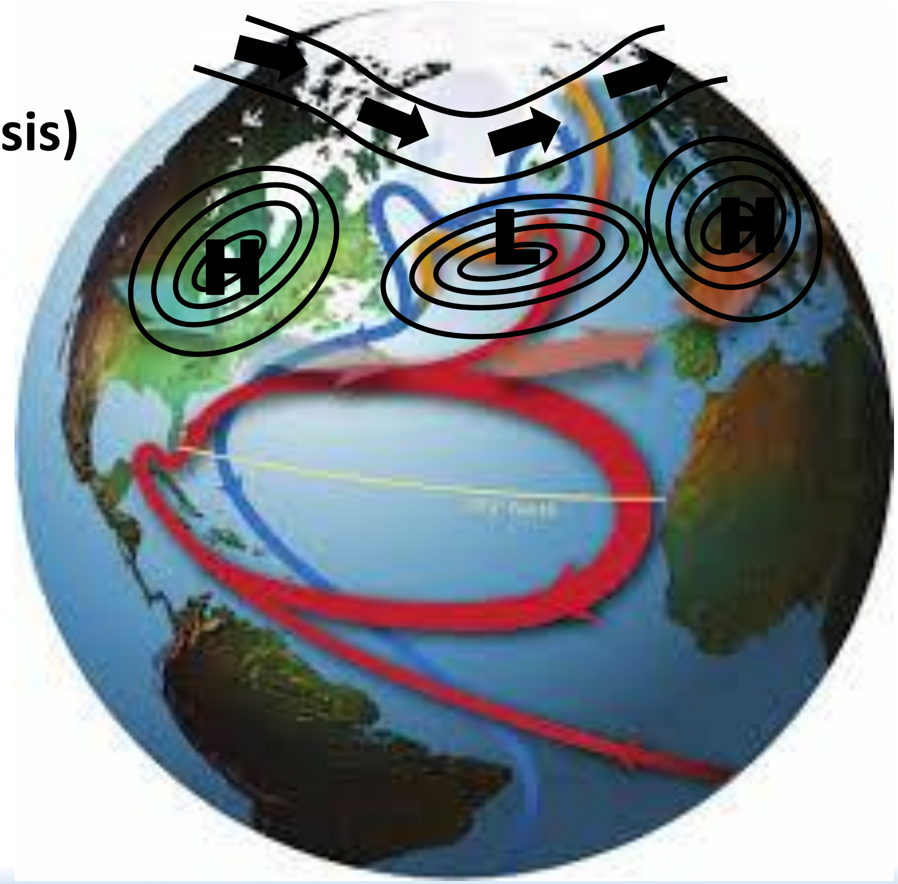
Multiple timescale coupled atmosphere-ocean data assimilation

(for climate prediction & reanalysis)



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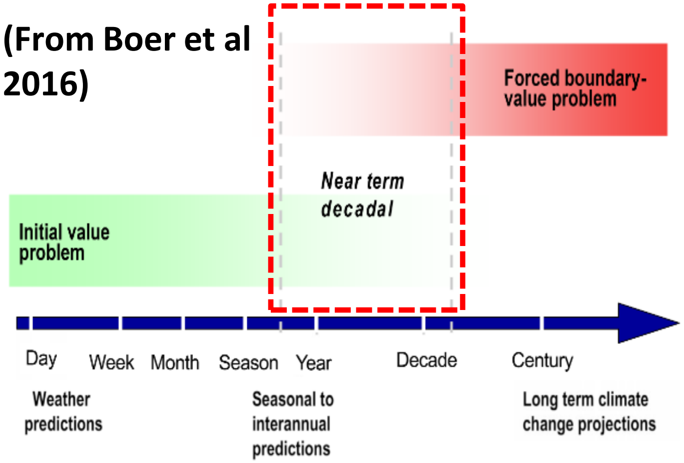
Motivation

Context: climate forecasting & reanalysis

- **Interannual to decadal** : **External forcing** & **initial conditions** important (Meehl et al. 2009, Hawkins & Sutton 2009)
- **Uninitialized** hindcasts: skill limited to **externally forced** variability over **continental & larger scales** (Sakaguchi et al. 2012)

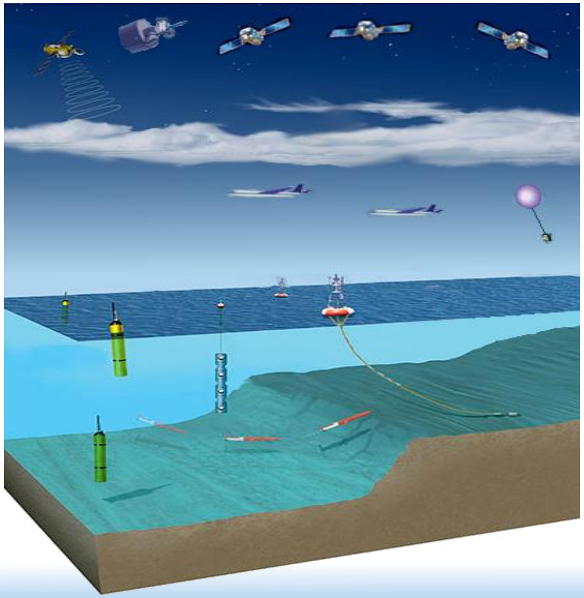
(From Boer et al 2016)



- **Coupled** system: **fast** atmosphere & **slow** (**deep**) ocean

Still unclear how to best initialize the coupled system (Meehl et al. 2014)

- **Slow** has the **memory** (source of predictability) but much **fewer observations** than **fast**



- Requires **coherent** analyses of **fast** & **slow** components

Strongly (& multiscale) coupled DA?

Challenges / overarching questions

- **Coherence** between initial conditions of **slow** & **fast** relies on **"cross-media" error covariances**
  - **Q1: What do these look like? How to reliably estimate?**
    Fast component is "noisy" (i.e. high-frequencies)…
- **Coupled system with wide variety of scales**
  - **Q2: Any benefits of multi-timescale DA?**
- **Slow** has the **memory** but **fewer observations** than in **fast**
  - **Q3: What role atmospheric obs. in initializing fast & slow components of a poorly observed ocean? … a one-way coupling perspective**

Approach

How to efficiently test ideas, prototype & evaluate strategies?

