Resolving the Global Stocktake

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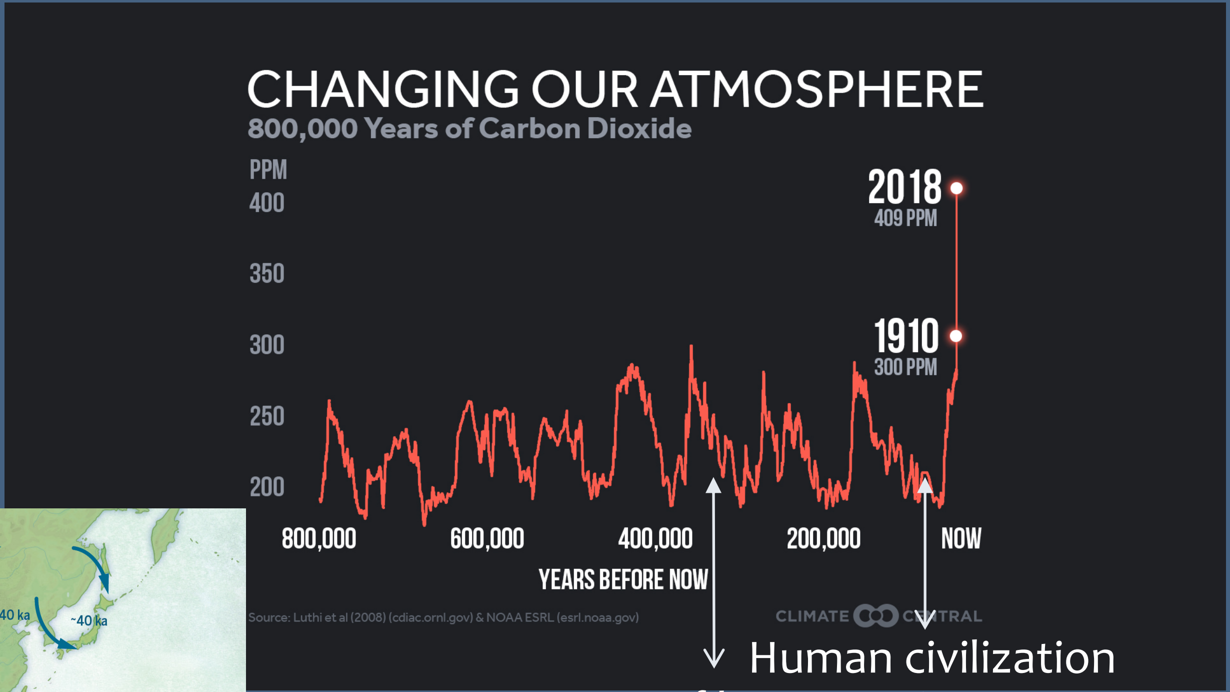
A generation like none other

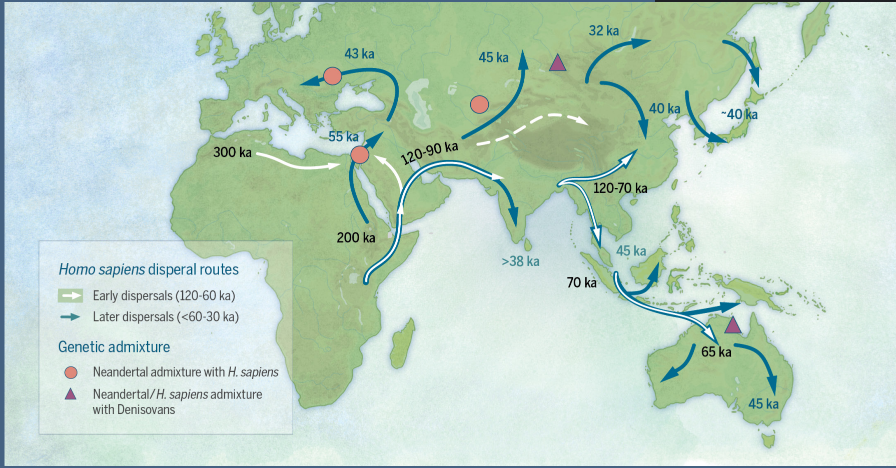
Our ancestors have never experienced this much CO_2.

Our progeny will experience a climate like no humans before.



Human civilization

Emergence of homo-sapiens



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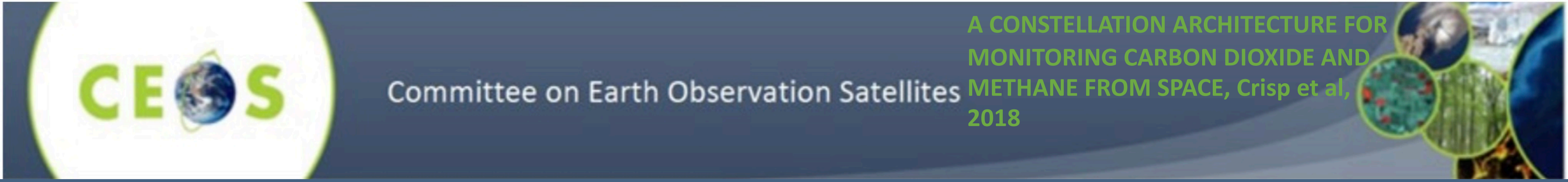
The Global Stocktake

The Global Stocktake every 5 years (starting in 2023) will assess progress and adjust commitments towards the Paris Accord.

How will emission commitments be related to concentration requirements?

