Assimilation of Earth Rotation Parameters into the Community Atmosphere Model

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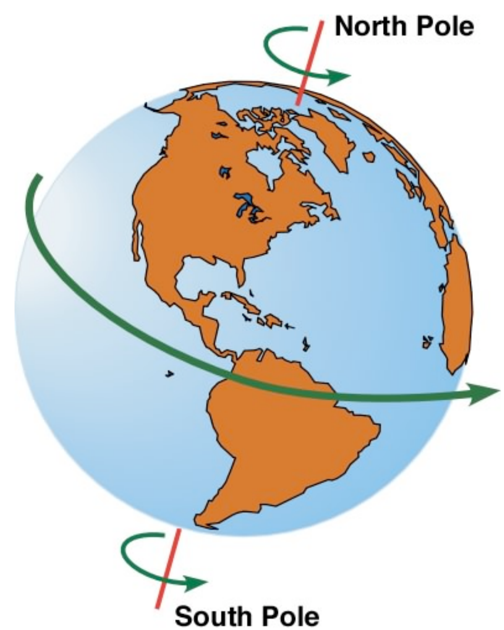
2012 SPARC Data Assimilation Workshop

Socorro, New Mexico



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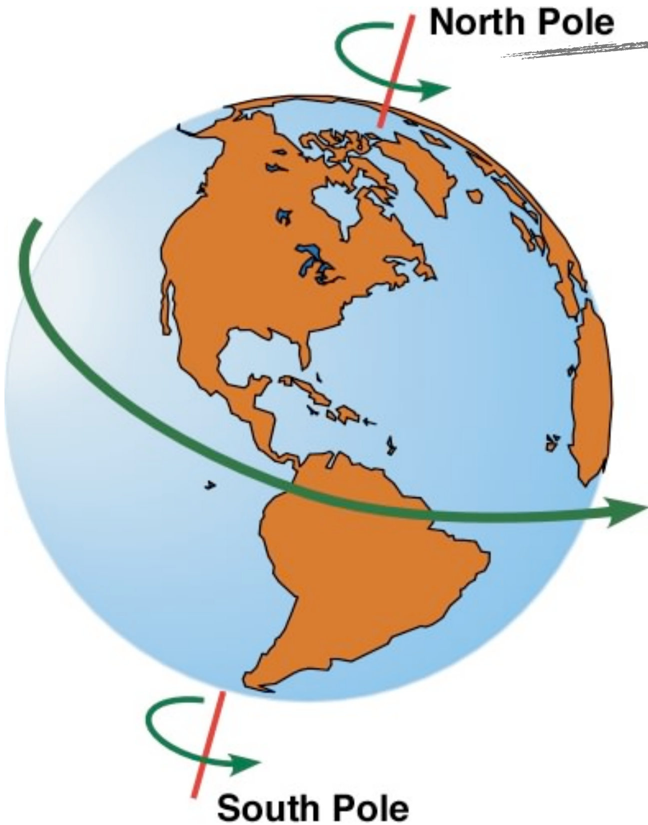
Motivation

Earth rotation varies in time.

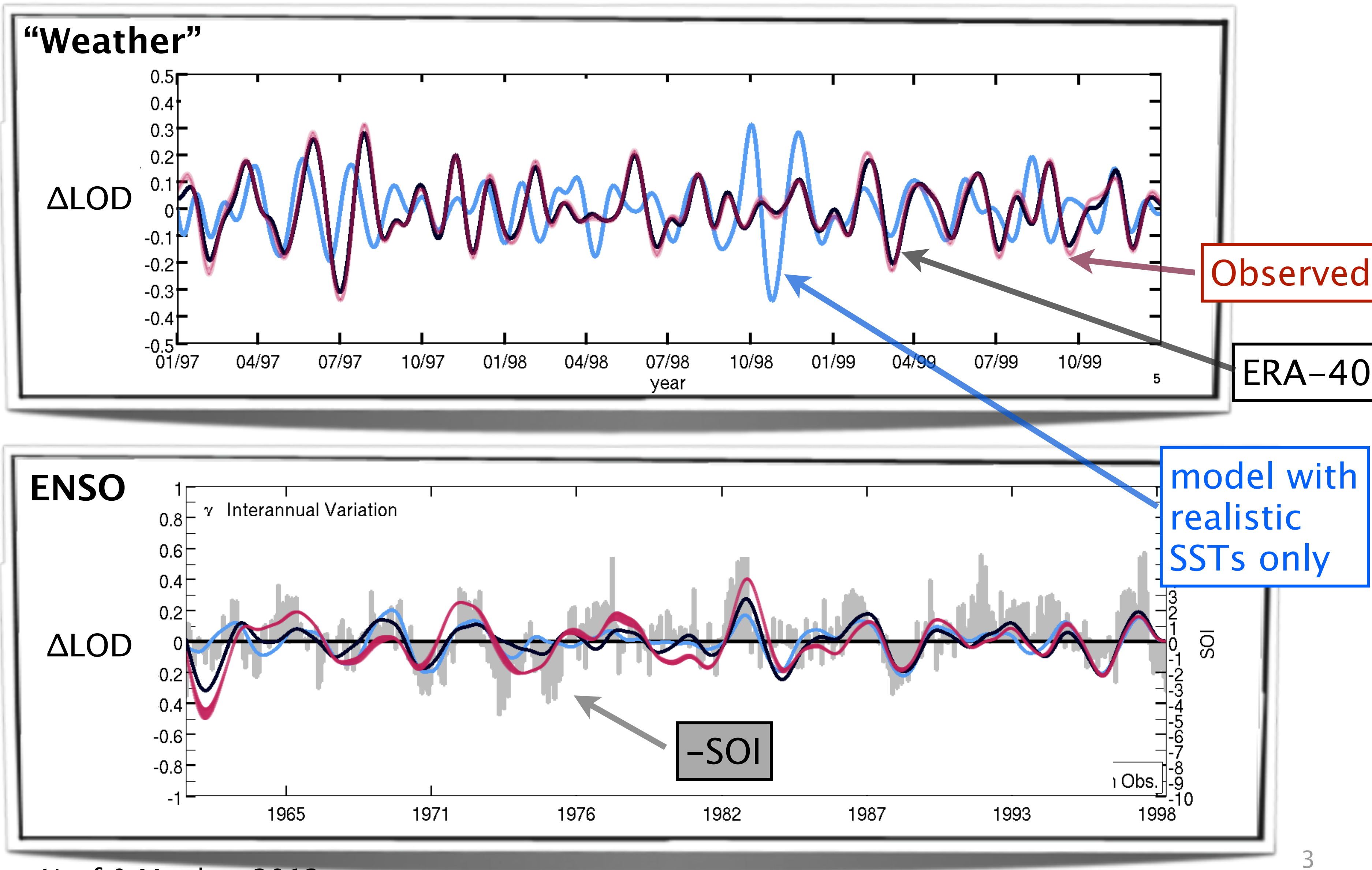


Polar Wobble
p_1, p_2

Changing rotation rate
(Length-of-day)
LOD

1. Changes are observed.
2. Reflect angular momentum of the fluid shell around the Earth, primarily the atmosphere.
3. Assimilation--> Earth rotation as a constraint upon atmosphere models.

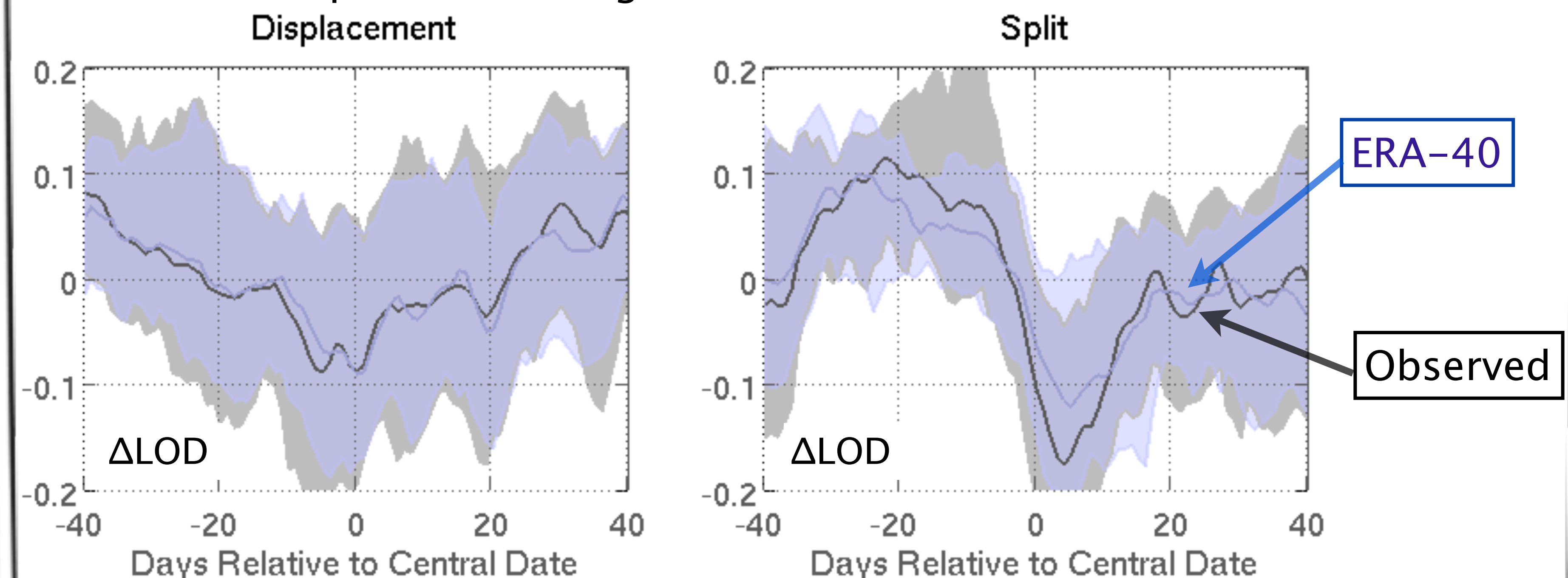
Atmospheric Effects on Earth Rotation (Examples)



