



Prospects for Decadal Predictions Models

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Background

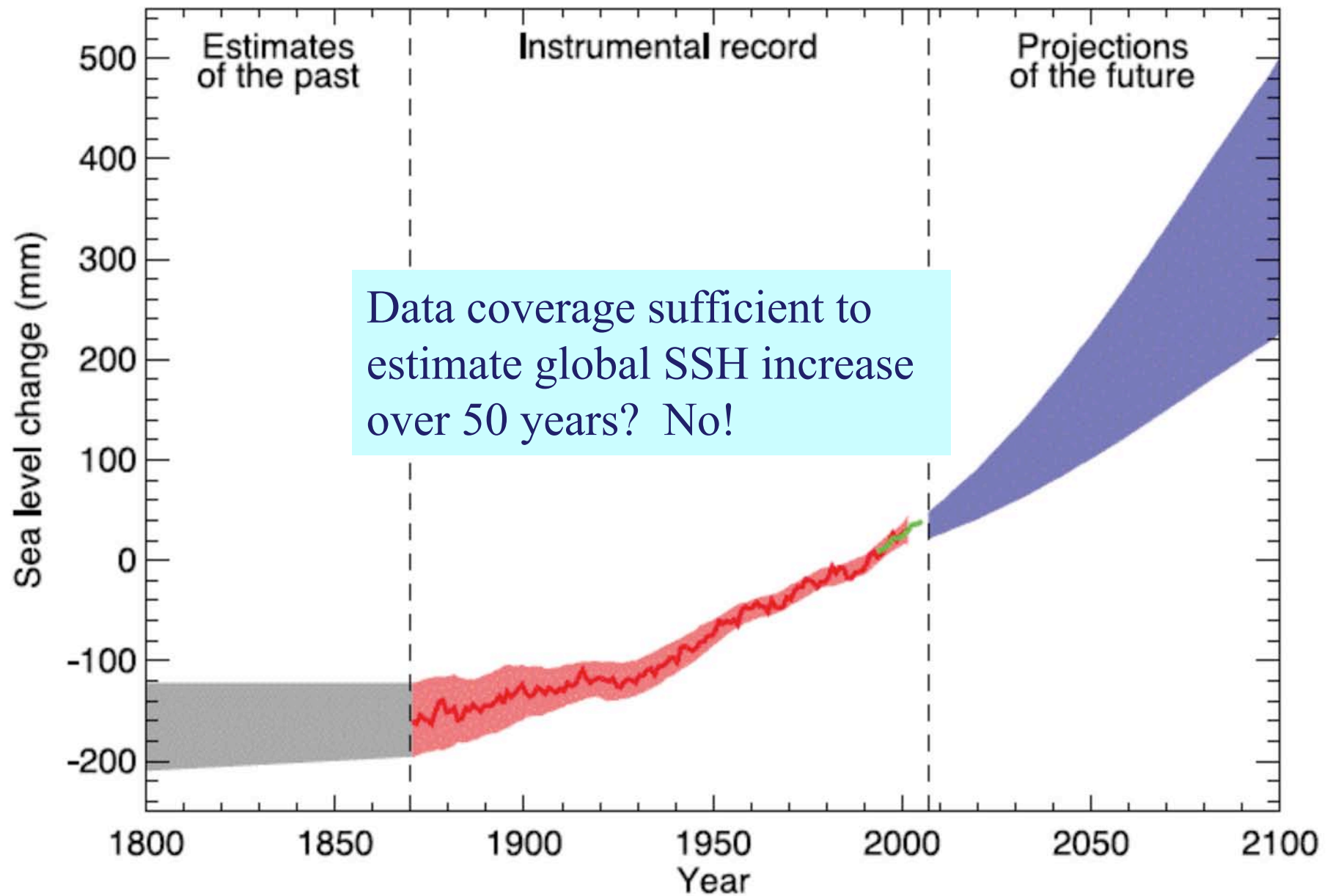
- Decadal predictions are politically requested (almost) more than long-term scenario runs.
- They will be part of the next AR, but they will be realized anyway on national level (e.g., CSC in Germany).

Background

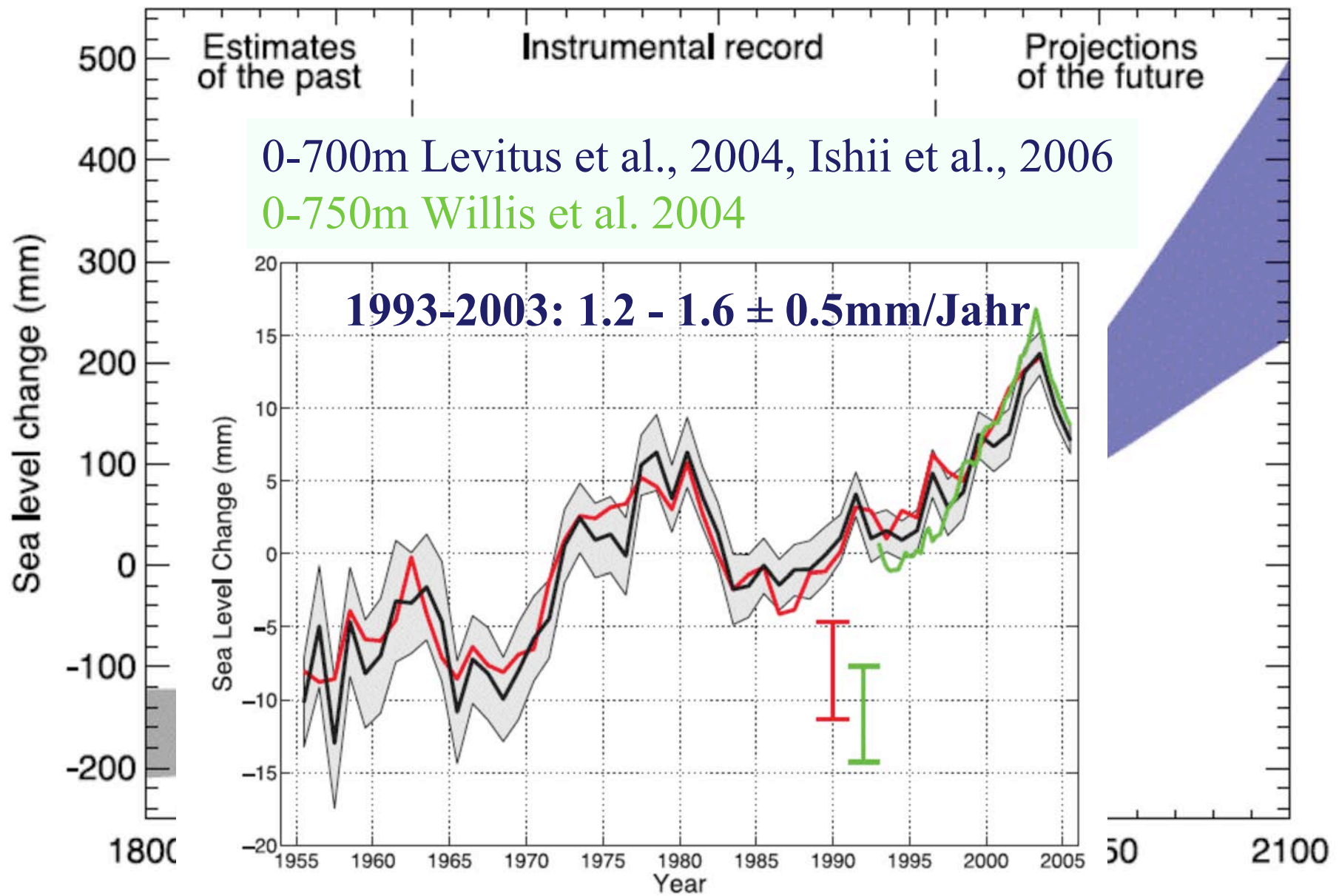
- There are many open scientific questions regarding predictability and predictable elements, mechanisms, etc.
- But: if decadal forecasts (10 – 30 years) are being realized, they need to be initialized by the present climate state.
- This holds especially for the ocean, certainly also for sea ice and land.

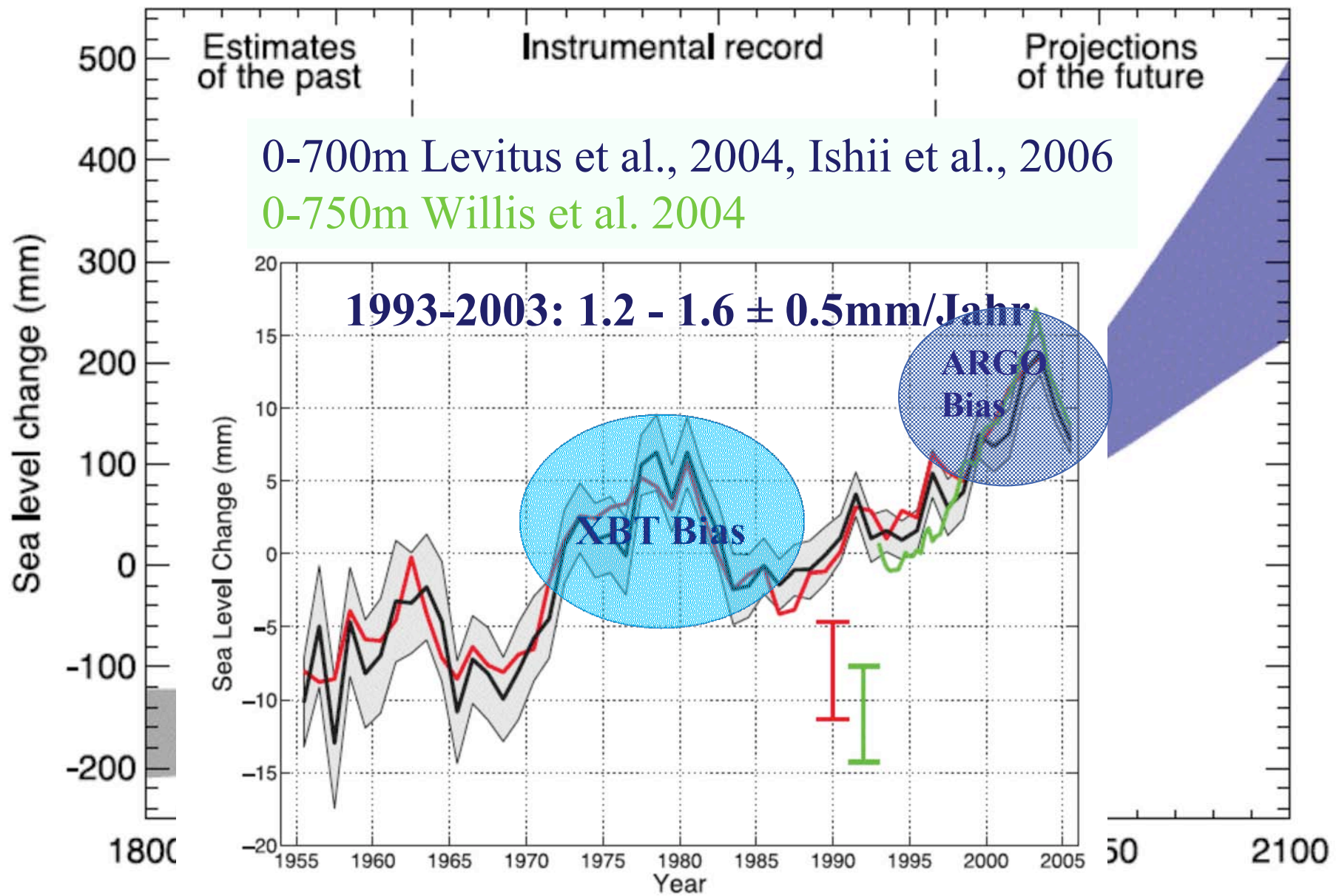
What are good initial conditions?