From emissions to concentrations—and back again



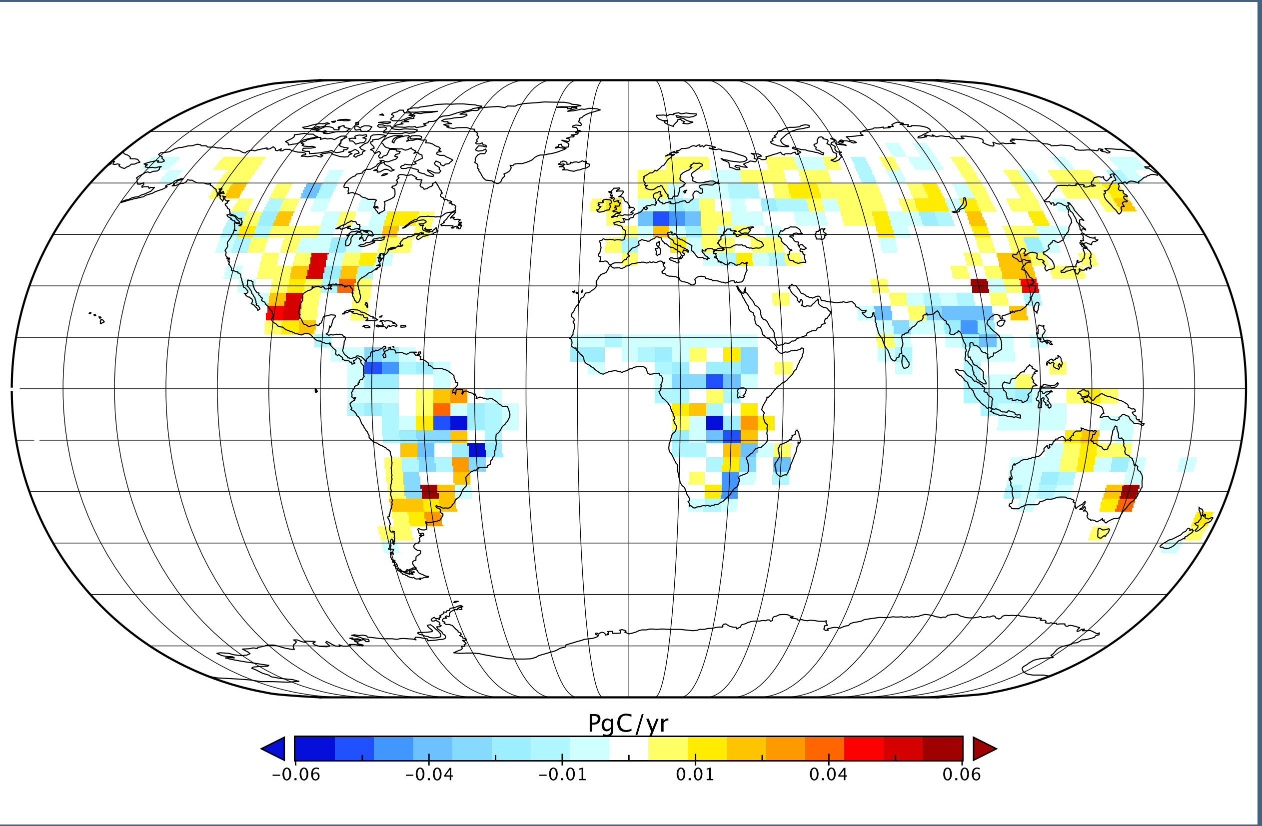
A CONSTELLATION ARCHITECTURE FOR MONITORING CARBON DIOXIDE AND METHANE FROM SPACE, Crisp et al, 2018

How well can we resolve fluxes given concentrations?

Triumvariate solution: What do you know?

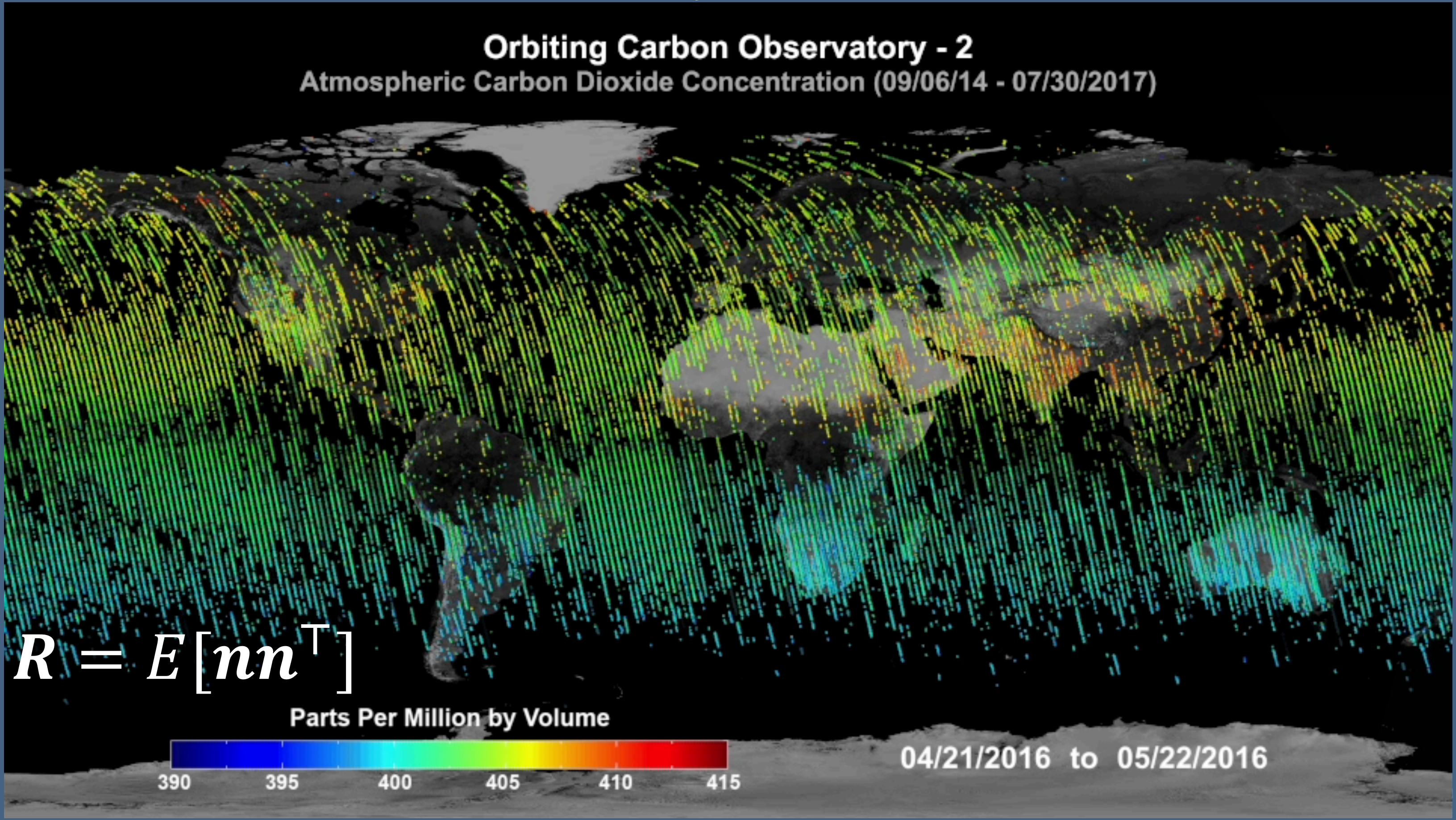
CMS-Flux total flux difference 2011-2010