- **Complex Earth system models problematic for such basic research**
  - Extremely expensive, especially for ensemble DA
    (small ensembles & limited experimentation, realizations, etc.)

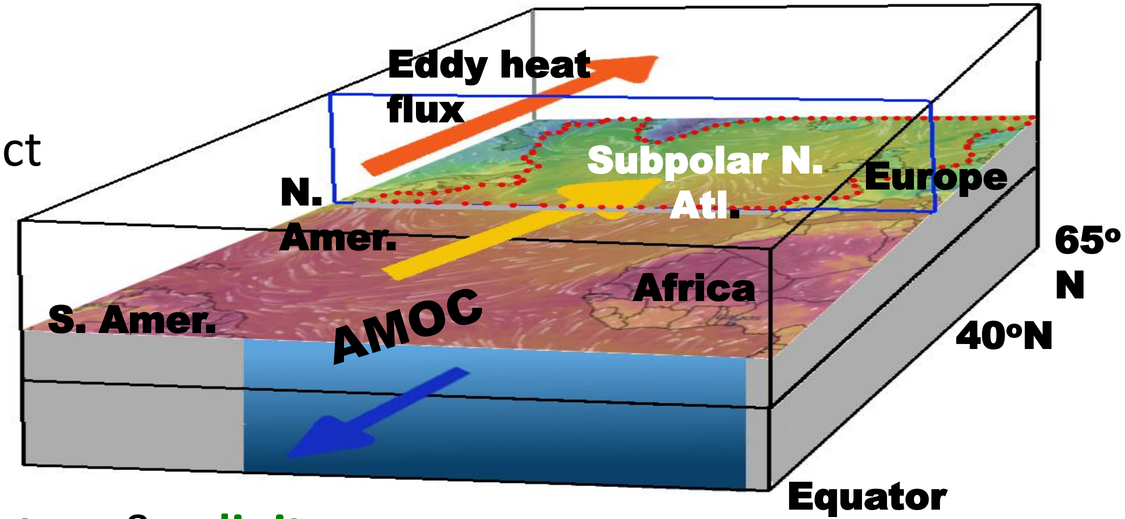
- **Motivates using simplified approach**:
  - **Low-order analog** of the coupled N. Atlantic climate system
    -> **few state variables**: obtained from comprehensive AOGCM output
  - **Offline** (i.e. “no cycling”) ensemble DA
    -> prior ensemble members drawn from states of long climate simulations
    -> same prior used at every analysis times
    :: uninformed prior (other than climatology of the model)

Cheap: Allows extensive numerical experimentation

Low-order analogue of N. Atlantic coupled system

[Inspired by Roebber (1995) & used in Tardif et al (2014, 2015)]

- **State variables**:
  - **Atmosphere**:
    - **- MSLP** along 40°N transect (“NAO” winds -> gyre)
    - **- Meridional eddy heat flux** across 40°N
  - **Ocean**:
    - **- subpolar upper temperature** & **salinity**
    - **- AMOC index** (max. overturning streamfunction in N. Atlantic) **[taken as *unobserved!*]**



- Data derived by **coarse-graining** of **state-of-the-art AOGCM** gridded output

  -> Simplified system but w/ **complex underlying (fast/slow) dynamics**

- **Monthly** data for above variables as basis for DA experimentation

  -> truth, observations (truth + random noise) & prior

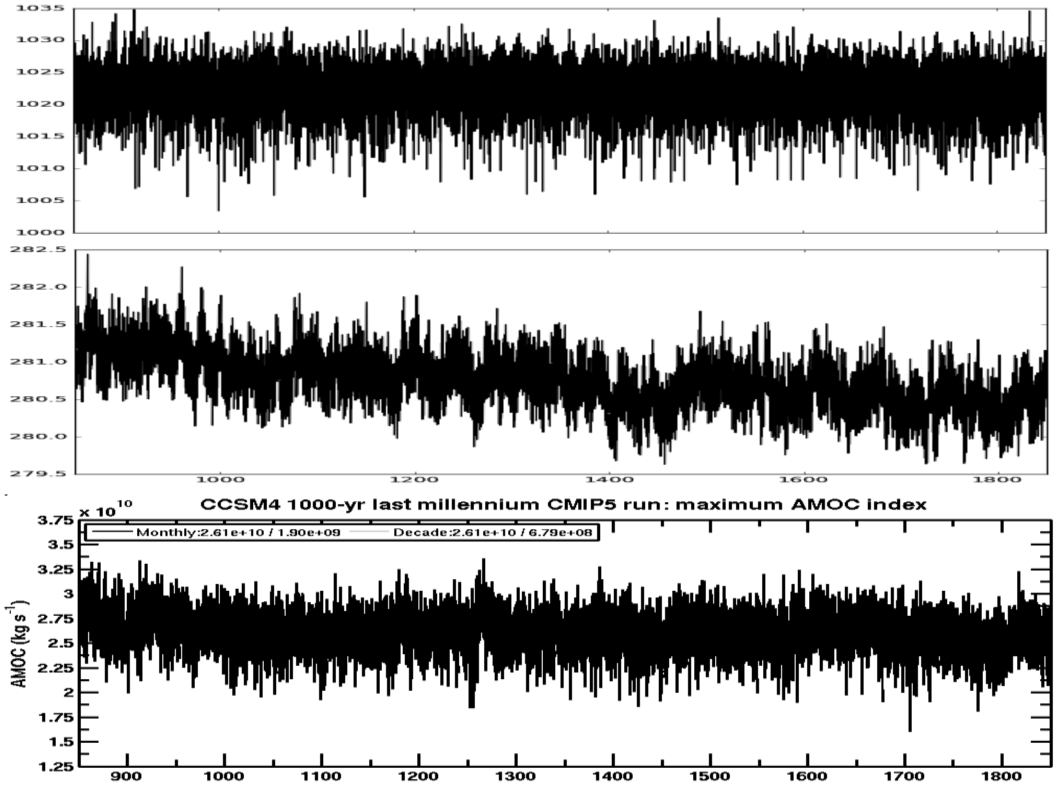
Low-order analogue of N. Atlantic coupled system

