# Constraining carbon cycle climate interaction with a coupled land-atmosphere carbon data assimilation

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# Ensemble $CO_2$ Data Assimilation

- **Local Ensemble Transform Kalman Filter** (LETKF, Hunt et al. 2007) data assimilation system has been applied to analyze atmospheric $CO_2$ (C) and surface $CO_2$ fluxes (CF) in addition to (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
  - It assimilates observations of meteorological variables and atmospheric $CO_2$ simultaneously
  - 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**

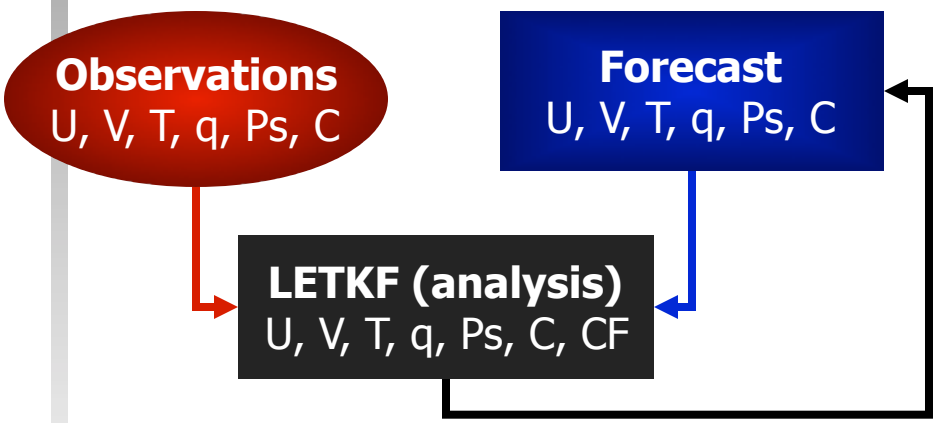
# Surface $CO_2$ flux estimation

- Parameter estimation in EnKF
  - State vector augmentation

$$\mathbf{X}^b = \begin{bmatrix} \mathbf{X} \\ \mathbf{CF} \end{bmatrix}$$

: model state vector (U, V, T, q, Ps, C)

: surface $CO_2$ flux




◆ During the **ensemble forecast**, **C** is forced by **CF** that is updated only by the analysis step.

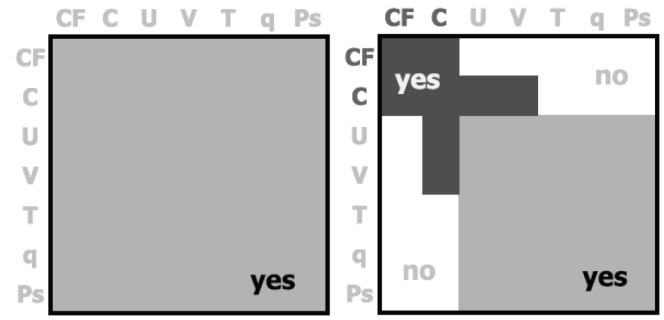
➔**Ensemble forecast** provides **multivariate background (forecast) error covariance** among U, V, T, q, Ps, C, and CF.

- Initial conditions: random states
- Surface boundary condition for the fluxes: persistence of the LETKF analysis

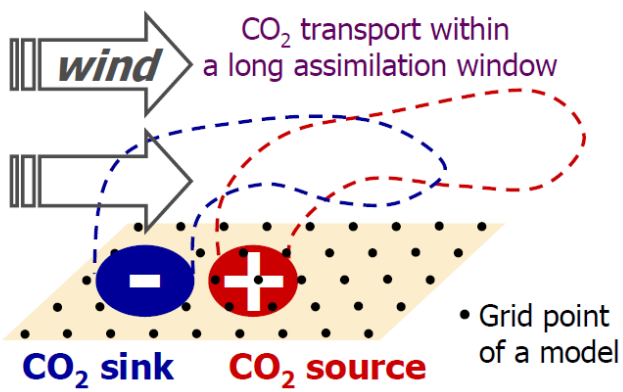
**No a priori information!**

# LETKF-C: other important advances

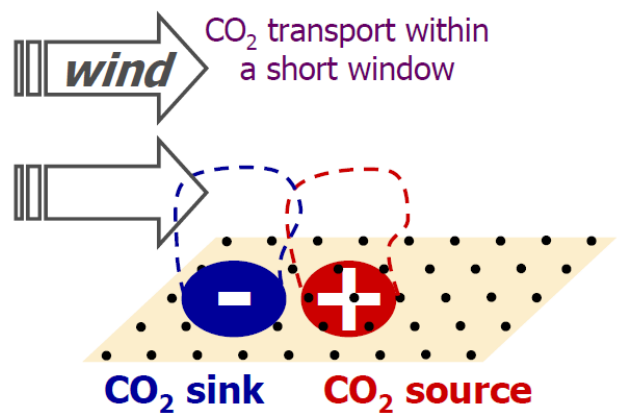
- Multivariate data assimilation with "**localization of variables**"
  - We zero out the error covariance between some variables, because $CO_2$ does not have a strong physical relation with every variables in the state vector. Reduces sampling errors!