$$B = E[(x - xb)(x - x_b)^T]$$



Bowman *et al*, *Earth and Space Sci.* , 2017

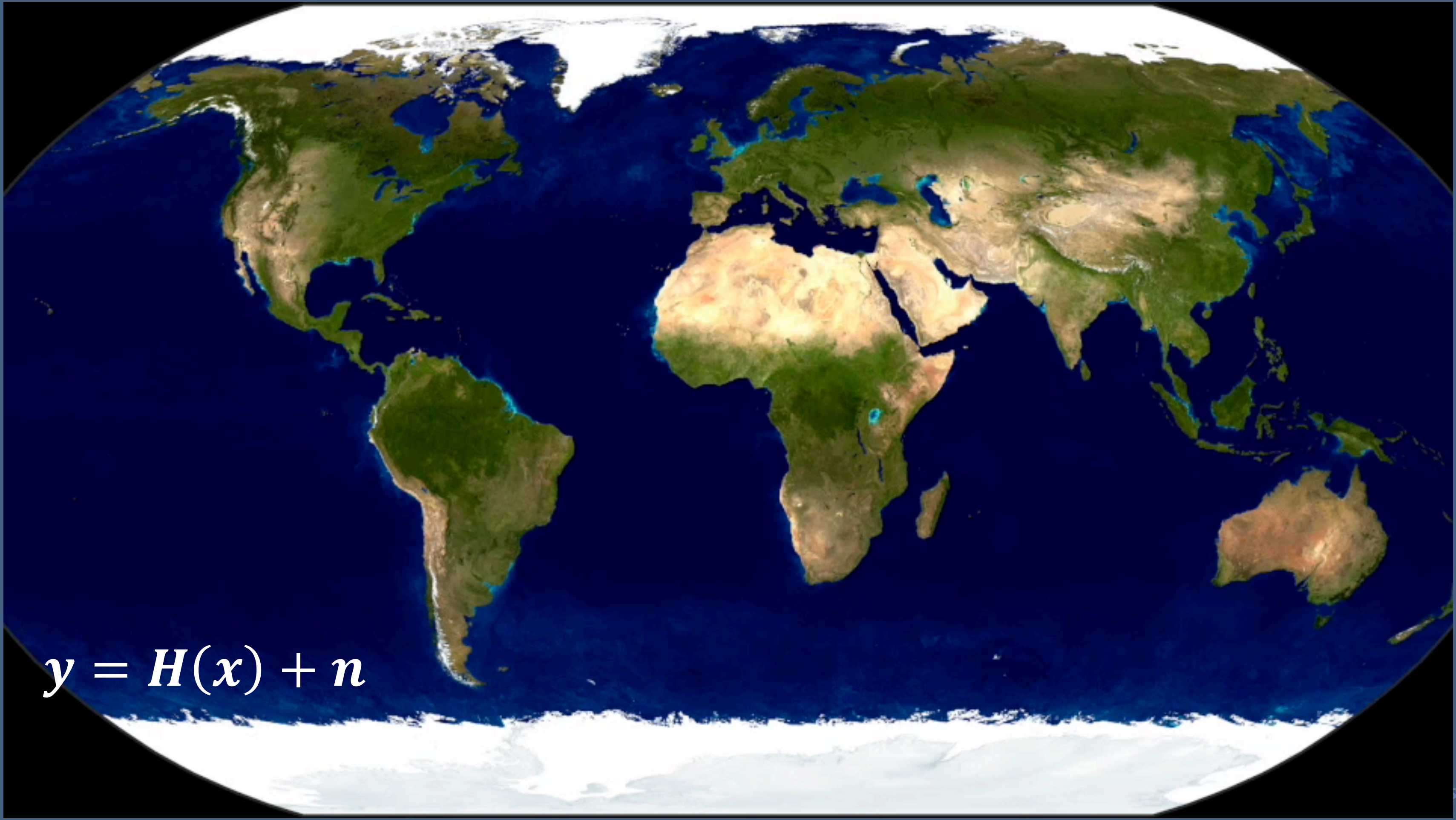
Triumvariate solution: What do you observe?