- Analogue data derived from:
  - Community Climate System Model version 4 (**CCSM4**) gridded output from CMIP5 archives
  - 1000-yr "**Last Millennium**" simulation (pre-industrial natural variability)

Atmosphere: 40°N MSLP

Ocean: Subpolar upper temperature

Ocean: Overturning circulation (AMOC index)



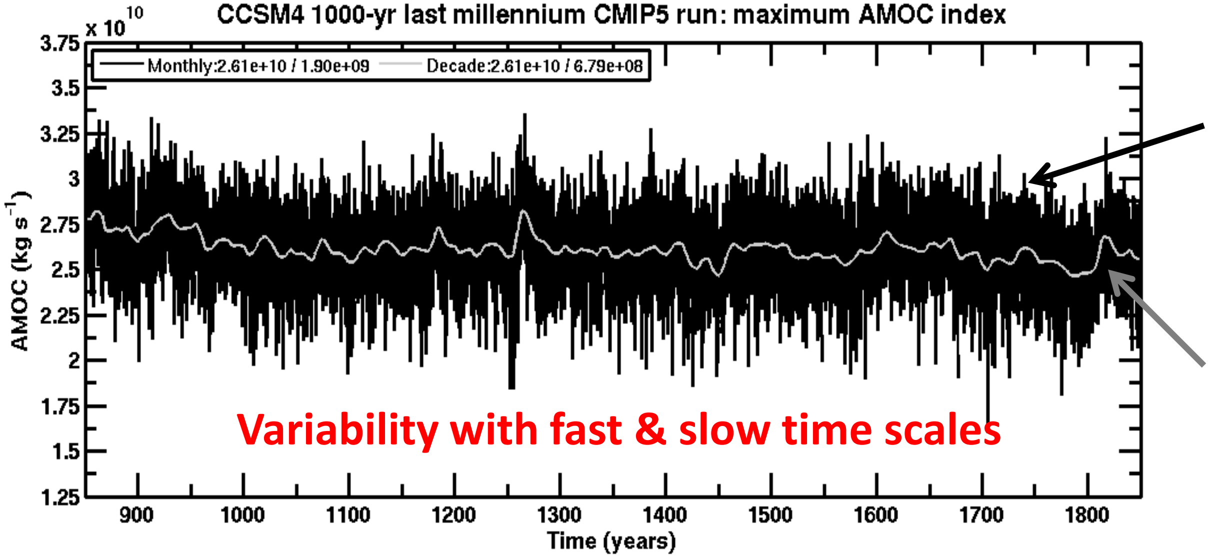
CCSM4 1000-yr last millennium CMIP5 run: maximum AMOC index

850 **Time (years)** **1850**

Low-order analogue of N. Atlantic coupled system

AMOC index

(Max. value of overturning streamfunction in N. Atlantic)



monthly

Variability with fast & slow time scales

10-yr running mean

***** How much of this *unobserved* component of the coupled system can we recover using coupled multiple timescale DA? *****

(by assimilating obs from other components of the low-order analogue)

(Strongly) Coupled atmosphere-ocean DA

Ensemble Kalman filter:

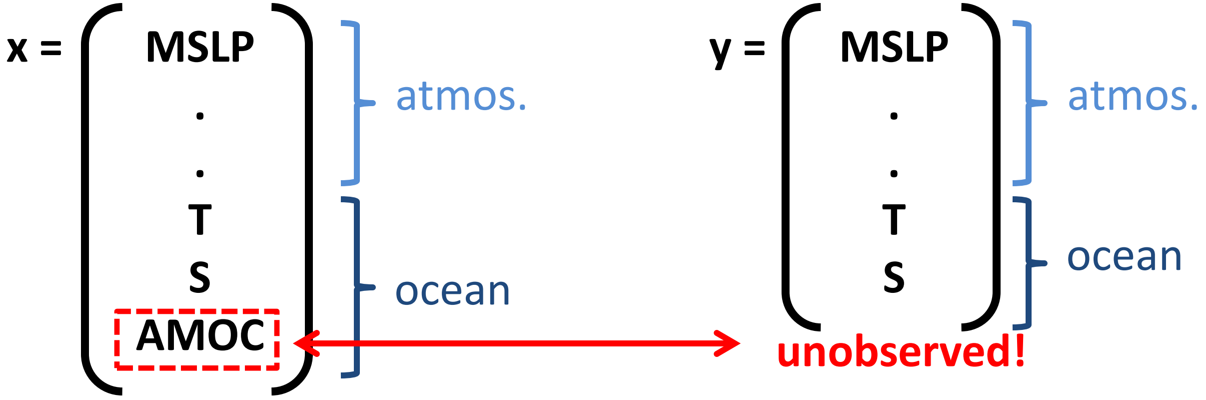
$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x}_b)$$

analysis

background

obs.

$\mathbf{y}_e$: model estimate of obs.



