Using SMOS observations in a carbon cycle data assimilation system

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ECMWF/ESA WS on low frequency passive microwave measurements
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Global Carbon Budget (GCP 2016)

9.3 ± 0.4 PgC/yr  91%

4.5 ± 0.1 PgC/yr
Atmosphere  44%

3.2 ± 0.8 PgC/yr
Land  31%

2.6 ± 0.5 PgC/yr
Oceans  25%

1.0 ± 0.5 PgC/yr  9%
Global budget of the CO$_2$ fluxes


Need for monitoring the land ecosystem sinks and sources at high spatial and temporal resolution to understand and forecast their evolution
Methods for the estimation of $\text{CO}_2$ fluxes

Most common methods to estimate the net $\text{CO}_2$ ecosystem exchange (NEE):

• Process models or diagnostic models based on local flux measurements, satellite measurements of vegetation indices and biomass data

• Atmospheric inversion systems assimilating atmospheric concentration data

**Carbon Cycle Data Assimilation Systems (CCDAS):**
Optimization of parameters in process models using ideally all types of data
The case for data assimilation

Large uncertainty from land to predict C-balance (GCP)

Available Observations

⇒ Carbon Cycle Data Assimilation System
  = ecophysiological constraints from forward modelling
  + observational constraints from inverse modelling
Low frequency passive microwave measurements (i.e. SMOS)

How are SMOS measurements linked to the carbon cycle?

- SMOS surface SM: Water and carbon cycles tightly coupled
- SMOS VOD: A proxy for aboveground biomass
Study objectives

ESA SMOS-NEE project: Assimilation of SMOS L3 soil moisture together with atmospheric CO$_2$ concentration:

• quantify the added value of SMOS soil moisture observations on constraining terrestrial carbon fluxes

• assess the potential of a SMOS based Level 4 NEE product

ESA-STSE ’SMOS + Vegetation’ project:

• improve the SMOS VOD product

• derive further SMOS L4 vegetation products (e.g. biomass)

• quantify the constraint of a SMOS VOD product on carbon and water fluxes, when assimilated individually and in conjunction with SMOS soil moisture and flask samples of atmospheric CO$_2$
Cost function: 
\[ J(x) = \frac{1}{2} \left[ (x - x_p)^t C_p^{-1} (x - x_p) + \sum (y - M(x))^t C_y^{-1} (y - M(x)) \right] \]
CCDAS methodology

- Based on process-based terrestrial ecosystem model (BETHY)
- Optimizing parameter values (~100) based on gradient method
- Hessian (2nd deriv.) to estimate posterior parameter uncertainty
- Error propagation by using linearised model

Scholze et al. (2007)
BETHY

Biosphere Energy-Transfer Hydrology (BETHY) scheme (Knorr 2000) with a number of extensions:

• Globally 0.5/0.25 degree
• Set up with meteorological driving fields for 2010-15
• 13 Plant functional types
• Estimating some 50-100 process parameters
• Derivative code generated with TAPENADE (Hascoet & Pascal, 2013)
Global SM assimilation

- Coarse resolution, 2 years (2010/11)
- Running 3-member ensembles from different starting points
- Baseline: in-situ atm. CO$_2$ (10 sites) concentrations only
- Baseline + SMOS daily soil moisture with variance/mean scaling
Results: process-parameters

CO₂ only

CO₂ & SMOS

Scholze et al. (2016)
Results: atm CO$_2$ (also for validation)

- **MLO**
  - CO$_2$ only
- **ALT**
  - CO$_2$ only
- **CO$_2$ & SMOS**
Results: soil moisture (RMS)

**CO₂ only**

RMS bethy_opt – smos SM in wdw. [mm] 2.4484 (TM2)

**CO₂ & SMOS**

RMS bethy_opt – smos SM in wdw. [mm] 2.2609 (TM2)
Results: CO$_2$ fluxes (NEP)

**CO$_2$ only**

optimised BETHY nep 2010–2011 [gC m$^{-2}$] (TM2)

**CO$_2$ & SMOS**

optimised BETHY nep 2010–2011 [gC m$^{-2}$] (TM2)
Results: CO$_2$ fluxes (NPP)
Validation: soil moisture at site level