$$R = E[nn^{\top}]$$

sa.gov

From what we observe to what we want to know: Transport

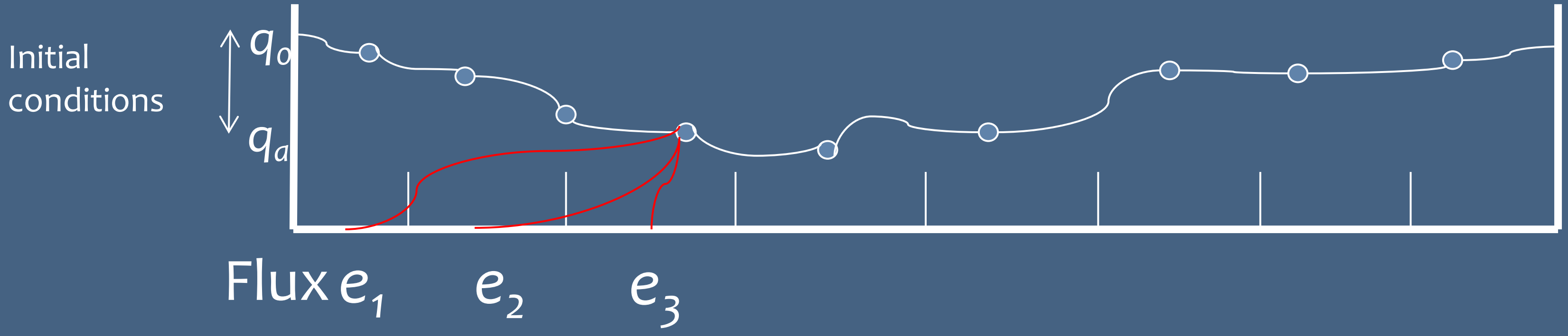


GEOS-Chem High Performance, C360

Courtesy, Sebastian Eastham, MIT

4D-variational assimilation

State vector $\mathbf{x} = \begin{bmatrix} \mathbf{q} \\ \mathbf{e} \end{bmatrix}$



$$J(\mathbf{x}) \equiv \frac{1}{2}(H\mathbf{x} - \mathbf{y})^T \mathbf{R}^{-1}(H\mathbf{x} - \mathbf{y}) + \frac{1}{2}(\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b)$$

forward model

model-data error covariance

data

prior

prior error covariance

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{B}^{1/2}(\mathbf{I} + \mathbf{B}^{1/2}\mathbf{H}^\top\mathbf{R}^{-1}\mathbf{H}\mathbf{B}^{1/2})^{-1}\mathbf{B}^{-1/2}\mathbf{H}^\top\mathbf{R}^{-1}(\mathbf{y} - \mathbf{H}(\mathbf{x}))$$

The Triumvirate solution

The linear inverse problem can be completely characterized by the observing system, transport, and flux uncertainty (Rodgers, 2000, Tarantola, 2005, Bousserez and Henze, 2015)

$$\mathbf{B}^{1/2}\mathbf{H}^{T}\mathbf{R}^{-1}\mathbf{H}\mathbf{B}^{1/2} = \sum_{i}^{p} \lambda_i \mathbf{v}_i \mathbf{v}_i^T$$

Characterization

Spantini et a, 2015 and Bousserez and Henze, 2018 showed how to choose the optimal k<<p.

But how to compute?

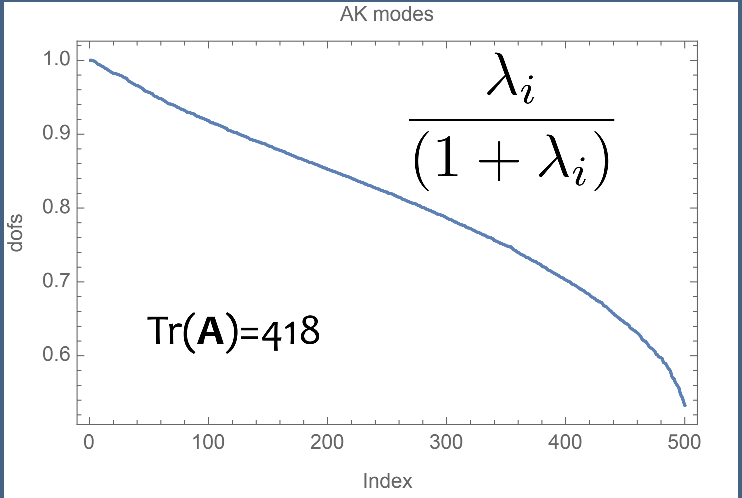
$$\mathbf{A} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{x}_{\text{true}}} = \mathbf{B}^{1/2} \left(\sum_{i=1}^{k} \frac{\lambda_i}{(1+\lambda_i)} \mathbf{v}_i \mathbf{v}_i^{\top} \right) \mathbf{B}^{-1/2}$$

Fast Randomized Optimal Approach for Diagnostic and Optimization (FRODO) computes the SVs ***efficiently*** (asynchronous parallelization) using new probabilistic algorithms for matrix decomposition (Bousserez and Henze, 2018, Halko et al, 2011).

The Averaging Kernel and the axes of variation

The averaging kernel (AK) describes the resolvable modes of variability

The degrees of freedom for signal (dofs) is a measure of the independent pieces of information in the inversion.