Coupled atmosphere-ocean DA

- **Ensemble DA & cross-media update**
  - **Assimilation of atmospheric obs. updating the ocean …**

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}(\mathbf{y} - \overbrace{\mathbf{H}\mathbf{x}_b}^{\mathbf{y}_e})$$

Cross-media covariances:

$\mathbf{y}^e$: obs. of fast -> **noisy**

$\mathbf{x}$: state vector, including **slow** variables

$$\mathbf{B}\mathbf{H}^T = cov(\mathbf{x}, \mathbf{y}_e)$$

Fast noise contaminates K

Consider assimilation of **time-averaged obs.**

=> Averaging over the noise -> increase cov. w/ slow component

=> Increase “observability” -> reduce obs. error variance (R) ~1/sqrt(N)

[Tardif et al. 2014, 2015; Lu et al. 2015]

Time-average DA

- **Assimilation of time-averaged observations**

[State vector]

$$\mathbf{x} = \overline{\mathbf{x}} + \mathbf{x}'$$

[Observations]

$$\mathbf{y} = \overline{\mathbf{y}} + \mathbf{y}'$$

Time averaging & Kalman-filter-update operators linear and commute

Time-mean: $\overline{\mathbf{x}}_a = \overline{\mathbf{x}}_b + \mathbf{K}_A(\overline{\mathbf{y}} - \overbrace{\mathbf{H}\overline{\mathbf{x}}_b}^{\mathbf{y}^e})$ $\mathbf{K}_A = \overline{\mathbf{x}}_b \mathbf{y}_e^T [\mathbf{y}_e \mathbf{y}_e^T + \mathbf{R}]^{-1}$

Deviations: $\mathbf{x}'_a = \mathbf{x}'_b + \mathbf{K}_P(\overline{\mathbf{y}} - \mathbf{H}\overline{\mathbf{x}}_b)$ $\mathbf{K}_P = \mathbf{x}'_b \mathbf{y}_e^T [\mathbf{y}_e \mathbf{y}_e^T + \mathbf{R}]^{-1}$

$\boxed{\mathbf{x}'_b \mathbf{y}_e^T \approx 0} \rightarrow \mathbf{x}'_a = \mathbf{x}'_b$ **just update time-mean**

Full state: $\mathbf{x}_a = \overline{\mathbf{x}}_a + \mathbf{x}'_b$

(Dirren & Hakim 2005; Huntley & Hakim 2010)

Multiple timescale DA

- **Assimilate obs. at “appropriate” time scale**

$$\mathrm{x}_b = \overline{\mathrm{x}}_b^{\tau 1} + \mathrm{x}'_b$$

Decompose at scale $\underline{\tau_1}$

$$\overline{\mathrm{x}}_a^{\tau 1} = \overline{\mathrm{x}}_b^{\tau 1} + \mathrm{K}_A(\underline{\overline{\mathrm{y}}_1^{\tau 1}} - \mathrm{H}\overline{\mathrm{x}}_b^{\tau 1})$$

Do update

$$\mathrm{x}_a = \overline{\mathrm{x}}_a^{\tau 1} + \mathrm{x}'_b$$

Recover full state

$$\mathrm{x}_b = \overline{\mathrm{x}}_b^{\tau 2} + \mathrm{x}'_b$$

Decompose at scale $\underline{\tau_2}$

$$\overline{\mathrm{x}}_a^{\tau 2} = \overline{\mathrm{x}}_b^{\tau 2} + \mathrm{K}_A(\underline{\overline{\mathrm{y}}_2^{\tau 2}} - \mathrm{H}\overline{\mathrm{x}}_b^{\tau 2})$$

Do update

$$\mathrm{x}_a = \overline{\mathrm{x}}_a^{\tau 2} + \mathrm{x}'_b$$

Recover full state

If at last step (i.e. y_2 shares same time scale as x_b : x'_b = 0

↓

End product is final analysis at time scale τ_2

CDA experiments

- **Ensemble square root filter** (Whitaker & Hamill 2002)
- Serial obs. processing
- Low-order system -> no localization
- Offline/no cycling -> no inflation
- "Reanalysis mode" -> all obs. available a-priori

simplifications

- **Perfect model experiments**, i.e. same model for truth & observations

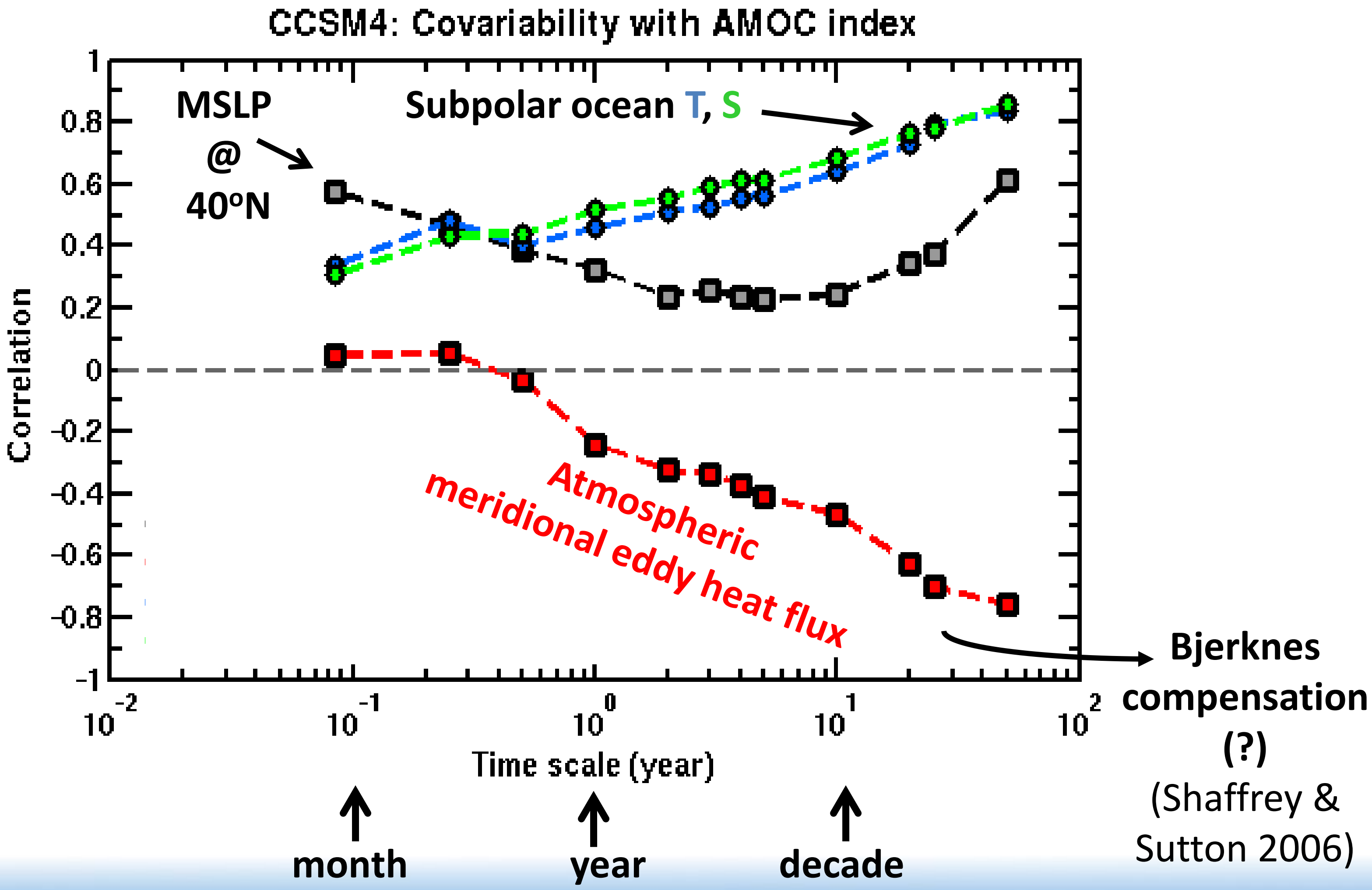
  -> obs.: random noise added (10% of climatological variance)
- Frequency of obs.: **monthly**

