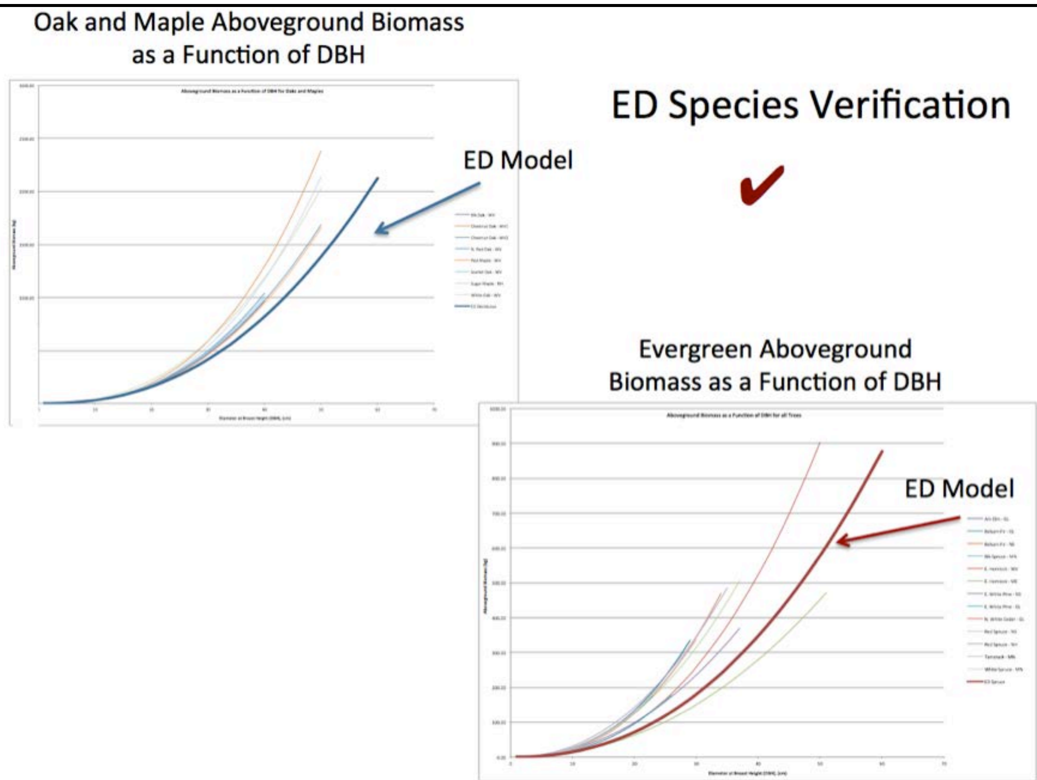


Figure 3.1.i. ED species curve validations. DBH/biomass for individual species curves are shown. ED uses a generalized allometric equations to represent different functional types. The ED model correctly captured the correct relationships after adjustment for use in CMS.

Results

Empirical modeling

We compared our four models (OLS, BMA, RF & QRF). Results were similar, with RMSE values of 79, 75, 66.5 and 63 Mg/ha for OLS, BMA, RF and QRF, respectively (Fig. 3.1.j). Total county biomass (Fig. 3.1.k) compared well in all methods. Results also compared well with estimates from FIA for forested lands (e.g 13.6 Tg for CMS vs 13.5 Tg). However, FIA estimates for non-forest (e.g. urban and suburban areas) were much lower than CMS estimates (2.1 Tg vs. 5.6 Tg) (Fig. 3.1.l). Maps of biomass from each method were generally quite similar, but showed some variation at local scales (Fig. 3.1.m).

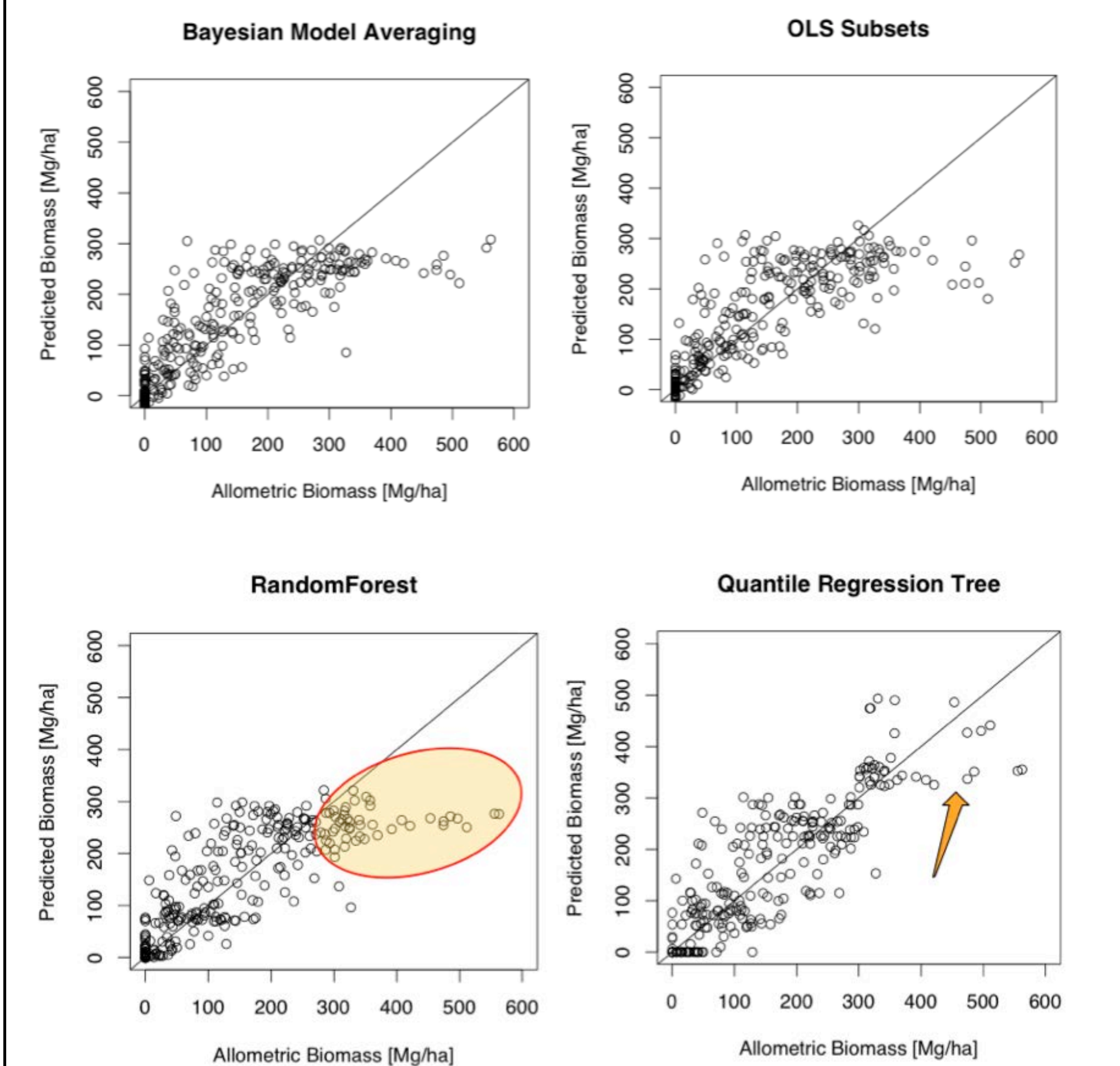


Figure 3.1.j. Results from four different approaches to biomass estimation. All models performed similarly however QRF is the only one that produces an unbiased estimate of higher biomass regions (essentially pushing the underestimates shown in the oval circle up to the 1:1 line).

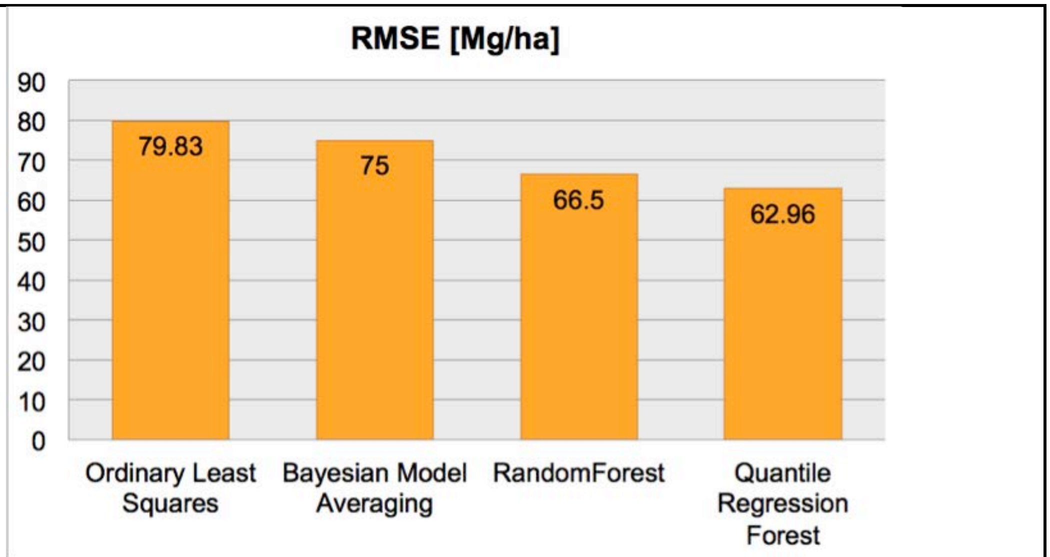


Figure 3.1.k. Results from four different empirical approaches (see Fig. 3.1.j). Although all models are similar, QRF performs significantly better than OLS approaches.

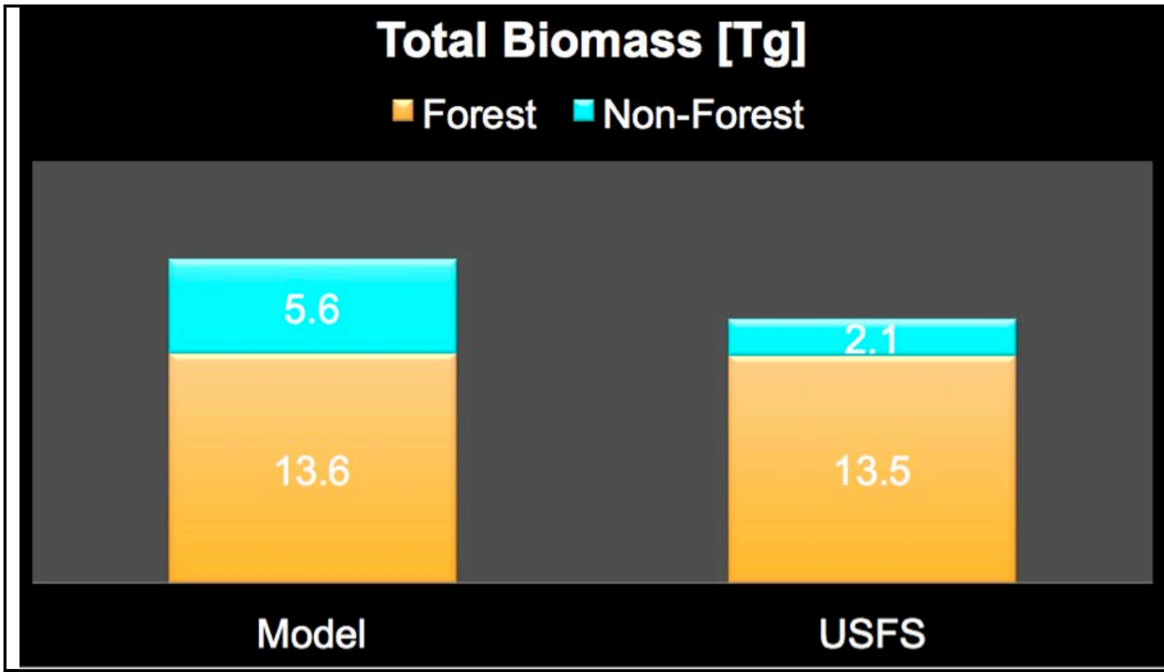


Figure 3.1.l. Comparison of one CMS estimate (BMA) of biomass with USFS-FIA plot estimates. Model and USFS results are essentially identical of forested areas (that is areas classified as forest by NLCD), but diverge strongly for non-forest areas. This is a reflection of the fragmented and suburban nature of the counties and shows that non-forest areas are a significant pool of carbon that must be accounted for properly.

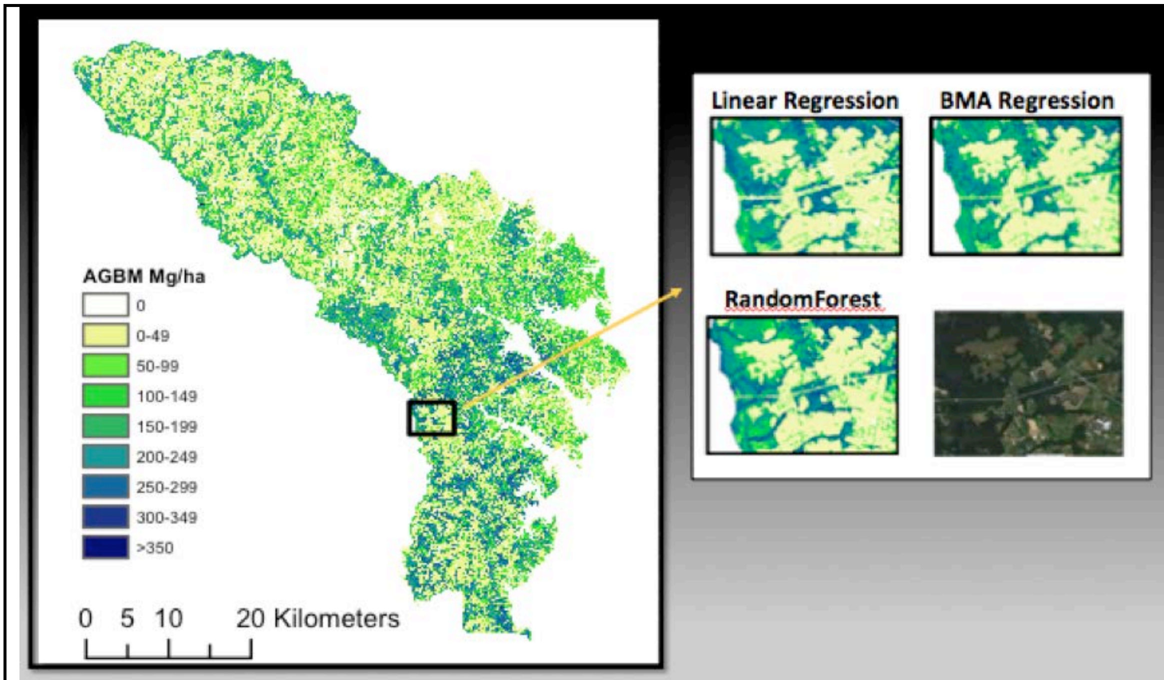


Figure 3.1.m. Above ground biomass for two Maryland counties. Map shown on left was generated using the BMA approach. Insets show detail of maps generated using different methods and visible imagery of the inset (bottom right).

Error maps

Providing estimates of uncertainty is critical for CMS. Both OLS and QRF provide clear and theoretically sound bases for providing such maps. Shown below (Fig. 3.1.m) is one such example (generated for BMA). For any 30 m pixel in the counties, the 5% and 95% confidence interval is known.

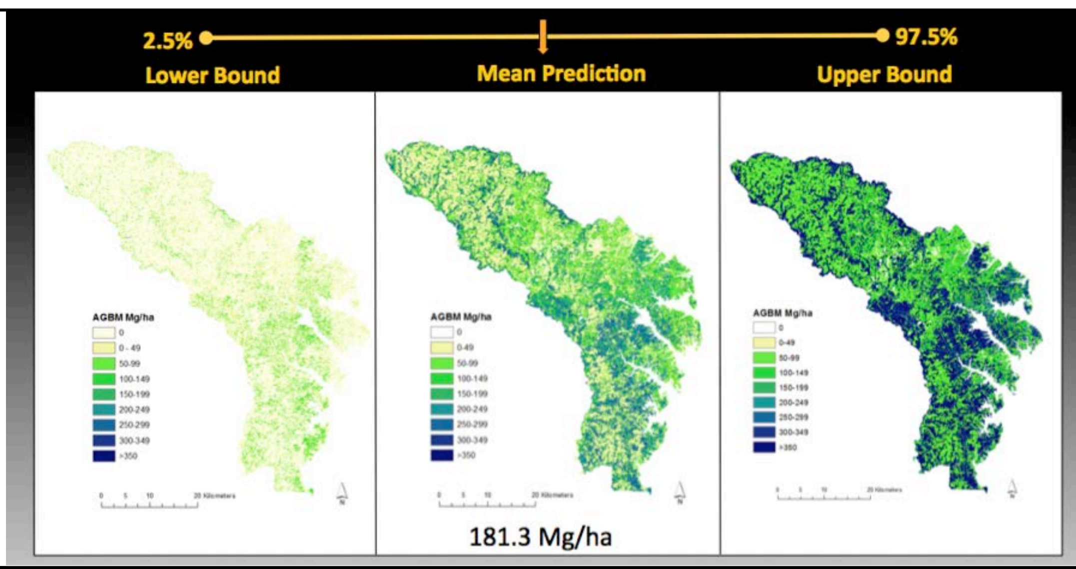


Figure 3.1.n. Error maps from BMA biomass predictions. Note that the lower and upper bound maps give the 95% confidence interval for any particular 30 m pixel.

Radar modeling

Biomass was also estimated using radar data alone. These results are similar to other radar modeling efforts, with saturation at high biomass (Fig. 3.1.n).

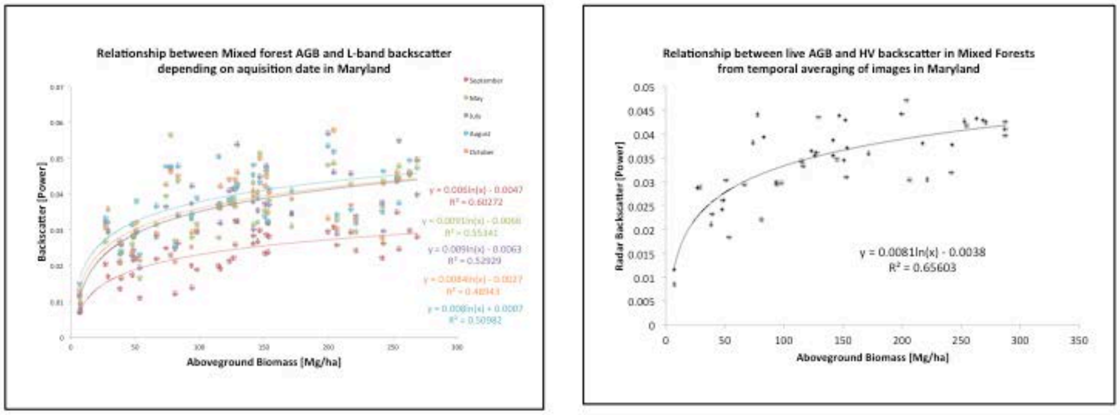


Figure 3.1.o. Relationship between PALSAR backscatter and biomass. Temporal averaging strengthens the relationship but still saturates at higher levels of biomass. Radar metrics were not picked by regression and machine learning models (mainly because of domination by lidar metrics).

ED carbon modeling

The ED model was run for the cases outlined earlier, from the simplest (and in theory least accurate) realization using no canopy structure and 1 degree climate and soil inputs, up to the most refined realization, using actual canopy heights from lidar, Landsat disturbance, 1 ha soils, and 0.25 degree climate. The results are summarized in Fig. 3.1.n. and maps of biomass are shown in Fig. 3.1.o.

ED Version	Input Description	Total AGB (dry wt kg)	Total C (Tg C)	Avg AGB (kg C/m2)	Avg AGB (Mg/ha)
1.0	1degclim1degsoil	4.90E+10	24.51	14.67	293.48
1.1	1deglim90msoil	5.53E+10	27.66	16.56	331.31
1.3	0.25clim90msoil	6.87E+10	34.35	20.57	411.30
1.4	1degclim90msoil(mask only)	3.87E+10	19.40	11.61	232.34
1.5	1degclim90msoil (mask+lidar)	4.54E+10	22.70	13.59	271.87
1.6	0.25clim90msoil (mask+lidar)	3.29E+10	16.46	9.86	197.17

Figure 3.1.p. Results from ED experiments. Using no height initialization and coarse soils and climate (V1.0 and left Fig. 3.1.o) results in far different biomass estimates relative to using lidar height initialization and fine-scale soils and climate (V1.6 and right Fig. 3.1.o).