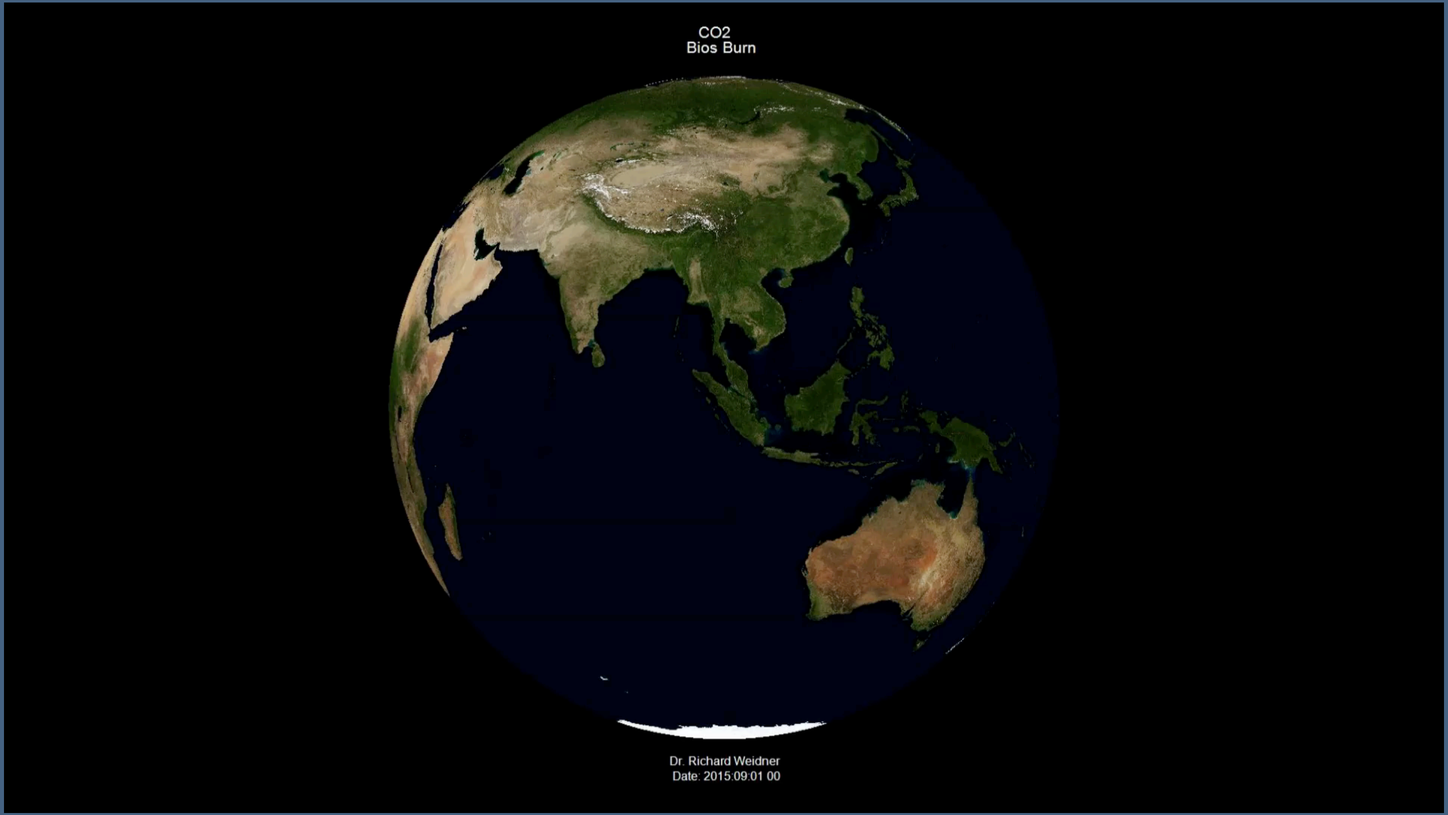


$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{A}(\mathbf{x} - \mathbf{x}_b) + \epsilon$$

$$\mathbf{A} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{x}_{\mathrm{true}}} = \mathbf{B}^{1/2} \left(\sum_{i=1}^{k} \frac{\lambda_i}{(1+\lambda_i)} \mathbf{v}_i \mathbf{v}_i^\top \right) \mathbf{B}^{-1/2}$$

OCO-2 can resolve 418 independent modes.
What about specific locations?

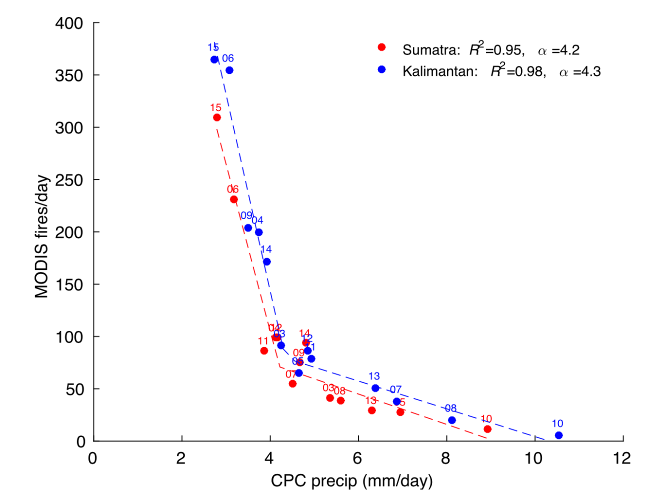
Atmospheric signature of Indonesian carbon in 2015



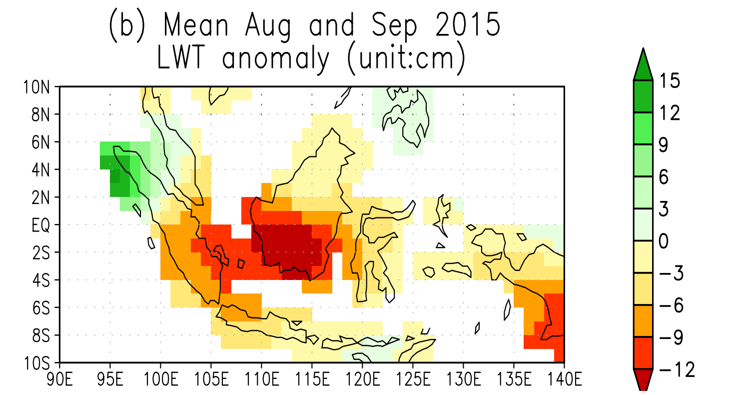
Tipping points: the hydrological context

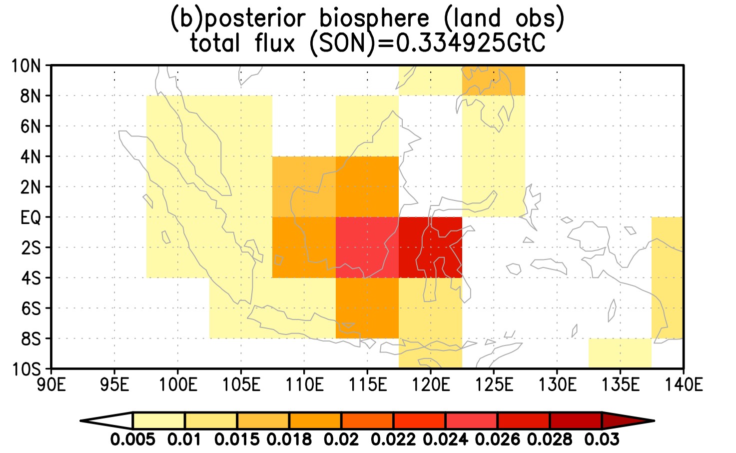
Centered on Kalimantan, GRACE gravity data shows a liquid water equivalent thickness (LWT) anomaly of -4 cm, 4x larger than then decadal mean anomaly.