- Generate AMOC analyses over 1000 years
- Run DA experiment w/ **various obs. availability scenarios**

  (atmosphere vs. ocean)
- Consider **2 time scales**: a **slow** (τ_1) and a **fast** (τ_2 = monthly)

Assimilated obs. vs. time scales

- Covariability w/ **AMOC index** vs **averaging time scale**

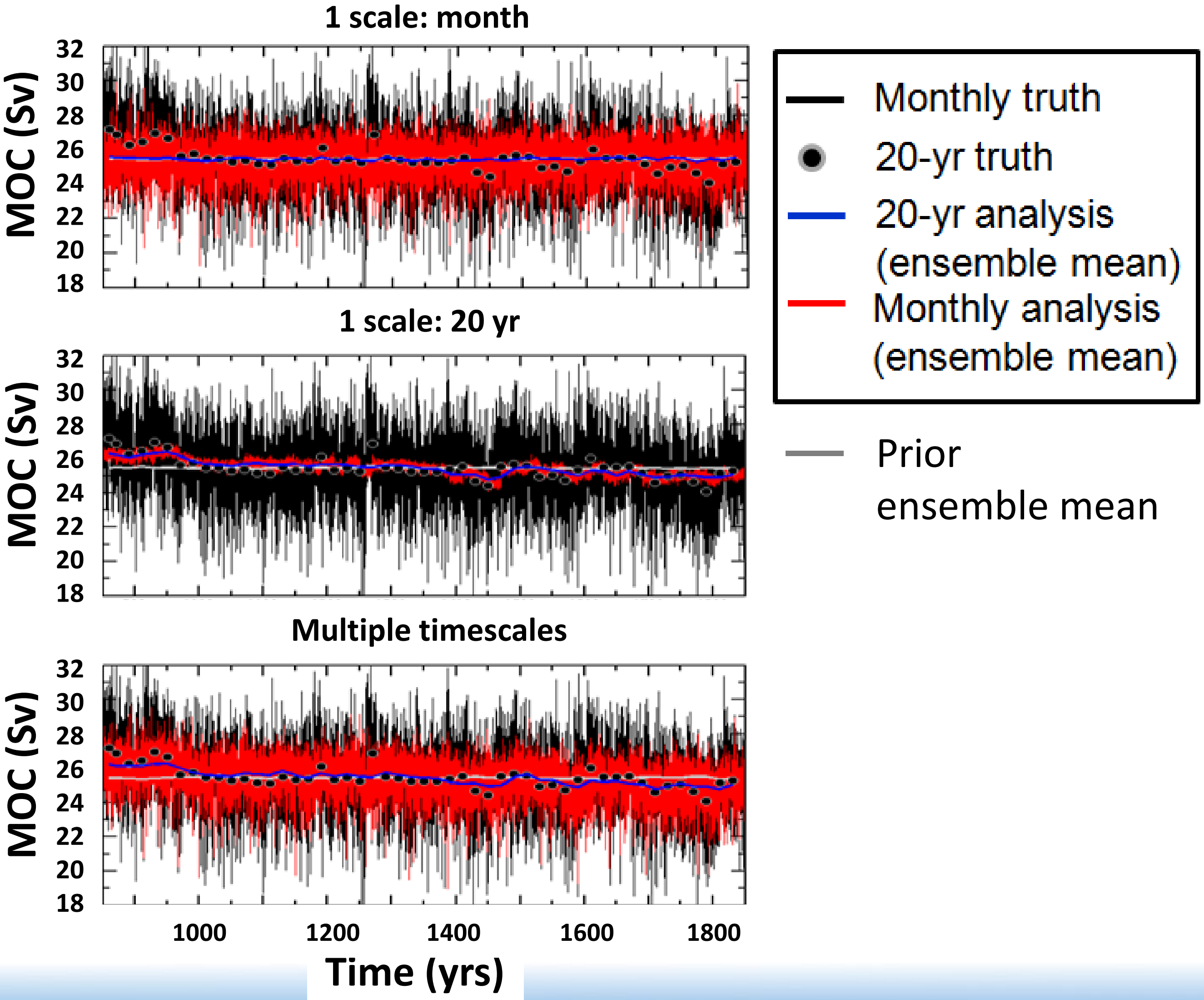


(Shaffrey & Sutton 2006)

Single vs. multiple timescale DA

Coupled DA of MSLP (atmosphere) and upper subpolar ocean T, S

Ensemble mean AMOC analyses



2 time scales:

τ_1 = 20 yrs

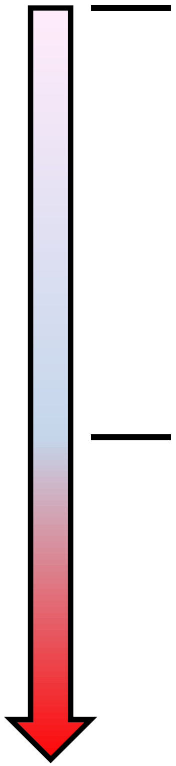
τ_2 = monthly

Verification metric

Coefficient of efficiency

(Nash and Sutcliffe 1970)

$$CE = 1 - \frac{\sum_{i=1}^{N}\left(\overset{\text{truth}}{\overset{\swarrow}{x_i}} - \overset{\text{analysis}}{\overset{\swarrow}{x_i^a}}\right)^2}{\sum_{i=1}^{N}\left(\underset{\text{truth}}{\underset{\uparrow}{x_i}} - \underset{\text{truth mean}}{\underset{\uparrow}{\bar{x}}}\right)^2}$$



1 **CE ≈ 1:**
analysis error variance
<<
climo. variance

0 **CE = 0:**
no information
over climatology

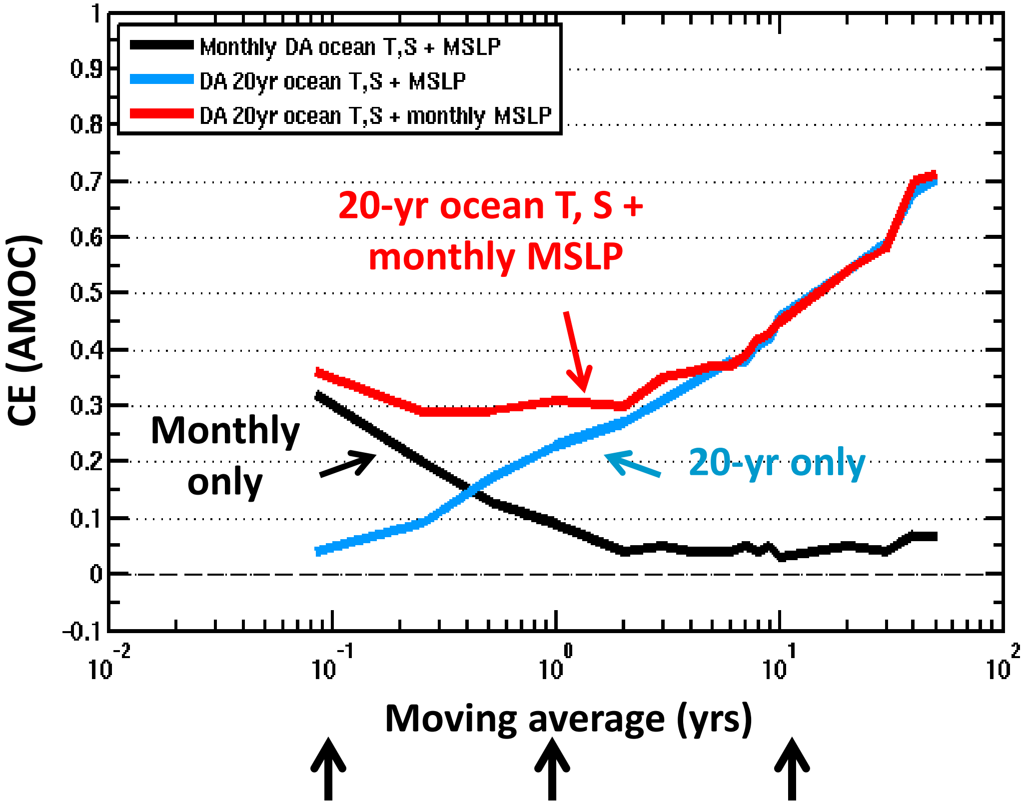
< 0 **CE < 0:**
Really bad!
(…bias)

Single vs. multiple timescale DA

Verification vs. time scales

(calculated with analyses covering full 1000 yrs)

CE for ensemble mean AMOC analyses



month **year** **decade**

2 time scales:

τ_1 = 20 yrs

τ_2 = monthly

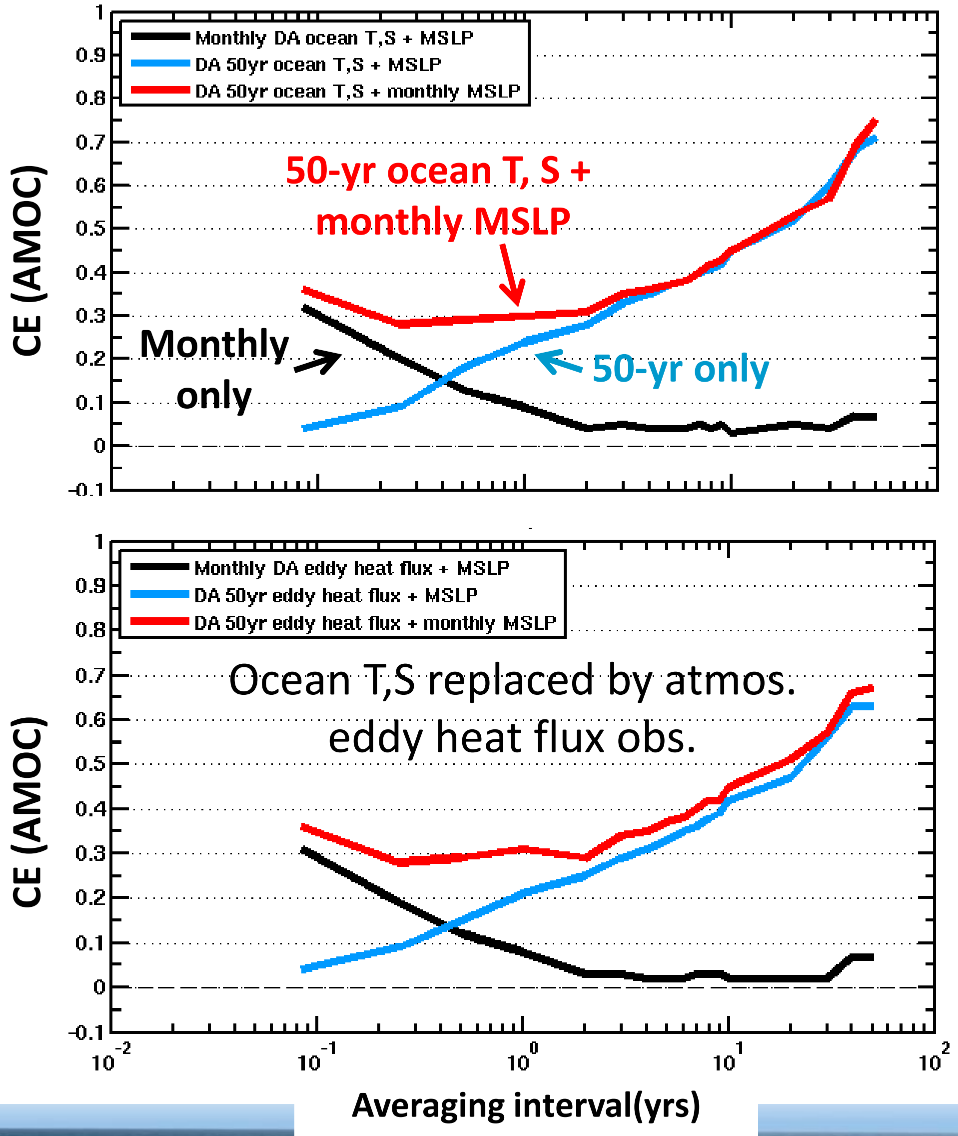
Multi-time scale DA: ocean vs. atmosphere-only