- Climate models have significant biases and internal errors.
- Existing ocean syntheses can serve as IC for the ocean module, but are they good IC for the coupled model?
- There are problems with obtaining initial conditions for sea ice.
- But other data have problems, too!



IPCC Report, 2007, MSSH rise in A1B scenario





Initialization Practices

- (Best) State Estimate
 - Data assimilation in the separate ocean model.
 - Leads to **initialization shocks**.
- Coupled Model Climate \neq Observed Climate
 - **Anomaly initialization**
- Coupled “modes” of coupled model \neq observed coupled “modes”
 - Initializing the **coupled modes**?

Generic Form of Assimilation:

$$J' = [\mathbf{x}(0) - \mathbf{x}_0]^T \mathbf{P}(0)^{-1} [\mathbf{x}(0) - \mathbf{x}_0]$$

initial conditions

$$+ \sum_{t=1}^{t_f} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)]^T \mathbf{R}(t)^{-1} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)]$$

observations

$$+ \sum_{t=0}^{t_f-1} \mathbf{u}(t)^T \mathbf{Q}(t)^{-1} \mathbf{u}(t)$$

control vector

$$\mathbf{x}(t+1) = \mathcal{L}[\mathbf{x}(t), \mathbf{B}\mathbf{q}(t), \mathbf{\Gamma} \mathbf{u}(t)]$$

GCM

- State estimation (data assimilation) is **least-squares fitting** of models to data.
- **Finding a minimum**, subject to the model, is a numerical, not a conceptual or mainly scientific problem.
- But the **nature of the minimum**, in addition to the model structure, depends directly on the **weight matrices** in J' and the assimilation window.
- If $\mathbf{P}, \mathbf{Q}, \mathbf{R}$ are incorrect, so is the solution.

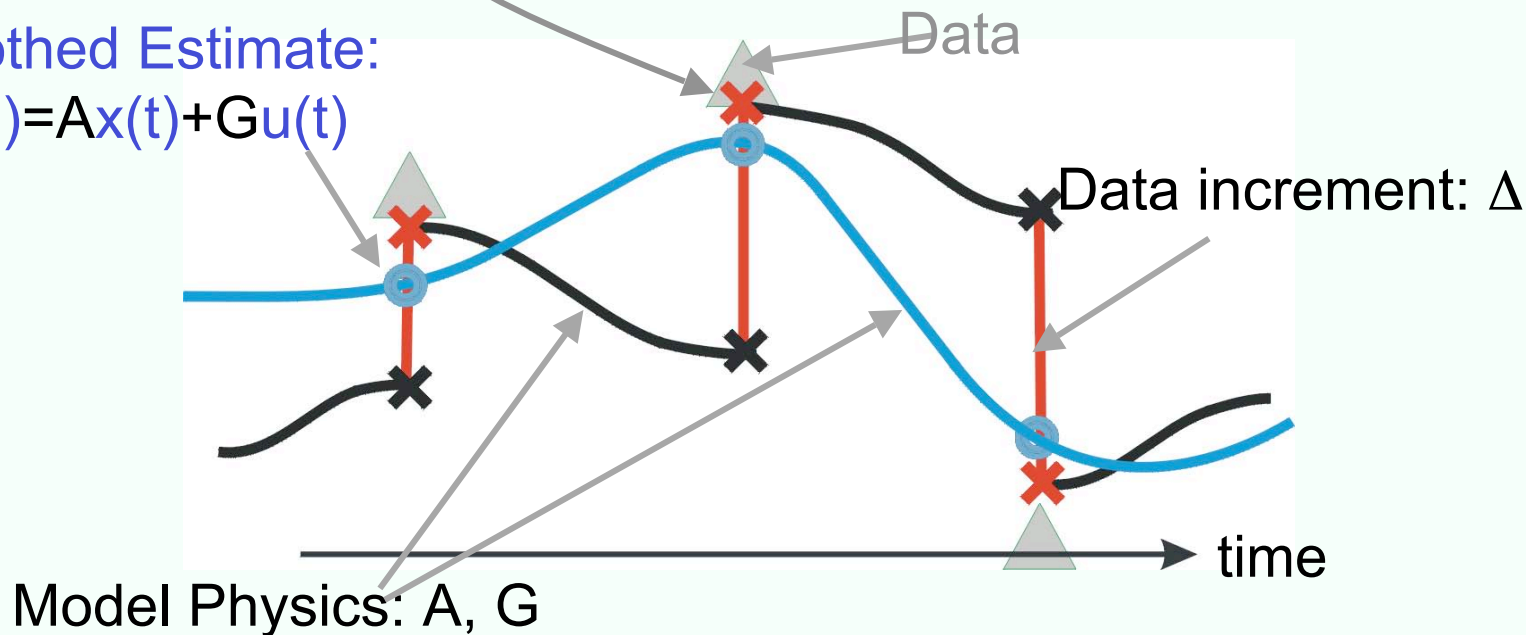
Climate Syntheses need to preserve first principles (Bengtsson et al., 2007).

The temporal evolution of data-assimilated estimates is physically inconsistent (e.g., budgets do not close) unless the assimilation's data increments are explicitly ascribed to physical processes (i.e., inverted).

Filtered Estimate: $x(t+1) = Ax(t) + Gu(t) + \Delta(t)$

x : model state, u : forcing etc, Δ : data increment

Smoothed Estimate:
 $x(t+1) = Ax(t) + Gu(t)$
















Fundamentals

- Filters merge the forecast with data at individual instances; i.e., they adjust the model state without conserving first principles.
- Smoothers estimate parameters to bring the model state into consistency with observations over time window; the final solution is a free model run!!!!

Ongoing Ocean Synthesis

- Several global ocean data assimilation products are available today that in principle can be used for climate model initialization.
- Underlying assimilation schemes range from simple and computationally efficient (e.g., optimal interpolation) to sophisticated and computationally intensive (e.g., adjoint and Kalman smoother).
- Intrinsically those efforts can be summarized as having three different goals, namely
 - climate-quality hindcasts,
 - high-resolution nowcasts, and
 - the best initialization of forecast models (SI).

Some Examples of Existing Syntheses

 K7	.K7 (Kyoto University)
 CRFS-A	.Cerfacs Stream-A (93-01), newer 3D VAR
 CRFS-2	.Cerfacs Stream 2 (62-01), old 3D VAR
 ECCOb	.ECCO-50yr, adjoint
 ECCOa	.ECCO-SIO, adjoint, iteration 69
 ECMWF	.ECMWF
 GFDL	.GFDL
 INGV	.INGV
 MOVE-G	.MOVE-G (Japan M. A.)
 ECCOc	.ECCO JPL RTS smoother
 MCTR	.Mercator 3D-VAR
 ECCOd	.ECCO-GODAEv2 Iteration 199 (adjoint)
 SODA	.SODA

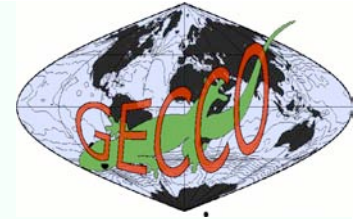
GSOP Synthesis Evaluation

Title	Central Purpose	Dynamical Consistency	Major Data Sets	Model and Configuration	Three-year Goals	Source
GECCO-50 year	Climate/climate variability of last 50 years. Open BCs for GIN Sea/NA model	Internally consistent. No sea ice.	CTD, MBT/XBT, Argo, TOGA/TAO, T/P-ERS-ENVISAT, Jason, AMSR/E/TMI SST, Quickscat, mean surface drifter vel., GRACE SSH, Levitus (1994), NCEP RA1	MITgcm, 1deg. 23 layers, no Arctic	Higher resol in vert./horiz., fully global, sea ice	A. Koehl
BLUElink	Global to regional mesoscale forecasting for apps. Ship routing, defence, ecosystem, ..., bcs for coastal models	No global constraints. Simplified ensemble KF	satellite SST, SSH, Argo, xbt, TAO	MOM4 + Chen hybrid mixed layer. Global 47 layers, 0.1 deg. resolution near Australia	Higher order mixed-layer. Eddy resolution in Indian and Pac. Ocean (1/8 deg. min) 1/16 deg near Australia	A. Schiller
ECMWF Ocean ReAnalysis (ORA) . Now version 3	Initialization of operational seasonal forecasts. Calibration of forecast skill	Allows (unphysical ?) sources of heat, salt. Jumps suppressed....	T, S profiles fr. XBTs, CTDs, Argo...; alt. anomalies (AVISO)	HOPE 1x1 + equat. refinement. partial step topog., Gregg/Tool mixing. No ice.	Variational scheme around NEMO	M. A. Balmaseda
ECCO-JPL	Monitor & understand ocean variability & impact on climate system, 1993-present.	Both filtering & smoothing products	T/P-Jason alt. in situ temperature profiles (GTS)	MITgcm 1 to 1/3deg resol. 46 layers. no arctic	global with arctic, seasonal to interannual forecasting; use salinity, gravity data. Switch to MOM.	I. Fukumori
INGV analysis	Ocean variability of last decades. Initialize ENSO forecasts. 1958-present	sequential OI	T&S profiles from EN3 package. 2006+ from CORIOLIS	OPA8.2, global, 2 deg. resol., 31 levels (ORCA2)	3-d var. use alt. data. new OPA called NEMO at 0.25 deg. horiz. res.	S. Masinia