Neef & Matthes 2012

Atmospheric Effects on Earth Rotation (Examples)

Sudden Stratospheric Warmings



Also:
NAM/SAM (Petrick et al., 2012; Marcus et al., 2012)
Blocking (Neef and Walther, in progress.)
MJO (Dickey et al., 1991)

Excitation of Earth Rotation by Angular Momentum Exchange

Polar Motion components

$$p_1 + \frac{\dot{p_2}}{\sigma_0} = \chi_1$$

$$-p_2 + \frac{\dot{p_2}}{\sigma_0} = \chi_2$$

Equatorial excitation functions

Length-of-day changes

$$\frac{\Delta \mathrm{LOD}}{\mathrm{LOD}_0} = \Delta\chi_3$$

Axial excitation

Barnes et al. (1983)
Gross (2009)

Atmospheric Excitation of Earth Rotation

Earth Rotation Variations ~ Variations in Atmospheric Angular Momentum

$$p_1 + \frac{\dot{p}_2}{\sigma_0} = \chi_1 = -\frac{R^3}{g(C-A)}\left[\frac{1.16}{\Omega}\int\int\int(u\sin\phi\cos\phi\cos\lambda - v\cos\phi\sin\lambda)\mathrm{d}\lambda\mathrm{d}\phi\mathrm{d}p + 1.10R\int\int p_s\sin\phi\cos^2\phi\cos\lambda\mathrm{d}\lambda\mathrm{d}\phi\right]$$

$$-p_2 + \frac{\dot{p}_1}{\sigma_0} = \chi_2 = -\frac{R^3}{g(C-A)}\left[\frac{1.61}{\Omega}\int\int\int(u\sin\phi\cos\phi\sin\lambda + v\cos\phi\cos\lambda)\mathrm{d}\lambda\mathrm{d}\phi\mathrm{d}p + 1.10R\int\int p_s\sin\phi\cos^2\phi\sin\lambda\mathrm{d}\lambda\mathrm{d}\phi\right]$$

$$\frac{\Delta\mathrm{LOD}}{\mathrm{LOD}_0} = \chi_3 = \frac{R^3}{C_m g}\left[\frac{0.997}{\Omega}\int\int\int u\cos^2\phi\mathrm{d}\lambda\mathrm{d}\phi\mathrm{d}p + R\int\int p_s\cos^3\phi\mathrm{d}\lambda\mathrm{d}\phi\right]$$

Earth Rotation Variations = Motion (relative AM) + Mass (moment of inertia)

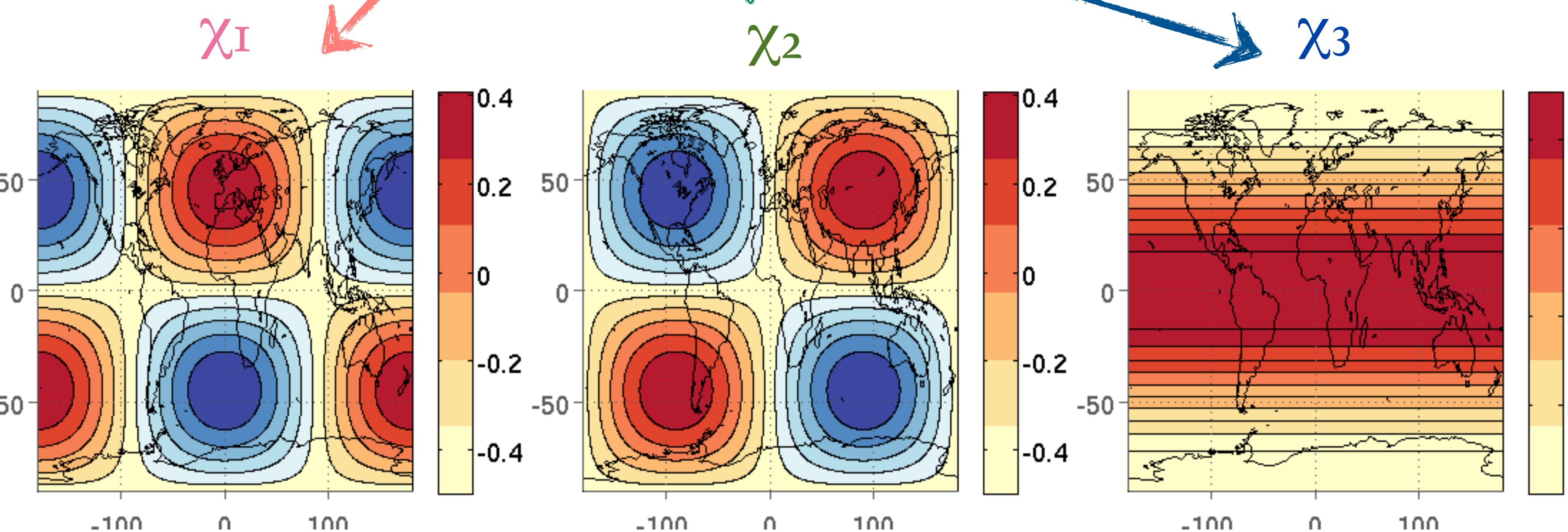
Barnes et al. (1983) Gross (2009)

Geographic Weighting Functions

$$p_1 + \frac{\dot{p}_2}{\sigma_0} = \chi_1 = -\frac{R^3}{g(C-A)}\left[\frac{1.16}{\Omega}\int\int\int(u\sin\phi\cos\phi\cos\lambda - v\cos\phi\sin\lambda)\mathrm{d}\lambda\mathrm{d}\phi\mathrm{d}p + 1.10R\int\int p_s\sin\phi\cos^2\phi\cos\lambda\mathrm{d}\lambda\mathrm{d}\phi\right]$$

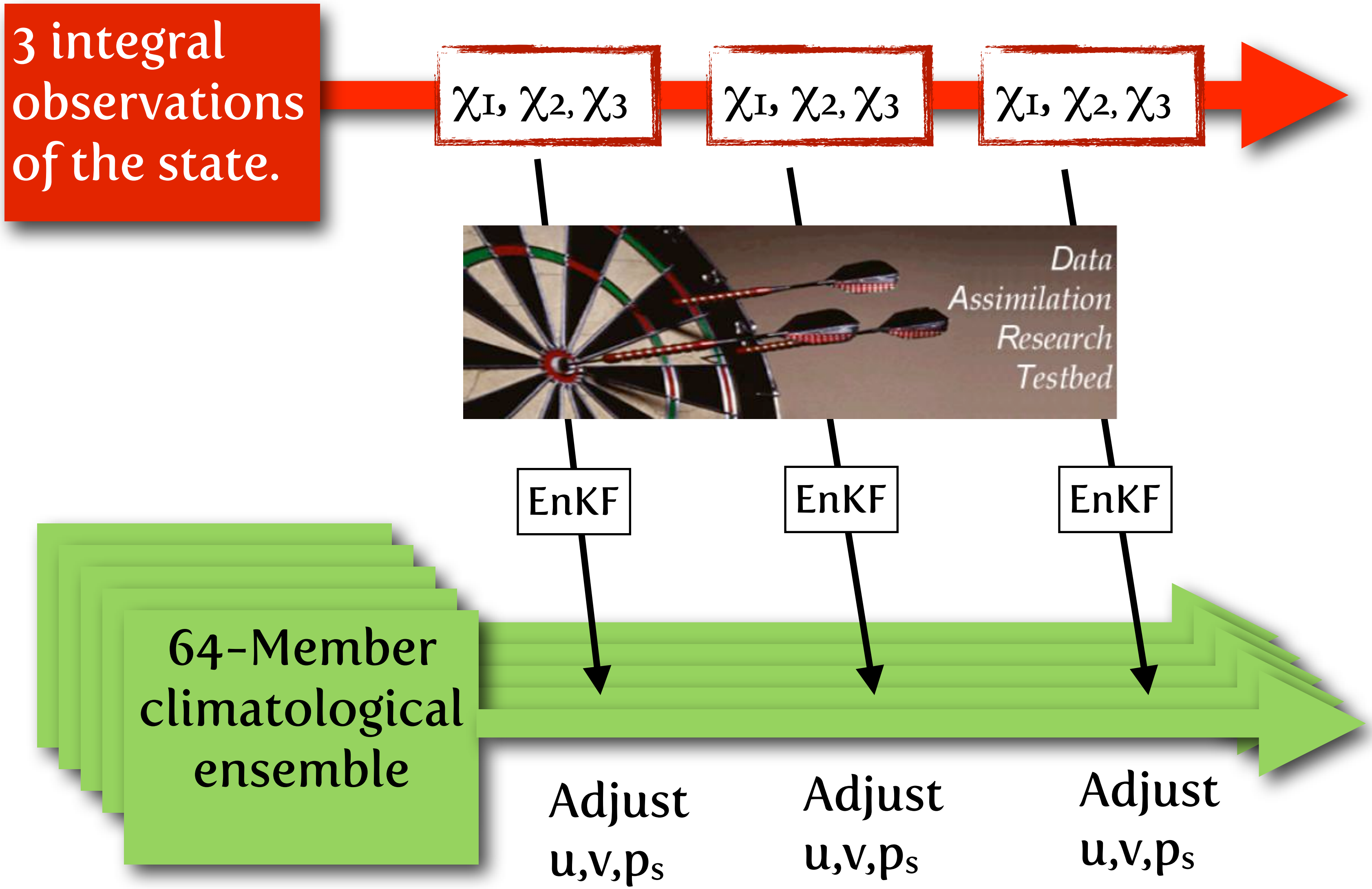
$$-p_2 + \frac{\dot{p}_1}{\sigma_0} = \chi_2 = -\frac{R^3}{g(C-A)}\left[\frac{1.61}{\Omega}\int\int\int(u\sin\phi\cos\phi\sin\lambda + v\cos\phi\cos\lambda)\mathrm{d}\lambda\mathrm{d}\phi\mathrm{d}p + 1.10R\int\int p_s\sin\phi\cos^2\phi\sin\lambda\mathrm{d}\lambda\mathrm{d}\phi\right]$$