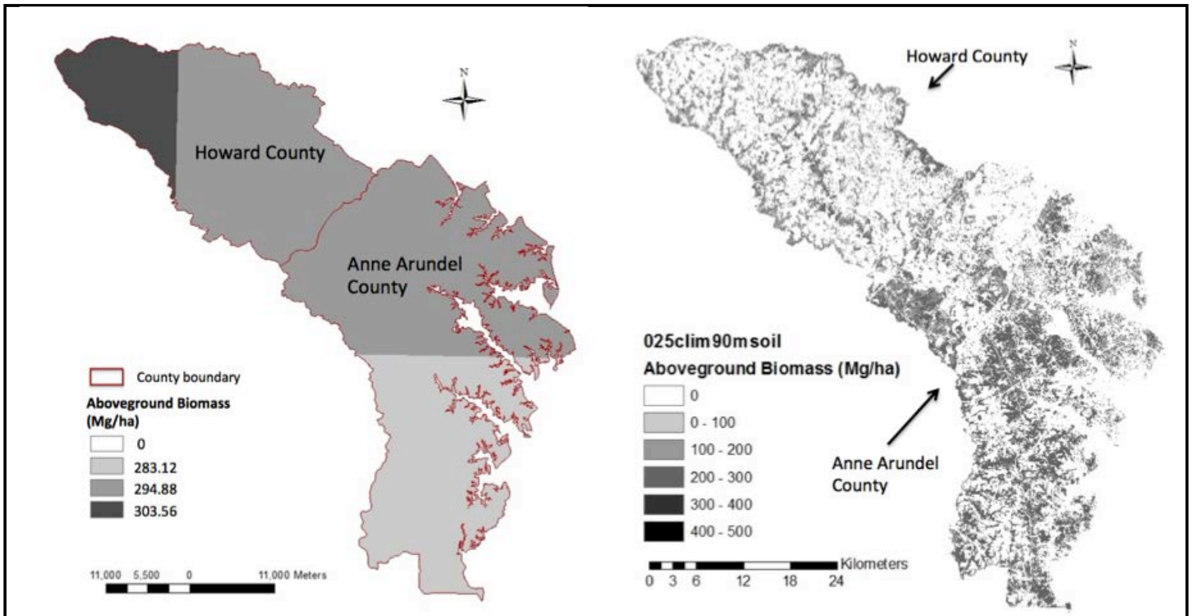


Figure 3.1.q. ED biomass results for V1.0 (left) and V1.6 (right). Clearly, carbon models must use high-resolution inputs to be effective for most CMS activities.

Considerations and Conclusions

Given the staleness of our lidar data and our limited field sampling, our results were quite encouraging. We conclude the following: (1) Existing lidar data sets are useful for biomass mapping in the U.S. at local scales, even if they are several years old and of low point density; (2) Rapid field-survey methods are accurate and appropriate; (3) Choice of statistical estimation method is not critical, though some methods appear more accurate; (4) High-resolution mapping is required to accurately estimate non-forest biomass; (5) County-based lidar data sets should form the basis of local CMS efforts, both in the U.S. and abroad; (6) Carbon modeling is critical but must have appropriate input data; in particular high-resolution canopy structure data and soils.

Publications

Rosette, J., J. Suárez, R. Nelson, S. Los, B. Cook, and P. North. Lidar remote sensing for biomass assessment. 2012. In L. Fatoyinbo (ed.) Remote Sensing of Biomass: Principles and Applications. InTech Open Access Publisher, http://www.intechweb.org, ISBN: 978-953-51-0313-4.

Finley, A. O., S. Banerjee, B. D. Cook, and J. B. Bradford. 2012. Hierarchical Bayesian spatial models for predicting multiple forest variables using waveform LiDAR, hyperspectral imagery, and large inventory datasets. International Journal of Applied Earth Observation and Geoinformation (in press). http://dx.doi.org/10.1016/j.jag.2012.04.007.

Dubayah *et al.* (in prep.). A Local-scale Carbon Monitoring System for Meeting National Climate Priorities. Carbon Management.

Hurtt *et al.* (in prep.). High Resolution Ecosystem Modeling for Carbon Monitoring. Carbon Management.

Cook et al. (in prep). G-LiHT: Goddard's LiDAR, Hyperspectral and Thermal airborne imager. Canadian Journal of Remote Sensing.

Rosette *et al.* (in prep.). Biomass change estimation within NASA's Carbon Monitoring System. Canadian Journal of Remote Sensing.

Rosette *et al.* (in prep.). Multi-sensor, high resolution remote sensing for forest assessment within NASA's Carbon Monitoring System initiative (CMS). European Journal of Remote Sensing.

Swatantran *et al.* (in prep.). Estimating Biomass Change in a Western and Eastern Forest. Remote Sensing of Environment.

Johnson et al. (in prep.). A Comparison of National Biomass Maps using FIA and CMS data.

3.2 Biomass national (S. Saatchi et al)

Participants
Bruce Chapman, Annmarie Eldering, Martha Farfan, Alexander Fore, Sangram Ganguly, Ziad Haddad, Thomas Hilker, Michael Lefsky, Shadi Oveisgharan, Sassan Saatchi, John Worden, Yifan Yu, Gong Zhang

Introduction
During the CMS-BP1 study, we developed forest aboveground biomass (AGB) products that are currently under evaluation and uncertainty analysis for a final release to the public by the end of FY2012 (September, 2012). These products provide the spatial distribution of forest height and biomass in all the US forestlands in the 48 conterminous states at 100 m (1-ha) spatial resolution (Fig. 3.2.a). The methodology is based on a previously developed combined parametric and non-parametric multi-scale spatial model (using satellite observations from optical passive sensors (MODIS and Landsat), synthetic aperture radar (SAR) observations (ALOS PALSAR at HH and HV polarizations), and Forest height derived from GLAS Lidar observations from ICESAT-I satellite. The products were developed to meet three objectives: (1) to use the FIA data as the source of inventory to train the spatial model and estimate the forest biomass over all forestlands; (2) to use GLAS Lidar forest height (H) and an AGB-H allometry derived from FIA inventory data for the US forest types to train the model for spatial mapping of biomass; and (3) to assess the uncertainty of the products by comparing with the county-scale FIA assessments of forest area and carbon stock and high resolution Lidar derived biomass map products acquired over selected US counties. The goal of the CMS-BP1 project is to produce a final product based on either FIA or GLAS training data or to combine the products to develop the final product with the least uncertainty.

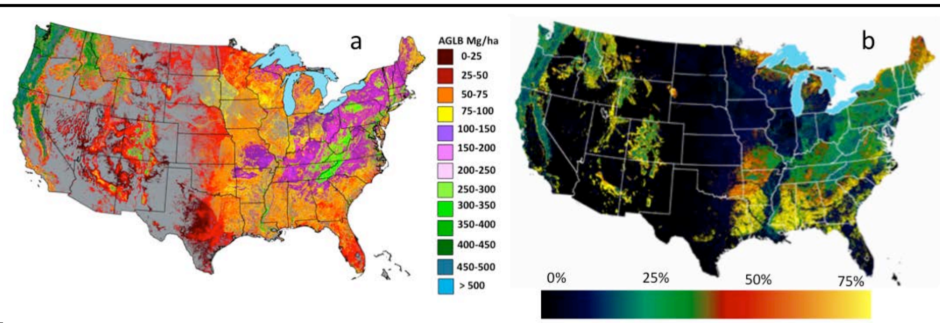


Figure 3.2.a. Unpublished preliminary aboveground biomass map of US forestlands at 100m spatial resolution (a) along with pixel level uncertainty derived from combining measurement, sampling, allometry, and prediction errors (b).

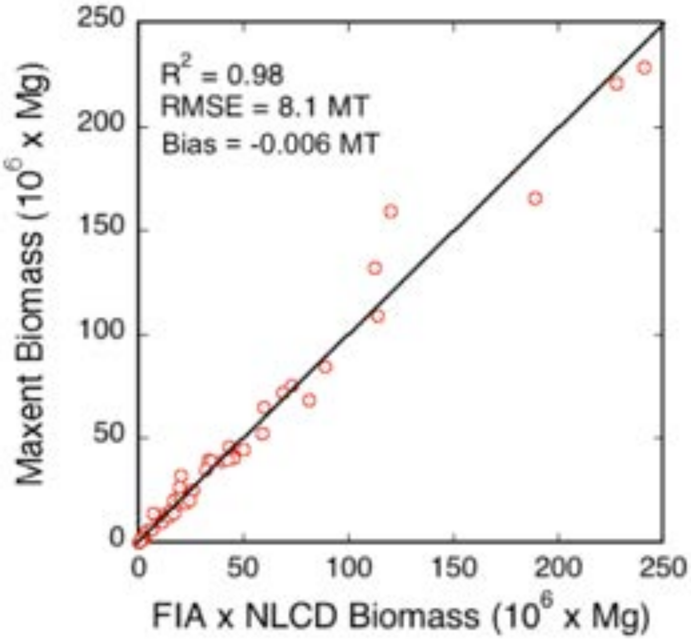


Figure 3.1.b. County scale comparison of CMS product derived from spatial modeling (MaxEnt) of GLAS Lidar height and FIA derived carbon stock using NLCD estimates of forest area in each county.

The methodology and the characteristics of the final products and the uncertainty analysis have been developed through a series of discussions with the CMS team members and science definition team. The overall approach was built based on the principles of transparency, consistency and completeness. These were the same principles used in the IPCC National GHG inventory guidelines (Penman et al., 2003). We also followed the IPCC good practice guidance in developing the CMS-BPI products such that they are accurate as far as can be judged (with relatively low or no bias at the US county or state scales) and uncertainties can be reduced as new information becomes available.

At the end of the CMS-BPI (September, 2012), all products and documentations will be released to the public. An error propagation model developed by the CMS team will produce an end-to-end uncertainty analysis of the methodology by taking into account the measurement, allometry, sampling, and prediction errors and propagating them throughout the system (Saatchi et al., 2011; CMS Science Definition Document, 2011). The preliminary results from the Phase I study suggest that: (1) We need to have a better definition of forestlands, that is the applied uniformly by all data producers—at present there are significant differences between the Forest Inventory and Assessment (FIA) area of forest cover and the USGS National Land Cover Data products. We will explicitly address this error in the Phase II study. (2) There are various errors associated with the allometry used in FIA data and in converting Lidar height to biomass that introduce large uncertainty in overall carbon stocks and fluxes. (3) Different satellite-based estimation models can provide precise and relatively unbiased estimates of forest biomass stock at large scales (counties and states), allowing the application of the CMS products for county and large-project-scale analysis. However, significant differences exist at the pixel scale (1 ha), suggesting a requirement for pixel scale uncertainty for CMS spatial products. Pixel scale uncertainties were particularly large in the eastern US where multiple species and fragmented forests dominate the landscape.

Data Products

ALOS PALSAR Radar wall-to-wall mosaic at 100 m resolution for the US and Alaska for three periods (2007,2008, 2010).

Landsat derived LAI and vegetation index (NDVI) product at 30 m resolution over continental US (circa 2005).

MODIS 250 m vegetation index for North America (Circa 2005).

Forest aboveground biomass map at 100 m resolution for the US.

Uncertainty of forest biomass products and comparison with published results.

Publications

Zhang et al. Mapping Stand Age of global primary forests Using Remote Sensing Data, submitted to JGR, 2013.

Ganguly, S., R. R. Nemani, G. Zhang, H. Hashimoto, C. Milesi, A. Michaelis, W. Wang, P. Votava, A. Samanta, F. Melton, J. L. Dungan, E. Vermote, F. Gao, Y. Knyazikhin, and R. B. Myneni (2012), Generating global leaf area index from Landsat: Algorithm formulation and demonstration, Remote Sensing of Environment, http://dx.doi.org/10.1016/j.rse.2011.10.032.

Zhang et al., Estimation of forest aboveground biomass in California using canopy height and leaf area index estimated from satellite data, Remote Sensing of Environment, In Press, 2013.

3.3 Flux (S. Pawson et al.)

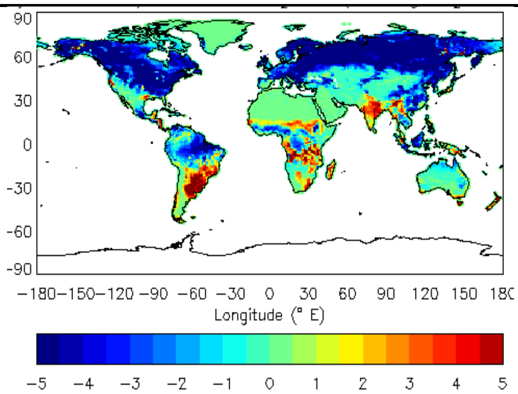
Participants
Kevin Bowman, Holger Brix, Joshua Fisher, Jim Collatz , Watson Gregg, Mike Gunson, Chris Hill, Randolph Kawa, Stephen Klooster, Meemong Lee, Junjie Liu, Dimitris Menemenlis, Lesley Ott, Steve Pawson, Aaron Polhamus, Christopher Potter, Cecile Rousseaux, Fanwei Zeng, Zhengxin Zhu

Introduction
The CMS Phase-1 "Flux-Pilot Project" (FPP) has computed global CO_2 fluxes between the land biosphere and the atmosphere and between the oceans and the atmosphere for several years, focusing on the period 2009-2011. The computations include some measures of uncertainty. Large volumes of space-based observations were used along with models of the physical and biological processes in the land and ocean, and transport in the atmosphere and ocean. Meteorological information for the system has mostly been obtained from NASA's GEOS-5 analyses (the Modern-Era Retrospective analysis for Research and Applications, MERRA dataset), themselves a product of in-situ and space-based observations and a global general circulation model. The GEOS-5 analyses and the unique satellite observations provide the unifying element of the "system of systems" used to compute carbon exchange. The major achievements of the FPP have been:

- The use of numerous satellite observations of different quantities of the Earth system along with complex models to compute fluxes of CO_2 at the interface of the atmosphere and the land/ocean.
- Computation of "bottom-up" CO_2 fluxes between the land biosphere and the atmosphere and between the ocean and the atmosphere, using two methods for each estimate.
- Including these "bottom-up" CO_2 fluxes, along with other known emissions, in an atmospheric transport model to compute global atmospheric CO_2 concentrations, which are subsequently evaluated using multiple types of atmospheric observations (e.g., surface networks; GOSAT data).
- The development and implementation of a new atmospheric inversion, based on the adjoint of the GEOS-Chem model, which has been used to derive new land-biosphere CO_2 fluxes that are consistent with GOSAT retrievals of atmospheric CO_2 concentrations.
- The exchange of ideas and information among team members with diverse expertise in the terrestrial biosphere, oceans, and atmosphere, which has heightened awareness of the processes involved at the interfaces of the systems and which has enhanced the progress towards coupling of these systems,

CO_2 Exchange Between the Land Biosphere and the Atmosphere
Carbon exchange between the atmosphere and the land biosphere was computed CASA-GFED. Meteorological information used was obtained from the GEOS-5/MERRA reanalyses (Rienecker et al., 2011), but constraints on vegetation were used from AVHRR in CASA-GFED.

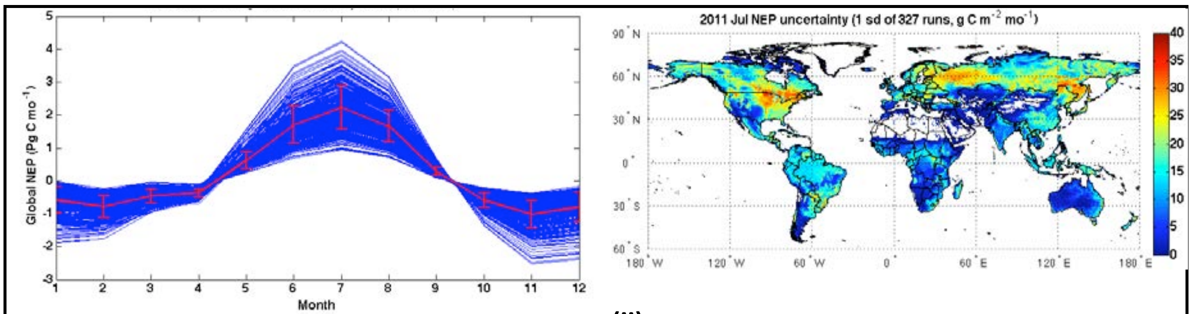
Figure 3.3.a illustrates the fluxes for July 2009. The Net Ecosystem Exchange (NEE) for CASA/GFED (Fig. 3.3.a.i) shows strong uptake over the northern vegetated regions, where photosynthesis dominates respiration in the summer months.



(i)

Figure 3.3.a. (i) The Net Ecosystem Exchange (NEE), the CO_2 flux from land biosphere to atmosphere, in July 2009 as computed by the CASA/GFED system.

Aside from differences among diagnostic models, uncertainty in NEP can arise from the choice of parameters chosen in any one model. This parametric uncertainty has been examined in CASA/GFED by varying three parameters by ±20%. These parameters cover uncertainties in the sensitivities to NPP, the temperature impacts on respiration, and the impacts of moisture stress. A 327-member ensemble of diagnostic computations reveals considerable range in the annual cycle of uptake and emission of carbon to the land biosphere (Fig. 3.3.b.i). The largest local responses occur in regions with the largest NEP (Fig. 3.3.b.ii).



(i) **(ii)**

Figure 3.3.b. (i) The monthly mean global NEP in 2011 for a 327-member ensemble of CASA/GFED computations, spanning a ±20% range of variability of three model parameters. (ii) The global distribution of standard deviation (over the ensemble members) of NEP in July 2011.

Ocean-Atmosphere CO_2 Fluxes

The NASA Ocean Biology Model (NOBM: Gregg and Casey, 2007) includes a physical ocean model along with biogeochemical process model. MERRA reanalysis products were used to force NOBM to estimate surface carbon inventories and fluxes in the global oceans. CO_2 exchange between ocean and atmosphere follows Wanninkof (1992), using the partial pressure difference across the interface and the surface wind speed. The model was spun up for 200 years using MERRA climatological forcing and atmospheric pCO_2 data for the year 2000. The model exhibited skill for ocean dissolved inorganic carbon (DIC), partial pressure of ocean CO_2 (pCO_2) and air-sea fluxes (FCO_2). The MERRA-forced model produced global mean differences of 0.02% (approximately 0.3 μM) for DIC, -0.3% (about -1.2 μatm;

model lower) for pCO_2, and -2.3% (-0.003 mol C m^{-2} y^{-1}) for FCO_2 compared to in situ estimates. Note that there is some uncertainty with the in-situ estimates, which are the public archives of in situ carbon data and estimates from the Lamont-Doherty Earth Observatory. Basin-scale distributions were significantly correlated with observations for all three variables ($r=0.97$, 0.76, and 0.73, $P<0.05$, respectively for DIC, pCO_2, and FCO_2). All major oceanographic basins were represented as sources to the atmosphere or sinks in agreement with in situ estimates. However, there were substantial basin-scale and local departures.

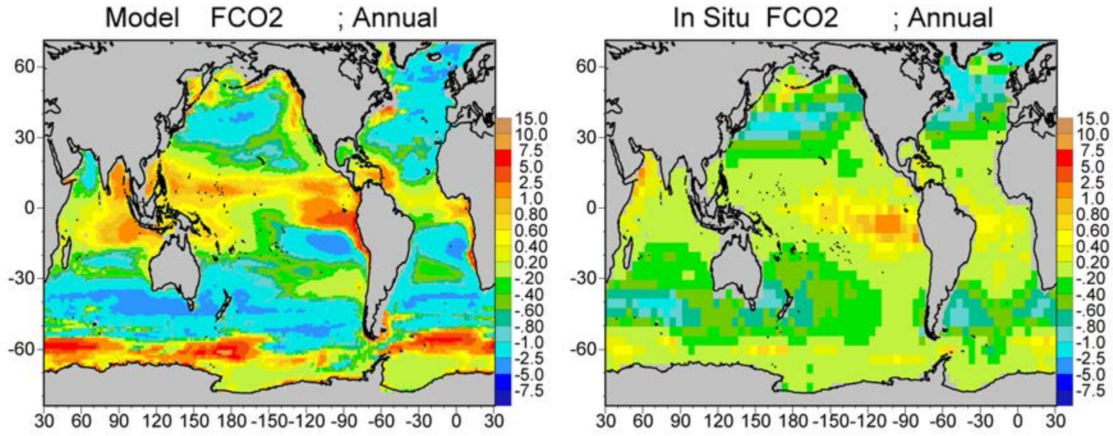


Figure 3.3.c. The annual mean ocean-atmosphere CO_2 flux (Mol C m^{-2} yr^{-1}) for 2009 computed from data-constrained NOBM (left) and the LDEO in-situ estimate (right).

The ECCO2-Darwin estimates of ocean-atmosphere CO_2 fluxes, computed at JPL/UCLA in collaboration with MIT, is a new product based on a data-constrained simulation of the time-evolving physical ocean state from the Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) project (Menemenlis et al., 2008). ECCO2 data constraints include sea surface height (Jason-1 and OSTM), sea surface temperature (AMSR-E), and vertical temperature and salinity profiles (ARGO). Biological components were provided by the Darwin project using a novel model of marine microbial communities (e.g., Follows and Dutkiewicz, 2011). Carbonate chemistry follows the simplified model proposed by Follows et al. (2006) and air-sea CO_2 exchange is parameterized as per Wanninkof et al. (1992). Substantial improvements were introduced into this system, leading to a shift in the fluxes between the first and second versions of the product (Fig. 5: pale blue and red lines).