2 time scales:

$$\begin{cases} \tau_1 = 50 \text{ yrs} \\ \tau_2 = 1 \text{ month} \end{cases}$$

- ▬ monthly only
- ▬ 50-yr only
- ▬ 50-yr ocean T,S or atmospheric meridional eddy heat flux + monthly MSLP

CE for ensemble mean AMOC analyses



50-yr ocean T, S + monthly MSLP

Monthly only

50-yr only

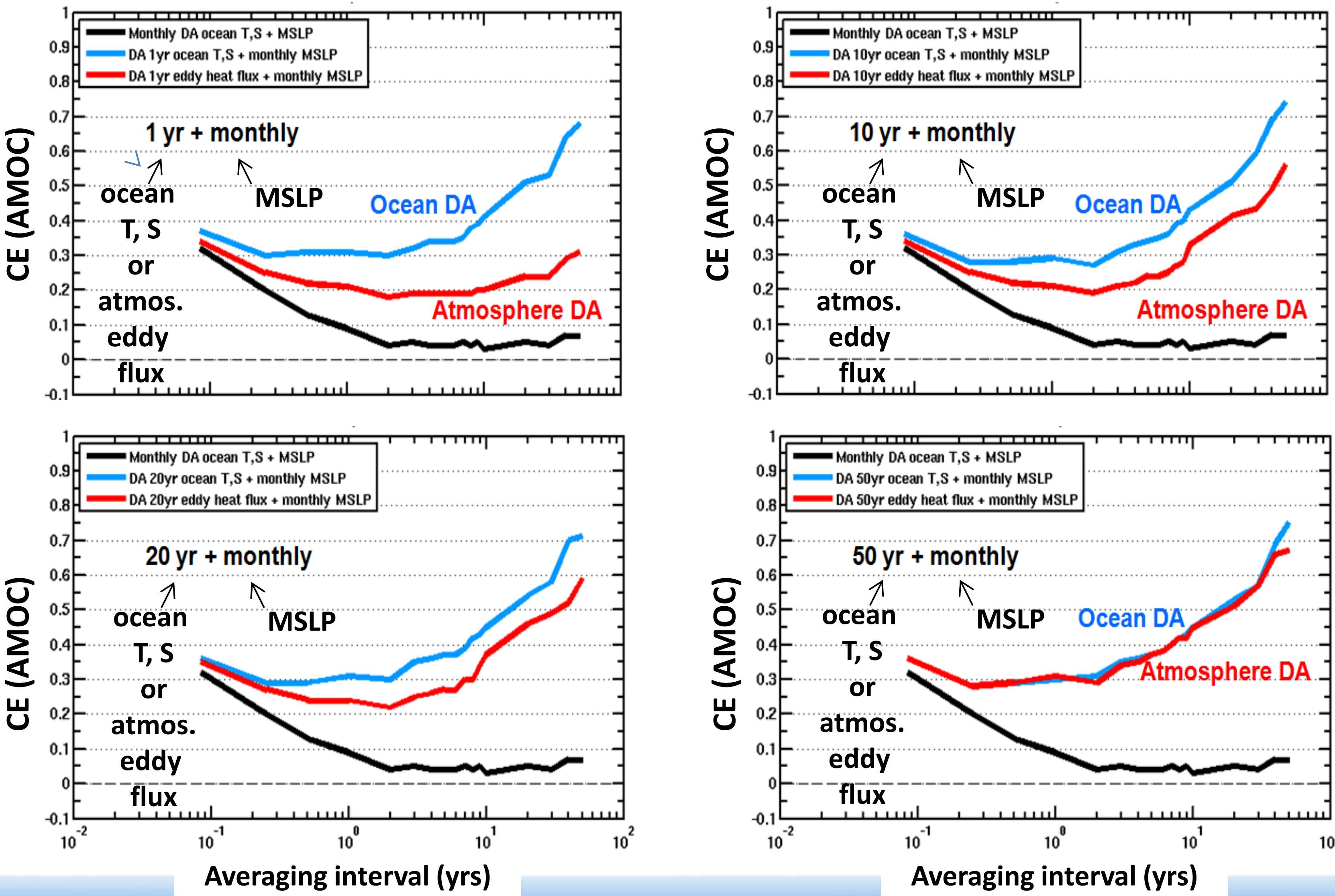
Ocean T,S replaced by atmos. eddy heat flux obs.