- **Short assimilation windows**: **6hr**, not weeks or months!




**Long windows: information gets blurred**




**Short windows: analysis can use the strong correlation between CO2 and surface fluxes**

# LETKF-C with SPEEDY-C

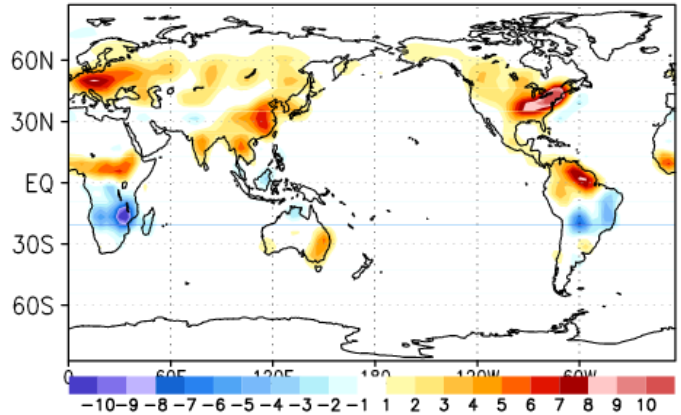
- Model: **SPEEDY-C** (Molteni, 2003; Kang, 2009)
  - Spectral AGCM model with T30L7
  - Prognostic variables: U, V, T, q, Ps, C
    - C (atmospheric $CO_2$): an inert tracer
  - Persistence forecast of CF
- Simulated observations
  - Rawinsonde observations of U, V, T, q, Ps
  - Ground-based observations of atmospheric $CO_2$
    - 18 hourly and 107 weekly data on the globe
  - Remote sensing data of column mixing $CO_2$
    - **AIRS** whose averaging kernel peaks at mid-troposphere
    - **GOSAT** whose averaging kernel is nearly uniform throughout the column
- Initial condition: random (no *a-priori* information)
- 20 ensembles

