Estimation of Global Surface Carbon Fluxes Using Advanced Data Assimilation

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Supported by NASA Grant NNX16AE44G and NIST FLAGG-UMD

NACP, 28 March 2017, Bethesda
We show the feasibility of estimating surface carbon fluxes within the LETKF-C framework through 3 different models and OSSEs:

1) LETKF-C (Kang et al., JGR 2011, 2012) tested in an intermediate-complexity model SPEEDY-C with excellent results.

2) The LETKF-C with NCAR CAM 3.5 model in OSSEs with realistic observation coverage.

3) The new GEOS-CHEM+VEGAS+LETKF-C system (Zeng, Liu, Kalnay, Asrar)

- Short assimilation windows are more accurate than long assimilation windows.
- Short assimilation windows combined with long observation windows give the best results.
- The same methodology can be applied to estimate surface fluxes of heat, moisture and momentum.
Ensemble CO$_2$ Data Assimilation

- The Local Ensemble Transform Kalman Filter (LETKF, Hunt et al. 2007) was applied to analyze atmospheric CO$_2$ (C) and surface CO$_2$ fluxes (CF) in addition to meteorological variables (U, V, T, q, Ps).
  - JGR: Kang et al., 2011, 2012. Unlike inverse methods, it assimilates atmospheric CO$_2$ as well as surface carbon fluxes.
  - Ensemble forecast within LETKF includes the uncertainty of surface CO$_2$ forcing as well as transport errors (forecast uncertainty of wind fields).
  - **It uses an assimilation window of only 6 hrs**
Surface \(\text{CO}_2\) fluxes are estimated as evolving parameters

- Parameter estimation in EnKF
  - State vector augmentation
    \[
    X^b = \begin{bmatrix}
    X \\
    \text{CF}
    \end{bmatrix}
    \]
    : model state vector (\(U, V, T, q, Ps, C\))
    : surface \(\text{CO}_2\) flux
  - Update \(\text{CF}\) as a part of the data assimilation process, *minimizing the analysis errors caused by surface \(\text{CO}_2\) forcing and atmospheric \(\text{CO}_2\) transport*

- During the *ensemble forecast*, \(C\) is forced by \(\text{CF}\), which is updated only by the analysis step.
- *Ensemble forecast* provides multivariate background (forecast) error covariance among \(U, V, T, q, Ps, C, \text{CF}\)
- The *LETKF analysis step* minimizes a combination of *background* and *observation* errors
LETKF-C with localization of variables

- **Multivariate data assimilation** with “localization of variables”:
  - We zero out the error covariance between some variables, because \( \text{CO}_2 \) does not have a strong physical relation with every variable in the state vector, so that sampling errors are reduced.
  - Analysis includes error covariance between atmospheric \( \text{CO}_2 \) and wind fields to take account for transport errors of \( \text{CO}_2 \).
  - Tested very successfully in simulation experiments, now widely used.

(Kang et al. 2011, JGR)
LETKF-C: other advances

- Advanced inflation methods:
  - Adaptive multiplicative inflation (Miyoshi, 2011)
  - Additive inflation for surface Carbon Fluxes.
- Vertical localization of column mixing CO$_2$ observations (GOSAT, OCO-2)
  - Emphasizes the lower levels of variability within the column, even though we use column observations whose sensitivity (averaging kernel) is ~ uniform in the vertical.
- We used a short (6-hour) assimilation window
- In contrast, CO$_2$ inversion methods adopt much longer window lengths (weeks to months).
- No a priori information needed on CO2 or surface CF.