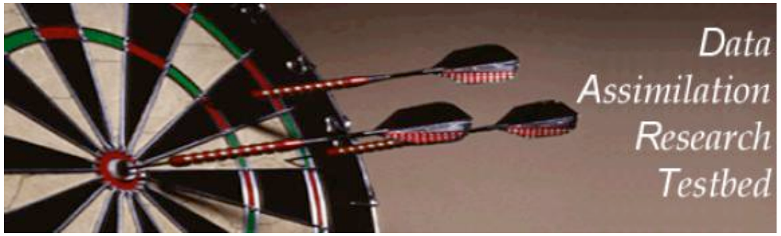
$$\frac{\Delta\mathrm{LOD}}{\mathrm{LOD}_0} = \chi_3 = \frac{R^3}{C_m g}\left[\frac{0.997}{\Omega}\int\int\int u\cos^2\phi\mathrm{d}\lambda\mathrm{d}\phi\mathrm{d}p + R\int\int p_s\cos^3\phi\mathrm{d}\lambda\mathrm{d}\phi\right]$$



Barnes et al. (1983) Gross (2009)

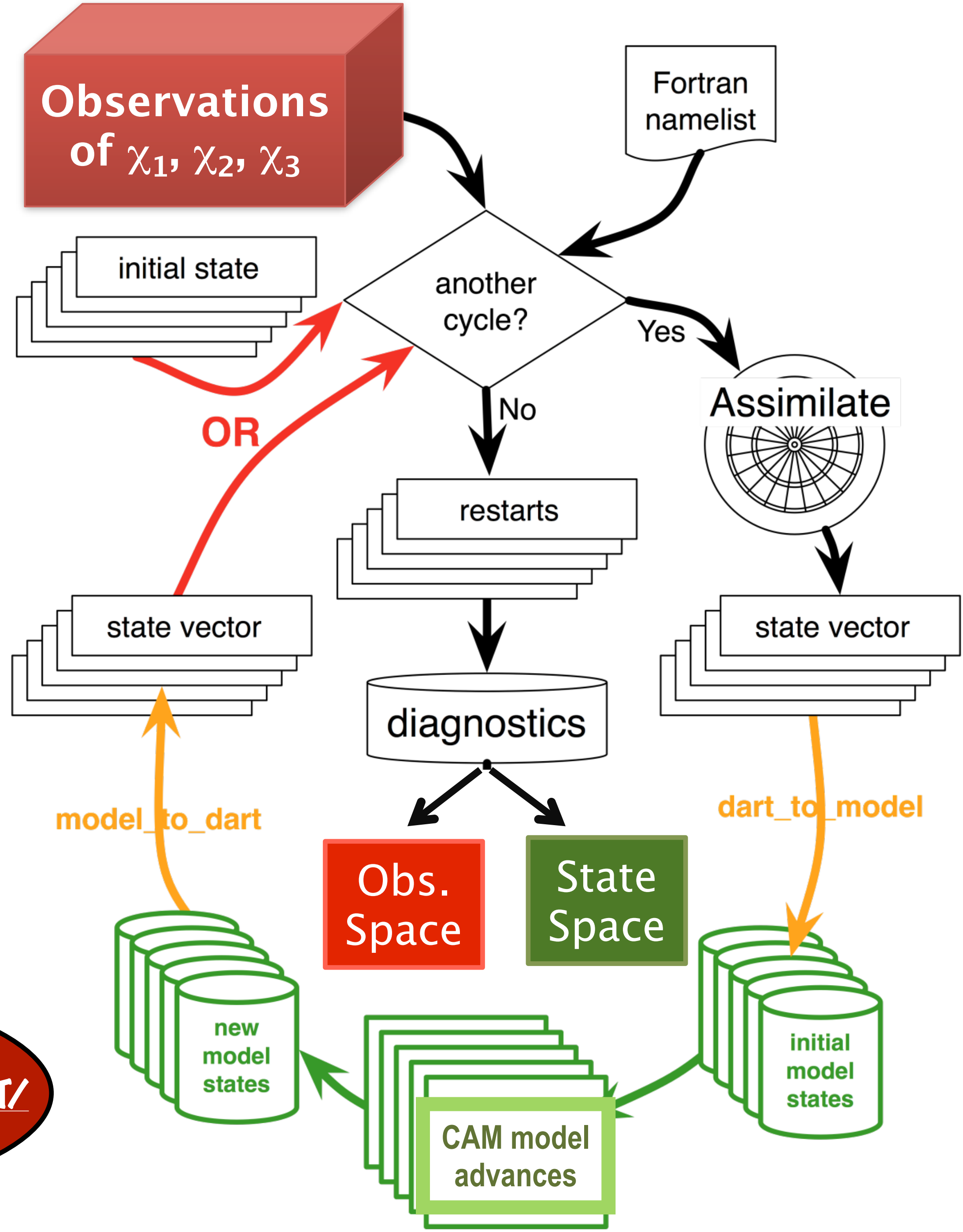
Assimilating Earth Rotation Using DART-CAM



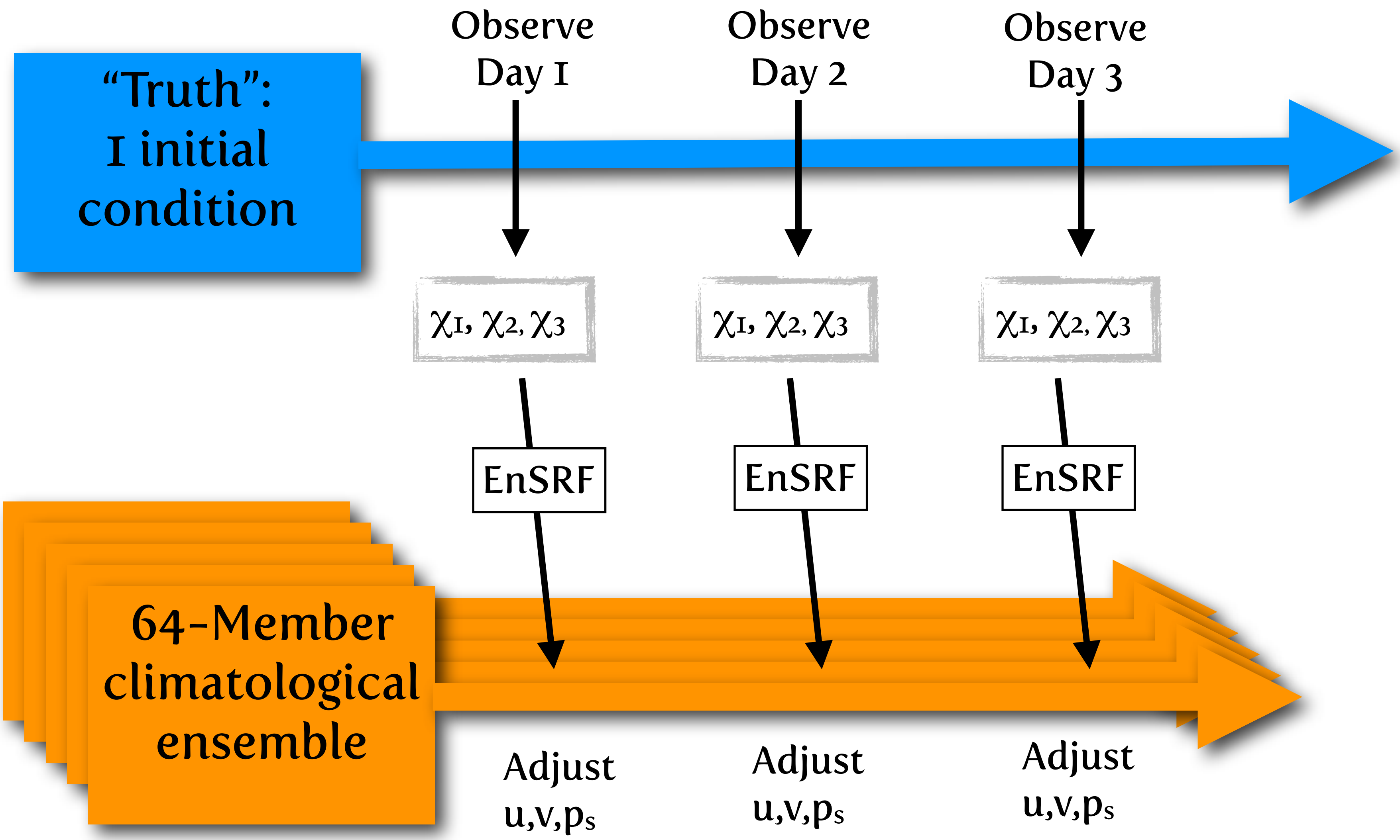


The Data Assimilation Research Testbed (DART)