w/ ocean DA

Atmosphere -only DA

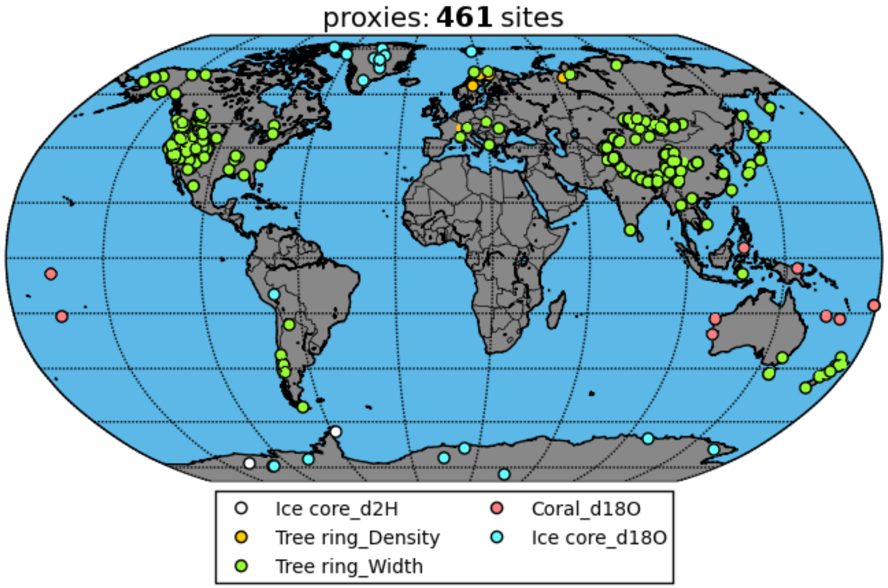
Multi-time scale DA: ocean vs. atmosphere-only

Atmosphere-only DA: vs. long time scale

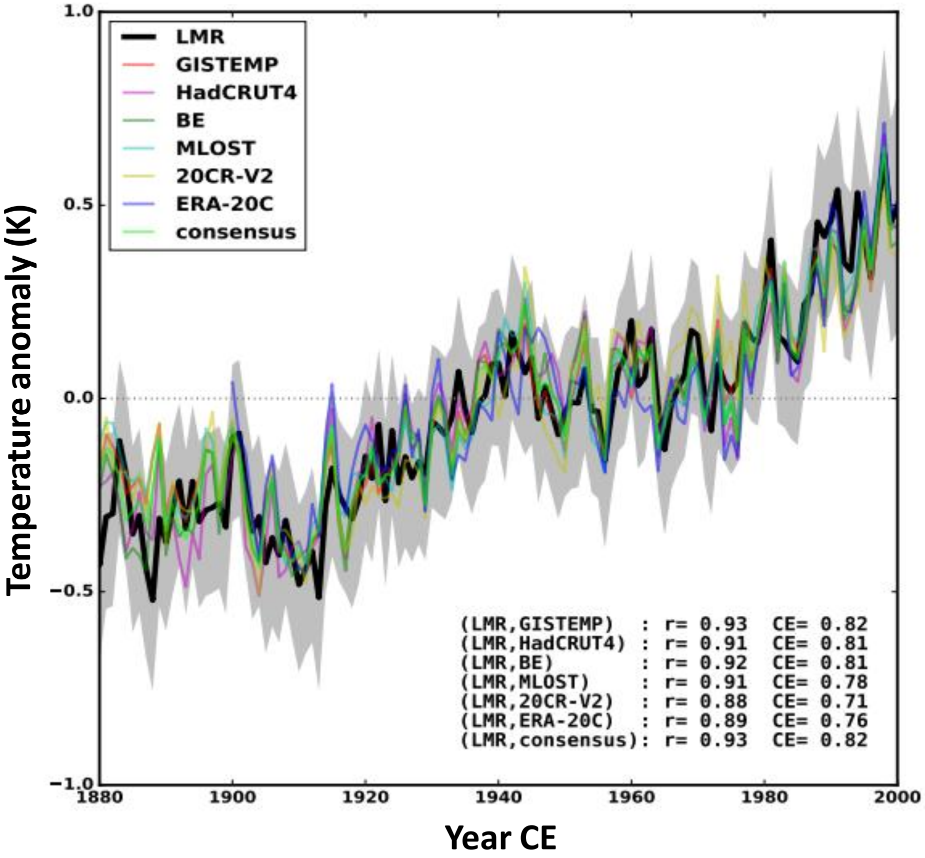


Toward application to real data…

- **Last Millennium Reanalysis (LMR)**
  - **Offline assimilation of paleoclimate data**
    - **Tree rings**
    - **Ice core & coral isotope ratios**
  - **Prior : CCSM4 "Last Millennium"**



LMR: reconstructed global mean temperature



Hakim, G. J., J. Emile-Geay, E. J. Steig, D. Noone, D. M. Anderson, R. Tardif, N. Steiger, and W. A. Perkins (2016), The last millennium climate reanalysis project: Framework and first results, J. Geophys. Res. Atmos.

Takeaways …

- **Q1:** Cross-media covariances, how to reliably estimate?

  A: Use **time-averaging** over **appropriate scale**

  - Averaging over “noise” in fast atmosphere = > enhances covariability w/ slow ocean

- **Q2**: Benefits from multiple timescale DA approach?

  A: Yes!

  - More accurate analyses of **fast & slow**
  - **Reduced errors** at **intermediate** (~annual) **scales** from DA of monthly & decadal.-avg. obs.

- **Q3**: What role atmospheric obs. in initializing ocean’s fast & slow components ?

  A: Can be **significant:**

  - Frequent DA for **fast ocean** component: Fast response to **winds, surface fluxes etc.**
  - **Less significant** role for constraining **slow**, if **ocean** *sufficiently* **well-observed**
  - **Fully coupled DA** of **time-averaged obs**. **important** when **poorly observed ocean** (w/ appropriate choice of assimilated obs.)