GSOP Synthesis Evaluation

MERCATOR-2	Global, weekly, forecasts. Init. cond. coupled ocean/atm. forecasts. BCs for regional models. Coherent desc. of ocean climate of last 25 years	Kalman filter. Thermodynamically balanced (instantaneous).	Reynolds SST, alt. anomalies, in situ temp. and salinity	OPA8.2 w. free surface, 31 levels, 2 deg. resol with 0.5deg. in tropics. TKE mixed layer. Flux formulation w. ERA-40	Longer reanalysis at 1/4deg 1957-2007	N. Ferry
CERFACS-ENSEMBLES	1960-2001, global understanding ocean climate; initialize coupled seasonal forecasts. Decadal forecasts plus climate studies	3d-var. multivariate balance. Increments in the momentum and tracer eqs., reduced temporal jumps	T & S profiles from QC ENSEMBLES (from WOD02)	OPA8.2 (ORCA config.) TKE, 2 deg., 31 levels. No ice	Use NEMO and assimilation using NEMOVAR. 1 deg. global	A. Weaver
SODA 2.0.2	Climate studies, mainly upper ocean. BCs for regional models. Biogeochemical studies. Last 50 years	No jumps. Simulation product.	WOD05 T&S, MBTs XBTs, CTDS, TAO, Pirata, Argo, satellite SST, alt., GPCC rainfall	POP2.x at 0.25 global (average) tropical 0.25x0.4 deg.. Versions of MOM.	extend back to 1900. biogeochemical changes	J. Carton
ECCO-GODAE MIT/AER	Decadal scale ocean circulation changes. global, daily values. Top-to-bottom ocean. High resolution S. Ocean & N. Atl.	Free running, adjusted model. No jumps	All alt. satellite anom., absolute alt; Gouretski/Koltermann clim., all Argo, hydrog., elephant seal, NCEP reanal., daily SST, ...	MITgcm in 3 configs. v2.xx 1deg., 23 levels; v4. 50 levels with full ice.	Full Arctic, full sea ice, all global scale data. Uncertainty estimates.	C. Wunsch

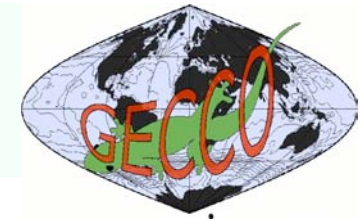
Example: The GECCO State Estimate



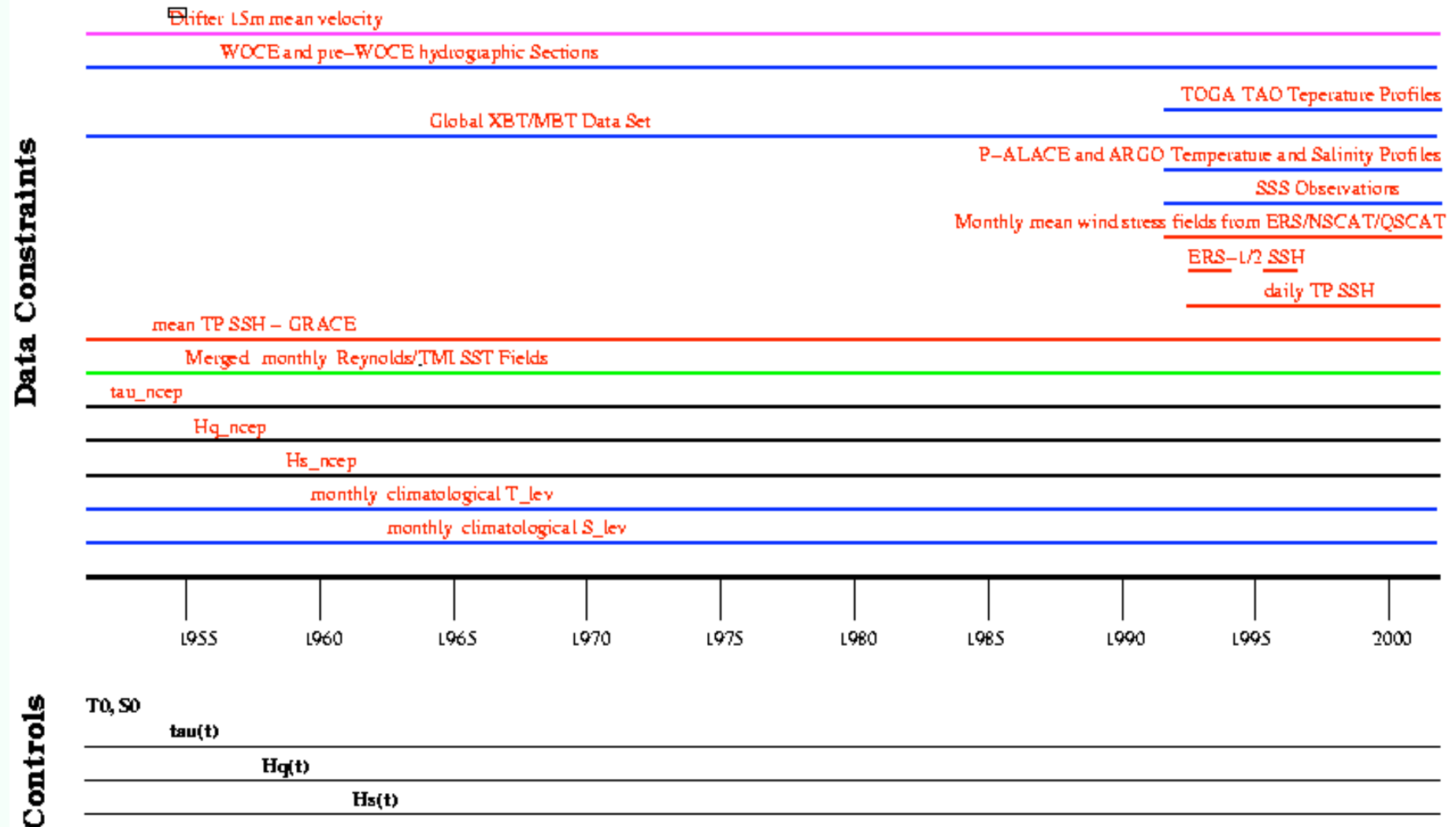
- Part of the **ECCO Consortium** Effort.
- **Ocean synthesis**, performed over the **period 1952 through 2001** on a 1° global grid with 23 layers in the vertical, using the ECCO/MIT adjoint technology (now being extended to present).
- **Optimization** started from Levitus and NCEP forcing and uses state of the art physics modules (GM, KPP).
- The models adjoint (obtained using TAF) is used to bring the model into consistency with most of the available ocean observations over the full period by **adjusting control parameters**.
- At this stage control parameters are the models initial temperature and salinity fields as well as the time varying surface forcing, leading to a dynamically self-consistent solution (next step is to include mixing).



Input Data Sets and Controls



Global 1° WOCE Synthesis 1952 through 2002

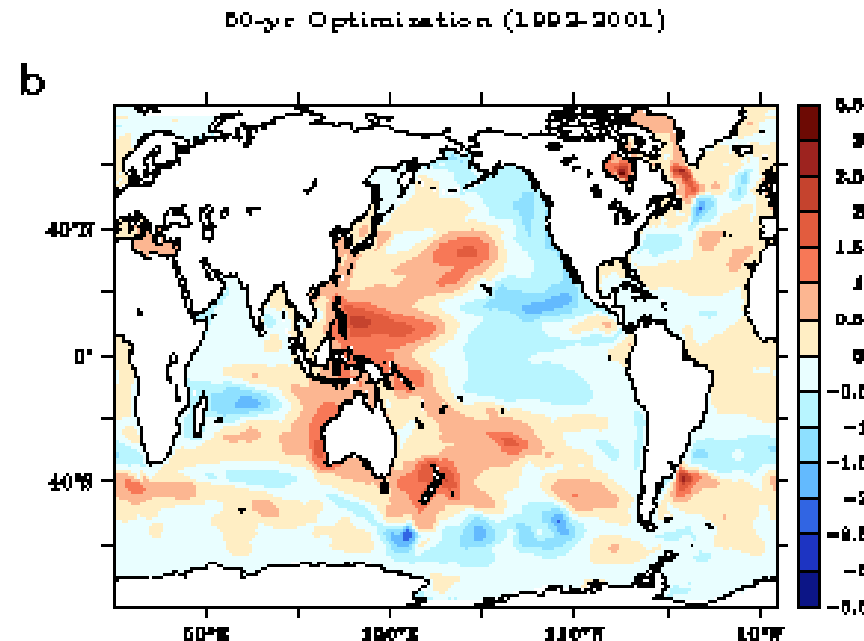
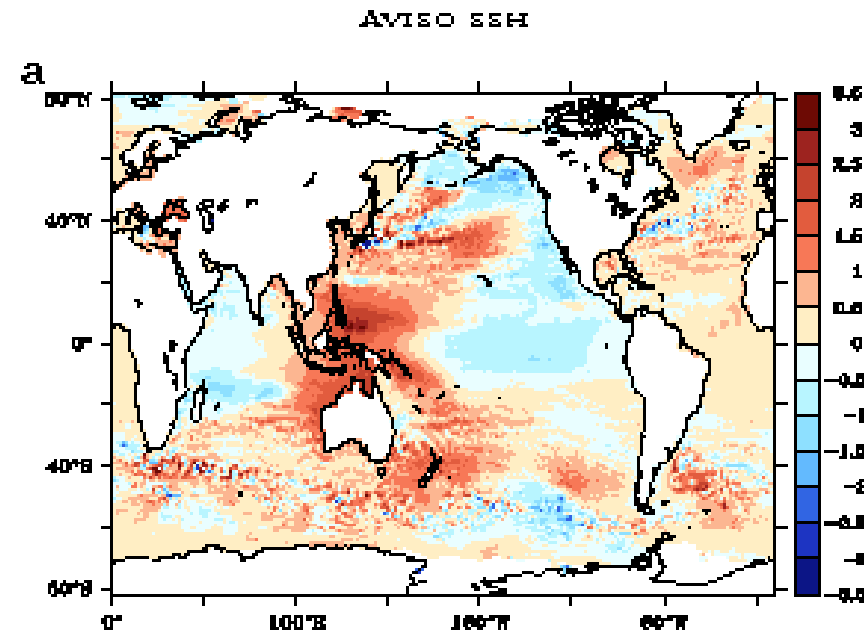


Köhl and Stammer (JPO, 2008; J.Clim. , 2008)