Figure 3.3.d. also shows two global carbon flux estimates from NOBM. The first (purple curve) shows the offline estimate included in Fig. 3.3.d. This slowly varying estimate is based on monthly surface winds and a specified atmospheric CO_2 partial pressure that does not account for spatial variations. The more recent, online, estimate represents an attempt to include the local characteristics of the flow, using pre-computed oceanic partial pressures along with local atmospheric partial pressures and wind speeds, varying continually in the GEOS-5 atmospheric model. This leads to much stronger day-to-day variations in the NOBM flux – in this regard bringing more similarity to the ECCO2-Darwin estimates. The two estimates have distinctly different seasonality.

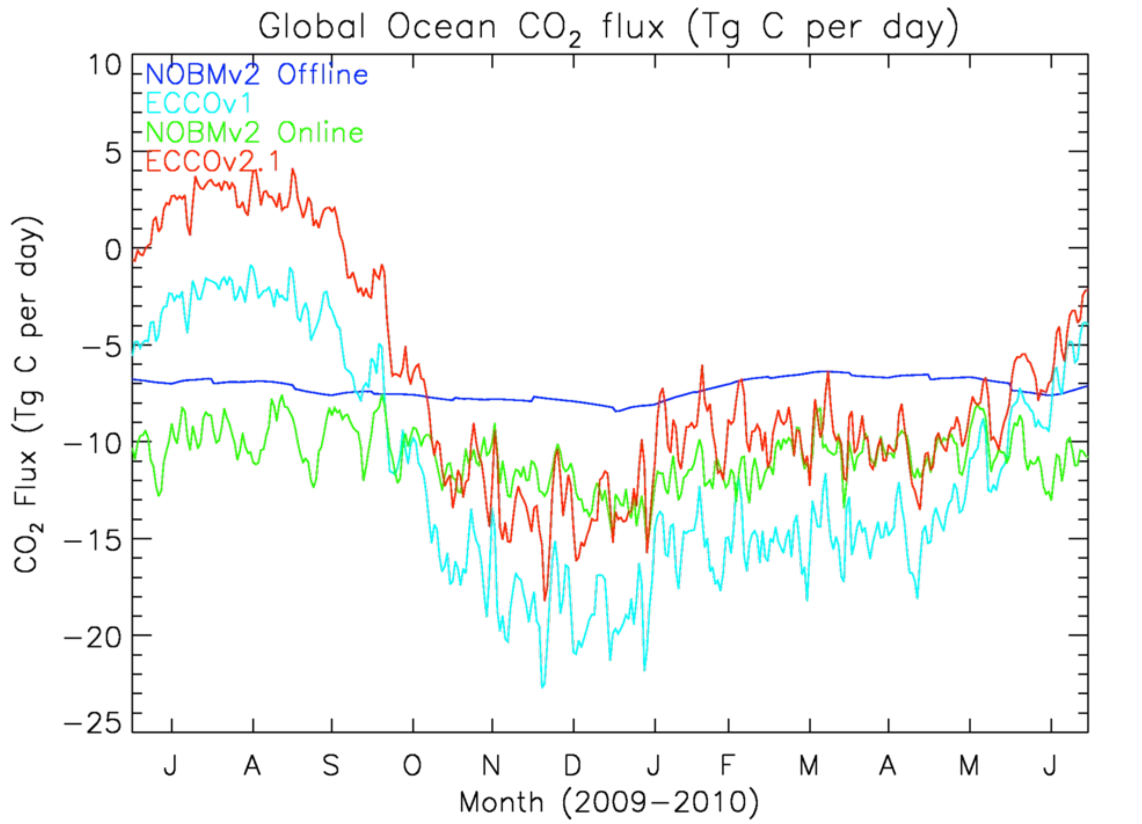


Figure 3.3.d. Time series of the global air-sea CO2 flux for July 2009 through June 2010 from two versions of ECCO2-Darwin (V1, blue line, and V2, red line). Two versions of NOBM are also shown: the purple line shows the "offline" version and the green line shows the "online" version.

Integrated Evaluation using GEOS-5 Transport Modeling

In addition to its use as part of the GEOS-5 data assimilation system, NASA's GEOS-5 model is used to transport constituents, with or without chemical destruction and loss (e.g., Ott et al., 2011). For the CMS project, GEOS-5 has been configured to simulate the emission, uptake and transport of several different CO_2 tracers representing differing combinations of land and ocean fluxes (CASA/GFED; NOBM or ECCO2-Darwin). Additional anthropogenic CO_2 sources were specified from the Carbon Dioxide Information Analysis Center dataset (CDIAC: Boden et al., 2011), to ensure that the major contributions to the atmospheric CO_2 budget were included. In this manner, different combinations of surface fluxes can be mapped to atmospheric CO_2 concentrations, which can be evaluated using in-situ CO_2 observations at the surface or from aircraft, and also to compute suitably weighted columns for comparison with space-based observations, such as GOSAT.

Evaluation of the different sets of fluxes has been performed against several observed datasets. Figure 3.3.e. shows the evaluation using Version 2.9 X_{CO2} retrievals from GOSAT (the ACOS product: O'Dell et al., 2012; Crisp et al. 2012) for the period December 2009 through January 2010. The GEOS-5 simulations were sampled according to the GOSAT observation locations, with appropriate kernels, and the retrievals were bias corrected appropriately.

(iii) OBS – Model (CASA/GFED,ECCO2) (iv) OBS – Model (CASA/GFED,NOBM)

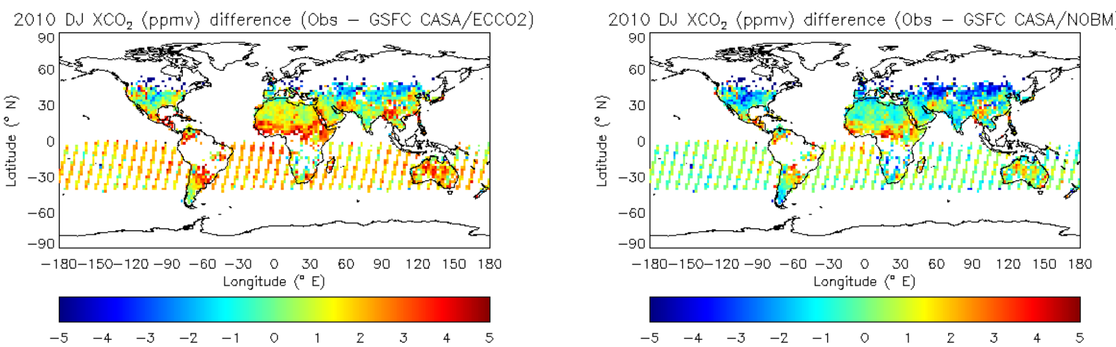


Figure 3.3.e. Differences of X_{CO2} (ppmv) between observations and the model aggregated over December 2009/January 2010. The observations are the GOSAT/ACOS Version 2.9 bias-corrected retrievals. The model fields subtracted from the observations represent the sampled X_{CO2} simulations from two **combinations of** one **land flux, \ CASA-GFED with two ocean fluxes, ECCO2-Darwin (left) and NOBM (right).**

Atmospheric Inversions using the Adjoint of GEOS-Chem

The total computed global-mean surface flux of CO_2 implies an atmospheric growth rate which is larger than that observed (the so-called missing sink of Fan et al., 1998). By using observed (or retrieved) atmospheric CO_2 concentrations, inverse methods constrain the total surface fluxes to match the observed growth rate. A new inverse method, based on the adjoint of the GEOS-Chem transport model and using GOSAT satellite observations, was developed at JPL for the FPP. Using a prior estimate of the flux, an optimization is performed that adjusts this “prior” flux map to account for the imbalance in atmospheric growth rate. The application to date has focused on using the CASA-GFED land biosphere flux as a “prior” and adjusting this flux to derive a “posterior” flux that leads to balanced regional atmospheric CO_2 growth rates.

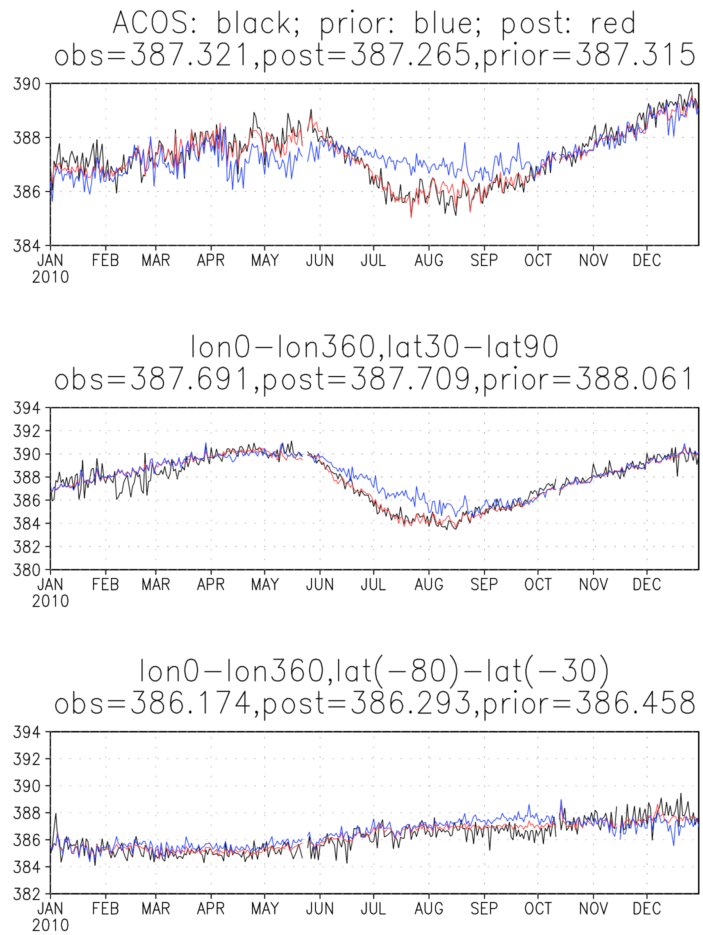


Figure 3.3.g. Comparison of ACOS-GOSAT v2.9 (filtered according to the user's guide) observations (black line), the X_{CO2} forced by the a priori flux (blue line) and the X_{CO2} forced by the posterior flux (red line) averaged over the globe (top panel), over 30°N-90°N (middle panel) and over 80°S-30°S.

Figure 3.3.g shows a comparison of X_{CO2} from GOSAT against the GEOS-Chem simulated distributions in three large geographical areas, showing that the concentrations using the prior distributions deviate somewhat from the observations, especially in the northern summer season, but the posterior estimate leads to better agreement. Flux maps (Figure 3.3.g) show regional changes between the posterior and prior fluxes, along with some latitudinal redistribution of fluxes, leading to an increase from 5.1 to 5.4GtC in the strength of the global terrestrial biosphere sink of Carbon in 2010.

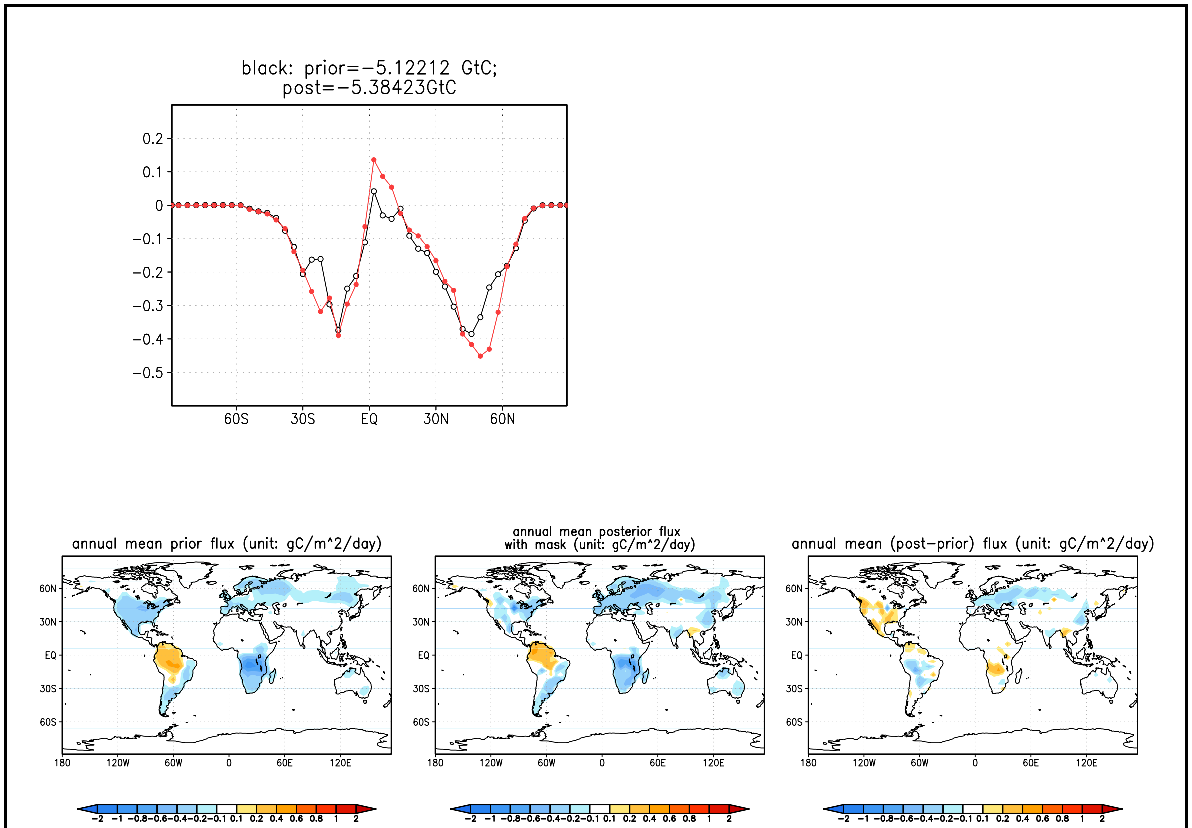


Figure 3.3.h. Top panel: zonal mean the a priori terrestrial biosphere flux (black line) and the posterior terrestrial biosphere flux (red line) for year 2010. Total flux for the a priori terrestrial biosphere is 5.1GtC sink, and the posterior estimates 5.4GtC sink. Bottom left: spatial distribution of the annual mean a priori flux (unit: gC/m^2/day); Bottom middle panel: spatial distribution of the annual mean posterior flux (unit: gC/m^2/day); Bottom right: the difference between the annual mean posterior flux and the a priori flux.

The posterior fluxes have been evaluated with two additional methods. First, the terrestrial CO_2 fluxes from the CMS flux inversion against the CO_2 fluxes from the MPI-BGC product, which was developed as an "upscaled" globally gridded produced from hundreds of individual eddy flux towers (FLUXNET). MPI-BGC provided a direct observational flux product for comparison. While the MPI-BGC product contained some biases/uncertainties, there were key areas of reliable comparison, particularly in the timing of maximum CO_2 uptake. Here we show that the CMS Flux product compares favorably to MPI-BGC over much of the world, especially in the N. Hemisphere, but diverges in areas such as Amazonia, parts of Africa, and Central Asia.

A second type of validation uses the "prior" and "posterior" fluxes in a different transport model (PCTM: Kawa et al., 2004). This model shows that the simulated CO_2 with the posterior fluxes is not in substantially better agreement with observations than the run with prior fluxes directly from CASA/GFED (Fig. 3.3.h). Such evaluation points to the need for careful assessment of the impacts of uncertainties in anthropogenic CO_2 emissions and of ocean fluxes on such inversions – these will be an important part of future investigations.

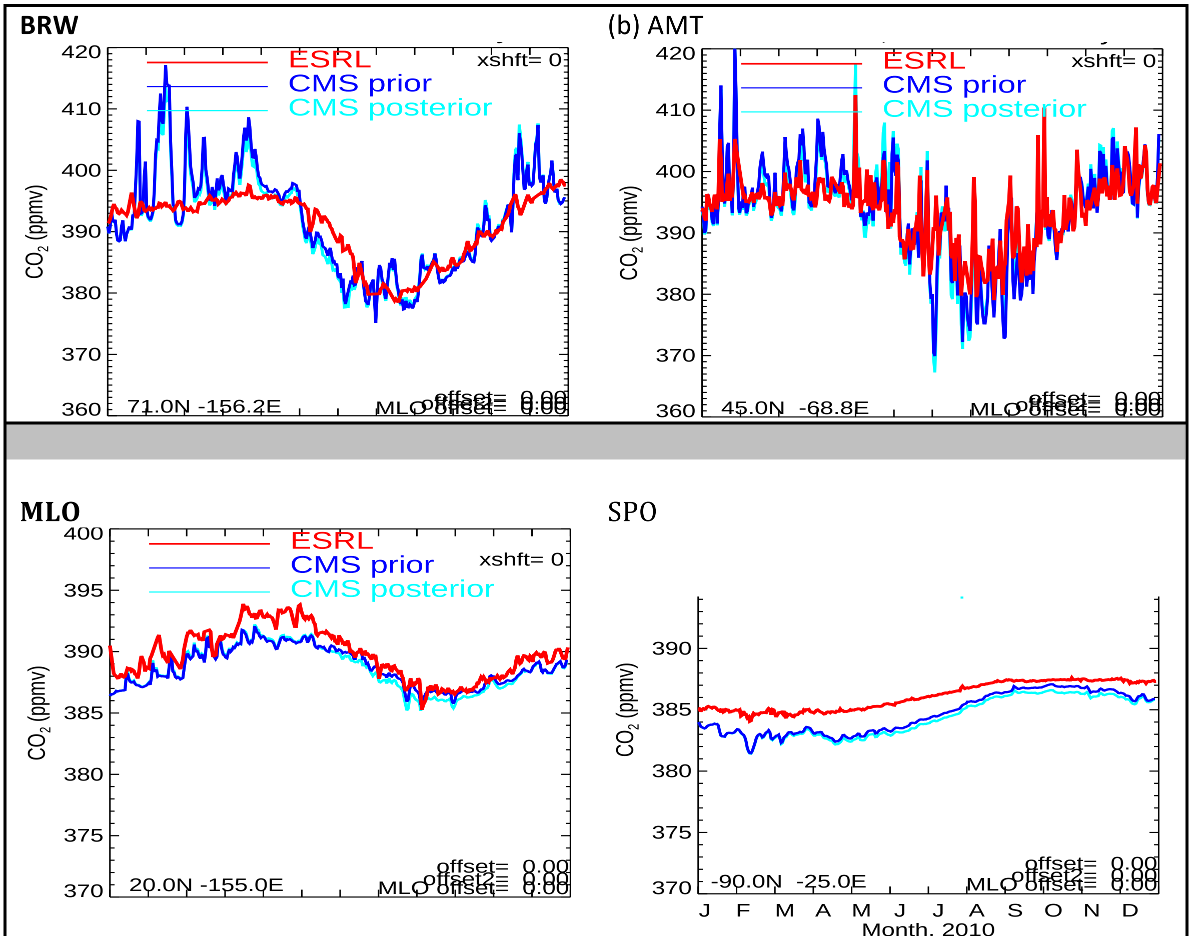


Figure 3.3.i. Differences of CO_2 (ppmv) between ESRL observations (red) and PCTM simulations using the prior (dark blue) and posterior (light blue) land biosphere flux distributions. Both simulations used identical anthropogenic emissions and ocean fluxes.

Summary

A complete "system of systems" has been combined in the CMS FPP. Bottom-up fluxes have been computed using model systems tightly constrained by observations of physical and biological parameters. Uncertainties have been estimated using different systems (two land biosphere and two ocean systems), examining parameter uncertainties in on land biosphere system, and in enhancing the atmosphere-ocean coupling. Mapping fluxes to atmospheric concentrations is achieved using transport modeling, which this provides an opportunity to evaluate combinations of fluxes against observations, demonstrating that some combinations of fluxes agree better with atmospheric CO_2 concentrations than others. Inverse modeling has been developed as a means of ensuring that the regional fluxes are in balance with atmospheric CO_2 concentrations measured from space, with a focus so far on adjusting the land biospheric fluxes to balance the budget.

The system is heavily dependent on NASA's GEOS-5 data assimilation and modeling capabilities, for which the meteorological fields are used for atmospheric transport and to constrain bottom-up fluxes (e.g., temperature and moisture). Sensitivities of CO_2 flux computations related to uncertainties in the analyses remain a focus of study. Propagation of uncertainty through the entire system is also a topic of future investigations: this includes

transport errors, the dispersion of surface flux uncertainty, and the impacts of uncertain anthropogenic fluxes on the interpretation (and inversions) of land biosphere fluxes.

While some combinations of fluxes display some skill in capturing variations in atmospheric CO_2 up to seasonal timescales, the global accumulation with all combinations is not balanced to the observed atmospheric growth rate of CO_2. This is at least partly because of process/model uncertainty in using satellite observations to constrain fluxes that are largely unobserved. The growth rate is a small residual between some very large emissions (combustion, respiration) and uptake (photosynthesis and growth) meaning that careful monitoring and enhancements in the model and observational components of the work needs to be continued into the future.

Publications

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Potter, C., S. Klooster, and V. Genovese, 2012, Net primary production of terrestrial ecosystems from 2000 to 2009, *Climatic Change, doi:10.1007/s10584-012-0460-2*.

