Monitoring of Net Ecosystem CO2 Exchange for the Soil Moisture Active Passive Mission

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Abstract – The NASA SMAP mission has a projected 2014 launch and will provide global mapping of surface soil moisture and freeze/thaw conditions using L-band (1.26 GHz) active and passive microwave remote sensing. SMAP science objectives include reducing uncertainty regarding land-atmosphere carbon exchange. An operational level 4 carbon (L4_C) product is planned for quantifying surface soil carbon stocks and net ecosystem CO_2 exchange (NEE) using model assimilated SMAP measurements with ancillary land cover and vegetation productivity inputs. We conducted an initial global implementation of the L4_C algorithms using MODIS productivity inputs and MERRA reanalysis daily soil moisture and temperature fields. The L4_C simulations are generally consistent with the distribution and magnitude of soil carbon stocks from global soil inventories. A model uncertainty analysis indicates anticipated NEE product accuracy within 30 g C m^2 yr^{-1} (1.6 g C m^2 day^{-1}) and similar to accuracies attained from tower measurements.

Key Words: SMAP, Soil Moisture Active Passive, carbon

1. INTRODUCTION

The Soil Moisture Active Passive (SMAP) mission is a NASA Decadal Survey mission, with projected launch in 2014 that will provide global mapping of soil moisture and its freeze/thaw (F/T) state. Primary SMAP science objectives include linking terrestrial water, energy, and carbon cycle processes, quantifying the net carbon flux in boreal landscapes and reducing uncertainties regarding the so-called missing carbon sink on land (Entekhabi et al. 2010). The SMAP satellite will be polar orbiting and will utilize contemporaneous L-band (1.26 GHz) active and passive microwave remote sensing to obtain surface soil moisture and landscape F/T retrievals under orbital 6 AM/PM equatorial crossings, with complete global coverage every 2–3 days. A set of SMAP operational land products is planned, including level 2/3 F/T and soil moisture products mapped to a global geographic grid, and higher order (level 4) soil moisture and carbon products derived from land model based assimilations using lower order SMAP retrievals. The SMAP level 2/3 soil moisture and F/T products will be derived at variable spatial scales ranging from 3–40 km resolution, while the level 4 soil moisture and carbon products will be spatially contiguous and derived at finer (≤ 9 km) resolution and daily temporal fidelity.

The SMAP level 4 carbon (L4_C) product is designed to address SMAP science objectives including linking terrestrial water, energy and carbon cycle processes, quantifying net carbon fluxes and reducing uncertainties regarding the purported missing carbon sink on land. The net ecosystem exchange (NEE) of CO_2 with the atmosphere is a fundamental measure of the balance between carbon uptake by vegetation gross primary production (GPP) and carbon losses through autotrophic (R_a) and heterotrophic (R_h) respiration. The L4_C product will quantify NEE and underlying soil moisture and temperature controls to vegetation productivity and ecosystem respiration. The L4_C algorithms utilize a simple soil decomposition and carbon flux model to quantify NEE and component carbon fluxes on a daily basis; an additional research product derived from the L4_C algorithms includes surface (≤10 cm depth) soil organic carbon stocks (kg C m^{-2}). Primary inputs to the L4_C algorithms include vegetation greenness index (NDVI) or GPP from satellite optical-IR remote sensing, and daily surface meteorology from global model reanalysis. The L4_C algorithms and remote sensing inputs are robust and have been verified using biophysical measurements from global CO_2 flux tower measurement networks, detailed ecosystem process model simulations and relatively fine scale remote sensing (Kimball et al. 2009). The L4_C algorithms are being evaluated over a global domain using available remote sensing inputs from MODIS and AMSR-E, and daily surface meteorology from the GMAO MERRA reanalysis. Several options are also being evaluated for potential operational production, including the use of alternative inputs and methods for estimating GPP and other ancillary remote sensing inputs for dynamic accounting of vegetation disturbance (e.g. fire) and succession on L4_C based NEE retrievals. The L4_C product accuracy is projected to be commensurate with similar estimates from in situ tower measurements and suitable for atmospheric model inversion based estimates of terrestrial carbon budgets; anticipated applications of these products include global biosphere assessment and monitoring of atmospheric CO_2 sequestration rates and source/sink activity.