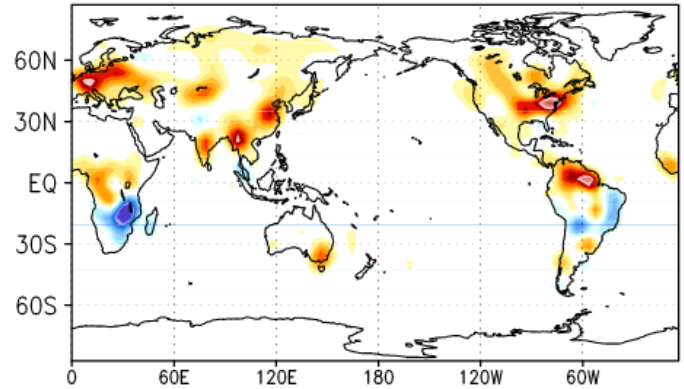
# Results

▼ True CF ▼

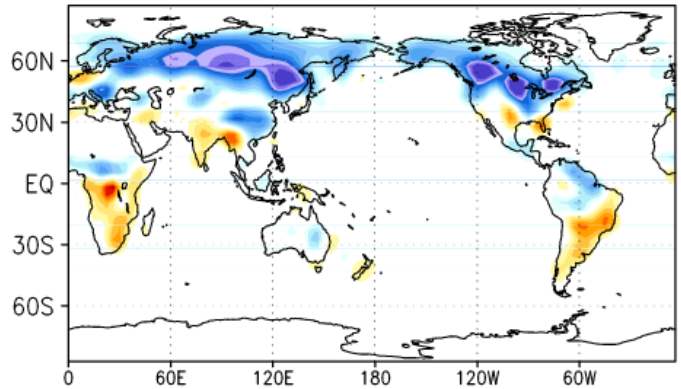
▼ Analysis of CF ▼

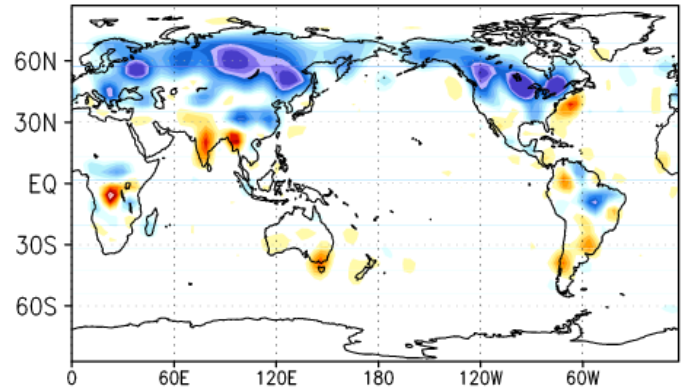
**00Z01APR ▶**
After three months of DA



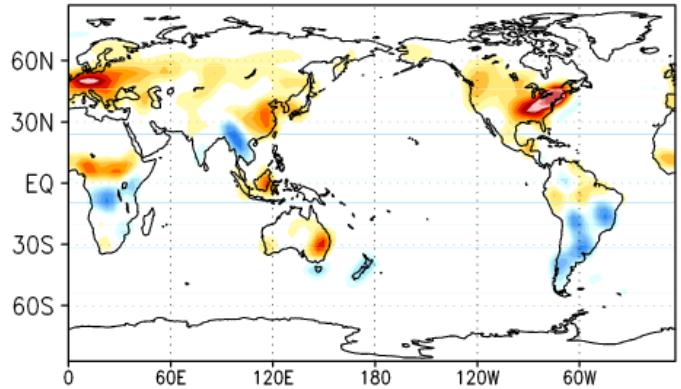

**00Z01AUG ▶**
After seven months of DA