Anderson et al. (2009)
http://www.image.ucar.edu/DAReS/DART/



Earth Rotation OSSEs using DART

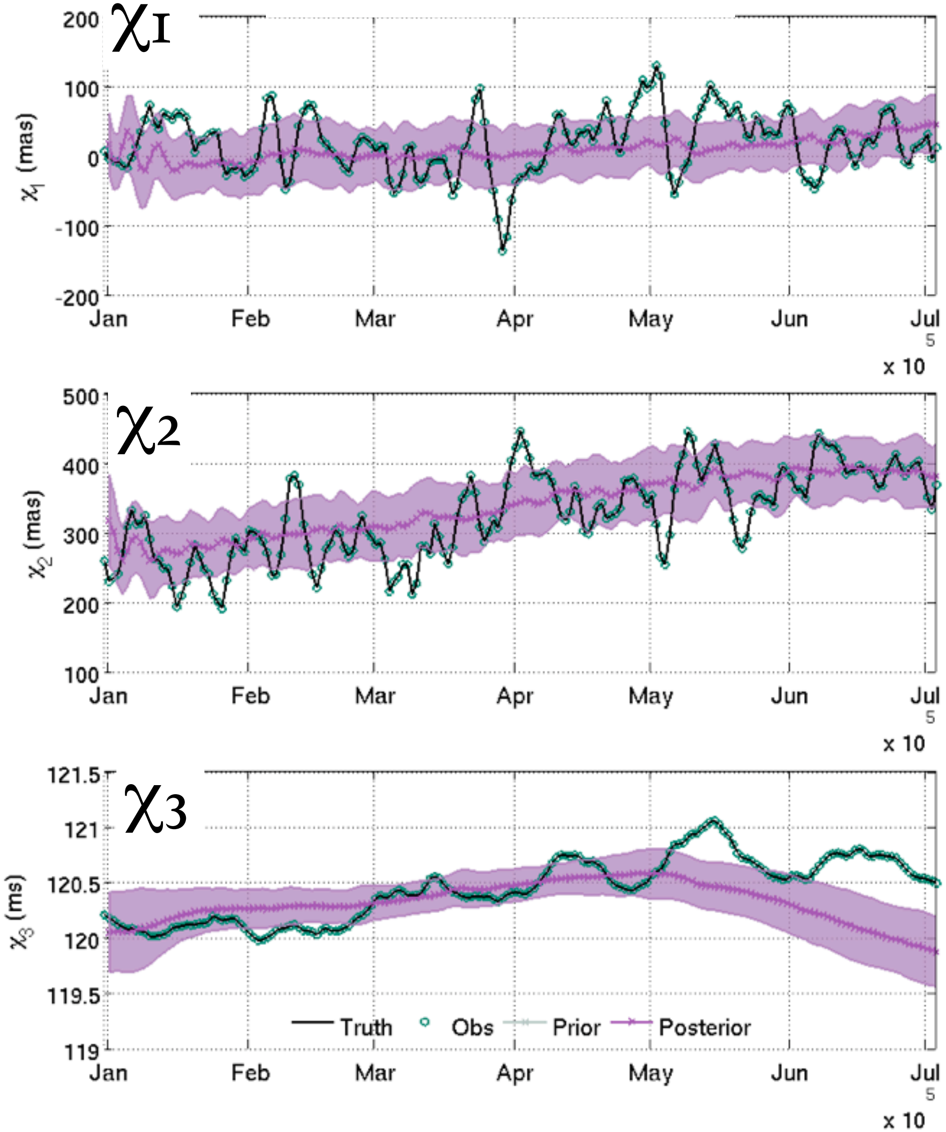


Given a perfect model and perfect observations, how well can we recover the truth?