2. METHODS

The SMAP L4_C algorithm framework is based on a simple 3-pool soil decomposition model (Kimball et al. 2009). NEE is computed on a daily basis as a residual between vegetation GPP and ecosystem respiration (R_{eco}, summation of autotrophic & heterotrophic components). The soil organic carbon (SOC) stock within the surface soil layer is computed as the sum of three coupled SOC pools ($\hat{C}$) of declining litter quality and associated decomposition rates. Vegetation net primary production (NPP) is derived from GPP assuming a biome-specific constant autotrophic respiration fraction, while R_h is computed from $\hat{C}$ and a soil decomposition rate computed from a prescribed optimal rate (*kopt*) reduced for suboptimal soil moisture (*SM*) and temperature (*T*) conditions; *SM* and *T* are dimensionless scalars (0=fully constrained; 1=no constraint) that are derived from ancillary soil moisture and temperature inputs using biome-specific response curves. The initial L4_C global implementation uses ancillary GPP inputs from MODIS (MOD17) and daily soil moisture and temperature inputs from the 0.5º resolution MERRA global reanalysis. The GMAO MERRA reanalysis is based on the GEOS-5 land model and is similar to the planned SMAP level 4 soil moisture (L4_SM) product that will provide the primary inputs to the L4_C algorithms under SMAP. Other L4_C algorithm modifications are being tested, including non steady-state disturbance and succession effects, internal GPP estimation using ancillary satellite NDVI inputs and use of SMAP F/T retrievals as an additional environmental control for the GPP and R_{eco} calculations.

3. RESULTS

An algorithm sensitivity study was conducted based on documented uncertainties in ancillary inputs, model assumptions, and resulting error propagations, including individual and combined effects on model outputs. The resulting error budget (Table 1) indicates expected NEE accuracy (RMSE) within 30 g C m^{-2} yr^{-1} (1.6 g C m^{-2} d^{-1}) and within the range of uncertainty for tower based observations (Baldocchi 2008). These results assume that errors are uncorrelated between soil moisture and temperature inputs and uncorrelated through time. The GPP inputs are also assumed to contribute a constant representative error. Actual model error may be larger or smaller depending on correlations between model inputs, model or measurement bias, and potential error in model representation of biophysical processes. While the L4_C baseline is expected to perform within the stated accuracy level, improved product accuracy is also feasible by implementing one or more options, including: 1) implementing the algorithm at a finer spatial resolution (e.g. 1-km vs. 9-km baseline) consistent with ancillary (e.g. MODIS) land cover and GPP inputs; 2) accounting for land cover disturbance and vegetation succession effects on the balance between vegetation productivity, SOC and R_{eco}, and 3) calibration of biome specific algorithm response functions using in situ measurements from representative tower sites.

Table 1. L4_C algorithm sensitivity analysis based on documented uncertainties from ancillary inputs and algorithm assumptions; expected errors are summarized for individual inputs and their cumulative effects on model outputs.

Type of Error	Error Source	Source Units	Range	Value	NEE Contribution (g C m^{-2} y^{-1})
Input Data	Temperature	°C	1.5–4	3.5	2.1
	Moisture	Vol. cm^3 cm^{-3}	0.04–0.10	0.05	1.9
	GPP	G C m^{-2} d^{-1}	1.0–2.0	1.5	4.4
Model Parameterization	Optimal Decomp. Rates/Response Curves	d^{-1}	0.001–0.01	0.0015	0.2
	Pool Representation/Steady State	g m^{-2}	100–1000	500	12.0
	Autotrophic Respiration Fraction	Dim.	0.05–0.15	0.1	1.5
Heterogeneity	Land Cover Heterogeneity (Soil Respiration)	g C m^{-1} yr^{-1}	10–95	95	25.0
Total NEE Error	Inputs Only	g C m^{-1} yr^{-1}			5.2
	Model Only	g C m^{-1} yr^{-1}			12.1
	Inputs + Model	g C m^{-1} yr^{-1}			13.2
	Inputs + Model + Het.	g C m^{-1} yr^{-1}			28.7

Tower eddy covariance based CO_2 flux data for selected representative land cover types from the global FLUXNET network (Baldocchi 2008) were used for L4_C algorithm calibration to determine the degree of product accuracy improvement over baseline, uncalibrated results. A Markov Chain Monte Carlo (MCMC) optimization was applied to minimize an objective function by adjusting biome-specific model parameters to selected, representative tower data, including calibrating soil moisture response characteristics for improved accuracy. The tower comparison results indicate generally favorable algorithm performance for NEE over a global domain ($R^2 > 0.6$; RMSE < 1.5 g C m^2 day). Additional model runs using alternative remote sensing and tower inputs are also being used to clarify internal error propagation and major sources of model uncertainty. These results indicate significant (up to 50% error reduction) improvement in L4_C results over the algorithm baseline and global domain.