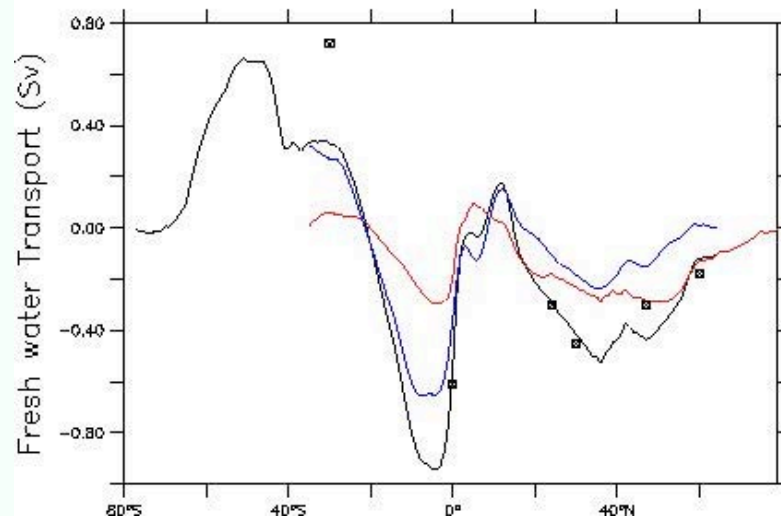
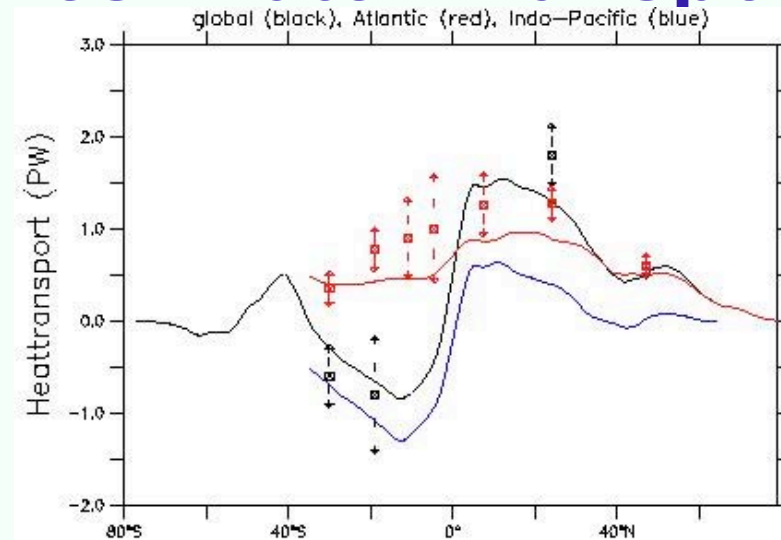
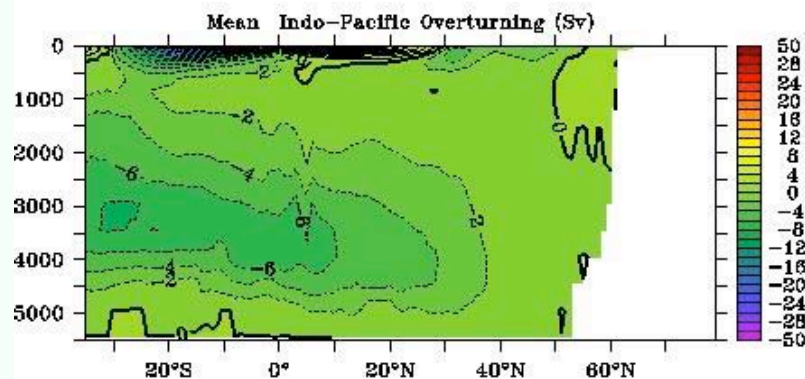
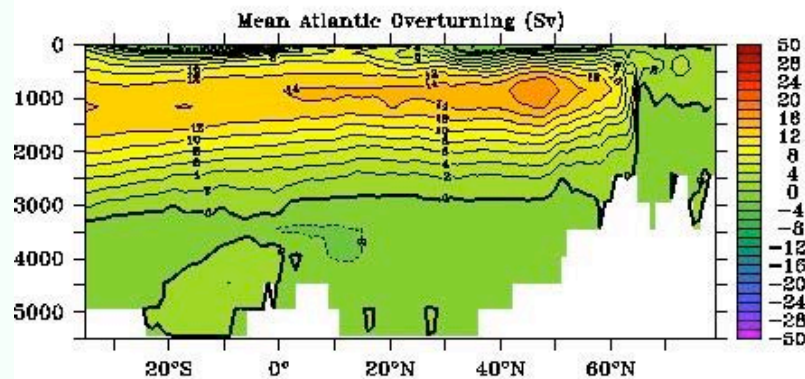
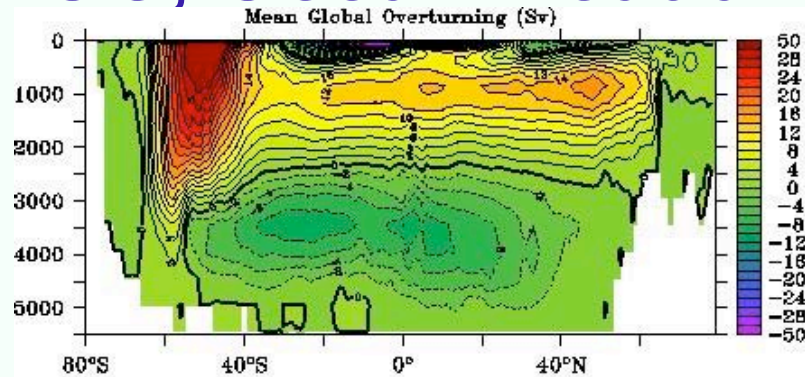
Example: SSH Trends 1992 - 2001

Observed Altimetry

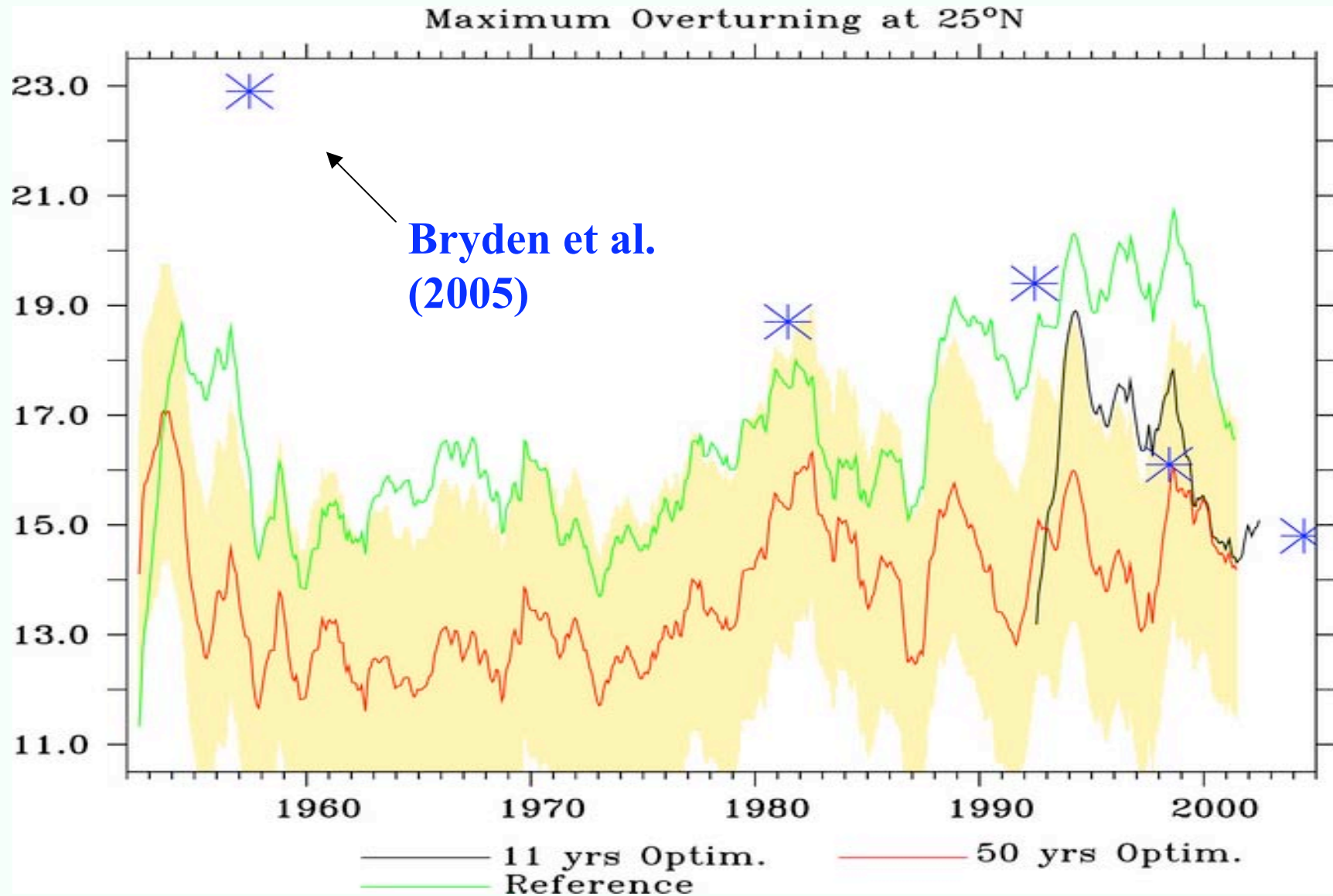
GECCO: most of the changes are due to changes in heat content. Those changes are primarily redistribution in the ocean due caused by changing winds, but partly also due to heat fluxes over the northern hemisphere.



