CO2 fluxes estimated with satellite, aircraft, and surface observations using an ensemble-based 4D data assimilation system

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This study discusses a method to efficiently utilize various observations to estimate surface CO2 flux estimations, and investigate the relative importance of different platform observation data (satellite, aircraft, and surface observations).
Transport model

CO2 observations

Data assimilation

CO2 flux & concentration
4D data assimilation system for carbon cycle

• **Forecast model:**
  
  FRCGC transport model coupled to CCSR/NIES AGCM @ T42L32
  
  (transport = grid-scale + parameterized convection and diffusion)

• **Data assimilation:**

  Local ensemble transform Kalman filter (LETKF) with state augmentation technique

The ensemble spread for CO2 flux is initialized such that the standard deviation is equal to the initial error
The LETKF is one of the ensemble square root filters in which the observations are assimilated to update only the ensemble mean by

$$\bar{x}^a = \bar{x}^f + K[y^o - H(\bar{x}^f)], \quad K = X^f \bar{P}^a (HX^f)^T R^{-1}$$

The ensemble perturbations are updated by transforming the background perturbations through a transform matrix $T$

$$X^a = X^f T, \quad T = [(K - 1)\bar{P}^a]^{1/2},$$

The analysis error covariance in ensemble space is given by

$$\bar{P}^a = [(K - 1)I + (HX^f)^T R^{-1} (HX^f)]^{-1},$$

The LETKF performs the analysis in ensemble space (rather than in model or obs space), which greatly reduces the computational cost.
The state vector augmentation method has been applied to simultaneously estimate the model state (met. & CO2 conc.) and the uncertain model parameter (surface CO2 flux).
Covariance inflation technique

Covariance inflation technique is used to avoid filter divergence caused by progressive underestimation of the model error covariance magnitude.

- Multiplicative inflation (Anderson and Anderson, 1999)
- Additive inflation (Whitaker et al., 2008)
- Conditional covariance inflation (e.g., Aksoy et al., 2006)

The analyzed standard deviation is inflated back to a minimum or maximum predefined value.
A 4D EnKf data assimilation system uses a trajectory that best fits all the observations in a data assimilation window. It provides an analysis in terms of the weights of the ensemble forecast members at the analysis time.

### 4D-LETKF vs. 3D-LETKF

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<tr>
<th></th>
<th>CO2 flux RMSE</th>
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<tbody>
<tr>
<td></td>
<td>3D</td>
<td>4D(3day)</td>
<td>4D(7day)</td>
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<tr>
<td>Surface</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>GOSAT</td>
<td>3.73</td>
<td>3.65</td>
<td>3.51</td>
</tr>
<tr>
<td>CONTRAIL</td>
<td>3.93</td>
<td>3.91</td>
<td>3.63</td>
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<td>3.61</td>
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When a long assimilation window (i.e., a 7-day window) or a long localization length (i.e., 1200 km) is used, the surface flux analysis suffers from large (both temporal and spatial) spurious correlations and is degraded.
Observation system simulation experiments (OSSEs)

Continuous and flask surface observations
Density: low
Error: small

GOSAT observations
Density: high
Error: relatively large

CONTRAIL aircraft observations
Density: high (+vertical profile)
Error: small
The increase in the vertical localization length allows an increased use of the upper tropospheric data in surface flux estimates, reducing the surface flux analysis error. 

In contrast, because of significant spurious correlations between variations in surface fluxes and lower stratospheric concentrations, the increase of the vertical localization length to lnP=1 has an adverse impact.
Although meteorological data assimilation can provide more constrains on the flux estimation, spurious correlations among meteorological variables and CO2 flux significantly degraded the flux analysis in (b). By considering variable localization, it's possible to stabilize and improve the CO2 flux analysis in (c).
Relative importance of different platform data

**Optimal data assimilation system**

- State augmentation method for parameter (i.e., surface flux estimations)
  - Localization: $h=1200$ km, $\log(P)=0.75$ hPa
  - Conditional covariance inflation
- Weight-interpolated column data assimilation
- 4D data assimilation with 3-day window

Initial RMSE = 5.4, Global mean absolute flux = 6.2
Surface flux error reduction rate [%]
GOSAT XCO2 and CONTRAIL vertical profile data provide strong additional constraints on the surface flux estimation.
By combining all the platform datasets, the data assimilation system significantly improved the global estimation of the surface CO2 fluxes by compensating for the unobserved areas.
Conclusions

The potential impacts of various types of CO2 concentration data obtained from surface, satellite (by the GOSAT project), and aircraft (by the CONTRAIL project) measurements on the estimation of surface CO2 fluxes have been investigated using an EnKF DA system.

• Conventional surface network data contributes to largest error reductions.
• GOSAT gives large flux error reduction over south-America and Africa.
• The impacts of CONTRAIL data are large over Europe, Australia, trop.-temp. Asia, and North America, where many vertical profiles data exist.
• By combining information obtained from all the data sets, the data assimilation system significantly improves the flux estimation globally.
• The simultaneous data assimilation system for all types of data is expected to improve our knowledge of the carbon cycle.