Field et al, 2016 PNAS reported a non-linear relationship between firecounts and precipitation below 4 mm/day



Fields et al, 2016 (PNAS)

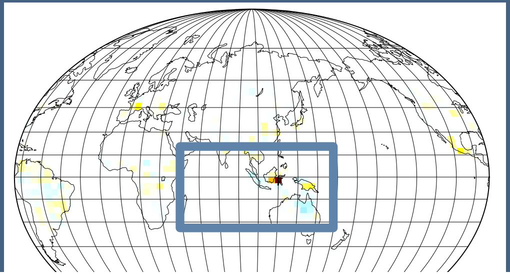


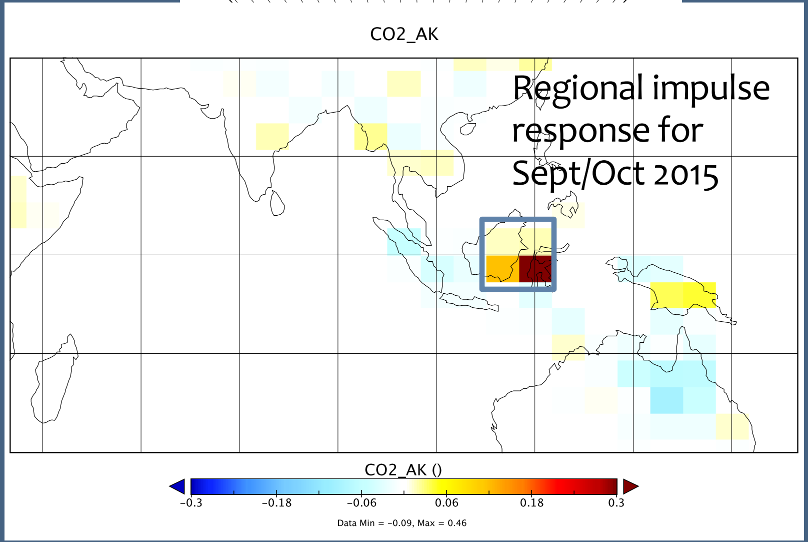


Resolving Indonesian Flux

The sensitivity of the CMS-Flux Indonesian flux estimate to the true flux is defined by the impulse response (IR):

$$\frac{\partial \hat{\mathbf{x}}}{\partial [\mathbf{x}]_{i \in L}}$$



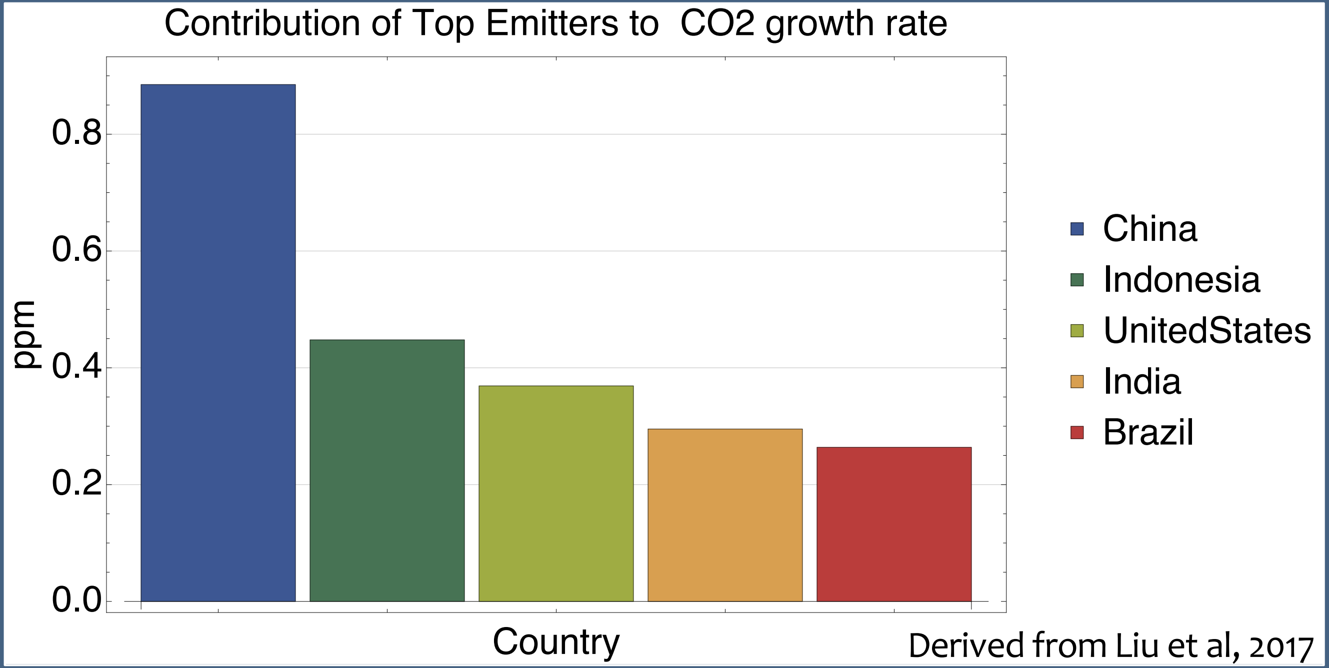


The IR response shows the fractional change in the OCO-2-constrained global flux if the *true* flux increased by 100%.

The IR can be approximated following techniques in Bousserez and Henze, 2018, which synthesize advances in probabilistic matrix decomposition and estimation techniques

The high values over Indonesia and Borneo (and weaker responses elsewhere) show that the the peak biomass burning in Sept/Oct 2015 is well resolved by CMS-Flux.