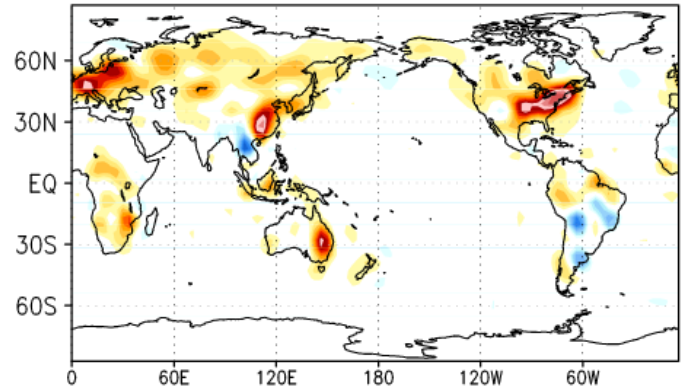


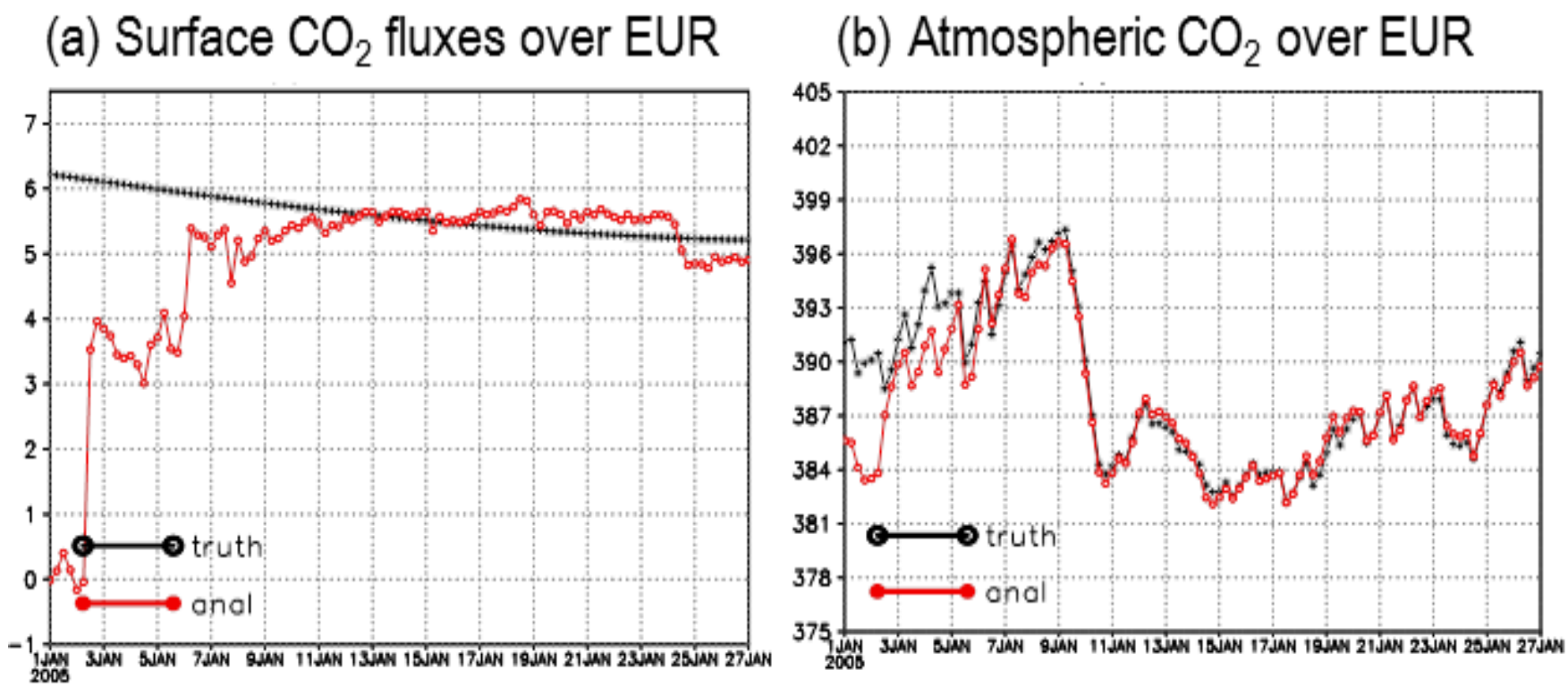

***We succeeded in estimating time-evolving CF at model-grid scale***

**00Z01JAN ▶**
After one year of DA



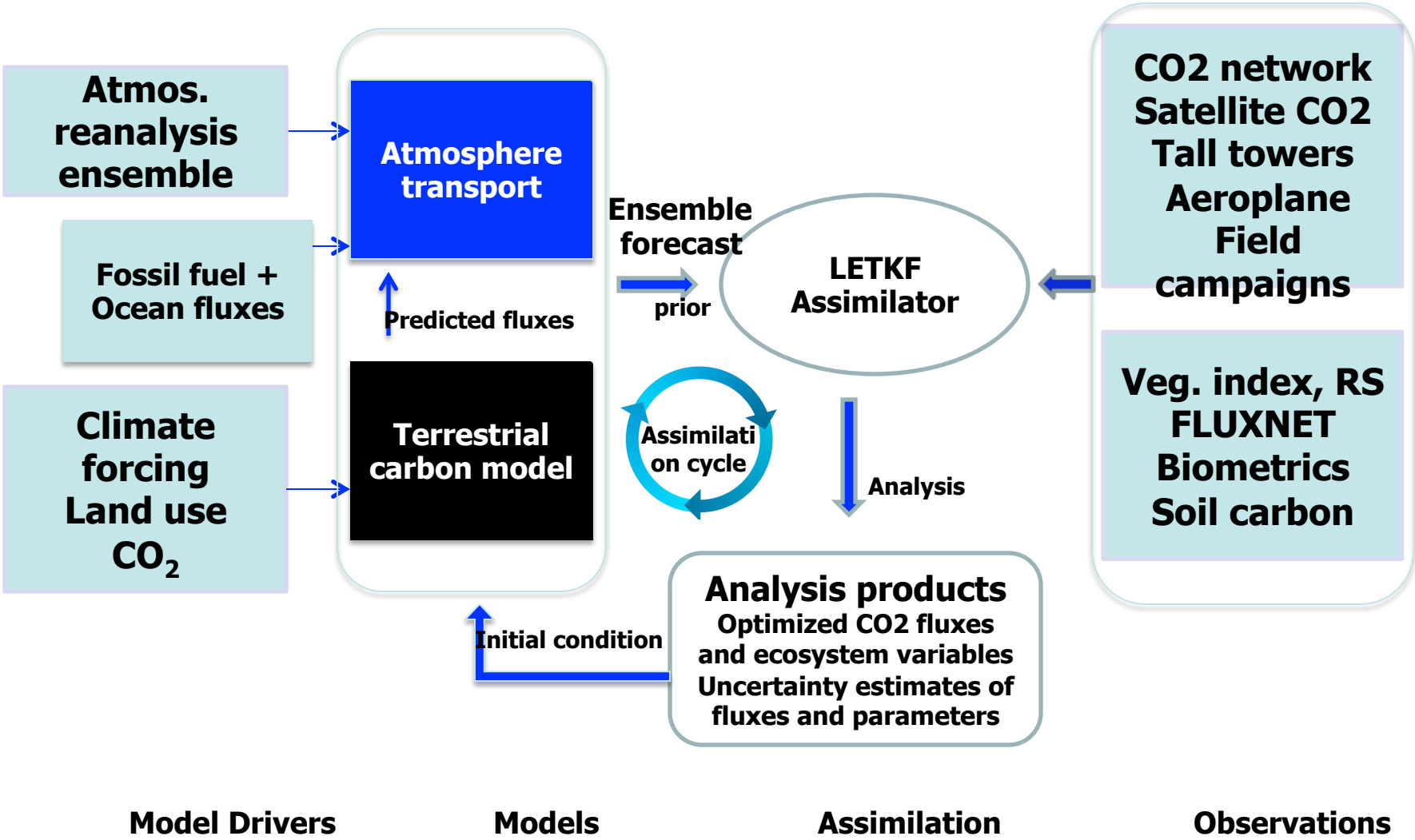