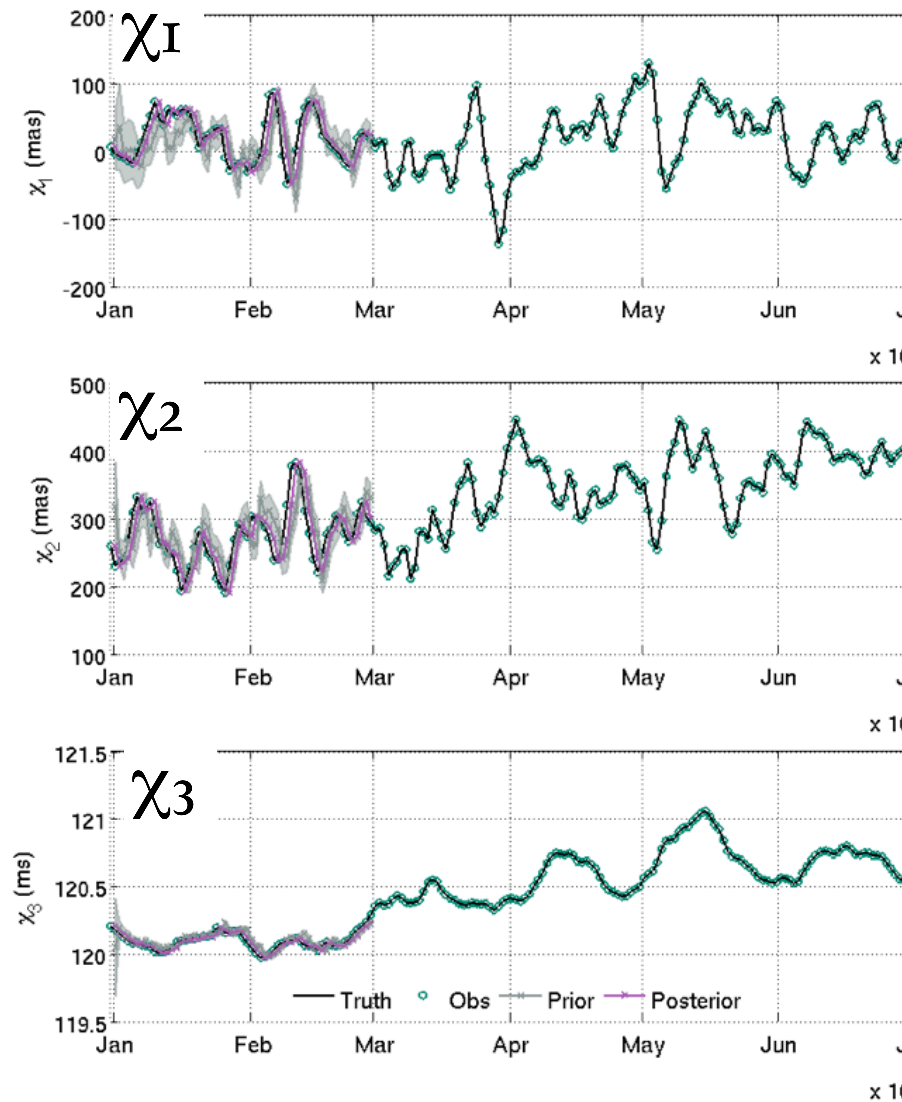
Observation Space

Truth Obs Prior Posterior

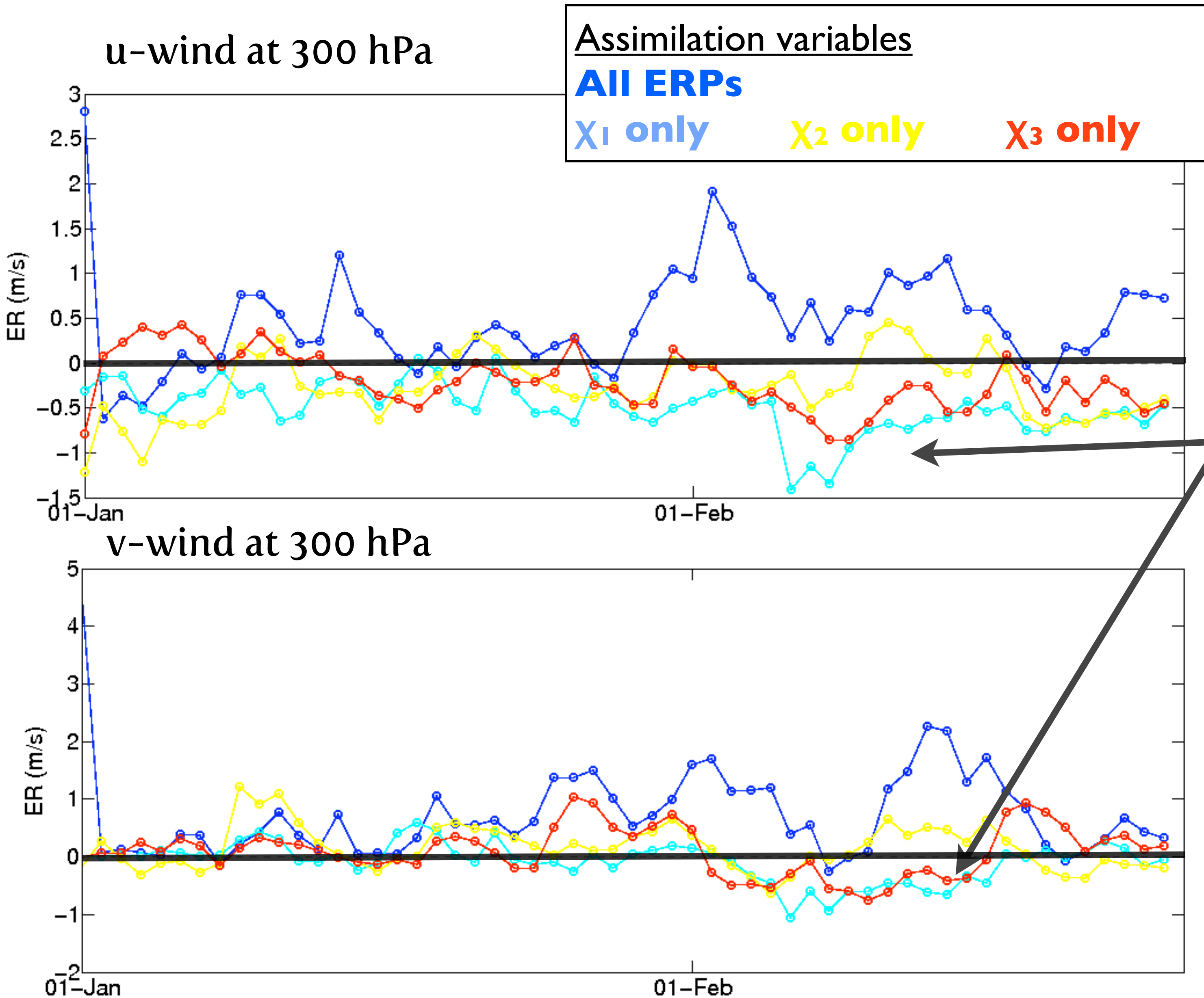
No Assimilation



With Assimilation



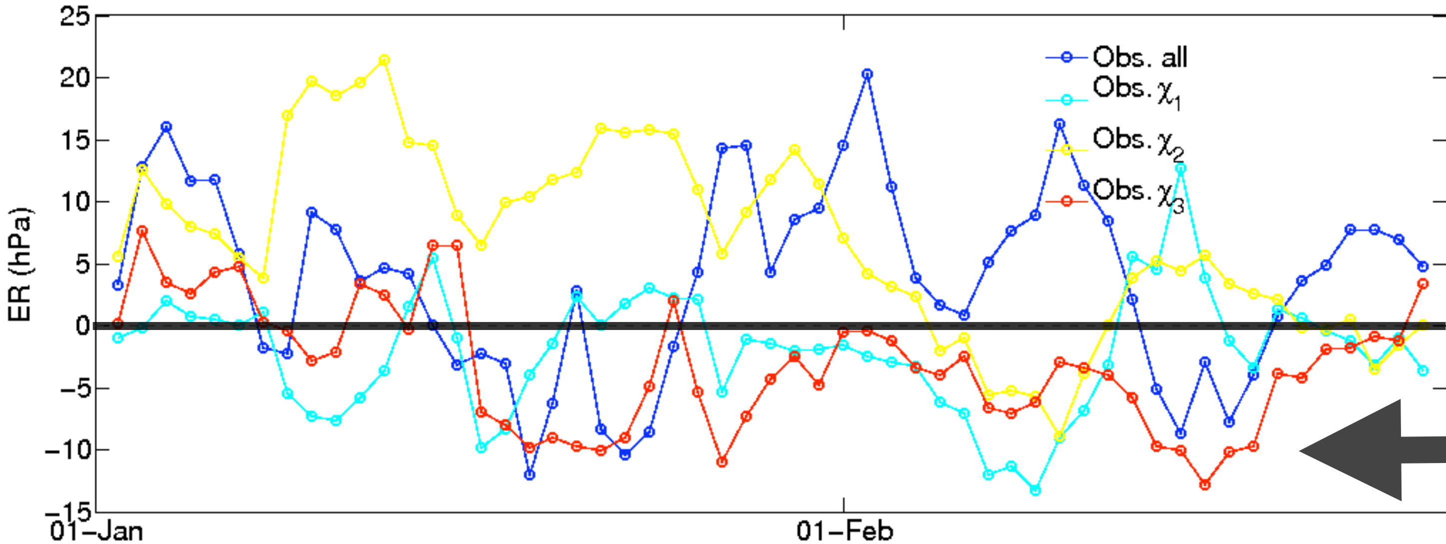
State Space: Error Reduction in Time



Improvement relative to no DA case: observing X1 and X3 yields the most improvements.

State Space: Error Reduction in Time

surface pressure



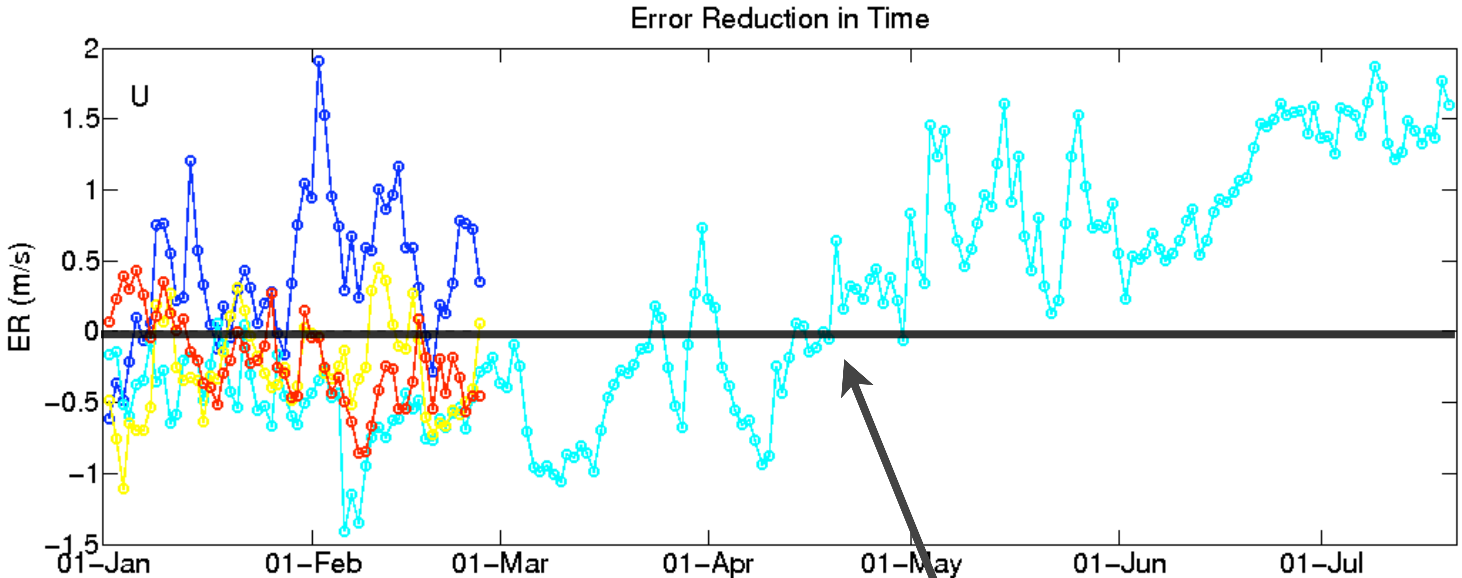
Some improvement relative to no-DA case.