A potential limitation of the baseline L4_C algorithms is that ancillary GPP inputs (e.g. from MODIS) may be unavailable during the SMAP mission period. Alternatively, vegetation greenness indices including the Normalized Difference Vegetation Index (NDVI) are widely available and can be used with a simple production efficiency model to derive the fraction of canopy absorbed photosynthetically active radiation (FPAR) and GPP. We evaluated an alternative GPP estimation scheme, whereby MODIS NDVI inputs were used to estimate GPP using a modified MOD17 production efficiency model (Zhao and Running 2010), MERRA surface meteorology and biome-specific empirical estimation of FPAR. Comparisons of the alternative GPP calculations against tower measurement based GPP from 149 FLUXNET sites were generally favorable (R^2 = 0.77; RMSE = 1.25 g C m^{-2} d^{-1}) and within the expected L4_C accuracy requirements.

Annual NEE was estimated over a global domain and 7-year record (2002–2008) at 0.5º spatial resolution using daily time series MERRA (soil moisture and temperature) and MODIS (GPP) inputs. The estimated global carbon (NEE) source (+) and sink (–) variability is strongly affected by tropical forest areas (Figure 1). Large NEE source activity in the tropics is partially driven by regional drought-induced GPP decline (Zhao and Running 2010), while the NEE patterns are also strongly influenced by characteristic global and seasonal patterns in SM and T constraints to R_h. Frozen temperatures are a dominant environmental constraint in January at high northern latitudes, while dry SM constraints become more widespread during the summer months. Tropical forests also show significant dry season SM limitations, while arid and semiarid regions show persistent strong to moderate SM constraints. SMAP is expected to provide enhanced (≤ 9-km) resolution SM, F/T and T fields for improved accuracy in defining associated environmental constraints to L4_C based respiration calculations. The SMAP L4_C product will also have >6-fold improved spatial resolution over these current simulations and will benefit from enhanced L-band sensitivity to soil moisture and F/T constraints to ecosystem processes.

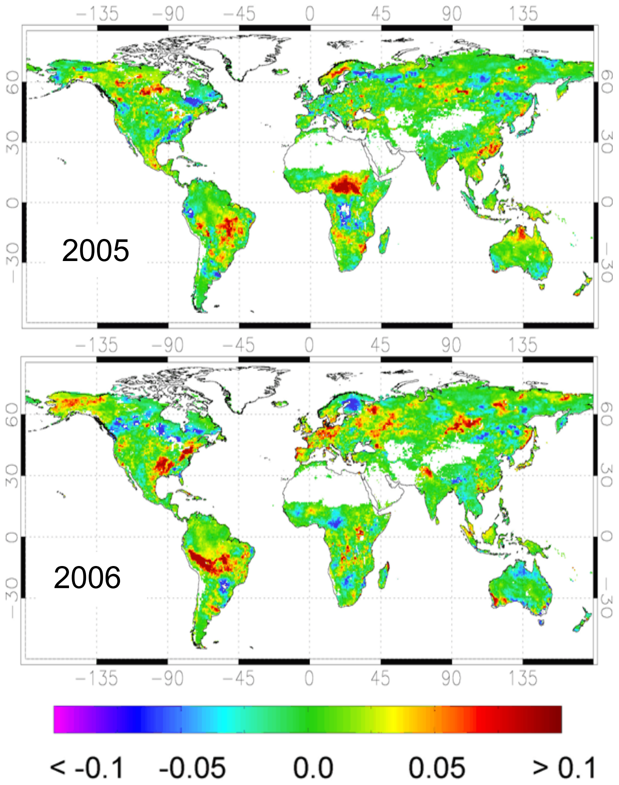

Figure 1. Annual NEE (kg C m^{-2} yr^{-1}) patterns for 2005 and 2006 derived using the L4_C algorithms and MERRA and MODIS daily inputs.

Surface (<10 cm depth) soil organic carbon (SOC) was also estimated from the L4_C simulations by assuming a dynamic steady state between satellite (MOD17) driven GPP calculations and R_h derived from MERRA soil moisture and temperature inputs. The SOC results were verified against independent soil inventory data from IGBP and site based inventory records (Global Soil Data Task 2000, Zinke et al. 1984). The resulting L4_C based SOC map and associated global probability density function (PDF) distributions of L4_C and inventory based SOC is shown in Figure 2. These results indicate similar SOC magnitudes and patterns, while differences are within the uncertainty range of global inventory records. The SMAP L4_C product will provide dynamic SOC estimates with improved (≤ 9-km) resolution and direct linkages to environmental controls to soil C stability.