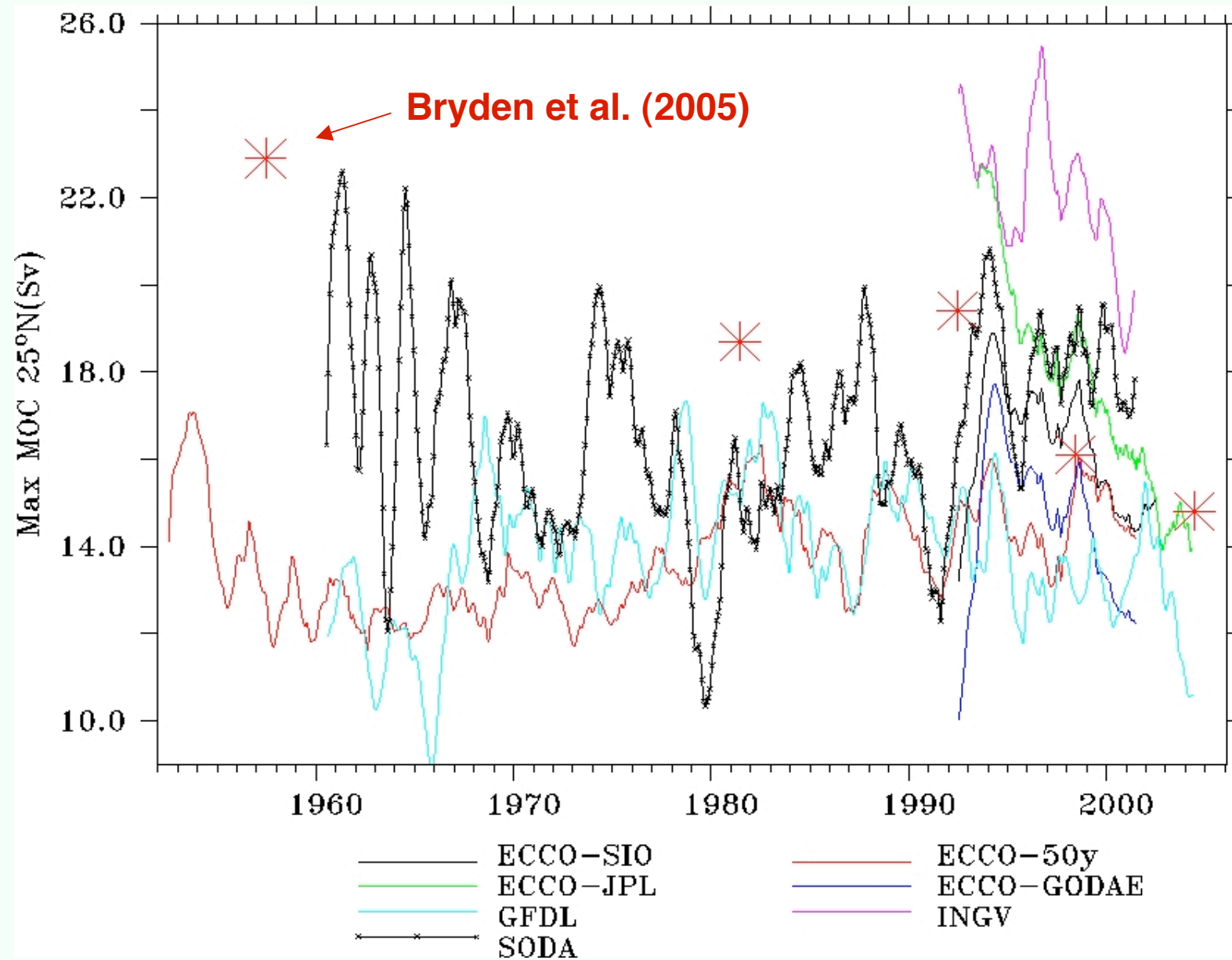
Estimates of un-observables: MOC, Ocean Heat and Freshwater Transports