Contributions to the CO2 growth rate



CMS-Flux was used to show that China was the highest and Indonesian region was the 2nd highest contributor (0.45 ppm) to total flux of the record CO2 growth rate in 2015.

Both those were due to different drivers.

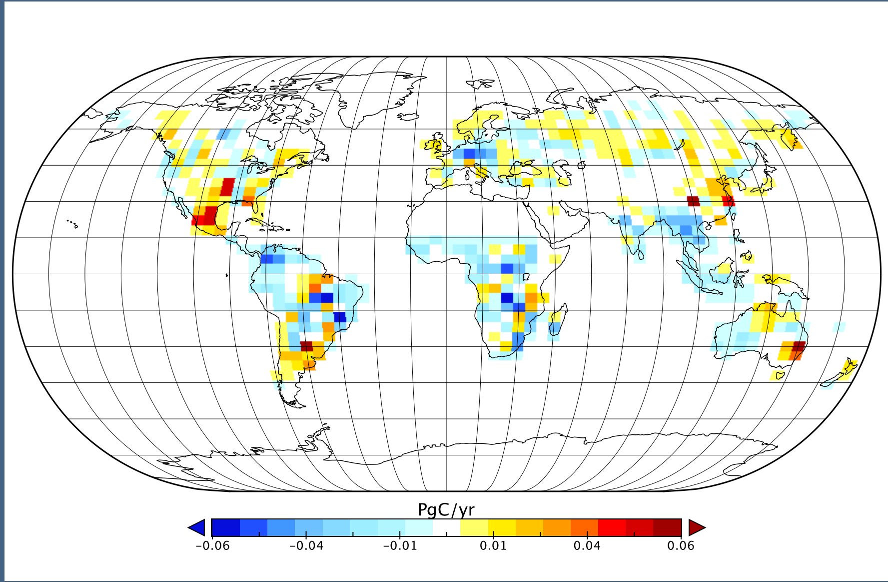
Conclusions

- The ability of carbon monitoring systems to support the global stocktake critically depend on their ability to resolve fluxes given concentrations.
- Application to CMS-Flux constrained by OCO-2 shows that OCO-2 can constrain ~420 independent modes (in the absence systematic errors) over a year.
- Impulse response analysis reveals that the resolution of the inversion is a complex function of space and time.
  - In Indonesia, IR analysis suggests that carbon fluxes could be resolved and consequently contribution to the atmospheric growth is independent of other spatial fluxes.

Characterization of inversions: the problem of scale

- What *patterns* of flux can be independently constrained?
    - What is the spatio-temporal resolution of the flux?
- How does the *a priori* influence the flux estimate?
- How correlated is the uncertainty in the flux?

CMS-Flux total flux difference 2011-2010



Bowman *et al*, *Earth and Space Sci.* , 2017

How well can OCO-2 resolve fluxes in time?

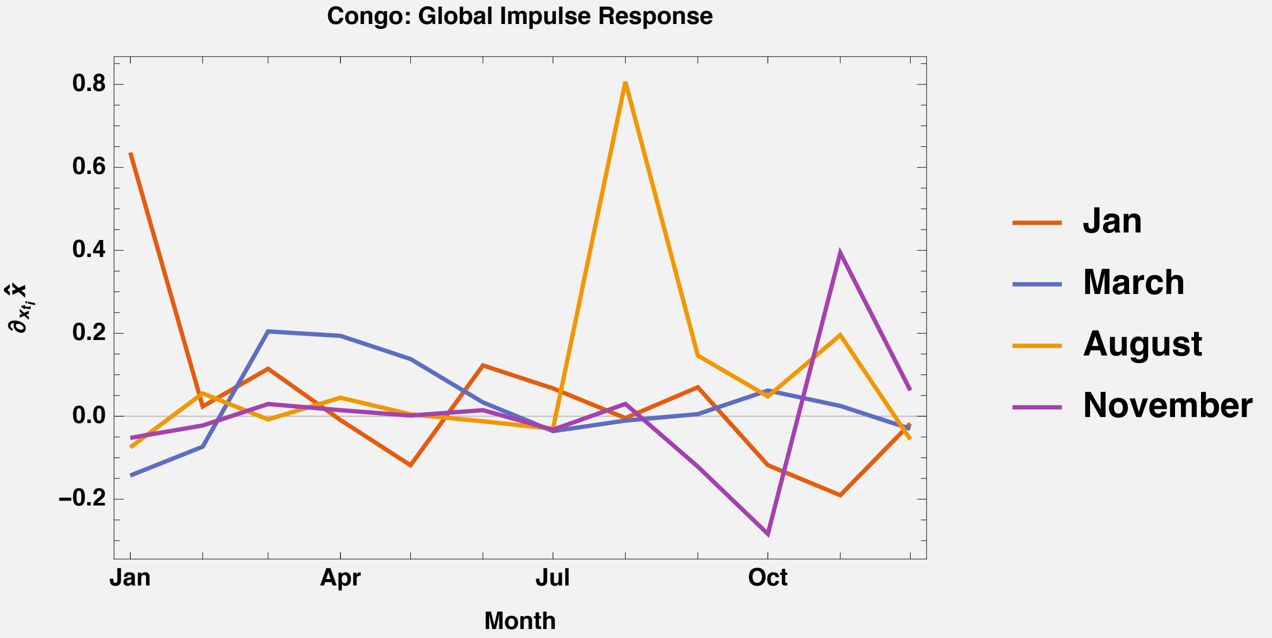
Integrate the Congo IR globally for each month.

January is well resolved but has non-negligible impacts of the following months.

March is poorly resolved and is strongly correlated with April and May, 2015.

August is well resolved.

November is negatively correlated with Oct.