(Kang et al. 2012, JGR)
Short Assimilation windows in LETKF-C

Short assimilation windows are closer to the truth than long windows, which blur the information.
1) LETKF-C with SPEEDY-C model

- **Model:** SPEEDY-C (Molteni, 2003; Kang, 2009)
  - Spectral AGCM model with T30L7
  - Prognostic variables: U, V, T, q, Ps, C
    - C (atmospheric CO₂): an inert tracer
  - **Persistence forecast of CF:** No terrestrial carbon model

- **Simulated observations**
  - Rawinsonde observations of U, V, T, q, Ps
  - Ground-based observations of atmospheric CO₂
    - 18 hourly and 107 weekly data on the globe
  - Remote sensing data of column mixing CO₂
    - AIRS whose averaging kernel peaks at mid-troposphere
    - GOSAT whose averaging kernel is nearly uniform throughout the column

- **Initial conditions:** random (no *a-priori* information)
- 20 ensemble members
**OSSE Results**

**00Z01APR** ►
After three months of DA

**00Z01AUG** ►
After seven months of DA

**00Z01JAN** ►
After one year of DA

We succeeded in estimating time-evolving CF at a model-grid scale
2) LETKF-C with NCAR CAM3.5

- **Model:** CAM 3.5 *(much more realistic than SPEEDY)*
  - Finite Volume dynamical core
  - 2.5°×1.9° of horizontal resolution with 26 layers in the vertical
  - C (atmospheric CO₂) is an inert tracer
  - Persistence forecast of CF

- **Simulated observations with realistic observation coverage**
  - Conventional data for U, V, T, q, Ps
  - Ground-based observations of atmospheric CO₂
    - ~10 hourly and ~100 weekly records on the globe
  - Remote sensing data of column mixing CO₂
    - AIRS whose averaging kernel peaks at mid-troposphere

- **Initial conditions:** random *(no a-priori information)*
- 64 ensembles
27 days of data assimilation

After ~10 days of spin-up the atmospheric CO2 and surface carbon fluxes were accurately estimated.
3) Coupled land-atmos-carbon data assimilation system (Zeng, Liu, Kalnay, Asrar)
OSSEs: Compare Short (1 day) and Long (7 days) assimilation windows

1 day: good results

FnetNgt/Fnetgtm/Fnetgt_spread GtC/y

RMSE: FnetAmNgm GtC/y
departure Assi–Nature

Nature

Assi

Fnet.1  t=15apr2015

Fnet.3  t=15apr2015

Fnet.1  t=15jul2015

Fnet.3  t=15jul2015

Fnet.1  t=15oct2015

Fnet.3  t=15oct2015
OSSEs: Compare Short (1 day) and Long (7 days) assimilation windows

7 days: worse results

FnetNgt/Fnetgtem/Fnetgt_spread GtC/y

RMSE: FnetAmNqm GtC/y
departure Assi–Nature
Best: a **short assimilation window** with a **long observation window**

1 day + 7 days: **best results**

FnetNgt/Fnetgtem/Fnetgt_spread GtC/y

RMSE: FnetAmNgm GtC/y departure Assi–Nature

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Nature

Assi

c02.1  t=15apr2015
c02.3  t=15apr2015
c02.1  t=15jul2015
c02.3  t=15jul2015
c02.1  t=15oct2015
c02.3  t=15oct2015
RMS errors for the 1-year OSSEs

The combination of short “assimilation windows” and long “observation windows” 1+7 days gives the best results

1 day 0.059
7 days 0.074
1+7 days 0.041
Conclusions

- We have shown the feasibility of estimating surface carbon fluxes within the LETKF-C framework through 3 different models/OSSEs:
  - 1) LETKF-C has been tested in an intermediate-complexity model SPEEDY-C with excellent results.
  - Multivariate data assimilation with “variable localization” (Kang et al. JGR2011, 2012)
  - 2) The LETKF-C with NCAR CAM 3.5 model showed very good performance in OSSEs with realistic observation coverage.
  - 3) The new GEOS-CHEM+VEGAS+LETKF-C system allows much more realistic experiments (Zeng, Liu, Kalnay, Asrar)
- Short assimilation windows (e.g., 1 day) are more accurate than long assimilation windows (e.g., 7 days).
- Short assimilation windows combined with long observation windows (1+7 days) give the best results.
- We are starting to perform observing system experiments assimilating real CO2 observations (Global View + OCO-2).

Support by NIST FLAGG-UMD and NASA grant NNX16AE44G