Comparison of maximum MOC at 25N

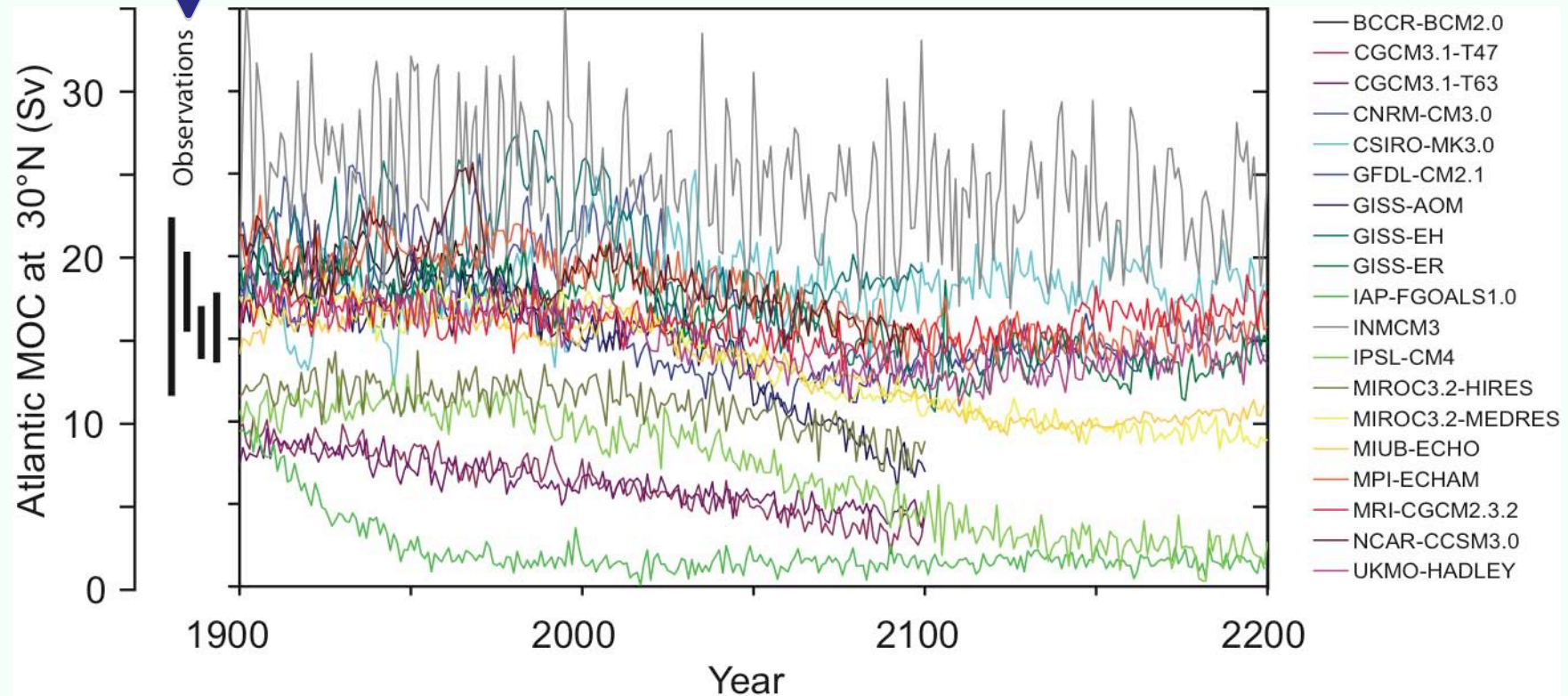


Max strength of Atlantic MOC at 25N



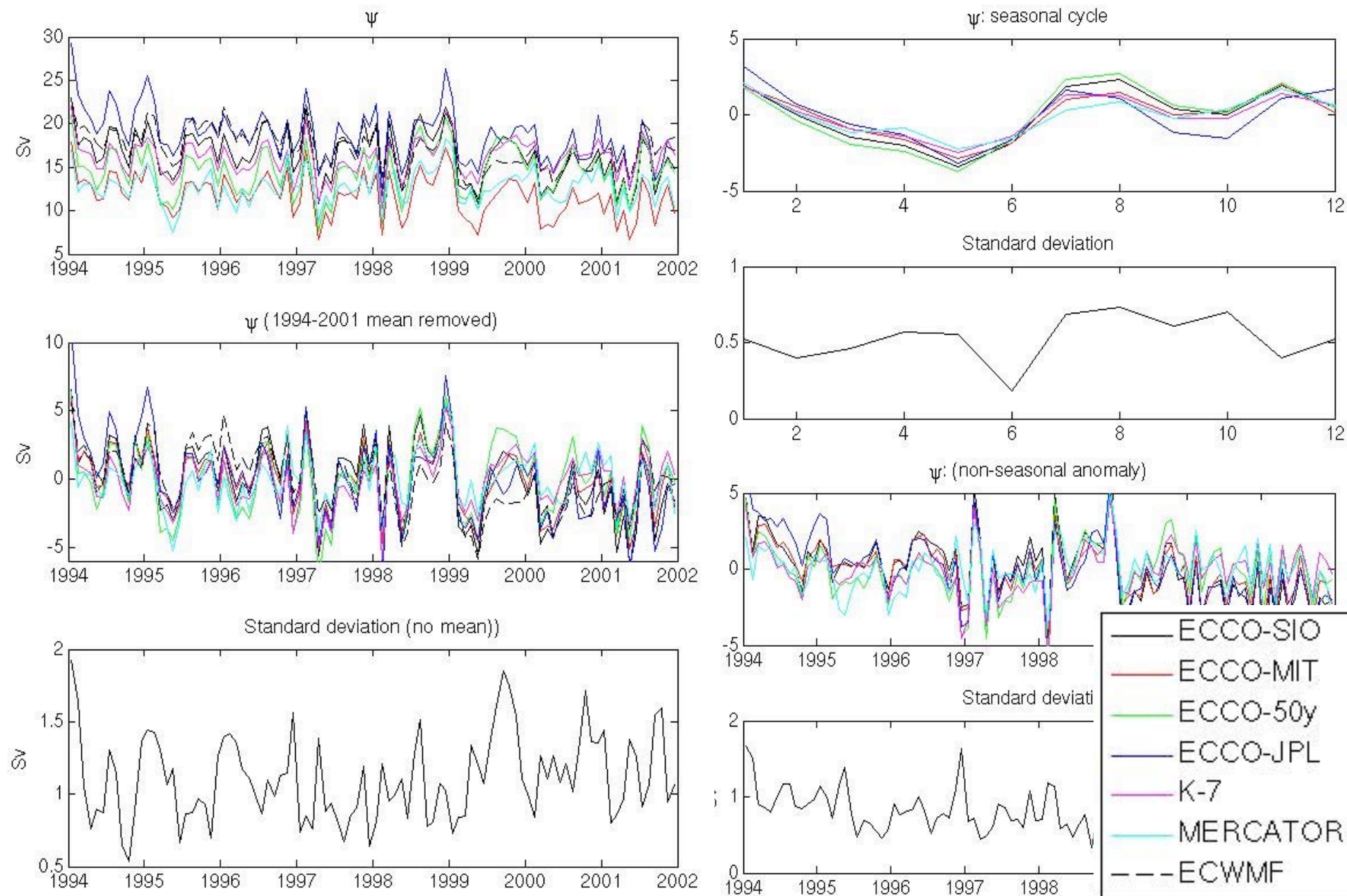
Obs. based
estimates

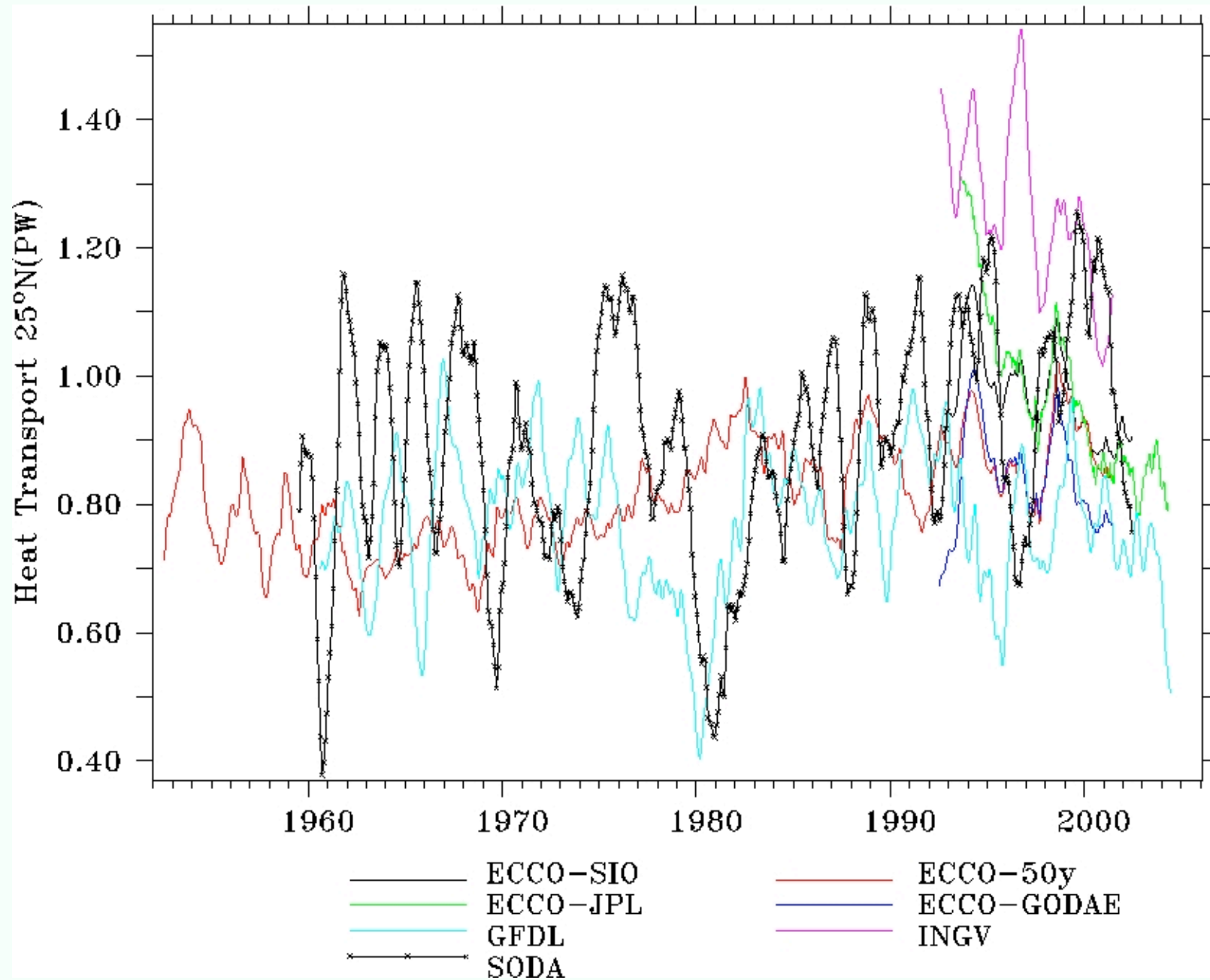
MOC Scenarios



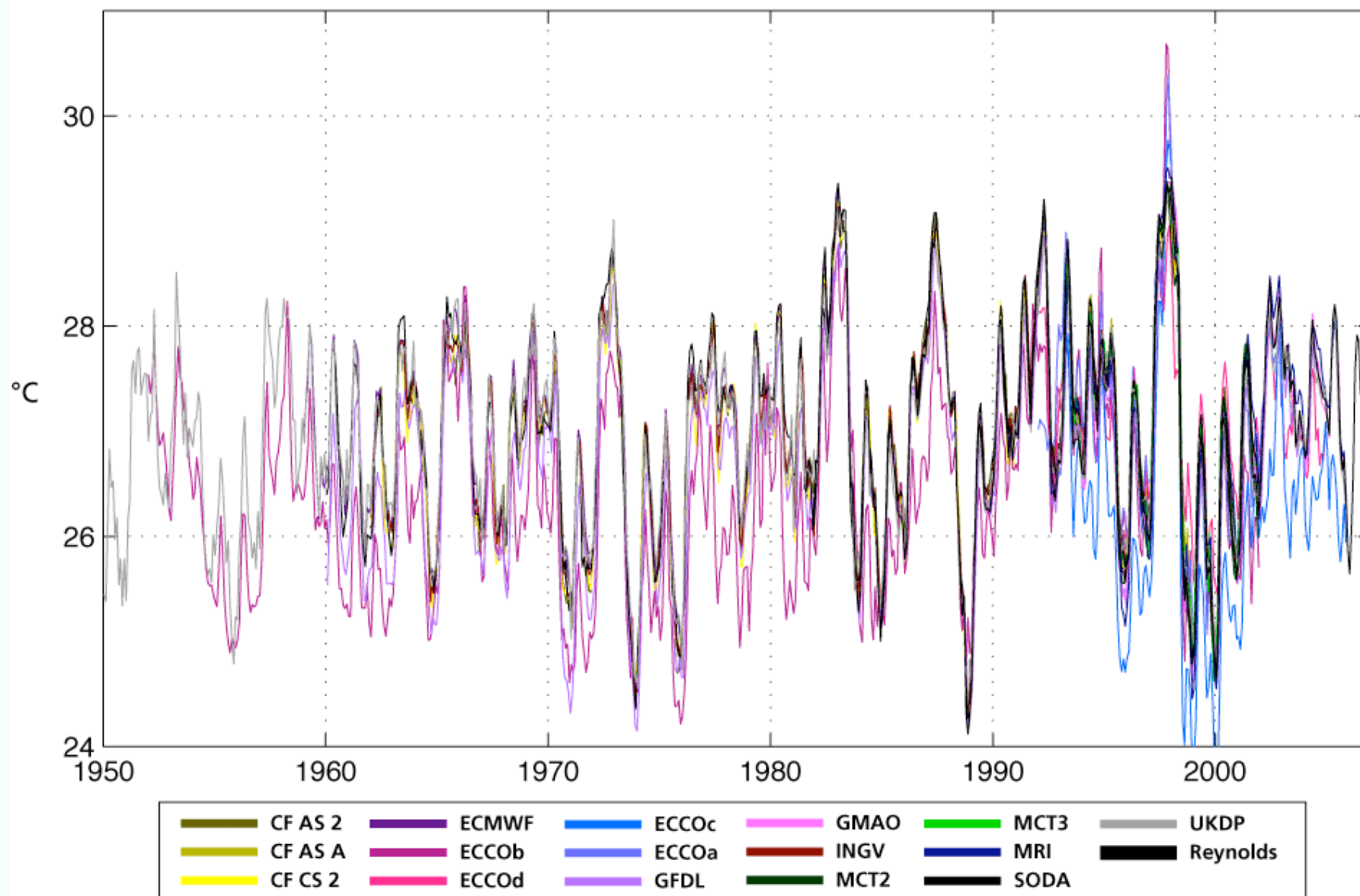
IPCC Report, 2007

MOC strength at 900 m (near the depth of MAX MOC strength) 25N





Nino3.4 SST



Advancements in Ocean Synthesis

- Improve input data sets.
- Improve estimation procedure:
 - Expand control space (mixing coefficients)
 - Include error covariances
 - Improve initialization procedure
- Expand model domain (truly global), include sea ice.

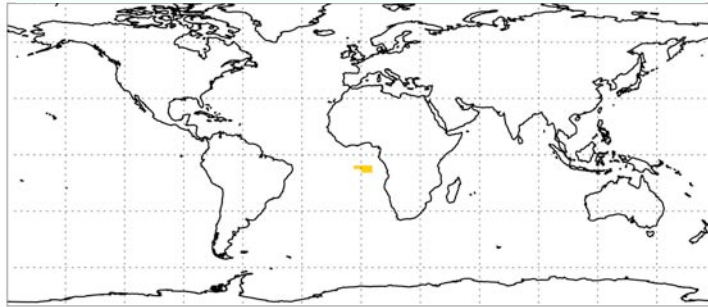
Is a best ocean synthesis the best initialization for climate models?

- Initialization schemes all suffer from the **inconsistencies between the interaction of the model and initial conditions.**
- E.g. the model winds along the eq. do not support the assimilation thermocline slope.
- Differences in surface forcing lead to **dramatic model drifts.**
- To mitigate **coupling shock** coupled model initialization schemes have been developed **using only anomalies.**

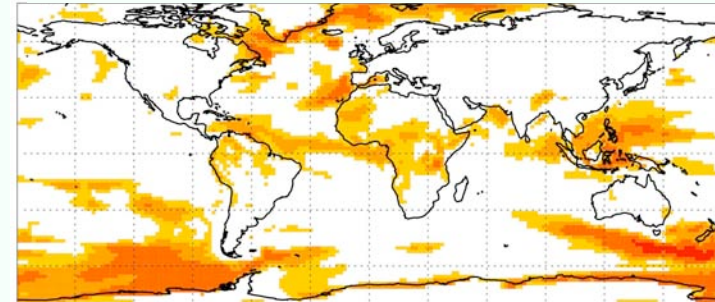
The hindcast experiments are closer to the assimilation experiment than the control experiment.

Anomaly correlation coefficient (ACC) for surface air temperatures:

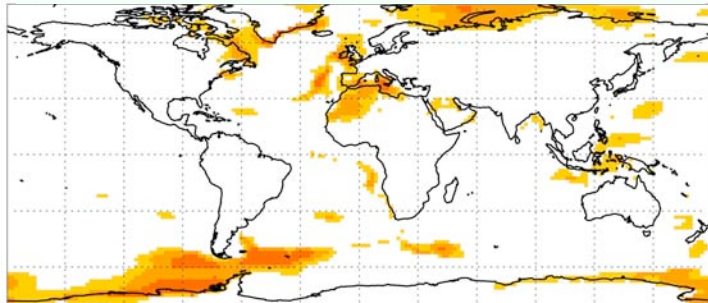
Control : Assimilation



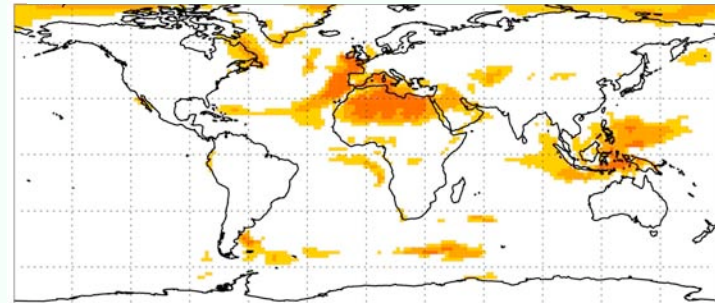
Hindcast year 1 : Assimilation



Hindcast year 2-4 : Assimilation



Hindcast Year 5-10 : Assimilation



Advancements in Prediction

- To advance predictive skills in SI and DEC:
 - Model Improvements - reducing systematic errors.
 - Better Constraining Initial Conditions of coupled model.
- Calls for data assimilation using coupled models.