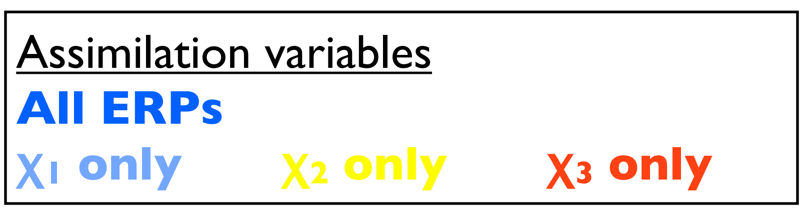
Assimilation variables

All ERPs

χ_1 only **χ_2 only** **χ_3 only**

State Space: Error Reduction in Time

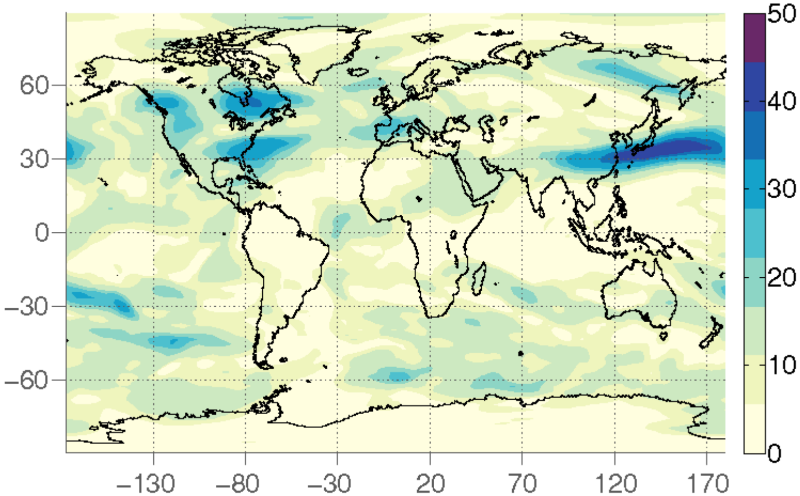




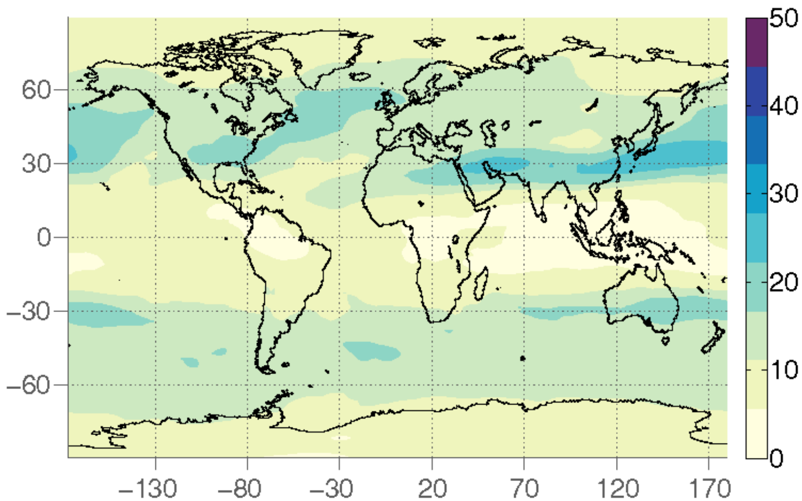
Complete filter divergence after about 4 months.

no assimilation

RMSE

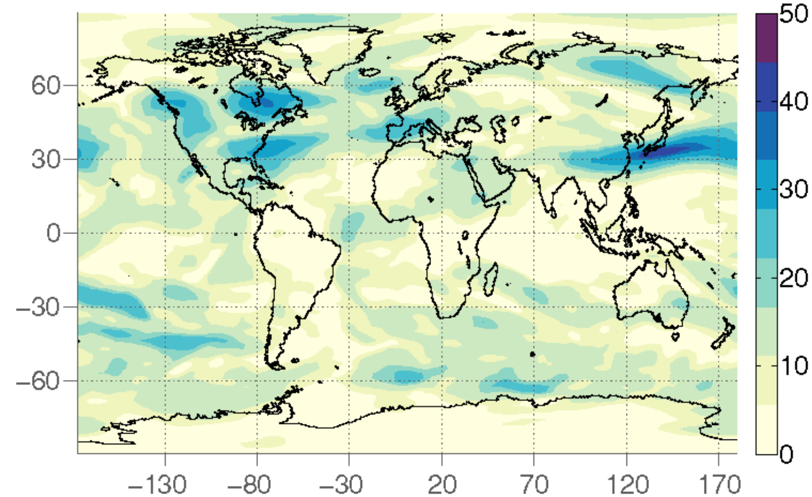


Ensemble spread

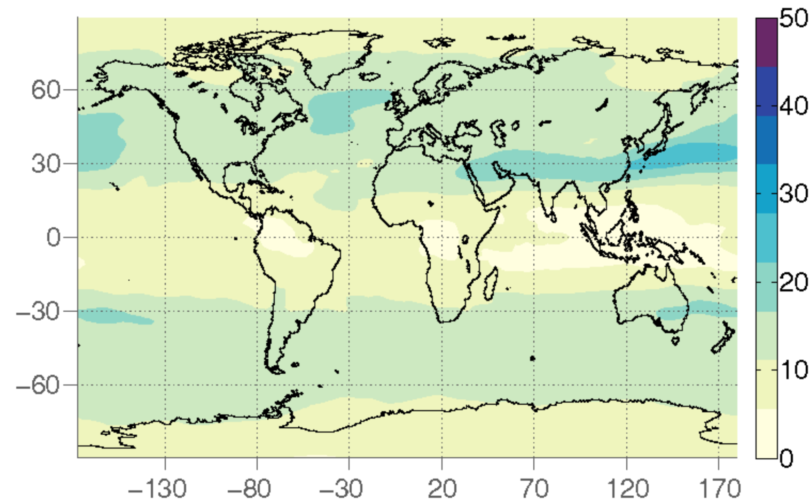


with assimilation (χ_I)

RMSE



Ensemble spread



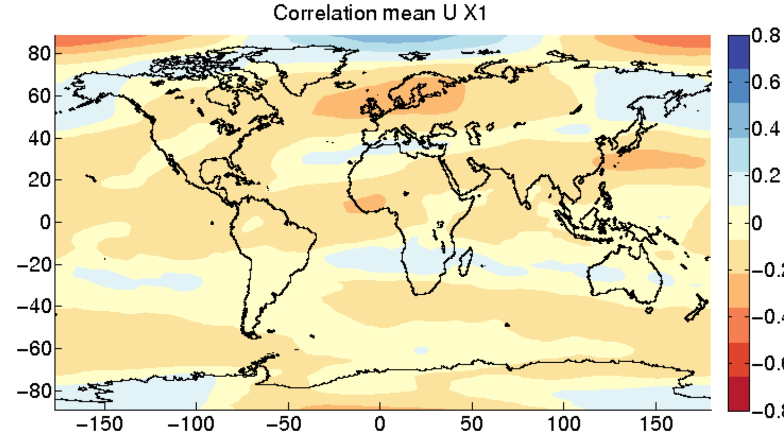
Towards localizing the Analysis Increment

Mean **ensemble correlations** between U-wind (300 hPa) and the global excitation functions.

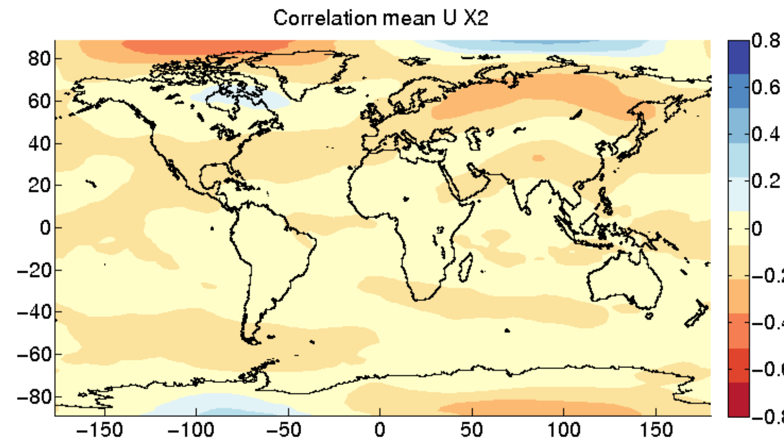
- Correlations make dynamical sense.
- Except for strange strong signal in polar regions
- But very small local correlations.

>> Localization may be difficult.

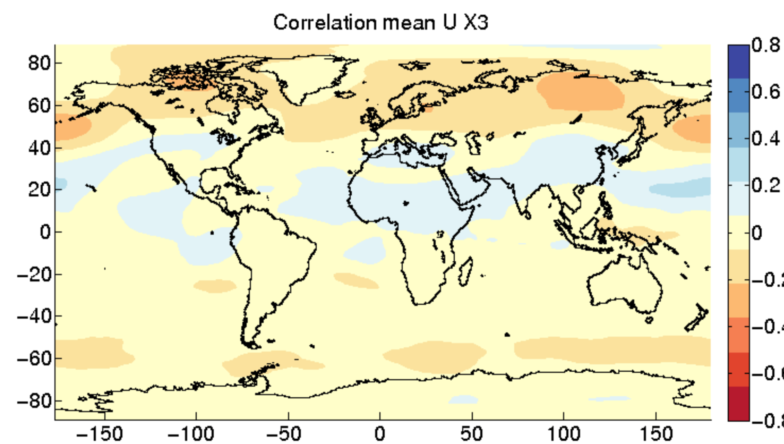
χ_1



χ_2



χ_3



Summary

- Observed Earth Rotation Parameters (ERPs) translate into atmospheric excitation functions, which are an integral constraint on the state.
- Assimilation best constrains the zonal wind field.
- Assimilating individual excitation functions generally improves things, but all three together makes the analysis worse.
- Improvement limited to ~ first 3 months of assimilation

Outlook: A New Type of Model Constraint?

- Localization: masking out regions with spurious localization.
- A better initial ensemble: constrain with uniform local observations first, then apply ERP observations.
- Can ERPs help to capture specific events, e.g. blocking?
- Once filter divergence is taken care of: application to longer timescales (6 months - years).
- Expansion to DART-CESM and DART-WACCM (2013).