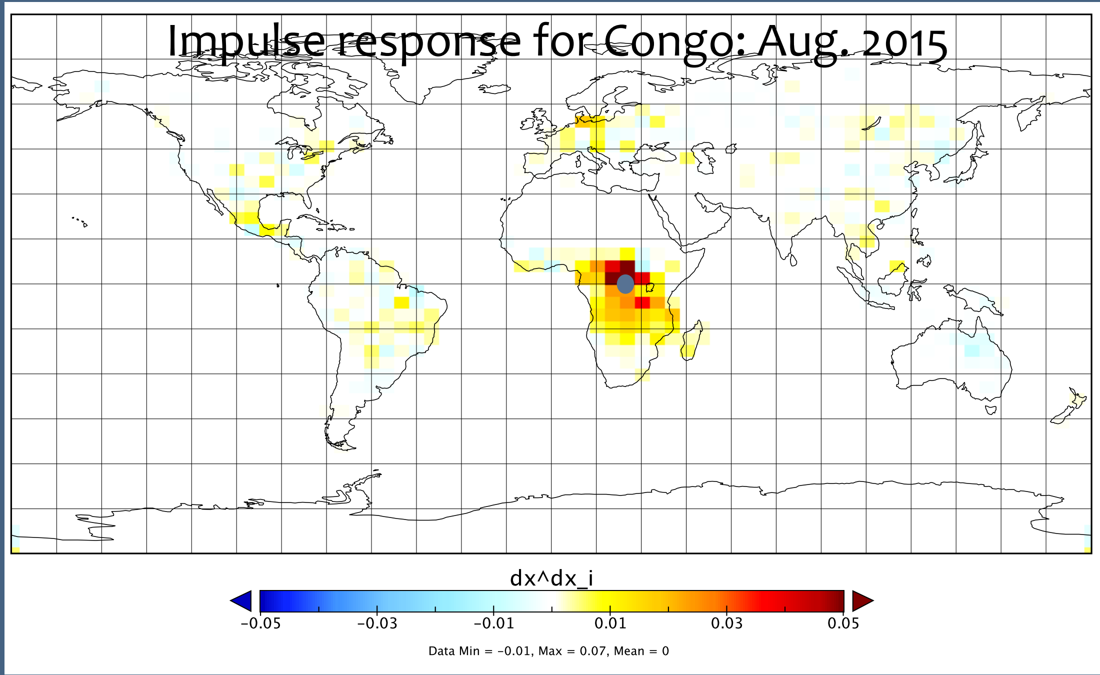


Flux resolution: Impulse response

The impulse response (IR) is the change in the flux estimate from the change in the actual fluxes at a particular grid box.

The IR is the column of the AK:

$$\mathbf{a}_i = \mathbf{A}\delta_i$$



Congo is a particularly interesting region in the carbon cycle. We'll choose one grid box: (0, 25E)

A change in the true flux at this one grid box in Aug., changes the estimate anisotropically over a roughly 15 ° x15° region.

OSSE Case: OCO-2, 2015

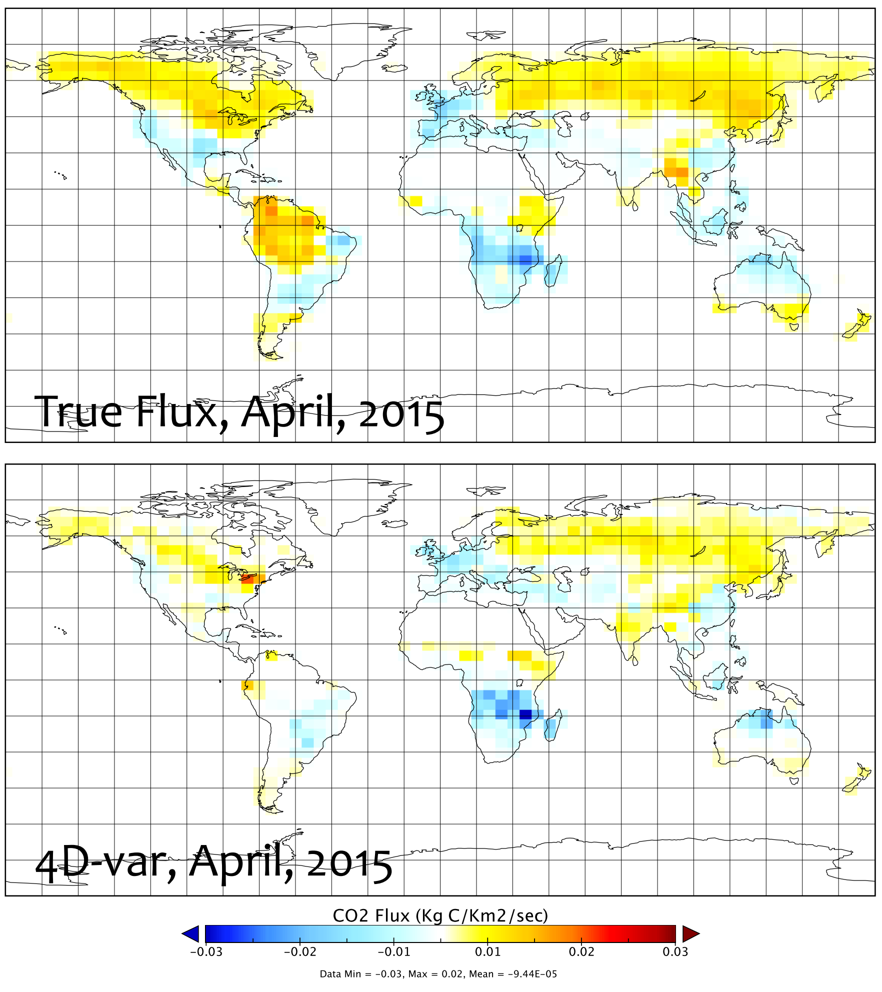
Flux estimates are computed for land using FRODO using 500 ensembles.

The "true" follow the priori fluxes Liu et al, 2017 and Bowman et al, 2017.

The "prior" fluxes use CARDAMOM (Bloom et al, 2016)

Flux uncertainty is simply 0.5.

What patterns are controlled?



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