“We need data assimilation for coupled models as a prediction and evaluation tool for weather and climate”

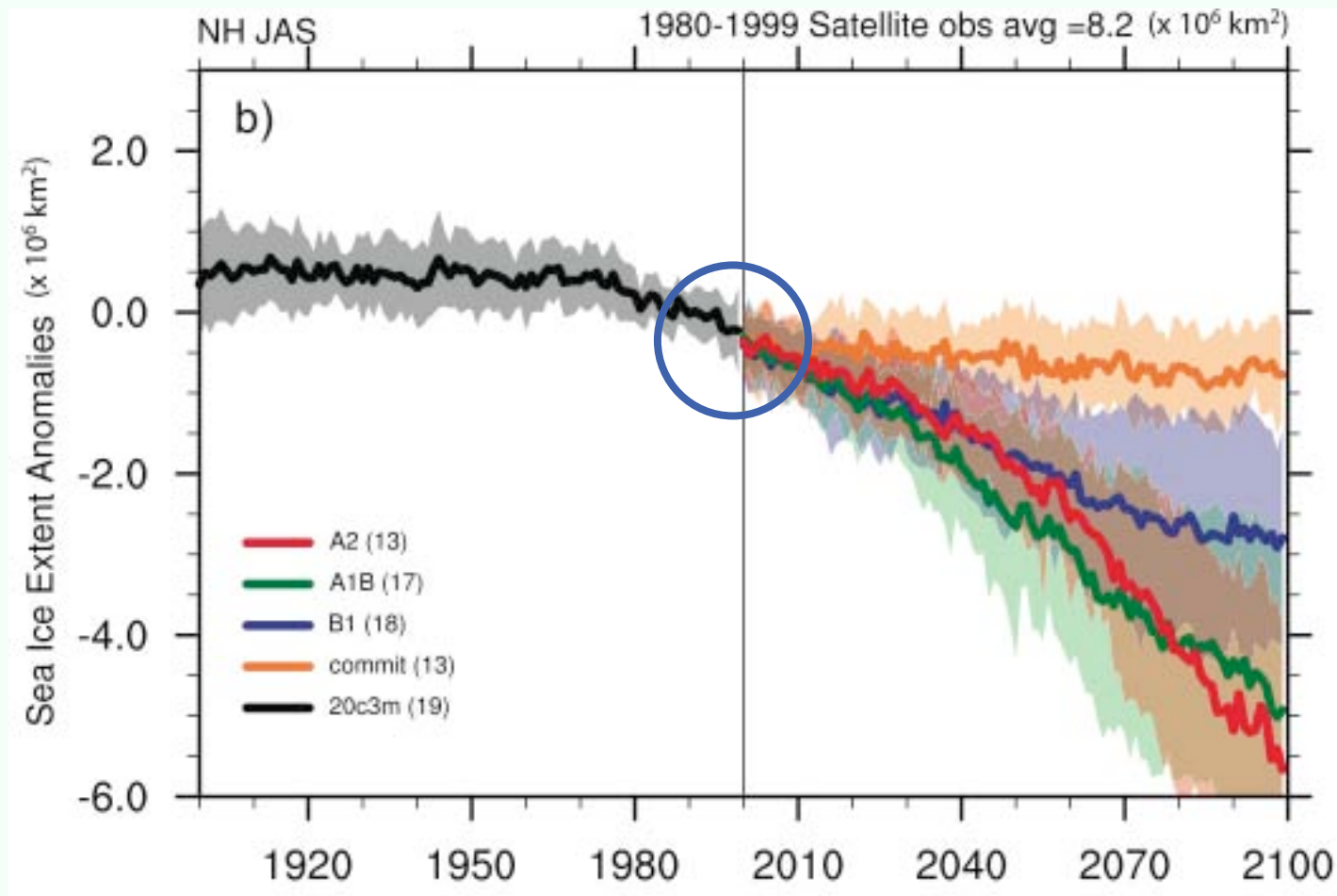
(B. Hoskin, Climate Modeling Summit, reading, May 6, 2008)

This becomes even more true in the context of decadal predictions.

Duality of Assimilating Models:

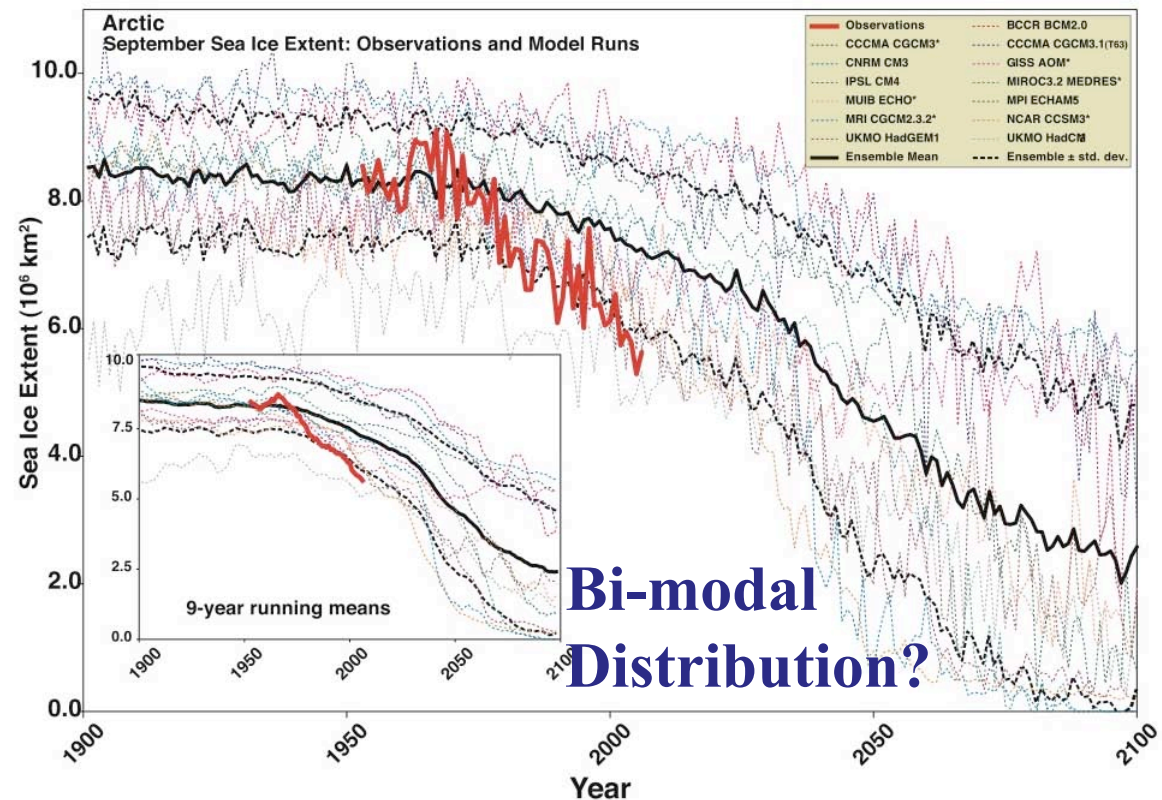
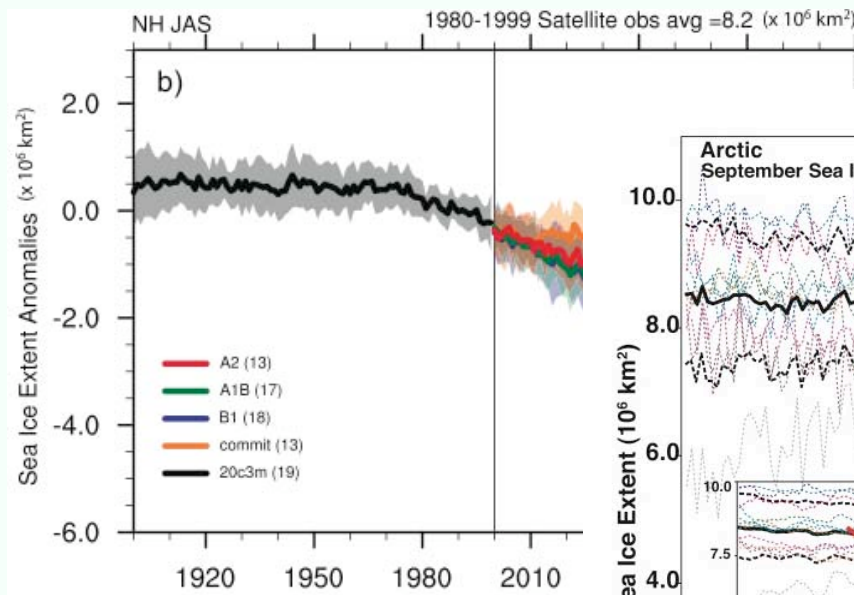
- Data assimilation
- Sensitivity Experiments
- Parameter Estimation

Multi-model simulated anomalies in sea ice extent for the 20th century



IPCC Report, 2007

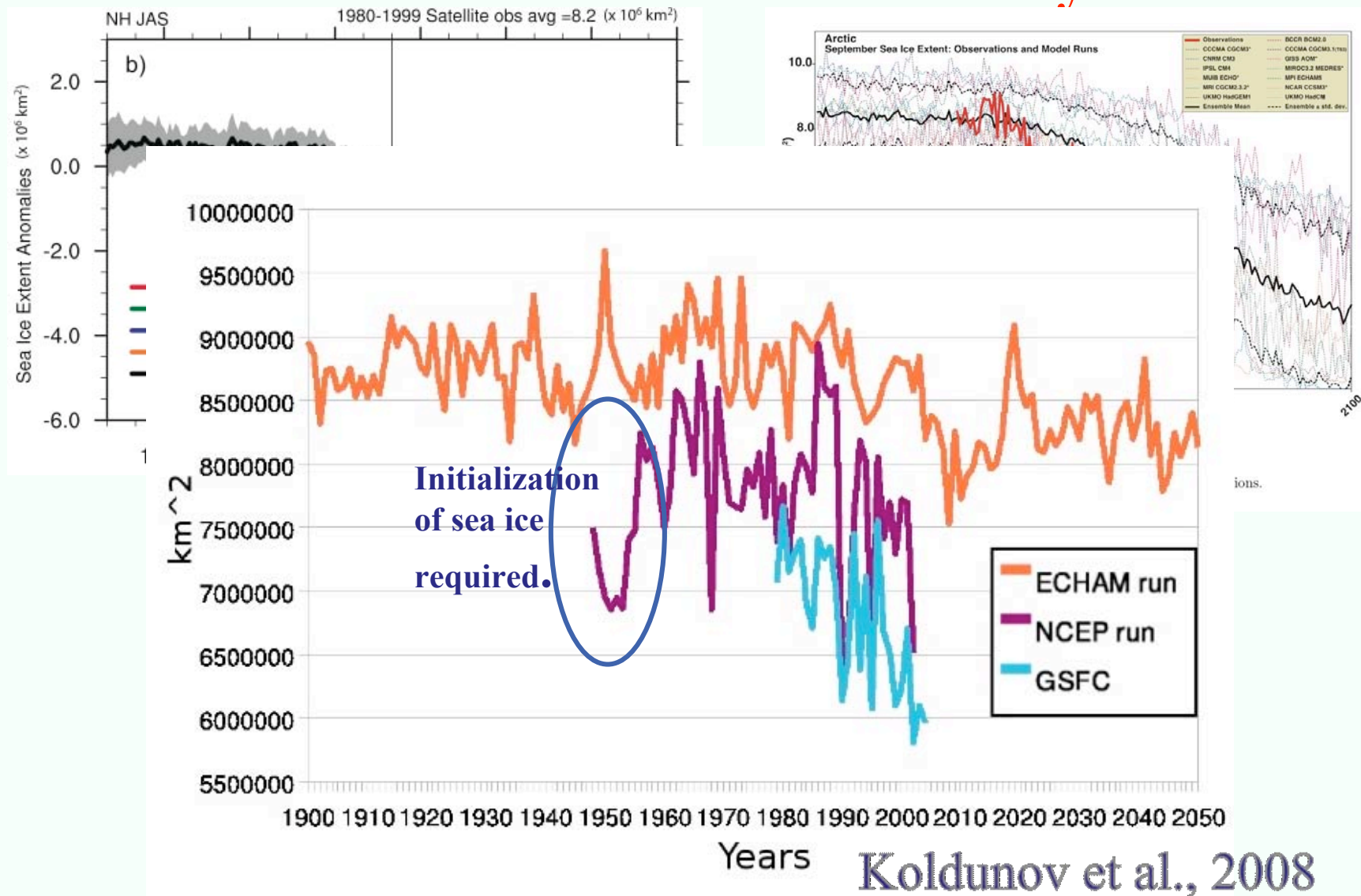
Multi-model simulated anomalies in sea ice extent for the 20th century