Potter, C., S. Klooster, V. Genovese, C. Hiatt, S. Boriah, V. Kumar, V. Mithal, and A. Garg, 2012, Terrestrial ecosystem carbon fluxes predicted from MODIS satellite data and large-scale disturbance modeling, *International Journal of Geosciences, doi:10.4236/ijg.2012*.

SCOPING STUDIES

4.1 Oceans (M. Behrenfeld et al)

Characterizing the Phytoplankton Component of Oceanic Particle Assemblages

Method/Approach

Analytical Measurements

For this approach, sample water containing phytoplankton and other particles is sorted with a rapid-sorting flow cytometer (BD-Influx). The sorting protocol allows isolation/separation of the phytoplankton from other forms of particulate carbon. The samples collected are small in volume, due to required sort times, and have low levels of phytoplankton biomass. These samples are therefore analytically evaluated for carbon using an extremely sensitive TOCN analyzer. This approach is the most direct measure of phytoplankton biomass. The two primary drawbacks of the approach are that the required sort time limits the total number of samples that can be collected and analyzed during a given cruise and the measurement requires tight control/excellent knowledge of background carbon contamination.

Liquid-Aperture Measurements

For this approach, sample water containing phytoplankton is injected into a custom-built, microfluidic Coulter-type instrument that allows particle counting, sizing, and fluorescence detection. The Liquid Aperture Counter (LAC) system will have multiple channels to cover particles ranging from 0.1 to 50 μo. Particle counting and sizing is based on electrical impedance. The advantage of using a liquid aperture, rather than the physical aperture of a Coulter counter, is that it allows large particles to pass through the system without clogging (the major issue preventing Coulter instruments from sizing ocean particles below ~ 1 μ). By coupling particle counting and sizing with chlorophyll fluorescence determinations, the phytoplankton population can be isolated and total cell volume evaluated, which can then be converted to carbon biomass. These assessments of C_{phyto} can be cross-calibrated with results of the Analytical Approach described above. The LAC approach has a number of very appealing attributes. In particular, it would allow essentially continuous assessment of C_{phyto} using flow-through seawater on a research vessel. Also, the mircofluidic chips can be cheaply and easily replicated once a successful prototype has been developed and demonstrated. The two primary drawbacks of the approach are that carbon is assessed from phytoplankton volume (rather than measured directly, as in the analytical approach) and that significant technology development has been required to achieve a successful prototype.

Products

Analytical Approach

The two central instruments for the analytical approach are a BD Influx flow cytometer and a Shimadzu TOCN (total organic carbon and nitrogen) analyzer. The two systems were set up in Year 1 of the project and measurement protocols established. Initial tests were conducted on multiple phytoplankton species in culture to determine the optimal settings for sorting cells. Tested species were:

1) the flagellates Micromonas pusilla and Dunaliella tertiolecta
2) the diatoms Thalassiosira weissflogii and Thalassiosira pseudonana
3) the cyanobacterium *Synechococcus*

Instrument parameters for maximizing cell yield (i.e. sort parameters, nozzle size, etc.) were selected to provide the highest yield of cells in a short period of time. In Year 1, we achieved sort efficiencies up to 75% with phytoplankton cultures.

The outcome of this work, combined with the laboratory experiments, has been published in Limnology and Oceanography Methods (Graff et al. 2012) and is the first publication of a measurement protocol for routinely measuring phytoplankton carbon in the field. Based on this success, we have since conducted two full-scale open ocean field deployments. The first of these was conducted in the tropical Pacific, in coordination with the NOAA Tropical Atmosphere Ocean (TAO) Program. This nearly two-month expedition spanned ocean conditions ranging from highly oligotrophic to the mesotrophic environment of the equatorial Pacific upwelling plume. The second campaign was completed in November 2012 and was conducted in the Atlantic ocean in coordination with the United Kingdom's Atlantic Meridional Transect (AMT) Program. This field deployment again lasted nearly 2 months and covered a wide range of ocean conditions, including high productivity shelf water, extreme oligotrophic conditions, the equatorial upwelling system off western Africa, and high productivity water at the northern edge of the Southern Ocean. During both cruises, a full complement of in situ measurements were conducted that included analytical measurements of particulate organic carbon (POC), phytoplankton pigments (HPLC), particle size distributions (Coulter), stimulated fluorescence, and optics (spectral attenuation, absorption, and backscattering). In addition, the AMT campaign included overflight measurements with an airborne lidar (HSRL) and polarimeter (RSP) in coordination with NASA's Langley, Wallops, and GISS centers. All of these data will contribute to the development of satellite-based algorithms for global C_{phyto} retrievals. Sample and data analyses from the two open ocean campaigns are currently underway, with publication of results to follow shortly thereafter.

Liquid-Aperture Counter (LAC) Approach
Development of the LAC system has proven to be technologically challenging. While progress was made during Year 1 and Year 2 of this project, problems were encountered with laser light contamination in the detection system and achieving adequate sensitivity in the impedance measurements. Nevertheless, we have now (as of October 2012) constructed a new chip design that promises to be successful. We are currently fine-tuning this design and conducting laboratory tests. Our aim is to have a successful prototype defined in 2013. Once established, the LAC system will be tested in the field and then deployed in parallel with the analytical measurements in open ocean field campaigns.

Priority Next Steps
1) Complete analysis of samples and data from first 2 field campaigns.
2) Publish results from field measurements
3) Complete LAC prototype
4) Validate/refine satellite C_{phyto} algorithm
5) Synthesis all results into a new global assessment of phytoplankton carbon stocks
6) Continue field deployments to construct a globally representative C_{phyto} database
7) Evaluate global changes in C_{phyto} stocks toward an attribution of observed variability

Publications/Presentations

J.R. Graff, A.J. Milligan, M.J. Behrenfeld. 2012, The measurement of phytoplankton biomass using flowcytometric sorting and elemental analysis of carbon. *Limnol. Oceanogr. Methods*. In press.
SOLAS Summer School. Remote Sensing of the Oceans. August 2011. Corsica, France.
Ocean Biology and Biogeochemistry Meeting. May 2011. Washington D.C.
Carbon Monitoring System Meeting. Oceans. November 2012. NASA GSFC

Related Figures

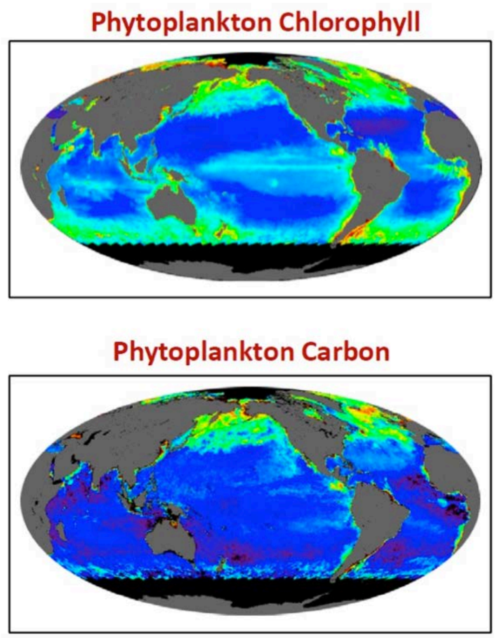

Figure 4.1.a The current CMS project aims to validate/revise global satellite assessments of ocean phytoplankton carbon stocks through the development of field-deployable techniques for measuring C_{phyto}. As shown in the two panels on the left, current assessments of global phytoplankton chlorophyll and carbon concentrations exhibit major differences in distributions. A major reason for this discrepancy is that chlorophyll is influenced both by variability in phytoplankton biomass and physiology. Monitoring ocean carbon requires direct assessment of C_{phyto}, but field measurement approaches have not been available to date. Current satellite assessments (e.g., lower panel) have thus been tested only using C_{phyto} proxies. The current study will allow validation of these products for carbon monitoring.

4.2 Oceans (S. Lohrenz et al)

Estimation of land-ocean-atmosphere carbon fluxes and exchanges in the Mississippi River watershed and northern Gulf of Mexico

Method/Approach

The Dynamic Land Ecosystem Model (DLEM) developed by Tian's group at Auburn University was used to generate modeled simulations of river fluxes of water, nutrients and organic and inorganic carbon to the Gulf of Mexico. The DLEM is a highly coupled (carbon, water, and nitrogen), process-based land ecosystem model aiming to simulate the variations of biogeography, hydrological cycle, plant physiological processes and soil biogeochemical cycles in land ecosystems driven by natural and anthropogenic forces such as changes in climate, atmospheric compositions, and land use. DLEM includes four components which focus on different processes: 1) biophysics, 2) plant physiology, 3) soil biogeochemistry, and 4) dynamic vegetation and land-use (Fig. 1). The biophysics component simulates the instantaneous fluxes of energy, water, and momentum within the land ecosystem and their exchanges among the atmosphere, land and riverine system. Plant physiology component simulates major physiological processes including photosynthesis, auto-trophic respiration, carbon and nutrient allocations, water and nutrients uptake, transpiration, leaf and root turnover, and plant phenology. The soil biogeochemistry component simulates the transformation of various carbon and nitrogen forms along the decomposition of soil organic matter. These processes include the mineralization/immobilization, nitrification/denitrification, decomposition, and methane production/oxidation. The dynamic vegetation and land use component simulates the vegetation dynamics caused by climate change and natural and human's disturbances.

Cai and Lohrenz and co-workers have been involved in mapping of surface water chemical and bio-optical properties in the northern Gulf of Mexico and this information is used to develop estimates of air-sea fluxes of carbon dioxide using both ship-based observations and satellite imagery as has been described previously More than 14 cruises have been carried out between June 2003 and Mar 2010 and have provided extensive information about CO_2 dynamics in the northern Gulf of Mexico. Observations included those from cruises of opportunity provided by EPA that were conducted during the spring, summer and fall seasons as their primary objective was to characterize conditions related to hypoxia. Additional cruise data from May 2008 and continuing through April 2010 was provided by an NSF-funded project known as GulfCarbon (www.gulfcarbon.org) which included five comprehensive field campaigns focusing on carbon and nutrient cycling and utilizing satellite remote sensing to extrapolate carbon dynamics to regional scales. These cruises encompass both wintertime and summertime periods. Thus, these datasets provide complete seasonal coverage for CO_2 as well as other supporting observations for estimation of air-sea fluxes.

We have made a preliminary attempt to derive the coastal-ocean exchanges using a mass balance approach using river input, air-sea CO_2 flux, and primary production and respiration rates measured by the EPA- and NSF-funded cruises, which include 10 cruises since 2006. A similar approach has been applied to global syntheses of continental margin carbon budgets (Cai et al. 2006) and carbon export fluxes in the U.S. Southeastern continental shelves (Cai et al. 2003 and Cai 2011). This effort will provide a basis for future Phase II work.

Products

Land-ocean carbon fluxes: DLEM-NE simulations suggest that total organic carbon (TOC, including DOC and POC) of about 5.0 Tg/year has been exported to the Gulf of Mexico. Exported TOC increased by 10% in the past half century from 1960s to the period 2000-

2008. The export of total nitrogen (TN) to the Gulf of Mexico has significantly increased by 34% from 1960s to the early 2000s as estimated by DLEM-NE. The increase in nitrogen delivery to Gulf of Mexico is mostly caused by land-use/land-cover change including nitrogen fertilizer application (in prep.). The spatial and temporal patterns of delivery of water, carbon, and nitrogen estimated by DLEM can characterize which region in the landscape and which season has major impacts on the ocean margin boundary and attribute the driving forces on land.

The consistency between observed and modeled fluxes provides a strong validation for using the DLEM as a predictive tool to examine consequences of climate and land-use change on delivery of nutrients and carbon to coastal waters.

Air-sea carbon dioxide exchange: Regarding coastal air-sea C exchange, a paper was recently published examining the stoichiometry of uptake ratios of C, N, and P in the outflow region of the Mississippi River. An additional manuscript is in review with L&O describing an unusually large plume event in March 2010, which dramatically influenced the net air-sea exchange of CO_2 in the region. Additional manuscripts are in preparation to assess air-sea fluxes of CO_2 on regional scales using both in situ and satellite based observations of $p$$CO_2$ (Fig. 4.1.a and Table 4.1.a). Members of the project team also participated in the recent NOAA Gulf of Mexico East Coast Carbon Cruise, which will provide additional data for this effort.

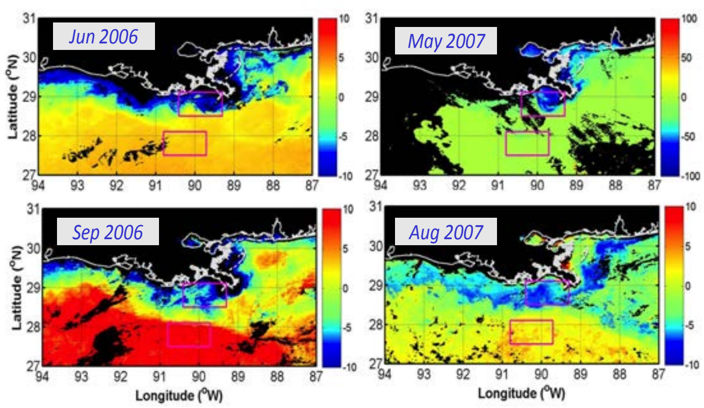

Fig. 4.1.a. Estimates of sea-to-air flux of carbon dioxide were made using a satellite approach modified from Lohrenz et al. [2010] and using the wind parameterization of Ho et al. [2006]. Large seasonal variations in fluxes were evident (units in mmol C m^{-2} d^{-1}). Note scale difference for May.

Table 4.1.a. Sea to air flux of CO_2 (mmol C m^{-2} d^{-1})

Date	**Plume**	**Shelf**	**Entire Image**
Jun 2006	-4.0 - -5.9	2.6 – 3.8	0.92 – 1.4
Sep 2006	-5.1 – -6.9	8.3 – 11.0	3.4 – 4.6
May 2007	-29 - -35	-2.9 - -3.5	-6.7 - -8.2
Aug 2007	-4.7 - -5.8	1.6 – 2.0	-0.58 - -0.71

Coastal-open ocean carbon fluxes: Preliminary efforts to develop a mass balance of coastal to open ocean C exchange have been made, but are subject to improved estimates of both land-ocean and air-sea fluxes as they are refined.

Availability: The project website (www.gulfcarbon.org) is being updated. The goal is to improve accessibility by making available on the NASA SeaBASS data server, CDIAC database, and other appropriate databases.

The pCO_2 data from 2006 to 2007 can be found on CDIAC website:

Cai, W.-J., Y. Wang, and W.-J. Huang. 2012. Sea Surface pCO2 measurements in the Gulf of Mexico during the Ocean Survey Vessel Bold cruises in 2006. http://cdiac.ornl.gov/ftp/oceans/UG_GoM_UW_Data/2006.data. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/OTG.UG_GOM_UW_2006.

Cai, W.-J., Y. Wang, and W.-J. Huang. 2012. Sea Surface pCO2 measurements in the Gulf of Mexico during the Ocean Survey Vessel Bold cruises in 2007. http://cdiac.ornl.gov/ftp/oceans/UG_GoM_UW_Data/2007.data. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/OTG.UG_GOM_UW_2007.

Strengths and Weaknesses

Improved information about coastal carbon fluxes is critically needed to better constrain the contribution of coastal margins to carbon sources and sinks and improve capabilities to attribute sources and sinks to different regions as well as reducing uncertainties in estimates. The Gulf of Mexico represents a potentially large region of uncertainty and, hence, better constraints on carbon dynamics in this region depend on improved estimates from the coastal margin. The results from this study provide one of the most extensive analyses of coastal margin carbon stocks and fluxes in this region.

A weakness of the current study is the need for further analysis of the air-sea fluxes of CO_2 and the application of new models that will allow extrapolation to annual and interannual time scales. Thus far, these analyses have been restricted to specific periods, but methods to extend these estimates will be pursued in a related Phase 2 project. More comprehensive uncertainty analyses are also needed for all products. The carbon mass balance estimates are preliminary at this stage, and through our Phase 2 collaboration, we will utilize an ocean biogeochemical model in parallel with observations to provide improved budgeting of carbon fluxes including coastal-ocean exchanges and air-sea fluxes. In addition, the work will be enhanced in our Phase 2 effort by coupling the terrestrial and ocean ecosystem models. This will allow the examination of how climate and land-use and land cover change scenarios impact the export of terrestrial materials and the consequences for coastal carbon cycling and ecosystem dynamics.

Priority Next Steps

Short Term

Our next steps will involve a Phase 2 project entitled "Development of observational tools and coupled models of land-ocean-atmospheric fluxes and exchanges in the Mississippi River watershed and Gulf of Mexico in support of carbon monitoring". The proposed research will employ a combination of models and remotely-sensed and in situ observations to develop georeferenced products and associated uncertainties for land-ocean exchange of carbon, air-sea exchanges of carbon dioxide, and coastal to open ocean exchanges of carbon. A major aspect of this proposed project will be to establish and populate geospatial portals for sharing and analysis of carbon datasets and products. The primary region of study will be the Mississippi River watershed and northern Gulf of Mexico. However, the model domain will also include the continental margins of Florida and the South Atlantic Bight. The proposed work is closely aligned with objectives of the NASA Carbon Monitoring System scoping effort and of the North American Carbon Program and will support National Climate Assessment activities. The effort will also contribute to NASA Coastal Carbon

Synthesis effort and international efforts to develop a North American carbon budget (CarboNA).

Next Steps
The unique nature of our approach, coupling models of terrestrial and ocean ecosystem dynamics and associated carbon processes, will allow for assessment of how societal and human-related LCLUC, as well as climate change, affect terrestrial carbon sources and sinks, export of materials to coastal margins, and associated carbon processes in the continental margins. Results would also benefit efforts to describe and predict how land cover and land use changes impact coastal water quality, including possible effects of coastal eutrophication, hypoxia, and ocean acidification. It is notable that the Southeastern United States has been identified as a strong candidate for a Mid Continent Intensive "Follow-On" experiment to better constrain terrestrial fluxes and this work would substantially complement such an effort. This project provides a true integration of the terrestrial and coastal margin, a system of high uncertainty in current global carbon budgets. Such information is needed to better understand linkages between land use changes and subsequent coastal processes that have been argued to play a role in water quality and hypoxia in coastal waters.

List of Publications Related to this Project

Chen, G., H. Tian, C. Zhang, M. Liu, W. Ren, W. Zhu, A. Chappelka, S. Prior and G. Lockaby. 2012. Drought in the Southern United States over the 20th century: Variability and its impacts on terrestrial ecosystem productivity and carbon storage. Climatic Change DOI 10.1007/s10584-012-0410-z

Guo, X., Cai, W.-J., Huang, W.-J., Wang, Y., Chen, F., Murrell, M.C., Lohrenz, S.E., Jiang, L.-Q., Dai, M., Hartmann, J., Lin, Q., & Culp, R. (2012). Carbon dynamics and community production in the Mississippi River plume. Limnology and Oceanography, 57(1), 1-17.

Hopkinson, C. S., W.-J. Cai, and X. Hu. 2012. Carbon sequestration in wetland dominated coastal systems: a global sink of rapidly diminishing magnitude. Current Opinion in Environmental Sustainability, 4:1-9.

Huang, W.-J., Cai, W.-J., Powell, R. T., Lohrenz, S. E., Wang, Y., Jiang, L.-Q. and Hopkinson, C. S. 2012. The stoichiometry of inorganic carbon and nutrient removal in the Mississippi River plume and adjacent continental shelf. Biogeosciences, 9, 1–12, 2012, doi:10.5194/bg-9-1-2012.

Huang, Wei-Jen, W.-J. Cai, R. M. Castelao, Y. Wang, S. E. Lohrenz. Impacts of a wind-driven cross-shelf large river plume on biological production and CO2 uptake in the Gulf of Mexico during spring. Submitted to L&O.

Huang, W.-J., Y. Wang, and W.-J. Cai (2012) Assessment of sample storage techniques for total alkalinity and dissolved inorganic carbon in seawater. Limnology and Oceanography-Methods:10, 711-717, DOI 10.4319/lom.2012.10.711.

Liu, M., Tian, H, Yang, Q., Yang, J., Song, X., Lohrenz, S. E., Cai, W.-J., Long-term Trends in Evapotranspiration and Runoff over the Drainage Basins of the Gulf of Mexico during 1901-2008, *Water Resources Research* (in revision).

Tian, H., C. Lu, G. Chen, B. Tao, S. Pan, S. Del Grosso, X. Xu, L. Bruhwiler, S. Wofsy, E. Kort, and S. Prior. 2012. Contemporary and projected biogenic fluxes of methane and nitrous oxide in terrestrial ecosystems of North America. Frontiers in Ecology and the Environment 10(10): 528–536, doi:10.1890/120057.

Tian, HQ, G. Chen, C. Zhang, M. Liu, G. Sun, A. Chappelka, W. Ren, X. Xu, C. Lu, S. Pan, H. Chen, D. Hui, S. McNulty, G. Lockaby and E. Vance. 2012. Century-scale response of ecosystem carbon storage to multifactorial global change in the Southern United States. Ecosystems DOI: 10.1007/s10021-012-9539-x

Xu, X. F., Tian, H. Q., Chen, G. S., Liu, M. L., Ren, W., Lu, C. Q., and Zhang, C. 2012. Multifactor controls on terrestrial N2O flux over North America from 1979 through 2010, Biogeosciences, 9, 1351-1366.