**CO₂ only**

**CO₂ & SMOS**
Relative flux (NEP & NPP) uncertainty reduction for 6 regions

Red: CO$_2$ only

Blue: CO$_2$ & SMOS

Percentage

NEP

NPP

NEP North America
NEP South America
NEP Europe
NEP Asia
NEP Africa
NEP Australia
NPP North America
NPP South America
NPP Europe
NPP Asia
NPP Africa
NPP Australia
Refined global SM assimilation

- Higher resolution (2 x 2 deg)
- Covering 2010-2015
- 2 Experiments: CO2 and SMOS+CO2
Comparison of carbon fluxes against independent data

CARBOSCOPE: Net flux from atmospheric inversion

FLUXNET: Photosynthesis from upscaled eddy covariance measurements
Regional carbon budgets
Towards VOD assimilation SMOS+VEG
L-VOD observation operator

L-VOD from SMOS fitted against AGB from Saatchi et al., 2017:

\[ f(AGB) = a \times \tan(b \times AGB) \]

\[ a = 0.81759 \]
\[ b = 0.0087253 \]

• 1.4 GHz
• right direction (i.e. AGB->VOD)
• through 0/0
• only two parameters to calibrate

on next slide we explain:

\[ VOD = f(NPP \times \tau_{\text{eff}}(PFT)) + D_0(PFT) \times LAI \]
L-VOD observation operator

More generalized approach, allowing for seasonal changes in VOD driven by leaf area. (Influence of vegetation water included in leaf area, wet leaves – dry branches...):

\[
\text{AGB} = \text{NPP} \times \tau_{\text{eff}}(\text{PFT}) \\
\text{VOD} = f(\text{AGB}) + D_0(\text{PFT}) \times \text{LAI}
\]

with total VOD for PFT mixture: \( \exp(-\text{VOD}_{\text{tot}}) = \sum_i f_i \exp(-\text{VOD}_i) \)

\( \tau_{\text{eff}} \): effective biomass turnover time
- PFT-dependent; grasses: small; trees/shrubs: large
- Accounts for NPP fraction going to AGB and differences in turnover time above/below ground
- Prior values/uncertainties could be obtained by comparing BETHY NPP with ABG data set

\( D_0 \): vegetation-optical depth at LAI=1
- A priori value 0, uncertainty \( \sim 0.5 \) (value for random leaf-angle distribution with diffraction/scattering)
NPP and L-VOD simulation

\[ VOD = f(AGB) + D_0(PFT) \times LAI, \]
\[ D_0 = 0 \]
L-VOD simulations

VOD = f(AGB) + \(D_0(PFT) \times LAI\),

\[D_0 = 0.1\]
VOD assimilation: Identical Twin

• 10 sites
• fast convergence
• for seven sites:
  – all parameters exactly recovered
  – pseudo-observations exactly matched
  – Final cost function gradient 0
• for three sites:
  – max parameter difference to truth below 5%
  – pseudo-observations almost exactly matched
  – gradient reduction by a factor of 50/1000/1.e6
  – needs further investigation
Identical twin experiment at site level

- pseudo observations of monthly VOD and SM from prior parameters for 2010-2015
- parameters are recovered after 10% perturbation
VOD assimilation

- Preliminary SMOS IC VOD product
- monthly median, 20% uncertainty
- first individually for each site
- then for all sites
- then for all but “problematic” sites
VOD assimilation single- vs multi-site

VOD assimilation multi-site

VOD assimilation multi-site
Conclusions

- Global experiments simultaneously assimilating SMOS soil moisture and atmospheric CO$_2$ (also at high resolution)
- Significant added value (unc. reduction) when assimilating both SM and CO$_2$ as compared to CO$_2$ only
- Developed observation operator for L-VOD based on AGB, parameters in $\text{VOD} = f(\text{AGB, LAI})$ are part of the optimisation
- First successful identical twin experiments at site level
- First successful L-VOD assimilation experiments at site level
- Work in progress:
  - assimilate SMOS L-VOD data at global level
  - combined assimilation SMOS L-VOD, SM and atm CO$_2$ concentration
  - Evaluation against independent data (e.g. carbon fluxes such as NEE and NPP, atmospheric CO$_2$)
- CCDAS combines process understanding with a range of observations, provides an integrated view on global carbon cycle and delivers elaborated products based on SMOS data as well as further data (e.g. FAPAR, SIF,...)