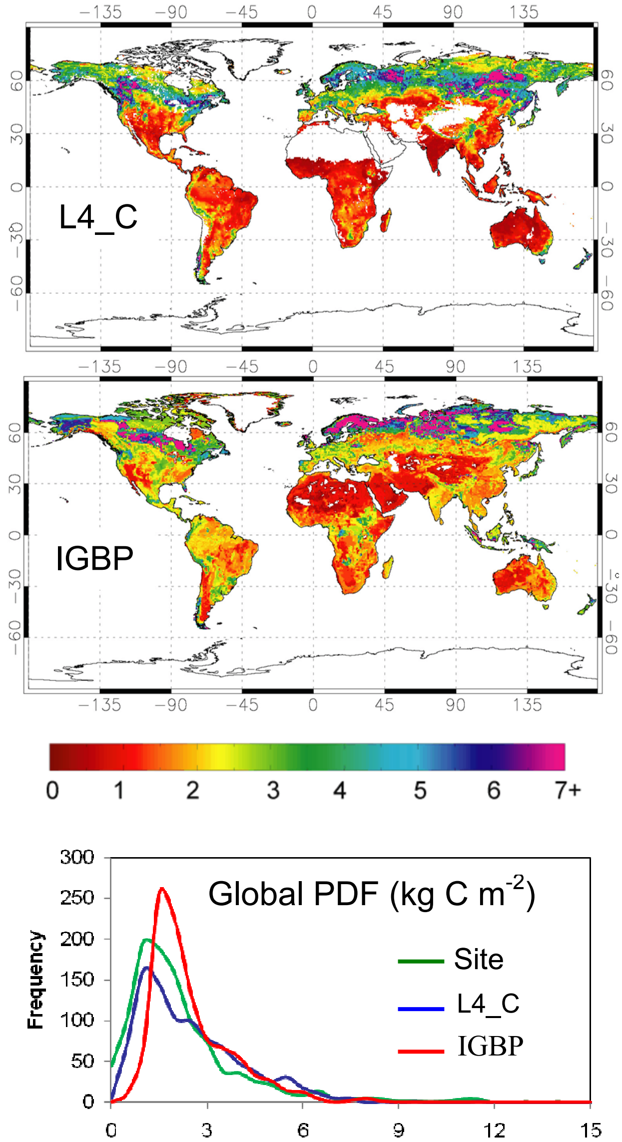

Figure 2. Estimated global surface (<10 cm depth) soil organic carbon (SOC) stocks (g C m^{-2}) derived using the L4_C algorithms and compared with other global SOC estimates; nonvegetated areas (in white) were masked from L4_C processing. Global PDF distributions of the L4_C results and alternative global soil inventory records is also shown.

4. CONCLUSIONS

SMAP is a Tier-1 NASA Decadal Survey mission with a planned 2014 launch and 3-year minimum mission cycle (Entekhabi et al. 2010). SMAP will provide combined satellite active and passive microwave (L-band) remote sensing of surface soil moisture and landscape freeze/thaw conditions, with an enhanced set of level 4 global products designed for ecosystem and hydrological studies and applications. The SMAP L4_C product will provide global estimates of net ecosystem CO_2 exchange, component carbon fluxes and underlying soil moisture, freeze/thaw and temperature controls at a measurement scale and accuracy level commensurate with tower CO_2 flux measurement based estimates. Initial sensitivity studies and global implementation of the L4_C algorithms indicate a mean RMS error for NEE within 30 g C m^{-2} yr^{-1} (1.6 g C m^{-2} d^{-1}), and within the estimated ±30–100 g C m^{-2} yr^{-1} accuracy of *in situ* tower measurements (Baldocchi 2008). The resulting soil carbon and NEE simulations also show expected global patterns and seasonal to annual variability consistent with other global observations and data sets. Additional improvement in L4_C accuracy is feasible through relatively minor adjustments to algorithm structure, calibration and implementation. The computation of NEE, its constituent carbon fluxes, and associated soil moisture and temperature controls to R_{eco} will enable mechanistic understanding of spatial and temporal variations in NEE. NEE is the primary measure of carbon exchange between the land and atmosphere and the L4_C products will be directly relevant to a range of applications including regional mapping and monitoring of terrestrial carbon stocks and atmospheric transport model inversions of terrestrial source-sink activity for atmospheric CO_2. The SMAP L4_C product will also advance our understanding of the way in which ecosystems respond to climate anomalies and their capacity to reinforce or mitigate global warming.

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ACKNOWLEDGEMENTS

Portions of this work were conducted at The University of Montana and Jet Propulsion Laboratory, California Institute of Technology under contract to the National Aeronautics and Space Administration.