Zhang, C., H. Tian, G. Chen, A. Chappelka, X. Xu, W. Ren, D. Hui, M. Liu, C. Lu, S. Pan, G. Lockaby. 2012. Impacts of Urbanization on Carbon Balance in Terrestrial Ecosystems of the Southern United States. Environmental Pollution 164, 89-101.

4.3 Oceans (M. Friedrichs et al)

Carbon budget Calculations for the U.S. Eastern Continental Shelf, in Support of the NASA Carbon Monitoring System

Approach

The research goals were primarily accomplished via our coupled biogeochemical circulation model (NENA). This model is based on the Regional Ocean Modeling System (ROMS), which is now widely used for shelf circulation and coupled physical-biological applications. The NENA model domain presently uses a 10-km horizontal resolution and 30 terrain-following vertical levels stretched to give high resolution in surface and bottom boundary layers, which is sufficient to capture the dominant dynamics governing shelf-wide circulation.

The biogeochemical model includes dissolved inorganic carbon (DIC), semi-labile dissolved organic carbon and nitrogen (DOC and DON), nitrate, ammonium, small and large particle C and N detrital pools, zooplankton, and phytoplankton. The alkalinity distribution follows that of salinity to first order, so alkalinity is specified as a function of salinity. Oxygen is included because it is sensitive to C cycle processes and has been extensively measured in our study region. Furthermore, in coastal regions hypoxic or anoxic conditions can develop and affect water quality, alter denitrification rates, and other benthic processes, and change how detrital material is processed in the water column (the last is likely small). Air-sea gas fluxes are calculated using model-predicted oxygen and CO_2 concentrations, atmospheric pCO_2 from monthly observations and optional transfer velocity parameterizations.

DLEM is a coupled (carbon, water, and nitrogen), process-based land ecosystem model that simulates variations of biogeography, hydrology, and biogeochemistry in land ecosystems driven by natural and anthropogenic forces such as changes in climate, atmospheric composition, and land use. DLEM couples the processes of carbon, nitrogen, and water as an integrated modeling system. The responses of land ecosystems to environmental changes result from interactions among the carbon, nitrogen and water cycles. DLEM includes four components that handle different major processes: 1) biophysics, 2) plant physiology, 3) soil biogeochemistry, and 4) dynamic vegetation and land use. The biophysics component simulates the instantaneous fluxes of energy, water, and momentum within the land ecosystem and their exchanges with the atmosphere and riverine systems. The plant physiology component simulates major physiological processes, including photosynthesis, autotrophic respiration, carbon and nutrient allocations, water and nutrient uptake, transpiration, leaf and root turnover, and plant phenology. The soil biogeochemistry component simulates mineralization/immobilization, decomposition, nitrification/denitrification, and methane production/oxidation. The dynamic vegetation and land use component simulates the vegetation dynamics caused by climate change and natural and human disturbances. DLEM has been validated and used to examine carbon and water cycling in different regions, including the US.

The models described above were used to compute the relevant carbon fluxes within the U.S. continental shelf region. Particular attention was paid to fluxes across the model boundaries, i.e. land-ocean (river input), shelf-ocean (offshore horizontal divergence), air-sea (air-sea CO2 exchange) and water-sediment (carbon burial).

In a second component of our analysis, we used a combination of satellite-derived DOC and POC products and flow fields from the NENA model to asses the seasonal and interannual variability of organic carbon stocks and cross-shelf transport along the US east coast. The satellite retrievals of DOC and POC concentrations are representative of the entire water column during the vertically well-mixed periods (autumn-winter) but only the near-surface during the stratified months in spring-summer. For this reason, a strategy is being considered to develop generalized vertical profiles of DOC and POC based on satellite retrievals to extrapolate concentrations below the mixed layer. These profiles were used to derive vertically-integrated estimates of organic carbon stocks and fluxes. For the lateral fluxes, the approach is to use the product of the OC concentrations (C(x, y, z)) and the corresponding x and y components of the volume transport (Tx(x, y, z), Ty(x, y, z)) at each grid point of the ocean model to obtain the fluxes at each grid point (x, y) and depth (z). So the flux components, Fx and Fy, are given by:

$Fx(x, y, z)= C(x, y, z)\times Tx(x, y, z)$

$Fy(x, y, z)= C(x, y, z)\times Ty(x, y, z)$

The total flux can then be vertically integrated and summed along a prescribed boundary (for instance, a bathymetry line) to obtain the total annual OC flux.

Products

Using the NENA model we have constructed a four-year (2004-2007) carbon budget for the U.S. eastern continental shelf within the 500-m isobath, which includes the Gulf of Maine (GOM), MAB and SAB (Fig. 4.3.a). We found that the continental shelf water column is generally a sink for atmospheric CO_2, with a 8.9 Tg C yr^{-1} flux into the ocean. The cross-shelf fluxes of DOC, POC and TIC are all exported offshore, with a total of 17.6 Tg C yr^{-1} to the open ocean. The carbon burial into the sediment (0.7 Tg C yr^{-1}) is an order of magnitude smaller than all the other carbon flux terms. The time series of the carbon fluxes for each of sub-region (Fig. 4.3.b) reveal significant seasonal fluctuations, but the values are quite different in the three subregions. For example, the GOM has more CO_2 absorbed into the ocean. In addition, the TIC horizontal divergence and Net Community Production (NCP) fluxes are larger in the GOM than in the MAB and SAB. On the contrary, all carbon fluxes in the MAB are less dynamic, and their values are much smaller. The SAB DOC and POC offshore divergence is more significant than that in GOM and MAB. Another difference is that the SAB annual TIC horizontal divergence is towards shore, whereas it is offshore in both the GOM and MAB.

Additional accomplishments for the second component of this project include:

- Development and evaluation of regional DOC and POC ocean color algorithms
- Development and testing of MatLab codes to process ocean model (NENA) 3D flow fields to calculate volume and POC/DOC transports
- Initial assessment of organic carbon stocks and off-shelf transport for the MAB
- Initial development of strategies to produce generalized vertical profiles of POC and DOC concentrations based on satellite retrievals, in situ profile data, and physical properties (mixed layer, density profiles).
- Figures show examples of the methodology being used for the MAB. Figure 4.3.c. shows the ocean model vertically integrated transport vectors and Figure 4.3.d. the DOC and POC lateral fluxes in Tg C/yr.

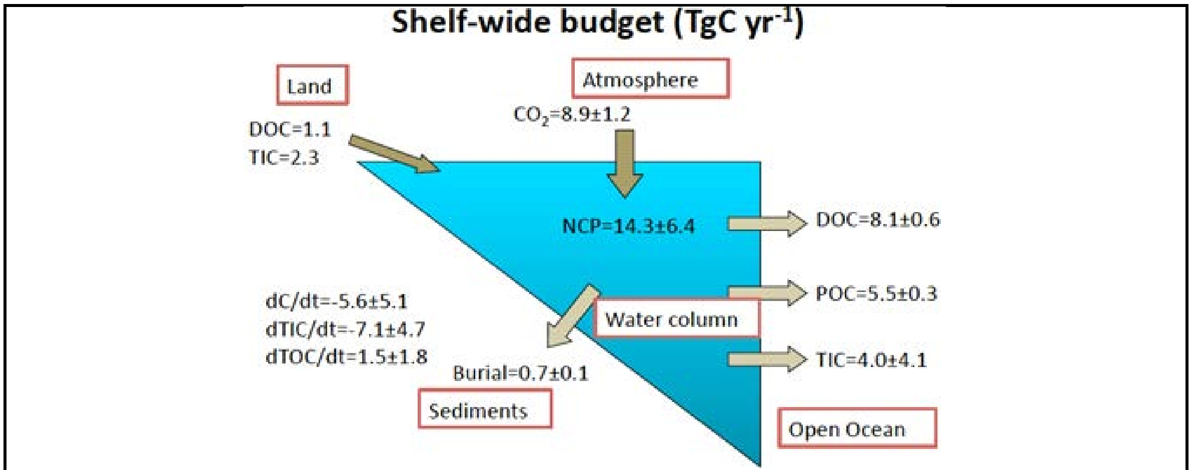

Figure 4.3.a. Carbon budget of the U.S. Continental shelf (i.e., GOM, MAB, and SAB) over 2004-2007.

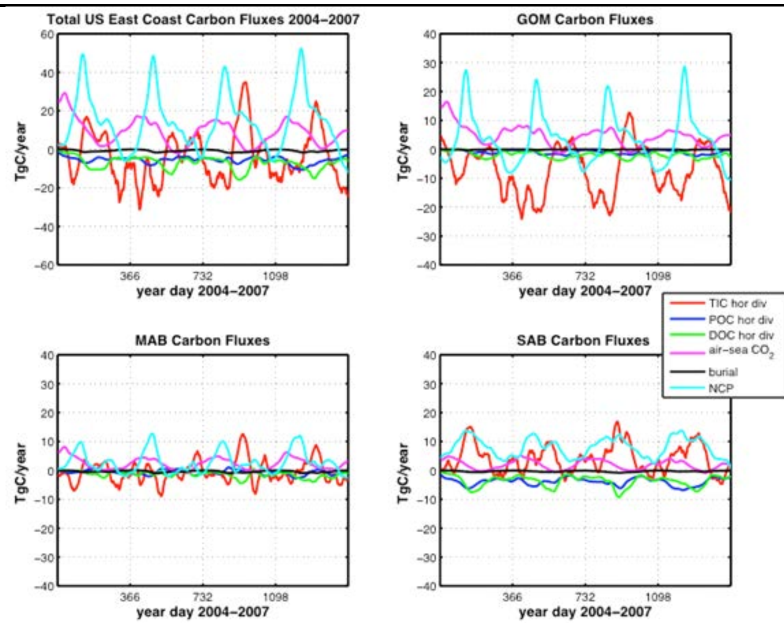

Figure 4.3.b. Time series of the carbon budget for the U.S. east continental shelf and for each sub-region between 2004-2007.

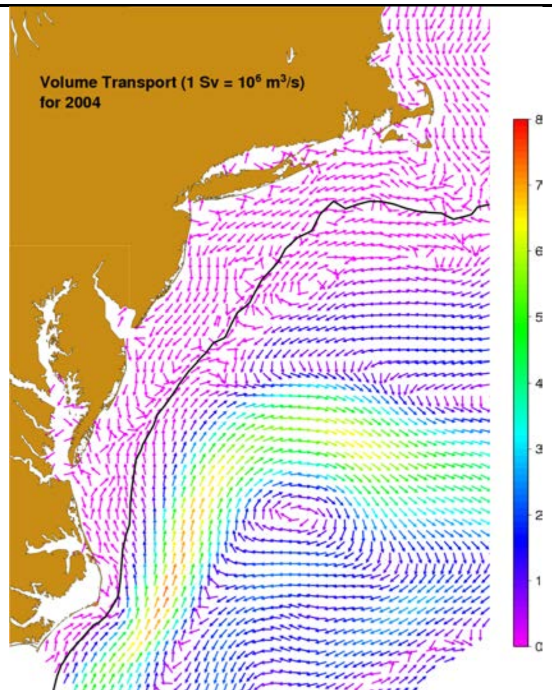

Fig. 4.3.c. Vertically integrated transport vectors derived from the ocean model with the 70-misobath superimposed (black line).

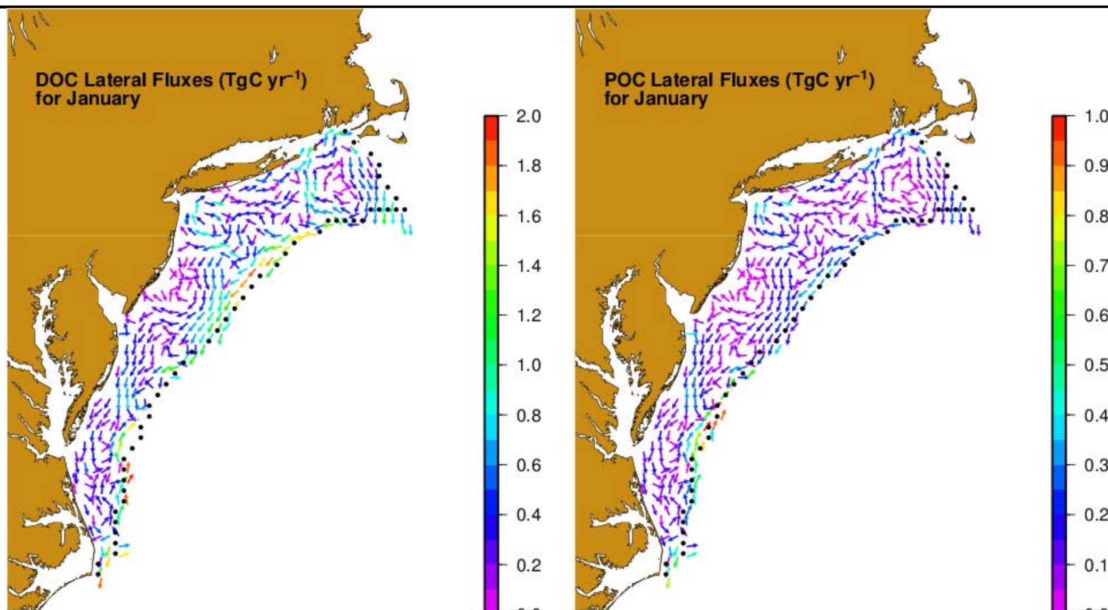

Fig. 4.3.d. Lateral fluxes of DOC (left) and POC (right) based on the MODISA entire mission January climatology and January 2004 NENA flow field. As an example, an arbitrary open boundary has been chosen that approximately follows the 100-m isobath.

4.4 Oceans (W. Gregg et al)

Does Ocean Chlorophyll Data Assimilation Improve the Representation on Global Inorganic Carbon?

Method/Approach

Using an established global model (NASA Ocean Biogeochemical Model, NOBM), global ocean chlorophyll data from MODIS-Aqua were assimilated for a period of 7 years, 2003 to 2010

Products

Accuracy: +2.9% global bias in pCO_2, -28.4% global bias in air-sea flux
Resolution: 1.25degrees longitude by 0.67degrees latitude
Domain: Global
Uncertainty: correlation coefficient=0.79 for pCO_2; =0.82 for air-sea flux (years 2003-2008 only due to availability of in situ data)
Status: initial evaluation complete
Availability: CMS website (ftp://gmaoftp.gsfc.nasa.gov/pub/data/Zhengzin/NOBM/)

Strengths and Weaknesses

The data assimilation was successful, and there were some ocean basins that showed improvement in pCO_2 and fluxes (South and North Indian, and Equatorial Atlantic). The distribution of pCO_2 and fluxes was improved as represented by the basin correlation, although the improvement was modest.

The ocean carbon system is complex and chlorophyll is only one of many components. Therefore, assimilating chlorophyll has a limited capability for improvement of inorganic carbon estimates. In regions where the inorganic carbon is dominated by process other than biology, e.g., physical processes (deep mixing and convection) and chemical processes (alkalinity and the carbonate cycle), the assimilation can actually lead to degraded representations.

Priority Next Steps (short term: 18 months, mid term: 3-5 years)

- 18 months: Attempt multi-variate data assimilation, including relationships between chlorophyll and other model carbon components (dissolved inorganic and organic carbon, and detritus).
- 3-5 years: Attempt comprehensive multi-variate and depth data assimilation and increase model complexity to include more carbon components

List of Publications, Presentations

Gregg, W.W., Casey, N.W., and Rousseaux, C.S., 2011. Does Ocean Color Data Assimilation Improve Estimates of Global Ocean Inorganic Carbon? Transactions of the American Geophysical Union.
Gregg, W.W., Casey, N.W., and Rousseaux, C.S., 2012. Global surface ocean carbon estimates in a model forced by MERRA. NASA Global Modeling and Assimilation Series, M. Suarez, ed. NASA Technical Memorandum 2012, in press.

Key Figures and Tables

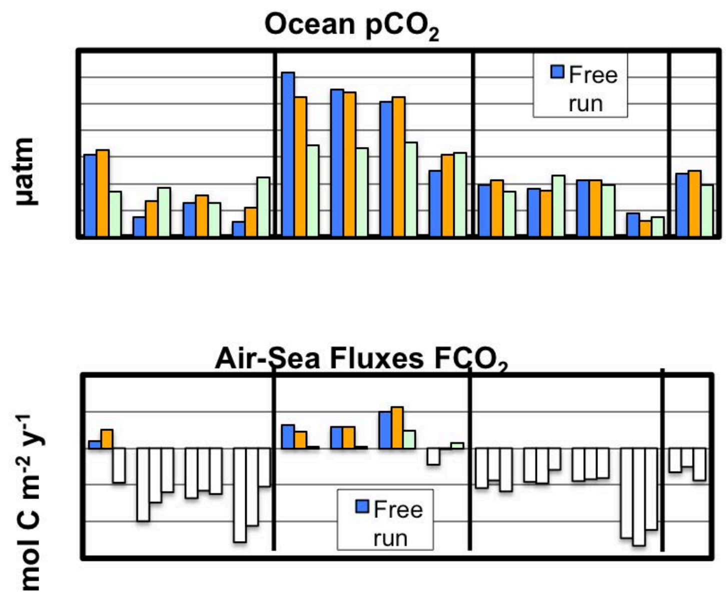

Fig. 4.4.a. Sometimes assimilation is better (3 basins). Sometimes worse (3 basins). Mostly the change is marginal

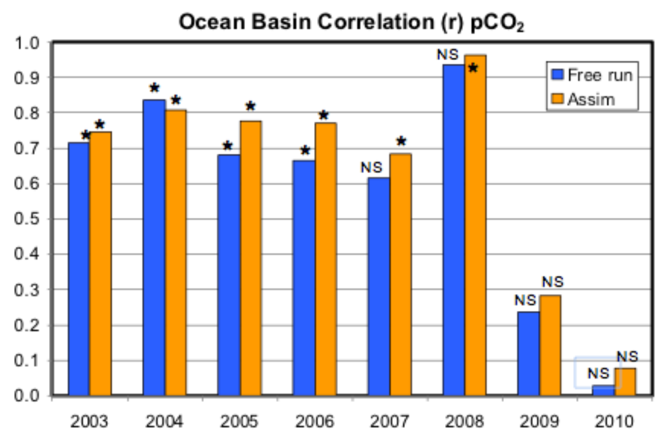

Fig. 4.4.b. Correlation with in situ data and estimates over major ocean basins*= statistically significant P<0.05 NS = not significant

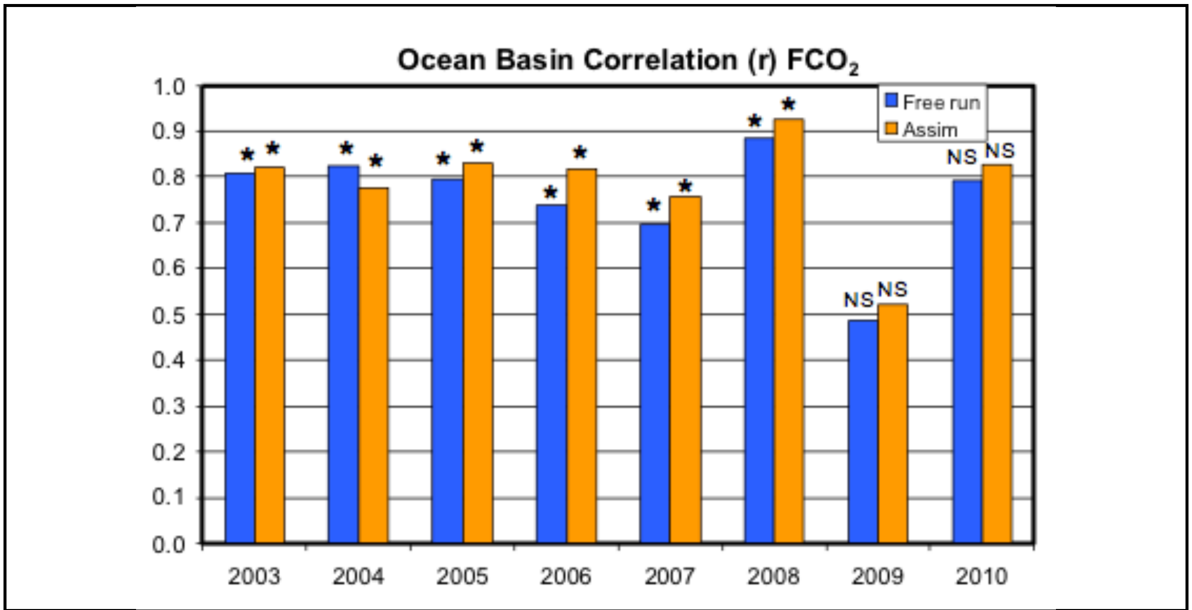

Fig.4.4.c. Assimilation modestly improves the correlation with in situ data Improves the global distribution of inorganic carbon