# LETKF-C with NCAR CAM3.5, 27 days of assimilation, real observation coverage

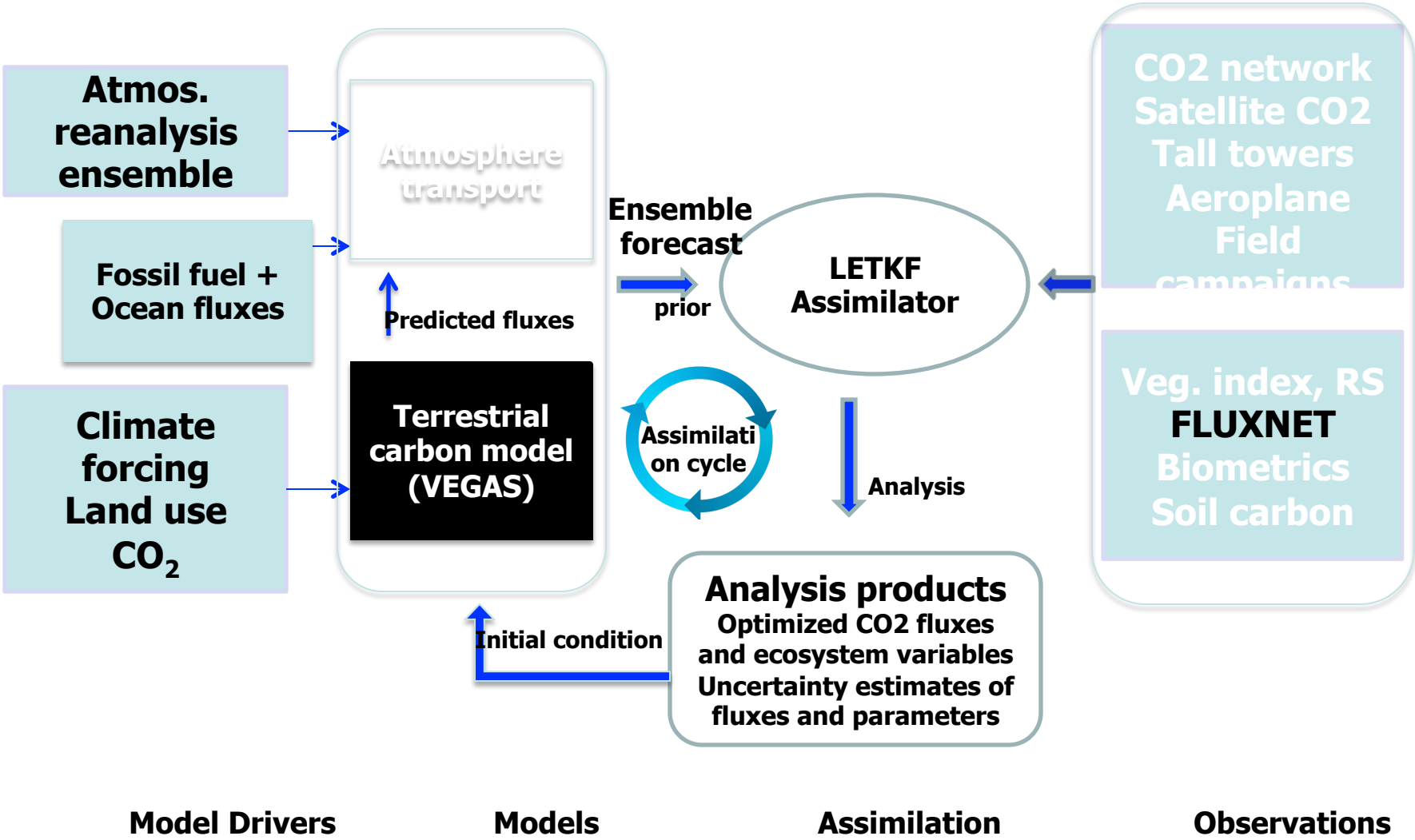



Even without any initial or land surface *a priori* information, after a spin-up of 10 days, the LETKF-C estimates rather well the surface fluxes and the atmospheric CO2.