References

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- **Barnes, R., et al. (1983)**, Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, Proc. Roy. Soc. London, 387, 31–73.
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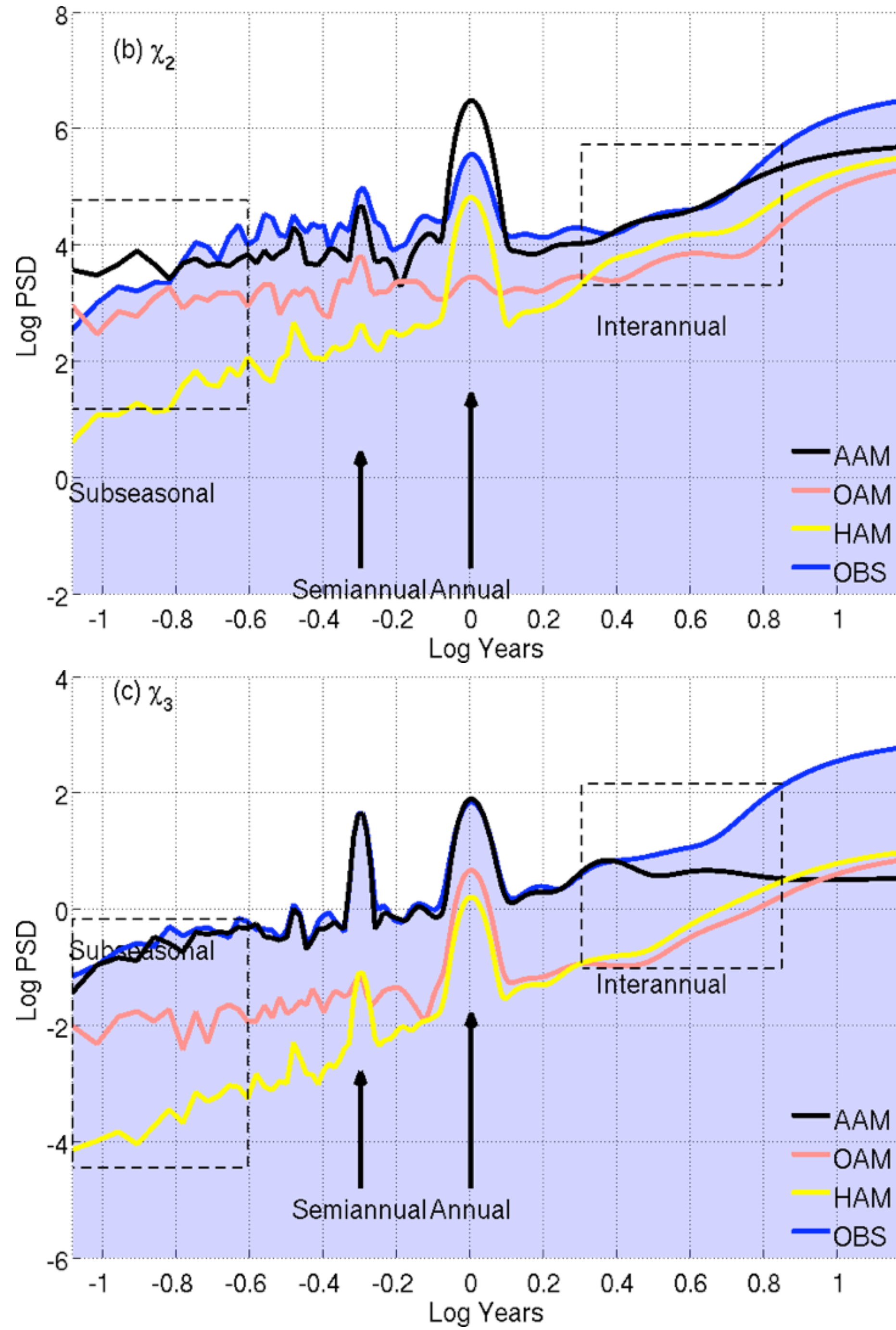
- **Marcus, S. L., et al. (2012)**, De- tection of the earth rotation response to a rapid fluctuation of Southern ocean circulation in november 2009, Geophys. Res. Lett., 39, L04,605, doi:10.1029/2011GL050671.
- **Neef and Matthes (2012)**, Comparison of Earth rotation excitation in data-constrained and unconstrained atmosphere models, J. Geophys. Res., 117, D02(107), doi: 10.1029/2011JD016555.
- **Raeder, K. et al. (2012)**, An Ensemble Data Assimilation System for CESM Atmospheric Models. J. Clim. doi:10.1175/JCLI-D-11-00395.1, in press.
- DART Website: http://www.image.ucar.edu/DAReS/DART/

Extras

Role of the Atmosphere in Excitation of AAM



Earth Angular Momentum

$$H_i(t) = I_{ij}(t)\omega_j(t) + h_j(t)$$

moment of inertia:
Depends on distribution of
mass around the Earth

relative angular
momentum:
Movements relative to the
the rotation vector ω

$$\frac{\mathrm{d}\vec{H}(t)}{\mathrm{d}t} = \vec{\tau} \Rightarrow \boxed{\mathrm{d}(I_{ij}\omega_j + h_i)/\mathrm{d}t + \epsilon_{ijk}\omega_j(I_{kl}\omega_l + h_k) = \tau_i}$$

Liouville equation

➡ If net external torques are zero, changes in relative AM and mass distribution are evened out by changes in the rotation vector.

Changes in Earth Angular Momentum

$$\mathrm{d}(I_{ij}\omega_j + h_i)/\mathrm{dt} + \epsilon_{ijk}\omega_j(I_{kl}\omega_l + h_k) = \tau_i$$

* Now assume very small perturbations in the MOI and relative AM (in each vector component!)

$$I_{ij}(t) = \begin{pmatrix} A & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & C \end{pmatrix} + \Delta I_{ij}(t) \qquad \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = \begin{pmatrix} m_1 \\ m_2 \\ 1 + m_3 \end{pmatrix} \Omega$$

$$\Rightarrow \begin{aligned} \dot{m}_1/\sigma_c + m_2 &= \chi_2 - \dot{\chi}_1/\Omega \\ \dot{m}_2/\sigma_c - m_1 &= -\chi_1 - \dot{\chi}_2/\Omega \\ \dot{m}_3 &= -\dot{\chi}_3 \end{aligned}$$

Excitation functions χ_i: nondimensionalized angular momentum exchange with Earth`s fluid shell

Barnes et al. (1983)

Atmospheric Angular Momentum

$$
\begin{aligned}
p_1 + \frac{\dot{p_2}}{\sigma_0} &= \chi_1 \\
-p_2 + \frac{\dot{p_2}}{\sigma_0} &= \chi_2 \\
\frac{\Delta \mathrm{LOD}}{\mathrm{LOD}_0} &= \Delta\chi_3
\end{aligned}
$$

$$
\begin{aligned}
\chi_1(t) &= \frac{1.608}{\Omega\,(C - A')}\left[0.684\Omega\Delta I_{13}(t) + \Delta\mathbf{h}(t)\right] \\
\chi_2(t) &= \frac{1.608}{\Omega\,(C - A')}\left[0.684\Omega\Delta\mathbf{I}_{23}(t) + \Delta\mathbf{h}(t)\right] \\
\chi_3(t) &= \frac{0.997}{\Omega C_m}\left[0.750\Omega\Delta I_{33}(t) + \Delta h_{33}(t)\right]
\end{aligned}
$$

Mass terms (moment of inertia)

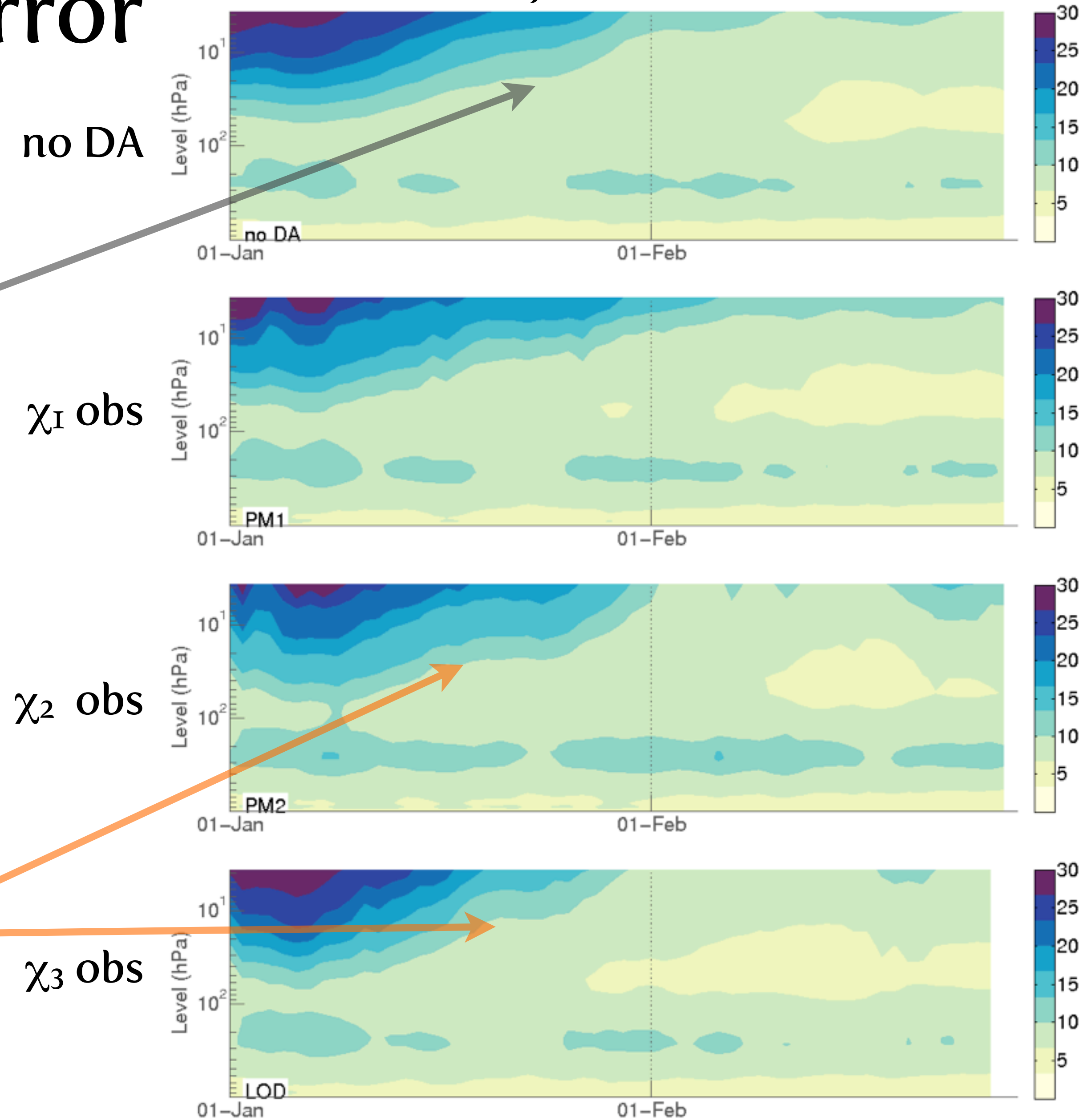
$$
\begin{aligned}
I_{13} &= -\int R^2 \cos\phi \sin\phi \cos\lambda dM \\
I_{23} &= -\int R^2 \cos\phi \sin\phi \sin\lambda dM \\
I_{33} &= \int R^2 \cos^2\phi dM
\end{aligned}
$$