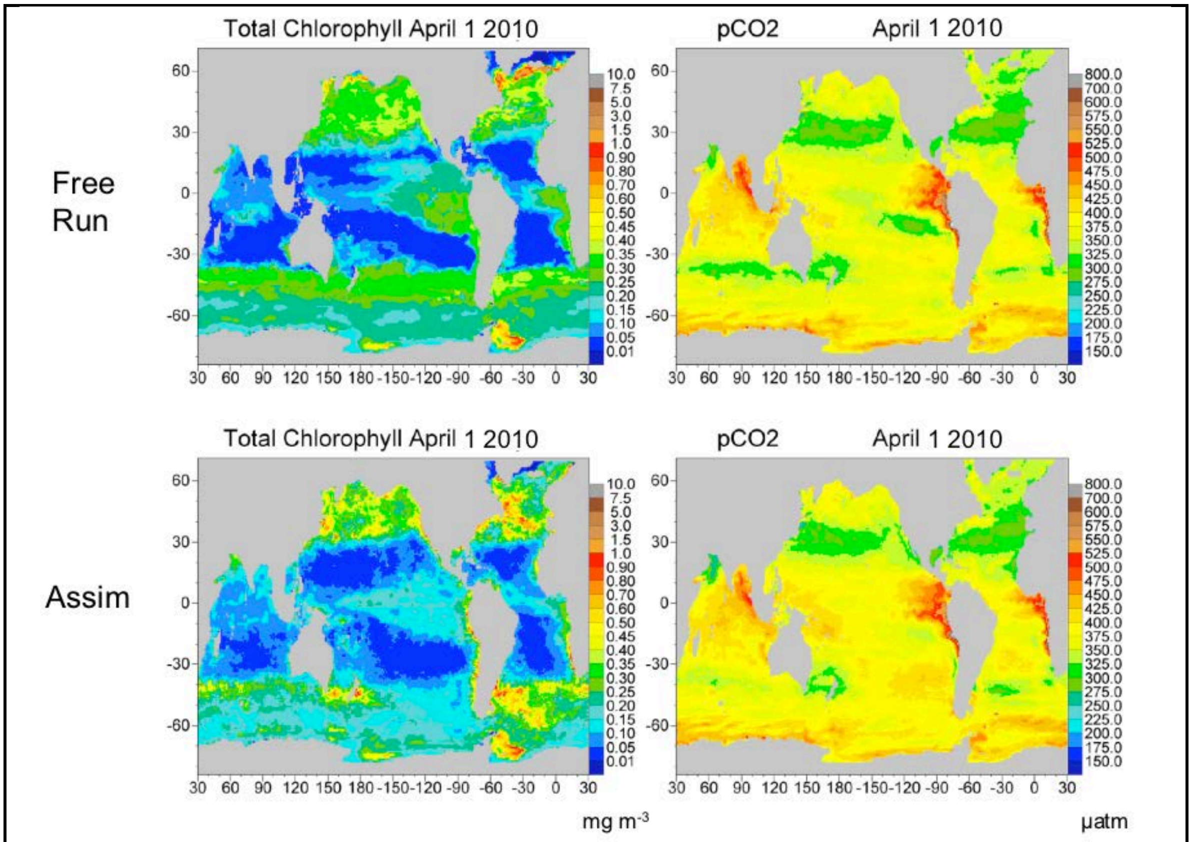

Fig. 4.4.d. Free run and assimilated chlorophyll, with resulting pCO_2 distributions.

4.5 User (M. Brown et al)

Policy, Management, and Decision Support

Summary

The focus of the NASA CMS Applications program is to demonstrate the value of CMS products to users from multiple domains. In order to accomplish this goal, it was essential to first define the user community membership and needs for both the biomass and flux products. This was the primary goal of the first six months of the CMS Applications program. During this time, we developed a framework to demonstrate the value of CMS data products for national public policy, as we had proposed. In addition, we provided support of CMS meetings, conducted community briefings to understand data requirements from end users and discuss CMS product specifications. We developed publications and policy documents relevant to both the CMS flux and biomass pilot products in terms of science and policy applications, and we broadened and updated the CMS website accordingly. In the remainder of the period, we continued community briefings and the development of publications and policy documents. Our efforts are now on stand-by. Macauley's contract with NASA for serving on the Science Definition Team runs through June 1, 2013, thus she has remaining time for additional work as the recently funded CMS activities begin again under FY13 efforts.

Framework

Policy implications and direct use of CMS prototype data in user communities' models and processes is a new component to the carbon cycle for scientists working on CMS. As the CMS Applications team, we have focused our efforts on developing a framework in which these information products could be better understood. This framework includes identification of the user community and identification of the attributes of measurements currently being used by the communities.

We are working to identify attributes of measurements being used for the major initiatives. Conversations with data users makes it clear that few individuals or organizations know the specific attributes of data that would be optimal for their organization decision-making processes. The users generally agree on the categories, but have poorly defined requirements beyond that of the overall need. The categories of attributes include

Accuracy: acceptable confidence interval
Resolution: spatial, spectral, and temporal
Geographic breadth: global, continental, national, regional, local

Many users simply use whatever data are trusted and readily available to them (much like many people use US census data without knowledge about the data's accuracy and limitations). We find that even when user communities do have a preference for specific data, they do not know the heritage of their data (for example, if they are derived from MODIS, Landsat, etc). We have learned through meetings of NASA's Socio-Economic Data and Applications Center (SEDAC) that efforts are underway for ISO-standard compliant "watermarks" on NASA data to allow NASA to trace use of these data. Our point of contact for that effort is John Moses (GSFC).

In order to be successful in communicating these attributes and to better understand the needs of the user communities, we would like to continue to sample as broad a community as possible as CMS continues. For follow on work, we would consider using a survey or questionnaire of CMS data users and other participants to better resolve the needs in both the flux and other CMS domains.

Publications and Policy documents

- Policy Brief #1: The CMS Biomass Product and its Contribution to Forest Conservation (in Appendices)
- Policy Brief #2: CMS and Ocean Resource Management: An Illustration of How Economic Value can be Imputed to CMS (in Appendices)
- Policy Brief #3: The Social Cost of Carbon: A Link Between CMS and Carbon
- Policy Developments at Other Federal Agencies (in Appendices)

Summary and Recommendations for FY13 CMS Applications

Our applications activities have communicated the value and use of CMS data products to a wide community, including potential users. We have also developed through our policy briefs a direct link between CMS data products and science, and public policy actions. These policy briefs show the potential economic value of a carbon monitoring system to the nation. Specific actions we would like to take include:

- Identifying additional potential users of new CMS data products developed during 2011 and 2012;
- Following the recommendations from September Biomass briefing, engage with the user community, including local, state and national governments who may use biomass information, and communicate the needs of this community back to CMS scientists;
- Following the recommendations from the January Flux briefing, engage with Federal and academic policy sectors to find appropriate product users for flux products.
- Continuing to track emerging policy developments for which CMS may have relevance, and summarizing these developments by continuing the series of internal policy issue briefs
- Identify the policy and decision making relevance for each FY13 CMS project and design communication strategies for each.
  Facilitate communication between CMS scientists and congressional leadership.

4.6 User (R. Duren et al)

CMS System Design Study
Progress Report
12 January 2012
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The CMS System Design task was started in Aug 2011 with the intention of providing an *initial* systematic study looking across the current and future NASA program of record – towards the ultimate delivery of policy-relevant data products. This task is intended to complement and look beyond the two existing pilot projects to help guide thinking about future needs. The task is expected to conclude in April 2012 with a briefing to the CMS SDT and program managers. The objectives of the study are to:

1. Engage users to define well-posed questions
2. Extract quantitative product performance goals to guide future study
3. Preliminary error analysis to predict future performance
4. Preliminary assessment of key performance sensitivities & gaps
5. Produce notional 10 year roadmap for future CMS product deployment (critical paths, incremental improvement, integration points, & key capability milestones)
6. Identify potential future needs for observations, data systems, models, & analysis; risks; opportunities; and architectural options for sustained CMS product delivery

The user engagement activity is being coordinated with the CMS Applications Task (Brown, MacCauley et al). As a result of those engagements a suite of four initial use-case scenarios have been developed; each aligned with specific policy questions and users. The following scenarios were reviewed with the science community at the September SDT meeting and the October CC&E workshop, as well as smaller dialogues with specific users such as the US EPA, CARB, and their international counterparts: 1) trend monitoring of fossil-fuel CO2 emissions from urban areas, 2) characterization of area sources of non-fossil fuel CO2 and CH4, 3) trend monitoring of major short-lived climate forcing agents (e.g., short-lived GHGs and aerosols) for developing countries, and 4) characterization of forest biomass stocks and disturbance monitoring for the US and the pan-tropics. These use-case scenarios have in turn been used to establish "level 1" performance goals[1] for key carbon data products for subsequent linking to relevant capabilities of mission data sets in the NASA program of record (and/or identification of gaps). These efforts have also identified functional needs for tools such as space-time resolved inventories to facilitate the application of inverse flux estimates to emission inventory testing.

A generalized analysis framework has also been developed, in consultation with the Biomass Pilot team, to evaluate uncertainties and sensitivities of biomass estimates for different lidar and radar data types and regression indices. This is now being applied to assess the variance in biomass estimates at different spatial scales for existing and future data sets including ICESAT-2, various flavors of DESDynI, and NASA airborne instruments.

[1] "level 1" here alludes to requirements typically associated with NASA missions (rather than data product levels)

We plan to review this methodology and results of the analysis with experts from the biomass pilot team in February to solicit their feedback before taking additional steps.

Additionally, a framework/taxonomy for representing key sources of uncertainty in carbon flux estimates has been developed and, in consultation with the Flux Pilot team, various analyses and Observing System Simulation Experiments (OSSEs) are being executed to help construct a flux error budget and explore the driving performance sensitivities. An initial set of OSSEs evaluating the sensitivity of flux estimate uncertainty to XCO_2 measurement precision and density based on GOSAT, OCO-2, OCO-3, and a hypothetical GeoCAPE implementation have been completed on a 2° x 2.5° grid with monthly resolution. These OSSE scenarios will be run again on a 0.5° x 0.625° grid with weekly resolution with results expected in early February. An effort is also being made to assess the sensitivity of flux estimates to transport model errors.

Finally, discussions are underway with members of the INFLUX team to quantify requirements on sensing of planetary boundary layer height and other meteorological parameters to minimize error sources in flux inversions on small spatial scales (e.g., < 10 km) – including consideration of airborne remote-sensing techniques.

Efforts in early 2012 will be focused on completing the above tasks and addressing architectural considerations for sustained CMS data product delivery. We are on schedule to report out to the SDT and HQ in the April timeframe (schedule TBD).

SCIENCE DEFINITION TEAM PROJECTS

5.1 Development of a Carbon Monitoring System from an Ensemble Coupled Data Assimilation Perspective (A. Arellano)

This proposal is in response to the NASA ROSES 2010 A.39 solicitation. In particular, this is a request to participate on the development and evaluation of the NASA Integrated Emission/Uptake "Flux" pilot product as member a of the Carbon Monitoring System Science Definition Team (SDT). The NASA Center-led pilot study aims to provide global maps of surface carbon fluxes that are constrained by atmospheric observations of CO2 using data assimilation tools to combine information from observations and model output. A critical component of this study is the characterization of errors associated with a) prior estimates of carbon fluxes, b) modeling atmospheric transport, and c) atmospheric carbon observations. The ensemble approach proposed in the pilot study is an extremely useful application in characterizing these errors. However, intrinsic in this approach is the need to generate realistic and reasonable ensemble perturbations. As a member of the team, I propose to augment the activities of the pilot study by providing ensemble simulations derived from propagation of these errors within a system that mimics a numerical weather prediction with chemistry. Ensemble simulations of atmospheric CO2 and CO (and preselected CO2 and CO tagged tracers) will be generated and analyzed using perturbed meteorology and/or surface fluxes in the Community Earth System Model (CESM1). In conjunction with CO2, relatively well-observed species like CO offers a unique opportunity to investigate errors associated with modeling constituent transport. This work is an extension of current ensemble DA capabilities of CESM's Community Atmosphere Model with Chemistry (CAM-Chem) and National Center for Atmospheric Research Data Assimilation Research Testbed (DART) (e.g. joint assimilation of MOPITT CO and meteorological observations by Arellano et al., 2010 and Arellano et al., 2007). Results will be provided as independent model data to SDT and the pilot study production team. Expertise in ensemble data assimilation, inverse modeling of CO sources (Arellano et al., 2004; Arellano and Hess, 2006) and use of satellite data (Edwards et al., 2009) will be provided during the course of the pilot study.

5.2 Developing a Framework for Evaluating CMS Pilot Products to Promote Engagement with the User Community (M. Brown)

The CMS Applications program focused on demonstrating the value of CMS products to users from multiple domains. In order to accomplish this goal, it was essential to first define the user community membership and needs for both the biomass and flux products. This was the primary goal of the first six months of the CMS Applications program. During this time, we also developed a framework to demonstrate the value of CMS data products for national public policy, as we had proposed. In addition, we provided support of CMS meetings, conducted community briefings, developed publications and policy documents, and are broadening and updating the CMS website. In the remainder of the period, we continued the community briefings and development of publications and policy documents. Through participation in the CMS science definition team, we coordinated two user briefings on the CMS system, wrote meeting reports about those briefings and conducted research meant to understand how scientists, data end users, and policy makers can communicate to establish an effective program for carbon monitoring.

The community of practice for CMS products includes (1) natural resource managers who work at a local level to manage and assess carbon-related resources and (2) policy makers who make decisions or influence policy that these managers seek to implement. Because the CMS has been a prototype system in development, seeking to demonstrate the use of remote sensing in quantifying carbon stocks and fluxes, we sought to inform key members of the community of practice about the ongoing efforts of the CMS program through briefings that would engage and inform potential users, while being careful to communicate the preliminary nature of the CMS products and production process.

Publications (2012)

M.E. Brown, M.K. Macauley (2012) Developing Earth Science Data and Models for Evaluating Climate Policy Outcomes. EOS Transactions AGU, *93*(34), 328, doi:10.1029/2012EO340007. *NASA Carbon Monitoring System: Characterizing Flux Uncertainty; Washington, D. C, 11 January 2012*

M. E. Brown, M. Macauley (2012), Bringing together users and developers of forest biomass maps, Eos Transactions AGU, 93(3), 32, doi:10.1029/2012EO030011. *NASA Carbon Monitoring System Briefing: Steps Towards Improved Measurements of Biomass and Resources for the Future; Washington, D. C., 9 September 2011* F

5.3 Biomass Burning Assistance for NASA's Carbon Monitoring System (N. French)

Project Activities
The work completed is described below for two these activities:

- Provide expert knowledge and guidance to the Flux pilot project team and full CMS program regarding the inclusion of biomass burning (wildland fire) in the terrestrial flux models NASA-CASA and CASA-GFED;
- Deliver any needed data or information on fire emissions for North America using the Wildland Fire Emissions Information System (WFEIS), which includes maintenance and improvement of the WFEIS.

Project Outputs
Summary data from WFEIS: Tables 1 and 2 show the outputs from WFEIS that can be used in comparing to GFED and NASA-CASA for CONUS and were provided to Collatz and Potter for comparison or use in the CASA models. These data outputs do not include an uncertainty metric because that is not currently a feature of WFEIS. Phase 2 plans are to develop a method of assigning an uncertainly to these outputs.
Journal article: McKenzie, D., N. H. F. French and R. D. Ottmar (2012). National database for calculating fuel available to wildfires. EOS 93(6): 57-58.

Summary of Project Activities
Summary of project activities reviewed above:

- Attended and participated in pilot project meetings and reviewing planning materials and outputs from the Flux pilot activity;
- Provided expert knowledge regarding the integration of biomass burning into flux estimates
- GFED is a reasonable and effective method for integrating biomass-burning emissions into the CASA terrestrial carbon model,
- NASA-CASA properly includes fire as a factor in the terrestrial system,
- Both models could use information from systems like WFEIS to improve there presentation of fire in their models, but the initial flux pilot approaches are adequate.
- Discussed at the SDT Flux Pilot meetings to use the CMS atmospheric sensing and inverse modeling approaches to look at relatively fine-scale and short-term events, such as large wildfires (e.g. in boreal North America) to assess the ability of the CMS flux assessment;
- Began collaboration with C Potter on improving the inclusion of fire in the NASA-CASA model based on outputs from WFEIS;
- Provided WFEIS output to Collatz and Potter on burned area and emissions for comparison with GFED and NASA-CASA.
- Completed WFEIS system maintenance and improvements;
- Prepared and published a short article on fire fuels for CONUS, a product created under a previous NASA grant and written up under these project funds.

Next Steps
The work stared under this Phase 1 CMS project will be continued under Phase 2 CMS and under a NASA Applications project, both funded through 2013. Specifically, Dr Collatz and Dr. Potter have discussed with me ideas to use WFEIS outputs to assess their respective

terrestrial carbon models and to integrate some of the WFEIS outputs into these approaches. Specific needs, which will be taken up by me or other Flux project team members, include:

- Apply WFEIS outputs on emissions by ecoregion, year or month (or day) to the assessments of NASA-CASA, which uses this type of information, but has not rigorously assessed the inputs they currently have. (short-term)
- Compare WFEIS 1-km emissions outputs with estimated uncertainly to the outputs used in GFED which are currently integrated into CASA-GFED. The data can be used to assess the current methods and to possibly improve the estimated emissions within the US. (short-term)
- Develop an uncertainty estimate with WFEIS output data.
- Re-visit the idea of using the Flux Pilot sensing and inverse modeling approach to view and quantify specific fire events which has major impacts on the atmosphere by injecting large amounts of carbon-rich smoke into the upper troposphere. There are several known events in the recent past that could be assessed. (This concept was discussed in the July 2011 Flux Pilot team meeting but was not able to be implemented in Phase 1 due to time constraints). (mid-term)

5.4 Assessing Potential Impacts of Ground Sample Bias in Global CMS Biomass Estimates, Now and in the DESDynl Era (S. Healey)

Sean Healey is proposed as a member of the Science Definition Team (SDT) of NASA's Carbon Monitoring System (CMS). He and the listed co-investigators are all affiliated with the Forest Service's FIA (Forest Inventory and Analysis) program, and as a group, they have extensive experience using FIA data both to develop official forest statistics and to calibrate and validate maps created with remotely sensed data. This proposal will add to the SDT a practical element related to the limits of FIA data and the data needs of the forest management community. In addition, independent research is proposed to leverage the properties of FIA's sample to better understand how CMS might perform both beyond the borders of the United States and in the DESDynI era. The optical satellite imagery which will form an important part of any near-term global CMS biomass product often does not offer good resolution of moderate and high levels of forest biomass. In the absence of predictors able to discriminate among levels of a particular target variable, many modeling approaches minimize prediction error by predicting toward the mean of the reference dataset. If that reference dataset is biased (not a representative sample), biomass predictions can be systematically skewed either up or down. While FIA in this country does comprise a representative sample, CMS in many parts of the globe will have to rely upon ad hoc collections of management inventory stand exams, which are often skewed toward harvestable (high biomass) conditions. Over large areas, the potential for even small systematic prediction bias may create very large errors in carbon storage estimates. We will use intentionally biased sub-samples of FIA data from the state of Oregon as reference data to test the effect of such bias upon state-level CMS estimates of biomass. In addition, using these same biased sub-samples, we will replace optical data in the CMS system with pseudo-data representing the higher correlation with biomass anticipated with DESDynI-based predictors. DESDynl's increased prediction precision may reduce the rate at which predictions default toward the mean and may therefore reduce propagation of ground sample bias in the CMS mapping process. These activities should shed light upon: 1) the likely effects of non-representative reference data on the global CMS biomass product, and 2) the degree to which DESDynI may diminish prediction error related to ground sample bias.

5.5 Biomass for Carbon Budgeting (R. Houghton)

R.A. Houghton is proposing to be a member of the Science Definition Team (SDT) for a Carbon Monitoring System (CMS). He would participate in development of the Biomass product. He has spent 25 years estimating the global net flux of carbon to the atmosphere from changes in land use, an estimation that requires information on biomass and carbon stocks. Over time his estimates have become more and more spatially detailed, and the next step is to co-locate changes in land use with carbon density at the spatial resolution of change. That will improve estimates of carbon flux enormously at all scales. The step after that will be to use multi-temporal, spatial data of aboveground biomass to estimate change more directly (without necessarily identifying land-use change first). That approach will identify additional sources and sinks of carbon, heretofore unobserved, and may help resolve and explain a large portion of the residual terrestrial sink. Both a one-time map of biomass and successive maps of biomass change will help with the monitoring, reporting, and verification of REDD and LULUCF, whether at the project or national level. Future demand for space-borne measurements of biomass and biomass change will only grow. The time is right for a carbon monitoring system, a major part of which will be measurement of aboveground biomass from space.