# The Joint Land-atmosphere Carbon LETKF-C Data Assimilation System



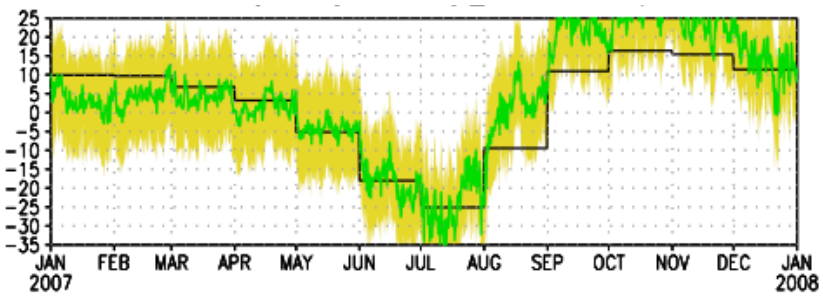
# LETKF-C first experiment: only carbon model (VEGAS) and FLUXNET observations



# Recent Results: Atmosphere Data Assimilation

**Experimental setup:**
- GlobalView-CO2 flask network
- 6hr assimilation window
- No prior flux (FFE+land+ocean)
- Additive inflation

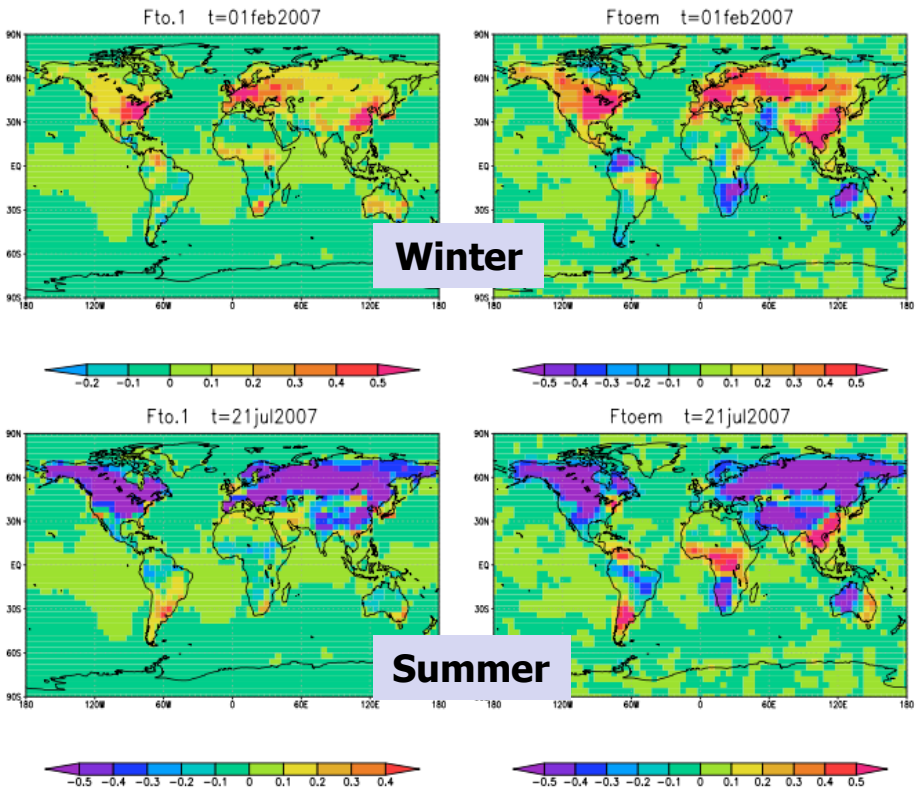
**Surface carbon fluxes seasonal cycle (global total; GtC/y)**




Black: Nature (truth)
Green: Assimilation result (ensemble mean)
Yellow: Uncertainty (ensemble spread)

**Surface carbon fluxes**

**Nature** **Assimilated (Ens.mean)**




**Winter: Fossil fuel emissions, major patterns captured; some spatial and intensity discrepancy**

**Summer: biosphere uptake well captured Tropics and SH (Australia, Africa, Amazon): poor constraint due to sparse data**

# Summary and Future Work

- We have shown the feasibility of simultaneous analysis of meteorological and carbon variables within LETKF-C framework through the simulation experiments with short windows.
- The LETKF-C has been tested in a intermediate-complexity model SPEEDY-C with excellent results: accurate analysis of surface fluxes without any a priori information.
- The LETKF-C with NCAR CAM 3.5 model also showed very good performance in OSSE with real observation coverage.
- Based on our results, ECMWF decided to try this approach! (Peters, 2013, pers. comm., "the new school").
- Zeng, Asrar et al. have separately tested LETKF-C coupled with VEGAS terrestrial model GEOSChem atmospheric transport mode,l with encouraging results.
- We plan to couple an atmospheric transport model (or reanalysis ensemble) with VEGAS with a powerful new **strong data assimilation coupling** (extra slide).