Motion terms (AM relative to Earth)

$$
\begin{aligned}
h_1 &= -\int R\left[u \sin\phi \cos\lambda - v \sin\lambda\right] dM \\
h_2 &= -\int R\left[u \sin\phi \sin\lambda + v \cos\lambda\right] dM \\
h_3 &= \int R u \cos\phi dM
\end{aligned}
$$

State Space Error

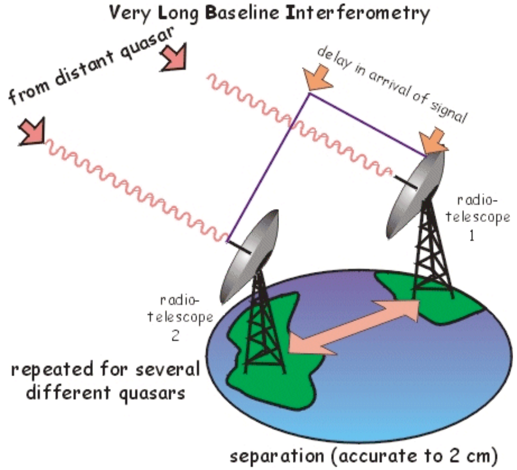
RMSE of u-wind at 300 hPa



Upper level damping in CAM gets rid of initial ensemble spread.

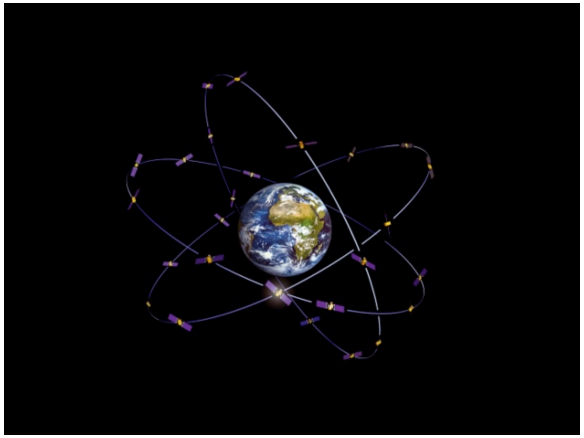
Initial ensemble bias in the stratosphere reduced faster with obs of χ_2 and χ_3 (!?)

Earth Rotation Measurements



Very Long Baseline Interferometry (VLBI)

Satellite & Lunar Laser Ranging (SLR, LLR)

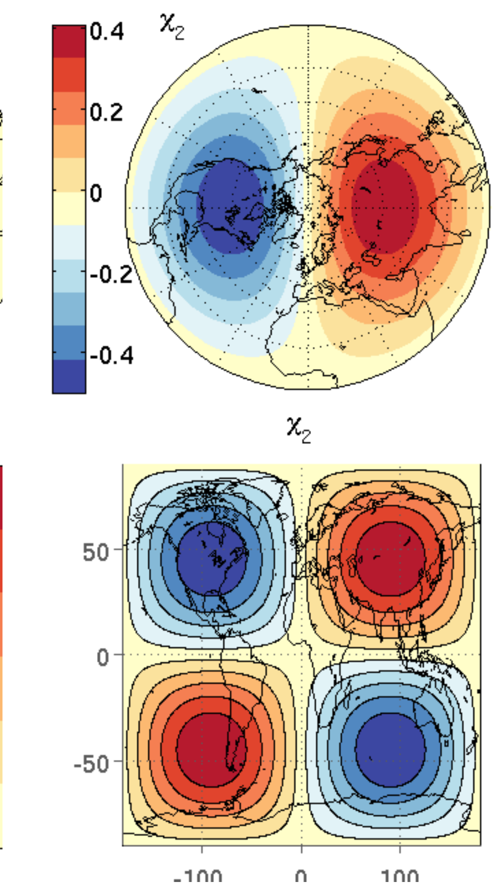


Global Positioning System (GPS)

Two angles of Polar Motion
p_1, p_2

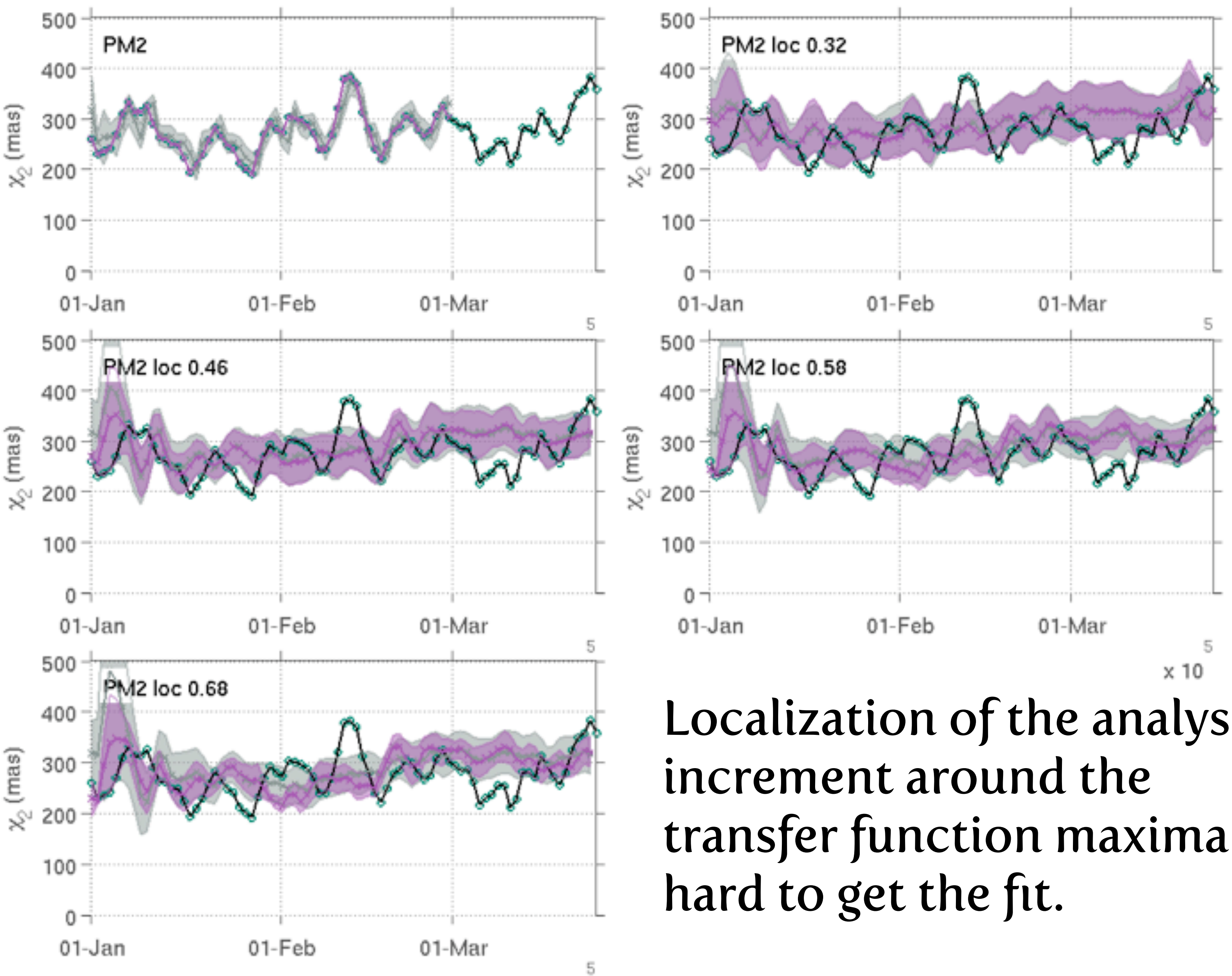
Length-of-day anomalies
LOD

Localization of the analysis increment around the transfer function maxima



<u>Idea:</u>
Observing only X2, localize the increment where the integral most strongly weights zonal wind.

$$\chi_2^{\mathrm{W}} = \frac{-1.43R^3}{\Omega(C-A)g}\int\int\int(\boxed{u\sin\phi\cos\phi\sin\lambda} + v\cos\phi\cos\lambda)\mathrm{d}\lambda\mathrm{d}\phi\mathrm{d}p$$



Localization of the analysis increment around the transfer function maxima: it's hard to get the fit.