5.6 Evaluation of Approaches for Assessing the Impacts of Natural Disturbances on Aboveground Carbon Storage in and Emissions from U.S. Forests - A Carbon Monitoring System Science Definition Team Proposal (E. Kasischke)

The principal investigator proposes a set of activities that will be carried out as a member of the Science Definition Team (SDT) for NASA's Biomass and Carbon Storage Pilot Product (BCSPP). The PI would provide expertise in the broad area of impacts of natural disturbances (fire, insects, and hurricanes) on forest carbon stocks, with a strong foundation in research on the impacts of fire on carbon cycling in boreal forests. The foundation for serving on the SDT is based on > 20 years of research on satellite mapping of fires, using SAR to estimate aboveground biomass in boreal and temperate forests, using VIS/IR data to assess post-disturbance vegetation recovery, developing approaches to estimate biomass consumption during fires, and developing approaches to use information derived from remote sensing data in carbon cycle models. The PI also has directed and carried out field studies used to develop and validate remote sensing information products and has access to or knows of data sets that can be used for validation activities associated with the BCSPP. The PI organized and led a disturbance synthesis activity for the North American Carbon Program that involved 100 researchers from the U.S., Canada, and Mexico. This activity not only provides an understanding of data sets needed to quantify the impacts of disturbance on terrestrial carbon budgets, but provides a foundation for liaisons with the broader scientific community (along with the extensive contacts the researcher has with scientists conducting carbon cycle research in the boreal forest). Specific expertise that the PI will provide to the BCSPP and its SDT include: (a) evaluation of the remotely-sensed data products being used in the BCSPP to map natural disturbances to forests; (b) evaluation of the approaches used to map aboveground biomass using PALSAR, with a specific focus on errors introduced by variations in soil moisture; (c) evaluate of approaches to estimate carbon consumed during fires; and (d) assessment of approaches needed to model how natural disturbances influence stand carbon cycle dynamics. The PI will provide written reports to the members of the BCSPP and SDT on his evaluations of specific products and approaches. The PI will also aid in identification of sites that could be used during validation activities, and identify additional field data sets that could be used. The PI will also participate in activities to define and develop products that can be used by policy makers and managers. Finally, the PI will work with members of the BCSPP and SDT in developing a plan for the development of global biomass product.

5.7 Mapping Biomass - Past Experiences and Future Directions in Data Fusion and Product Validation (J. Kellndorfer)

With the successful inclusion of REDD+ in the UNFCCC agreement of the Conference of the Parties 16 in Cancun, accurate and scientifically defendable measurements of forest carbon fluxes are ever more important. The science community is called to the task to provide solid data sets and methods for tracking forest carbon fluxes and assess accuracies, which are suitable for a carbon-trading framework. This initiative by NASA to lead the effort of global mapping is a welcome and needed step forward, in particular to gain broader community assessment of what is possible, and where there are limitations in current approaches to carbon flux measurements and monitoring. The PI and collaborators are keen to work with NASA HQ and Centers on the CMS biomass mapping pilot study. Presently, the PI is leading several related projects on biomass mapping with a major subset of data sets proposed for the biomass mapping pilot study. Also, he is leading a pan-tropical mapping project of forest cover and structure with ALOS-PALSAR radar data. Extension of gained expertise to global scale mapping is core to the PIâ€™s interest in reducing uncertainties in global carbon flux estimates from land cover change. Furthermore, as a member of the DESDynI Ecosystem Structure Science Study Group, keen interest in preparation for this mission is aligned with involvement in this pilot activity.

5.8 Development and Evaluation of Pilot Projects for a Carbon Monitoring System (M. Macauley)

The Carbon Monitoring System Science Definition Team (CMS SDT) will play a pivotal role in the stewardship of the CMS biomass and carbon flux pilot products during their research phase to help shape their policy relevance. My commitment in serving on the CMS SDT is to further the CMS goal of bringing enhanced understanding of carbon cycle science to bear in informing public policy. I bring experience as a research economist working to advance understanding of the public benefits of Earth science data and their economic value for decision making, including the role of measurement and monitoring of physical attributes of the carbon cycle in climate policy. I have led international teams of researchers using Earth science data products to improve resource management and have extensive experience in policy advisory roles to enhance the link between data and their application. The most salient climate policy issues for the CMS pilot products include newly emerging requirements of federal regulation of greenhouse gases (GHG), particularly under the Clean Air Act (CAA); a host of new regional and state initiatives; the longstanding challenge of improving GHG inventories under the United Nations Framework Convention on Climate Change (UNFCCC); and ongoing international concerns relating to the need for development of globally consistent measures and transparent means of measuring, monitoring, reporting, and validating (MMRV) biogenic sequestration and carbon fluxes. In serving on the CMS SDT, my commitment would be to identify, interpret, and integrate the aspects of these issues that are most relevant to the pilot projects. I propose three tasks to support this effort. One task is to provide guidance for ascertaining how good is good enough in the development of the CMS pilot products. Given the constraints of time and funding for the pilot products, to what extent can and should they be designed not only to enhance carbon science, but to support public decisions? What are the highest priorities and who will make use of the products in serving the public? What is the role of uncertainty characterization in the application of the products for policy? The second task includes characterization of the economic importance of the CMS data products. This effort would enable the CMS to align with priorities set forth by the Office of Management and Budget (OMB) asking agencies to better assess the impact of their science, technology, and innovation investments (OMB 2010). The economic value of carbon cycle data products is underappreciated. In the case of carbon management, for example, federal agencies estimate that the management of biogenic carbon sequestration can reduce the economic cost of stabilizing GHGs by as much as 80 percent (US EIA 2009, 2010; US EPA 2009, US CBO 2009a). However, these agencies emphasize that realizing these savings will require significantly improved means of measurement and monitoring of carbon sources, sinks and fluxes. This sets the stage for demonstrating the value of CMS products. For this task, I will draw from my research on the value of information to outline a framework relevant for the CMS to use in defining and conveying the economic significance of its data products. The third task is to support the CMS goal of enhancing its relationships with the broader academic, applications, and user communities as well as activities of other agencies. For this task, I identify initial communities and propose a set of meetings, briefings, and other opportunities for the CMS SDT to engage with these groups. Taken together, these tasks will balance CMS science and its policy relevance in serving the public, integrate CMS products with decision making, and put in place a framework for CMS to continue to meet these goals going forward.

5.9 Carbon Monitoring System Science Definition Team membership proposal (Integrated Emission/Uptake Pilot Product) (A. Michalak)

Through this proposal, Dr. Anna M. Michalak is requesting to become a member of the NASA Carbon Monitoring System Science Definition Team (SDT) for the Integrated Emission / Uptake ("Flux") Pilot Product. Dr. Michalak will contribute to each of the key activities of the SDT, and brings considerable expertise to each aspect of the SDTâ€™s role. In addition, several ongoing project currently led by Dr. Michalak had direct relevance to these roles outlined in the call for proposals. In brief, the SDT roles and Dr. Michalakâ's expertise are: (i) Review and provide scientific and technical input regarding the overall development plan for a pilot product (Dr. Michalak has over a decade of experience in inverse modeling, including a proven track record in estimating carbon fluxes using atmospheric observations); (ii) Recommend refinements to the product development approach, algorithms, and/or models (Dr. Michalak has pioneered the development of the geostatistical approach to atmospheric inverse modeling, has developed approaches for parameterizing inversions including covariance parameter estimation, has coordinated the computational development associated with large-scale atmospheric inverse problems); (iii) Provide guidance for the development of an evaluation plan that includes both validation and characterization of uncertainties associated with a product and participate in product evaluation activities (Dr. Michalak's research group has made substantial contributions to uncertainty assessment in atmospheric inverse modeling and the evaluation of flux estimates); (iv) Provide guidance on the nature of the data sets and initial pilot product(s) to be produced and how they may be used for carbon policy and carbon management decisions (Dr. Michalak is co-lead for the development of the new U.S. Carbon Cycle Science Plan); (v) Provide liaison with the broader science, applications, and user communities or the related activities of other U.S. Federal agencies (Dr. Michalak has worked with the Carbon Cycle Interagency Working Group through her work on the U.S. Carbon Cycle Science Plan, has been an associate member of the OCO science team, has been the co-lead of the ASCENDS science definition committee, etc.); (vi) Work in close association with NASA HQ and the NASA Center-led teams implementing the development of the pilot products to achieve the CMS goals (Dr. Michalak has long-standing collaborations with carbon scientists at JPL and GSFC). Dr. Michalak is the PI on several research projects that are directly relevant to the Flux Pilot Product, including three ongoing NASA-funded projects, one ongoing NSF-funded project, and one ongoing DoE-funded project.

5.10 Carbon Monitoring (H. Shugart)

This proposal is a response to funding opportunity number NNH10ZDA001N-CMS. The PI, H.H. Shugart, proposes for membership on the Science Definition Team for the Carbon Monitoring System (CMS) as a scientific and technical expert. He has worked on several projects in the past with NASA centers, notably Goddard and Langley Space Flight Centers and the Jet Propulsion Laboratory. He is enthusiastic for the opportunity to continue to work with the NASA Centers in the production and validation of the two CMS pilot products. Much of the PI's research for the last several years has emphasized the importance of understanding the structure of vegetation and the influence of vegetation structure on the compositional and functional dynamics of natural vegetation. The PI is familiar with a variety of forest survey systems used for the development of basic data for the quantification of biomass levels in forests and other ecosystems. He also is familiar with process-based carbon-flux models and has reviewed these models in scholarly books. He has worked with several different approaches to modeling the carbon dynamics of forests and other ecosystems. The PI has used vegetation data and global-carbon-budget-related data for several decades. He currently serves on the ad hoc committee for the DESDynI satellite system and as a NASA observer on the European Space Agency BIOMASS satellite instrument team. He has several different channels for liaison with other Federal Agencies and with the international community as well. Over his career, the PI has worked in close association with NASA-HQ and the NASA Center-led teams on planning and research design projects. He is enthusiastic about the goals go the carbon monitoring systems and its importance to national and international environmental science and policy. The intent of this proposal is to show from the PI's past and present scientific work an indication of his potential contribution to the several capabilities and products that are outlined in the NSPIRES announcement.

5.11 Proposal to be a member of the Science Definition Team for Carbon Monitoring System (G. Sun)

Introduction

PI has proposed to test the algorithms for biomass estimation from lidar and SAR data; improve data processing method and algorithm for biomass mapping in mountainous areas; and investigate the scale issue when the biomass estimation models developed at one scale being used in another scale.
Our 3D incoherent backscattering model was modified into a coherent model and the height of scattering centers of various forest canopies were simulated and compared with waveform indices derives from Laser Vegetation Imaging System (LVIS) waveforms. A look-up table was built by use of forest growth model, 3D radar backscatter model, and the inversion of forest biomass estimation from inversion was tested.

Regional biomass mapping from SAR data (backscattering coefficient, height of scattering phase center) requires terrain correction of radar backscattering coefficient. It has also be found that when using a DEM to calculate the height of scattering phase center from InSAR DTM (such as SRTM elevation data) the co-registration accuracy of these two DTM/DEM are very important.The biomass estimation from Laser Vegetation Imaging System (LVIS) was developed using data at footprint scale and tested at various plot scales (0.25 – 1.0 ha).

Achievements

The Influences of Forest Structures on Height of Scattering Phase Center

Forest canopy height is an important indicator of standing biomass for management purposes as well as for the assessment of carbon storage. Height of scattering phase center (HSPC) derived from interferometric synthetic aperture radar can be used to estimate forest height and biomass. The influence of forest structures on HSPC is not clear, especially at L band. In the study, a coherent version of the three-dimensional radar backscatter model of forest canopies (Sun & Ranson, 1995) has been modified to a coherent model. The model is examined by layered forest scene and validated by HSPC of Shuttle Radar Topography Mission (SRTM). The sensitivity of HSPC to forest stand parameters were studies using the coherence model. The results showed that HSPC is nearly linearly increases with forest height and the effect of forest density on HSPC is very weak. The relationships between HSPC and maximum forest height, mean forest height, and Lorey's height (basal area weighted mean height) are investigated. HSPC has the highest correlation with Lorey's height (Fig. 5.3.a).

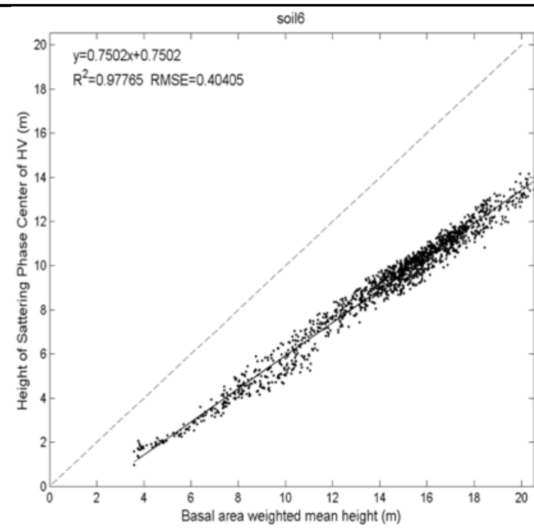

Fig. 5.3.a. Height of scattering phase center vs. Lorey's height of forest stands.

Retrieval of Forest Biomass from ALOS PALSAR Data Using a Lookup Table Method

The feasibility and problems of forest biomass estimations based on lookup table (LUT) methods using ALOS PALSAR data were investigated. By use of the forest structures from a forest growth model as inputs to a 3D radar backscattering model, a lookup table was built. Two types of searching methods (Nearest Distance (ND) and Distance Threshold (DT)) were used to find solutions from lookup table. When a simulated dataset was used to test the lookup table, the RMSE of biomass estimation were 39.133 Mg/ha (R^2=0.748) from ND and 26.699 Mg/ha (R^2=0.886) from DT using dual-polarization data for forest with medium rough soil surface. All results showed that DT was superior to ND. Comparisons of biomass from forest inventory data with that inversed from look up table using DT method over eight forest farms showed RMSE of 18.564 Mg/ha and 15.392 Mg/ha from PALSAR data with and without correction of the scattering mechanism, respectively. For the entire Lushuihe forest Bureau, the errors of the biomass estimation were -13.76 Mg/ha (-8.6%) and -5.54 Mg/ha (-3.5%) using PALSAR data with and without correction of scattering mechanisms due to terrain, respectively. The results showed that the LUT method has the ability to consider the influence of terrain on scattering mechanism and that the PALSAR data without terrain-correction of scattering mechanism could be directly used for biomass estimation using the lookup table method. Fig. 5.3.b. Shows the inversion results using the search method DT. The paper by Ni at al. (2012) describes the LUT method in detail.

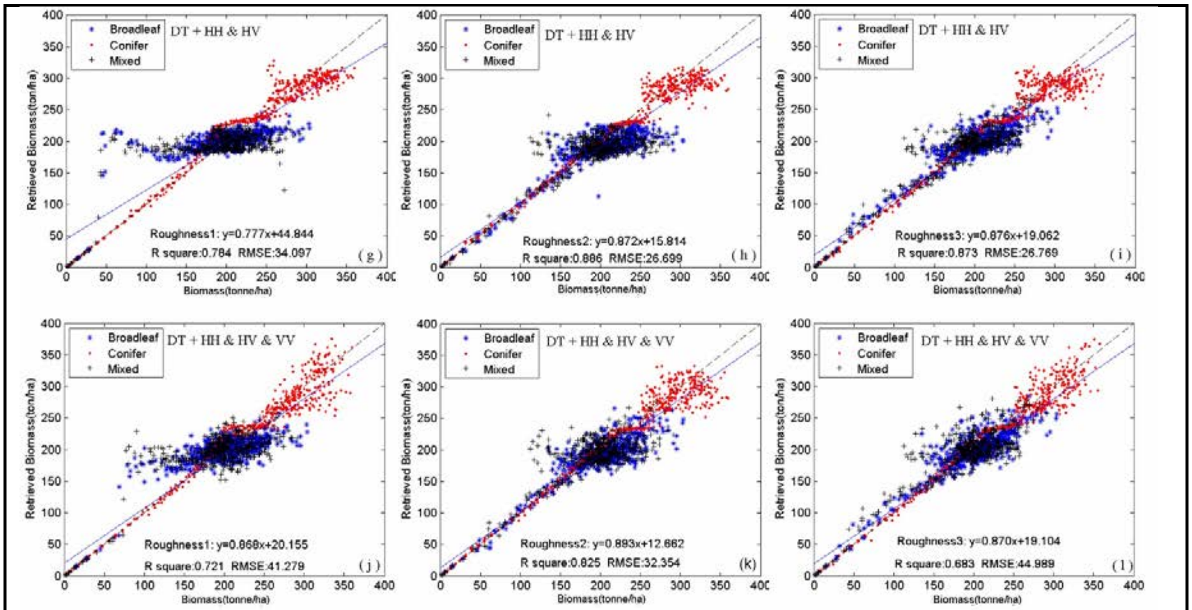

Fig.5.3.b. The performance of biomass inversion using different datasets and searching method DT. The soil surface roughness changes from rough (column one: g, j) to smooth (the last column: i, j) while the soil moisture was mesic and ground slope was zero.

Accurate automatic co-registration of two DTM/DEMs

The differences of two digital terrain models(DTMs) derived from airborne interferometric SAR (InSAR) data of a short and a long wavelength have been used for the estimation of forest vertical structure. When the spaceborne repeat-pass InSAR data are used the atmospheric effects need to be considered. A simple method for the reduction of atmospheric effect in spaceborne repeat-pass interferometry is proposed in this letter. By subtracting a simulated interferogram using Shuttle Radar Topography Mission (SRTM) DTM from the interferogram of a pair of Phased Array Type L-Band Synthetic Aperture Radar (PALSAR) InSAR data, the remaining phase includes the phase caused by the height differences of scattering phase centers (SPC)at C and L bands and the phases caused by atmosphere effects and other changes during the PALSAR repeat-pass period. A low-pass spatial filtering can reveal the atmospheric effect in the phase image because of its low spatial frequency feature. The proper filtering windows size can be determined by the changes of standard deviation of filtered phase images with the increases of window size. It should be near a constant when only the atmospheric effect remains. The results showed that after the atmospheric effect reduction the difference between SRTM-DTM and PALSAR-DTM reduced from 60.17m±16.2m to near zero (0.52m±4.3m) at bare surfaces, and the correlation (R^2) between mean forest height and the difference between SRTM-DTM and PALSAR-DTM was significantly increased from 0.021 to 0.608.

Fig. 5.3.c shows an example at Sierra, CA. By comparing B and C, it can be seen that the pattern of terrain is obvious in the map of height of the scattering phase center (HSPC) if the original geo-referenced SRTM and NED were used. After the accurate co-registration, these patterns have disappeared in (C). The polygon in the images delineates the area covered by LVIS (Laser Vegetation Imaging System) data, and Fig. 5.3.c-D shows the height of waveform centroid (RH50) calculated from LVIS data. After co-registration, the correlation between HSPC and RH50 improved from a R^2 0f 0.19 to 0.51 for images with 30m pixels. Researches

have shown high correlation between HSPC and RH50 at field plot scales. Fig. 5.3.d shows that the co-registration is necessary.

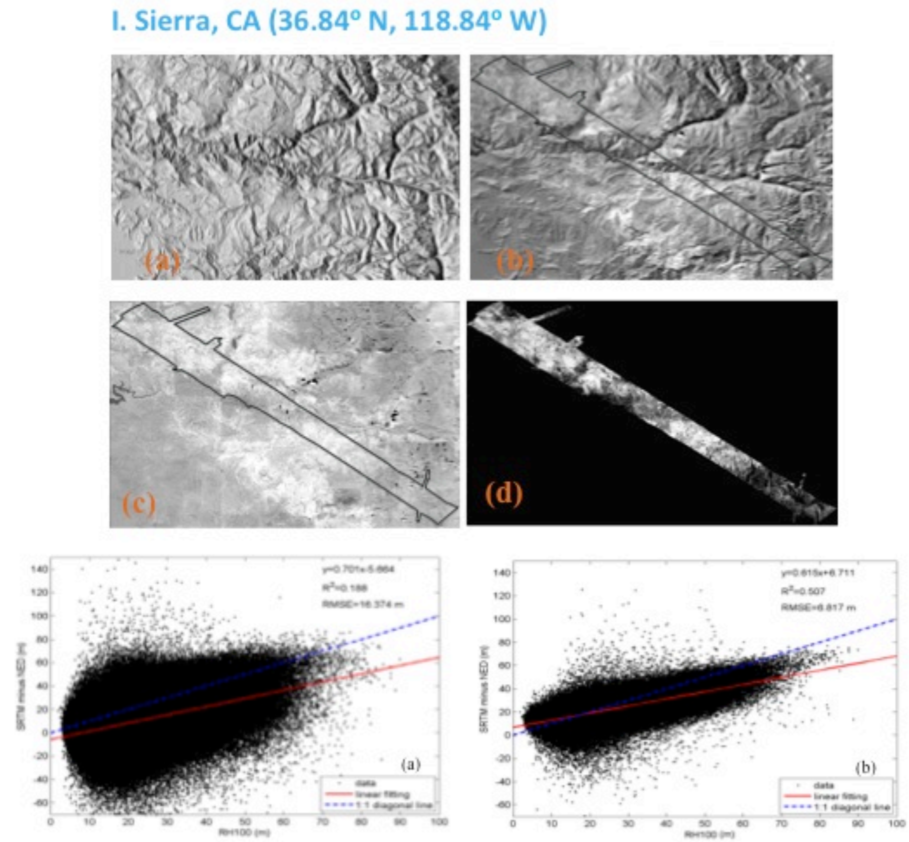

Fig. 5.3.c. Effects of co-registration on the calculation of the height of scattering phase center (HSPC) from SRTM and NED (National Elevation Data) DTM/DEMs: a) DEM of the study area; b) HSPC (SRTM minus NED) from original geo-referenced data; c) HSPC after accurate co-registration of SRTM and NED (error <0.1 pixel); d) RH50 (height of the waveform centroid) from LVIS data. Two plots: a) correlation between HSPC and RH50 before co-registration: Y = 0.7X-5.6, R2 =0.19, RMSE=16.4m; and b) correlation between HSPC and RH50 after co-registration: Y = 0.6X+6.7, R2 =0.51, RMSE=6.8m.