## S. Zhang et al. (GFDL): Standard (weak) coupling: The ocean sees only ocean obs., and the atmosphere sees only atm. obs

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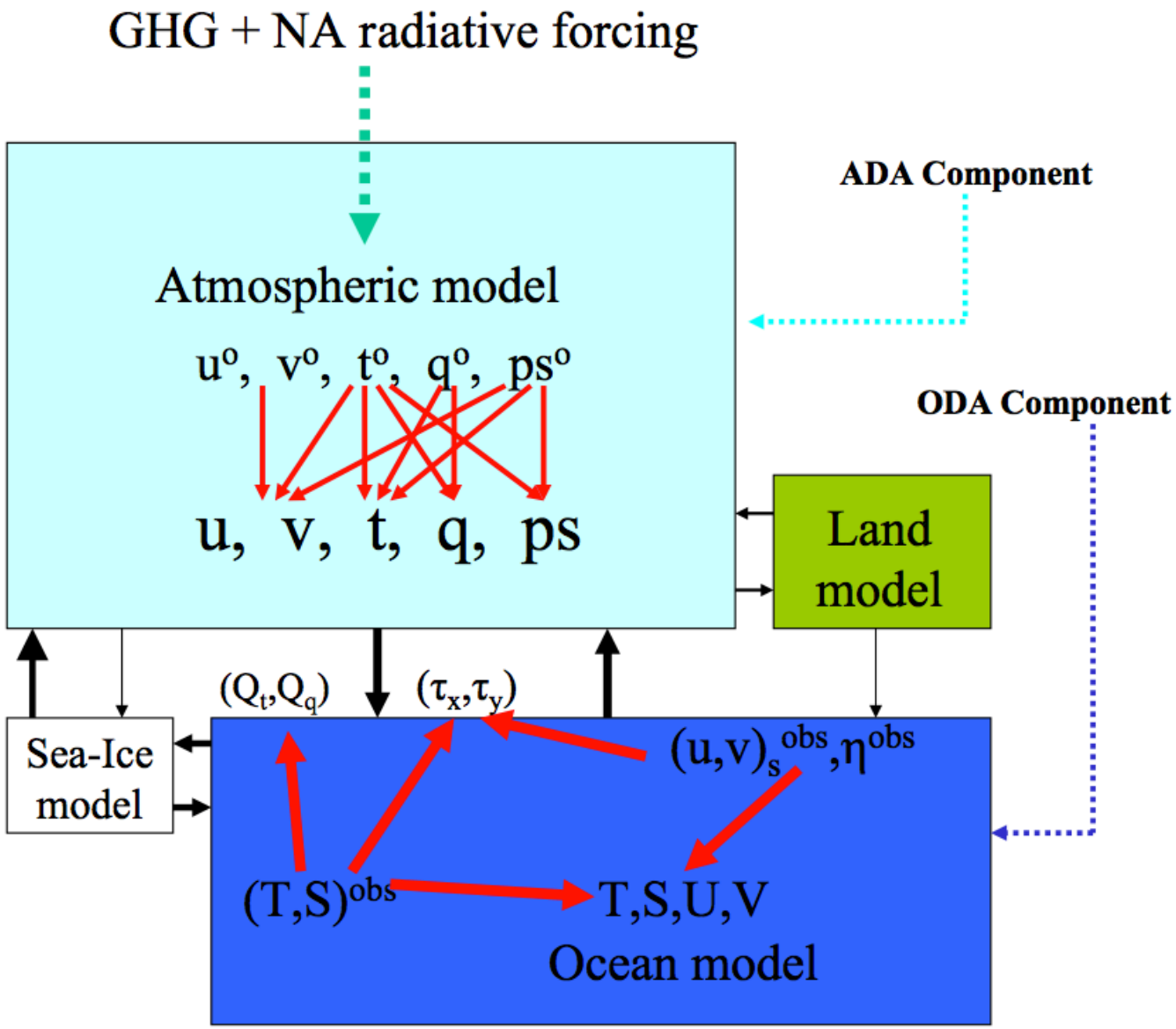
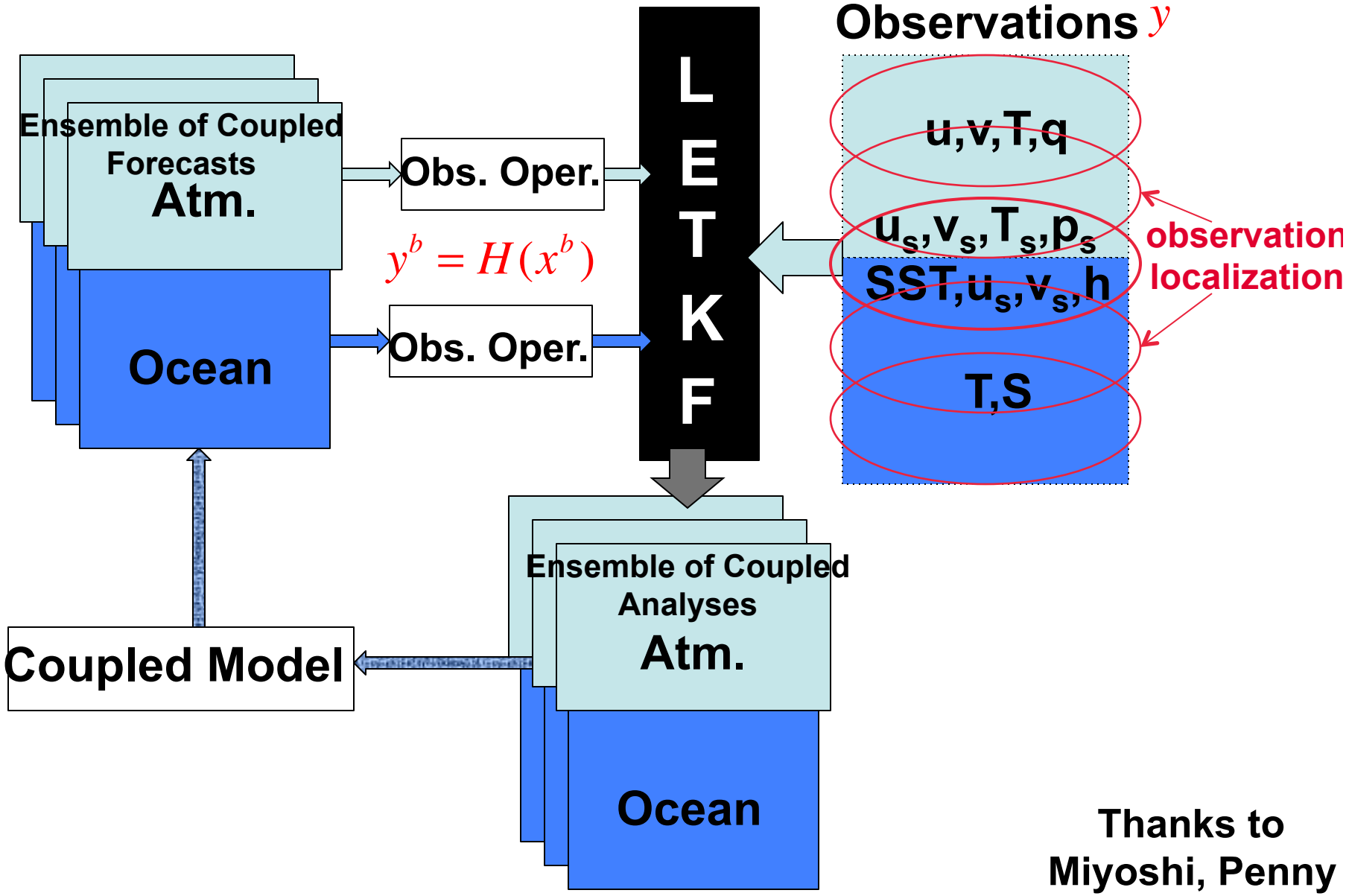


# Our strongly coupled LETKF assimilation




Thanks to Miyoshi, Penny

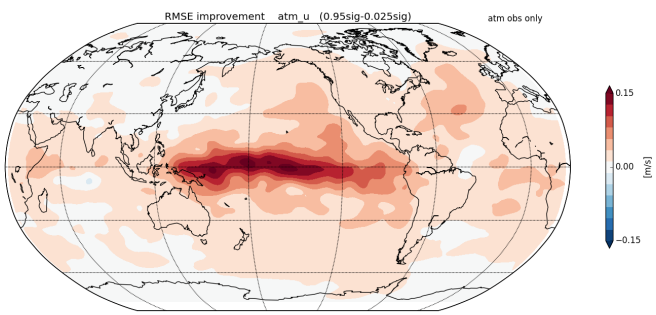
# Impact of strong coupling of the ocean -atmosphere LETKF (Travis Sluka)

- SPEEDY-NEMO coupled model (from F. Kucharski, ICTP)
- Standard (weak) coupling: data not coupled, only the model.
- Strong coupling: the ocean sees the atmospheric observations and the atmosphere sees the ocean observations

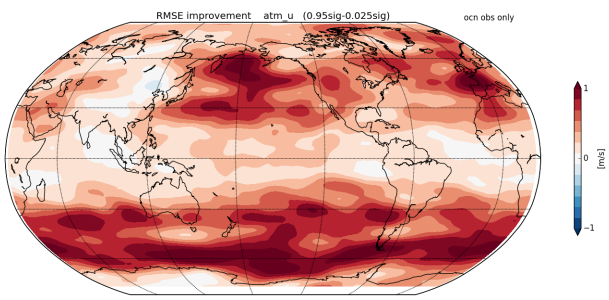
**First experiments: a) Only atmos obs; b) Only ocean obs**

- CONTROL: Only the atmosphere assimilates atmos. obs. (and vva).
- Strongly coupled DA: ocean also sees atmos. obs. (and vva).

**Atmos. obs. only**




**Ocean obs. only**




Difference of atm wind error between standard and strongly coupled DA.
**Red means strongly coupled is better than the standard DA method.**