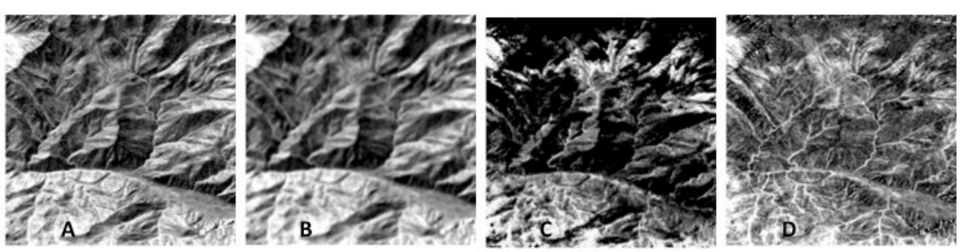

Fig. 5.3.d. A small area extracted from a) SRTM minus NED using original data; B) averages of the a using a 5x5 window; C) biomass map of WHRC derived from SRTM minus NED data; and d) SRTM minus NED after co-registration.

Mapping Forest Above-ground Biomass from LVIS Waveform Data

This study explored the forest biomass prediction and dynamic monitoring from LiDAR waveform metrics at different scales ranging from footprint-level (20m diameter, circle) to one hectare plot-level. The models developed using field measurements at footprints were applied to all LVIS waveforms within the study sites. Plots at 0.25-ha, 0.5-ha and 1-ha were used to validate the biomass averaged from footprints measured in these plots. The effect of forest disturbances on LiDAR biomass prediction models was investigated in the study. The results show that: 1) the prediction accuracy of disturbance-specific models at footprint-level was acceptable at various plot-levels. The R^2 and RMSE at 1-ha scale are 0.79 and 25.0 Mg/ha for undisturbed group, and 0.78 and 23.7 Mg/ha for disturbed group; 2) the differences between biomass prediction models for disturbed and non-disturbed forests were statistically significant; and 3) the footprint-level models developed using 2009 data could be applied to 2003 data for forest biomass change estimation.

Field samples include footprints in disturbed (triangles) and un-disturbed (square) areas. The difference of regression models for disturbed and un-disturbed samples is statistically significant (by T-tests), but the validation using field plots showed that the disturbance-specific models didn't perform better than the combined model.

It is relatively easier to conduct field measurements at the waveform footprints of large-footprint lidars with the accurate differential GPS instruments. The biomass models at the footprint-level by all four LVIS RH metrics have R^2 values ranging from 0.70 to 0.86. The RH50 and RH75 metrics perform similarly in terms of R^2, RMSE and RRE. The single variable regression model using RH50 was selected for the prediction model at the footprint-level for all data as it explains the greatest proportion of variance (R^2 = 0.86) (Fig. 5.3.e), and has the lowest residual error (RMSE = 30.1 Mg/ha) and relative error (RRE = 25.1%).

The best multi-regression model from step-wise regression (both directions) selected RH25 and RH75. The relation was: Bio = 16.4 + 7.6*RH25 + 10.2*RH75, with multiple R^2: 0.90, RSE: 26.94 Mg/ha, F-statistic: 491.1 on 2 and 106 degrees of freedom, and a p-value < 2.2e-16. The performance of single-independent and multi-independent were very close. The results of the validation at 1-ha plot-level from footprint-level disturbance-specific models were shown in Table 5.3.a.

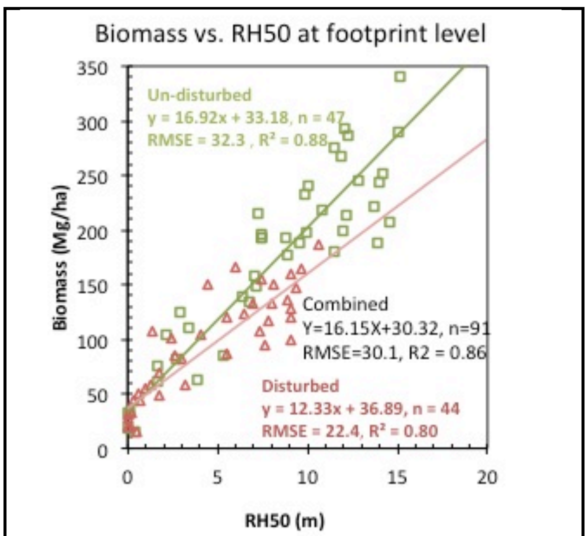

Fig. 5.3.e. Regression relations between biomass and RH50.

Table 5.3.a. Evaluation of the footprint-level combined RH50 and RH75 modelsby plot-level field data in 2009 and 2003.

Model	Year	Plot-size	N	Mean of field ($Mg{\cdot}ha^{-1}$)	Mean of predict ($Mg{\cdot}ha^{-1}$)	R^2	RMSE ($Mg{\cdot}ha^{-1}$)	RMSE (%)	Bias ($Mg{\cdot}ha^{-1}$)	Bias (%)
RH50	2009	0.25ha	105	143.6	144.5	0.79	32.6	22.7	+0.8	+0.6
		0.5ha	52	142.7	144.4	0.83	28.5	20.0	+2.2	+1.5
		1.0 ha	22	143.8	145.8	0.91	22.4	15.6	+2.0	+1.4
	2003	0.5ha	17	151.0	168.0	0.53	50.4	33.4	+17.0	+11.2
RH75	2009	0.25ha	105	143.6	147.1	0.72	37.3	26.0	+3.5	+2.4
		0.5ha	52	142.7	147.7	0.76	33.8	23.7	+4.9	+3.5
		1.0 ha	22	143.8	144.6	0.84	28.5	19.8	+0.8	+0.5
	2003	0.5ha	17	151.0	162.9	0.54	46.6	30.9	+11.9	+7.9

N: number of sample; Mean of field: mean biomass averaged over samples at plot-level; Mean of predict: mean predicted biomass averaged over samples at plot-level; Bolded are models with best performance at corresponding scale and year; The biomass estimation models developed from limited field data (measurements of ~100 20m LVIS footprints) were applied to all LVIS footprints in our study area and generate a forest biomass map with adequate accuracy.

The biomass estimation model using RH50 was applied to LVIS data acquired in 2003 and 2009 (Fig. 5.3.f), and the change of the biomass from 2003 to 2009 was analyzed (Fig. 5.3.g).

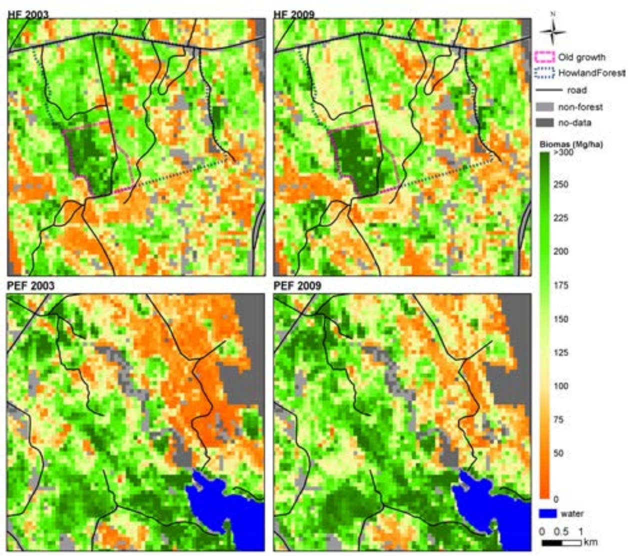

Fig. 5.3.f. Biomass maps of 2003 and 2009: HF – Howland Forest; PEF - Penobscot Experimental Forest.

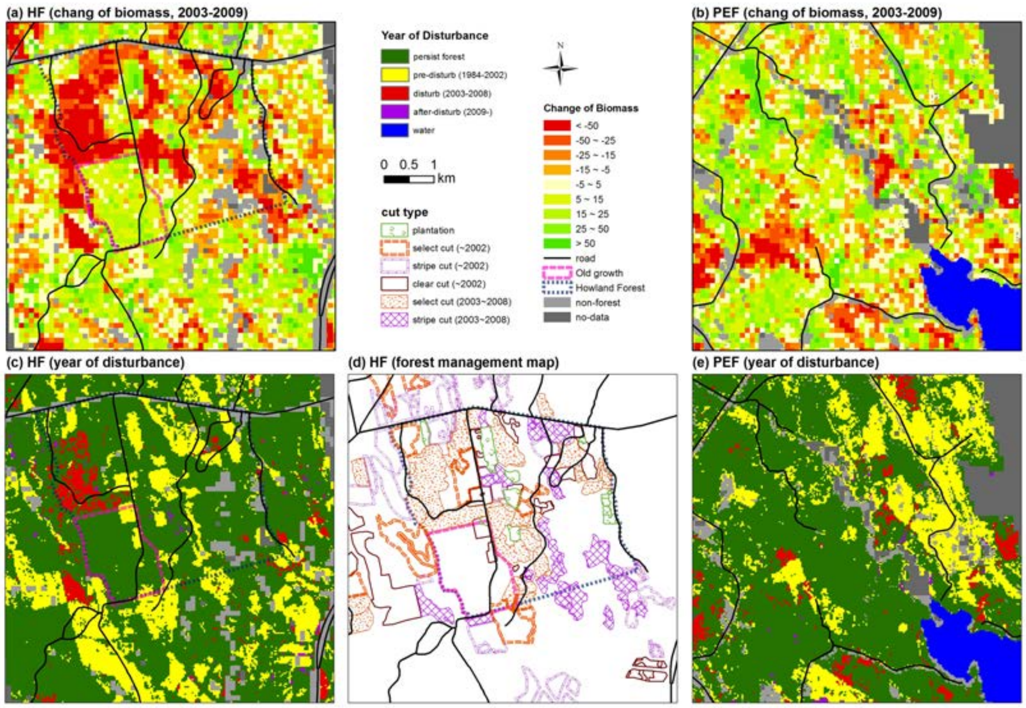

Fig. 5.3.g. Change of biomass for HF site (a) and PEF site (b) from 2003 to 2009 at 1-ha level by the combined RH50 models. The (c) and (e) are years of disturbances: disturbances prior to 2002 (yellow), between 2003 and 2008 (red), and after the 2009 (purple). (d) is the forest management map of HF created from information from private owner (international paper company) and Google images. The plantation (is the polygons outlined by solid green lines and filled with hollow. The select and strip cuts prior to 2002 are outlined with orange double long dashed lines. And dark red double long dotted lines, respectively. The select-cut during 2003 to 2008 is outlined by orange dot filled and solid lines. The stripe-cut between 2003 and 2008 is outlined by purple crosshatch filled and solid lines. At HF site, pink polygon is old-growth forest; and dark blue polygon is the outline of reserved area.

Publications

Ni, W., G. Sun, et al., Retrieval of Forest Biomass from ALOS PALSAR Data Using a Lookup Table Method, submitted to TGARS, J-STARS, (in press).

Huang, W., G. Sun et al., Mapping Forest Above-ground Biomass and its Changes from LVIS Waveform Data, submitted to RSE.

Ni, W., G. Sun et al., The Influences of Forest Structures on Height of Scattering Phase Center in Single Pass Interferometry at L-band, to be submitted to TGARS.

5.12 Data Fusion, Error Analysis, and a Global Biomass Product: Proposal for Membership on the Carbon Monitoring System Science Definition Team (R. Treuhaft)

This proposal for Robert Treuhaft's (proposer) membership in the Carbon Monitoring System (CMS) Science Definition Team (SDT) pertains to the Biomass and Carbon Storage Pilot Product (BCSP). In order to develop national and eventually global carbon storage and change products, the proposer will focus on the following objectives: 1) Organize a systematic review of all technical approaches to remote biomass estimation, including their interrelations and complementarity, for the use of SDT members in guiding core efforts; 2) Review and recommend refinements to data fusion strategies, providing guidance on systematic, and, where possible, model-based modes of combining data types; 3) Guide quantitative error analysis used to validate the BCSP, addressing errors in both field and remotely sensed biomass estimates; and 4) Develop a plan for global biomass monitoring articulating the technical challenges and possible alternative data fusion strategies for tropical forests. The first objective will address the wide variety of approaches to biomass estimation to bring all SDT members to the "same page". In the second objective, "data fusion" means the combining of several observations to estimate one quantity, biomass in this case. Undoubtedly a variety of sensors will be needed to estimate biomass with the best accuracy and coverage. The third objective on error analysis is aimed at a quantitative evaluation plan in the form of an error budget, modeled after more recent publications in which both remote sensing and field measurement errors are considered. The fourth objective addresses the plans for a global biomass product by concentrating on the complexities and challenges of remote sensing of tropical forests outside of the continental United States. The approach and methodology of the proposal is based on a conceptual picture which breaks biomass estimation into three categories: 1) Model-based estimation uses structural features of forests, such as height or profile moments, estimated from remote sensing data, along with ancillary data types to derive correlations between the remote sensing data and biomass. 2) Structure-based estimation draws correlations between structural features of forests from either lidar or InSAR. 3) Observation-based estimation uses remote sensing observations directly without first estimating structure. Because the BCSP must be a multi-sensor product, the first two objectives are significant in that they will enable guidance from the SDT on the optimal use of many different sensors toward the most accurate biomass estimates. Parameter estimation approaches used by the proposer in previous work will be part of his guidance as to methods for combining data types. The third objective on error analysis is significant in that the SDT is charged to establish an evaluation plan for the BCSP. The significance of developing a plan for global monitoring lies in the inclusion of tropical forests in biomass estimation algorithms. Because they are the most complex forest target, constitute about 50% of the Earth's biomass, and there have been a few different approaches to biomass estimation in tropical forests published, it will be important for the SDT to guide the Centers regarding tropical forests in a global product. The proposer has spent most his time in the last 6 years working on tropical forests. The proposer's experience in the correspondence between bulk canopy structural characteristics from lidar or interferometric SAR and biomass will also contribute to actuating the above objectives.

5.13 Quantifying the accuracy and uncertainty in remote sensing products of land use change: implications for carbon monitoring (C. Woodcock)

We propose to contribute to the Biomass Pilot of the carbon monitoring system by working closely with and providing guidance to the investigators involved in the estimation of land use change rates. Our experience concerning the effect of uncertainty in estimates on land use change rates on terrestrial carbon budgets indicates: (1) close attention to accuracy assessment is essential; (2) integration of the accuracy assessment results into the final estimates of land use change rates often leads to surprising large differences from the original remote-sensing based rates and (3) quantifying the uncertainty (or confidence intervals) in the land use change rates is the best measure of the value of remote sensing estimates; and (4) large uncertainties in land use change rates translate into large uncertainties in terrestrial carbon budgets. Our guidance and recommendations will derive from our experience over the past few years quantifying the effect of land use change on terrestrial carbon budgets in a variety of locations around the world (Olofsson et al., 2010; Kummerle et al., 2010; Jeon et al., 2011b). Additionally, we propose to serve as a liaison to several key groups with significant interest and expertise related to carbon monitoring. Woodcock is Team Leader for the Landsat Science Team and will facilitate coordination of efforts as they relate to the Landsat Program. Woodcock also serves as Co-Chair of the Land Cover Implementation Team in GOFC-GOLD (Global Observation of Forests and Land Cover Dynamics), and will serve as liaison to this group of international scholars that has worked for over a decade to promote monitoring of the world's forests, including carbon dynamics. As part of his role in GOFC-GOLD, Woodcock is involved in the GEO Forest Carbon Tracking Task, and can work to coordinate efforts between the NASA Carbon Monitoring System and this international group. Similarly, Woodcock contributes to the GOFC-GOLD Sourcebook for REDD reporting.

5.14 Providing Scientific and Technical Guidance to the Development and Evaluation of the Integrated Flux Pilot Product: Forcing Evaluation, Parameter Optimization, Uncertainty Assessment and Product Validation (J. Xiao)

Summary

During the 18 months of the project, I have actively participated in the CMS SDT and telecom meetings and have provided scientific and technical guidance to the development and evaluation of the CMS Pilot Flux Products. I have provided the following scientific and technical guidance and insights: (1) improve the overall development plan for the Flux Product; (2) evaluate and/or calibrate key spatial input data to the CASA models that can lead to significant biases in flux estimates; (3) optimize the key parameters of CASA models using carbon fluxes measured at eddy covariance flux towers (e.g., FLUXNET) and state-of-the-art data assimilation techniques; (4) identify missing components from the current development plan (e.g., disturbances); and (5) conduct uncertainty assessment of the bottom-up flux estimates derived from CASA models.

In addition to provide scientific and technical guidance and insights, I have upscaled FLUXNET observations from the tower footprint to the global scale and produced global gridded flux estimates (EC-MOD) for the period 2000-2010. To develop the global EC-MOD flux product, I have assembled and processed several global databases: FLUXNET synthesis database, MODIS data streams, and MERRA data. This product consists of ecosystem carbon and water fluxes: gross primary productivity (GPP), ecosystem respiration, net ecosystem exchange (NEE), and evapotranspiration (ET).

I have also used the resulting EC-MOD dataset to examine the magnitude, patterns, and interannual variability of carbon and water fluxes at the global scale for the period 2000-2010. In particular, our results show that extreme climate events (e.g., drought) and disturbances (e.g., fires) are the dominant sources of the interannual variability of global land-atmosphere carbon fluxes.

I have provided my global EC-MOD flux estimates to the CMS pilot flux project team (Dr. Josh Fisher et al.). EC-MOD has been used to evaluate and validate the CMS Pilot Flux Products at regional to global scales for the CMS Pilot Flux Product period (July 2009 – June 2010) using a suite of statistical measures.

With support from this grant, a series of journal articles and book chapters have been published or are in press/preparation. I have also given a series of invited talks and presentations at professional meetings and workshops.

Research products

During the 18 months of the project, I have upscaled FLUXNET observations from the tower footprint to the global scale and produced global gridded flux estimates for the period 2000-2010. These flux estimates are constrained by eddy covariance (EC) flux observations and MODIS data streams, and are thus referred to as EC-MOD. EC-MOD flux estimates consist of gross primary productivity (GPP), net ecosystem exchange (NEE), ecosystem respiration (ER), and evapotranspiration (ET). These flux estimates have a spatial resolution of 0.05 degree and a temporal resolution of 8 day. I have provided EC-MOD to the CMS pilot flux project team (Dr. Josh Fisher et al.) for the evaluation and validation of the CMS Pilot Flux Products.

To develop the global EC-MOD flux estimates, I have assembled and processed the following global data sets:
(1) FLUXNET synthesis database
(2) MODIS data streams
(3) MERRA data
I have also provided the following scientific and technical guidance and insights: (1) improve overall development plan for the Flux Product; (2) evaluate and/or calibrate key spatial input data to the CASA models that can lead to significant biases in flux estimates; (3) optimize the key parameters of CASA models using carbon fluxes measured at eddy covariance flux towers (e.g., FLUXNET) and state-of-the-art data assimilation techniques; (4)) identify missing components from the current development plan (e.g., disturbances); and (5) conduct uncertainty assessment of the bottom-up flux estimates derived from CASA models.

Technical report
Assessment of global carbon and water fluxes
I used EC-MOD to assess the magnitude, patterns, and interannual variability of global ecosystem carbon and water fluxes as well water use efficiency. In particular, our results show that extreme climate events (e.g., drought) and disturbances (e.g., fires) are the dominant sources of the interannual variability of global land-atmosphere carbon fluxes. The severe extended droughts, particularly the 2005 drought, substantially reduced annual GPP, and also reduced net carbon uptake at regional scales. Extreme climate events and disturbances are projected to become more frequent and more severe during the remainder of the 21st century, and will likely have larger impacts on ecosystem carbon dynamics.

Evaluation and validation of the CMS Pilot Flux Products
I provided the global EC-MOD flux estimates to the CMS flux project team (Dr. Josh Fisher et al.). Fisher used EC-MOD fluxes to evaluate and validate the CMS Pilot Flux Products. Because all flux estimates contain uncertainties, these comparisons cannot be viewed as "validation", but will nonetheless be informative concerning the consistency of various gridded flux estimates. The juxtaposition of these approaches will also provide complementary information to global ecosystem carbon exchange and valuable information on future improvement of these approaches. MPI-BGC and EC-MOD (and CABLE) are "greener" than the others indicating that these products exhibit large carbon sinks at mean annual aggregates than the CMS Flux Pilot Products (NASA-CASA, CASA-GFED, and ACOS/CMS). Compared with MPI-BGC (0.5 degree), EC-MOD is closer to the CMS Flux Products likely because of the finer resolution of EC-MOD (0.05 degree).