**Bi-modal
Distribution?**

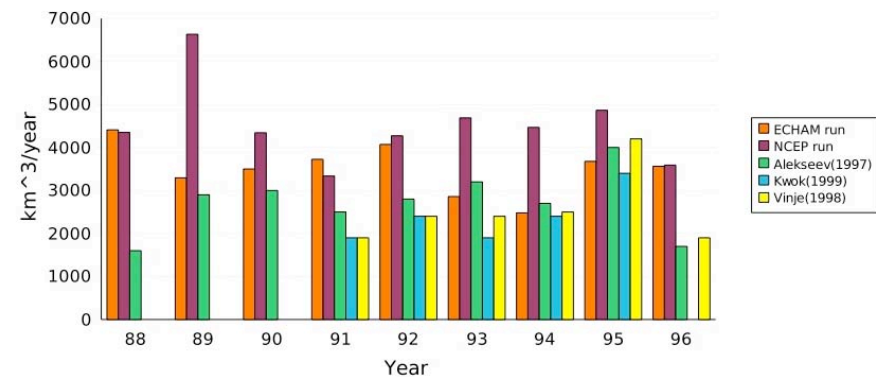
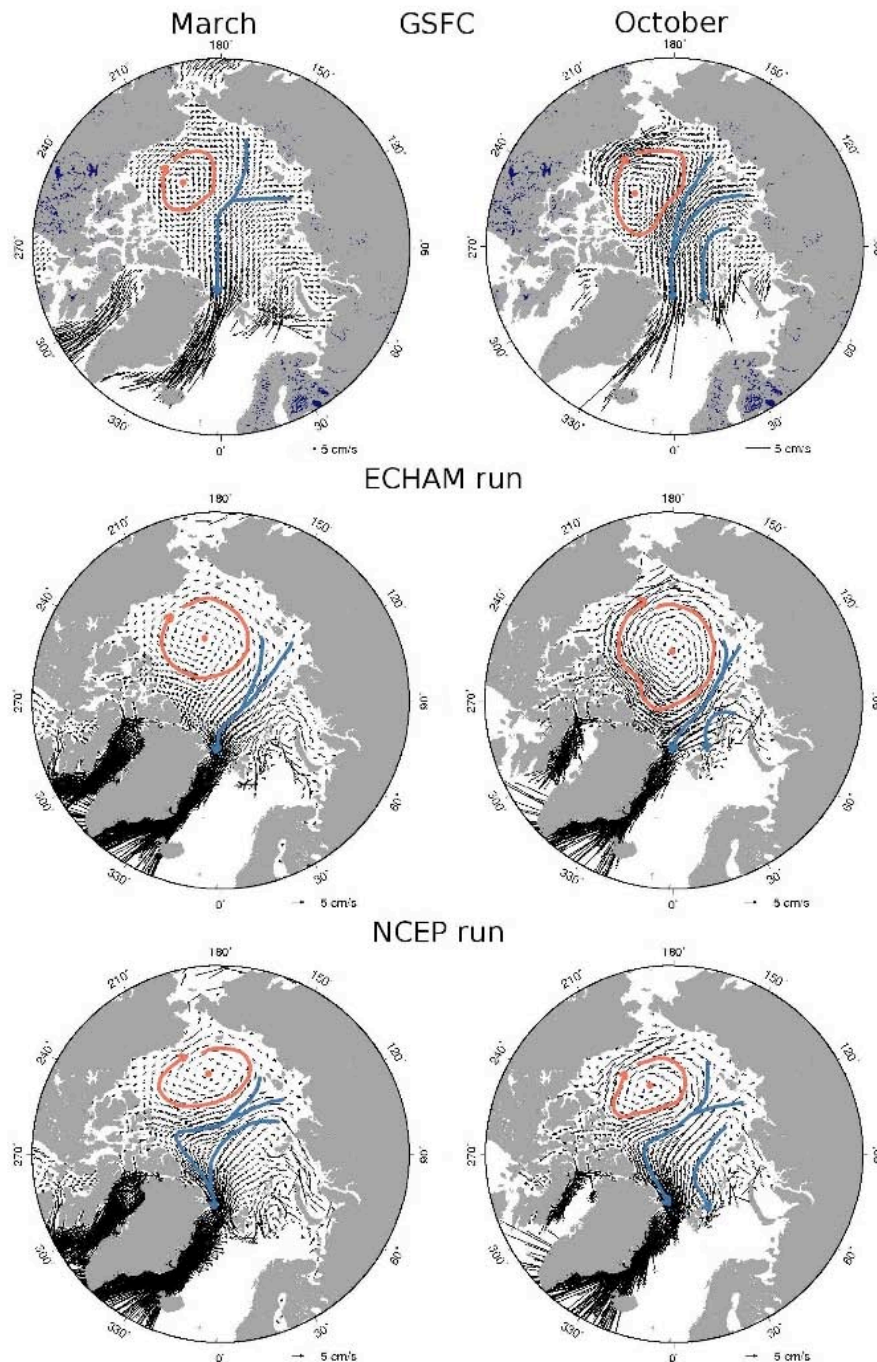
Stroeve et al., 2007. Thick orange line are observations.

Multi-model simulated anomalies in sea ice extent for the 20th century



Koldunov et al., 2008

Improving the Fram Strait Ice Transport Simulations

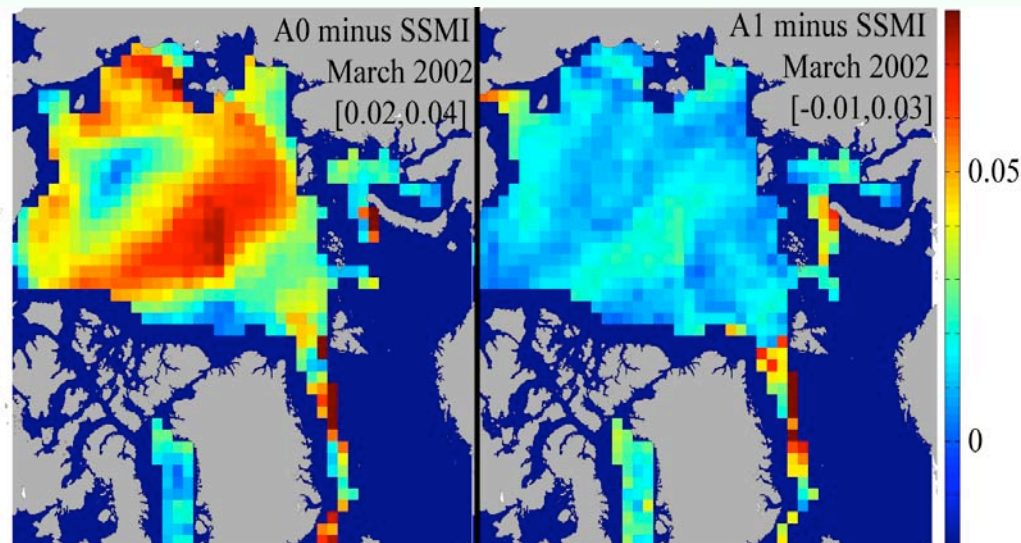
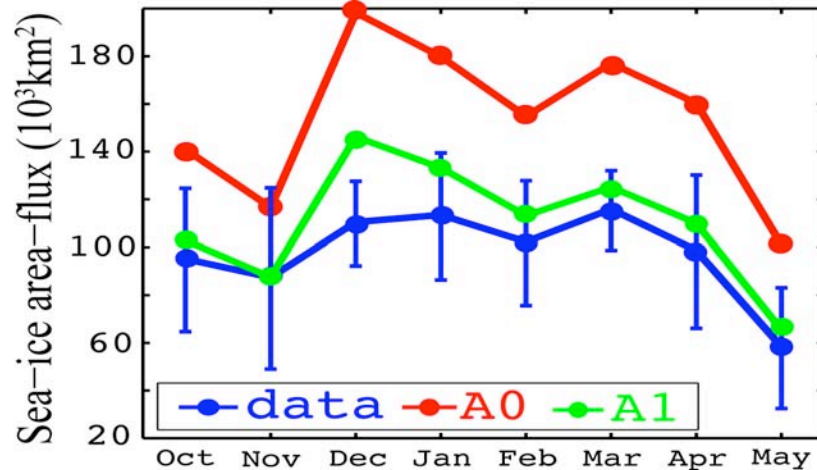


Koldunov et al., 2008

Adjusting Drag coefficients

Heimbach, Menemenlis et al., 2008

Monthly ice fluxes across Fram Strait showing ECCO2 regional optimized solution A1 producing results that are more consistent with observations compared to A0.



Sea-ice velocity difference (m/s, Model minus Data) for March 2002. Numbers in brackets are [MEAN,STD].

Four-Dimensional Variational Coupled Data Assimilation by K7 (T. Awaji, 2007)

1. Oceanic initial condition
2. Bulk parameters controlling Air-sea fluxes of

Momentum

$$F_v = -\rho\alpha_M C_M |\mathbf{v}|\mathbf{v}$$

Sensible heat

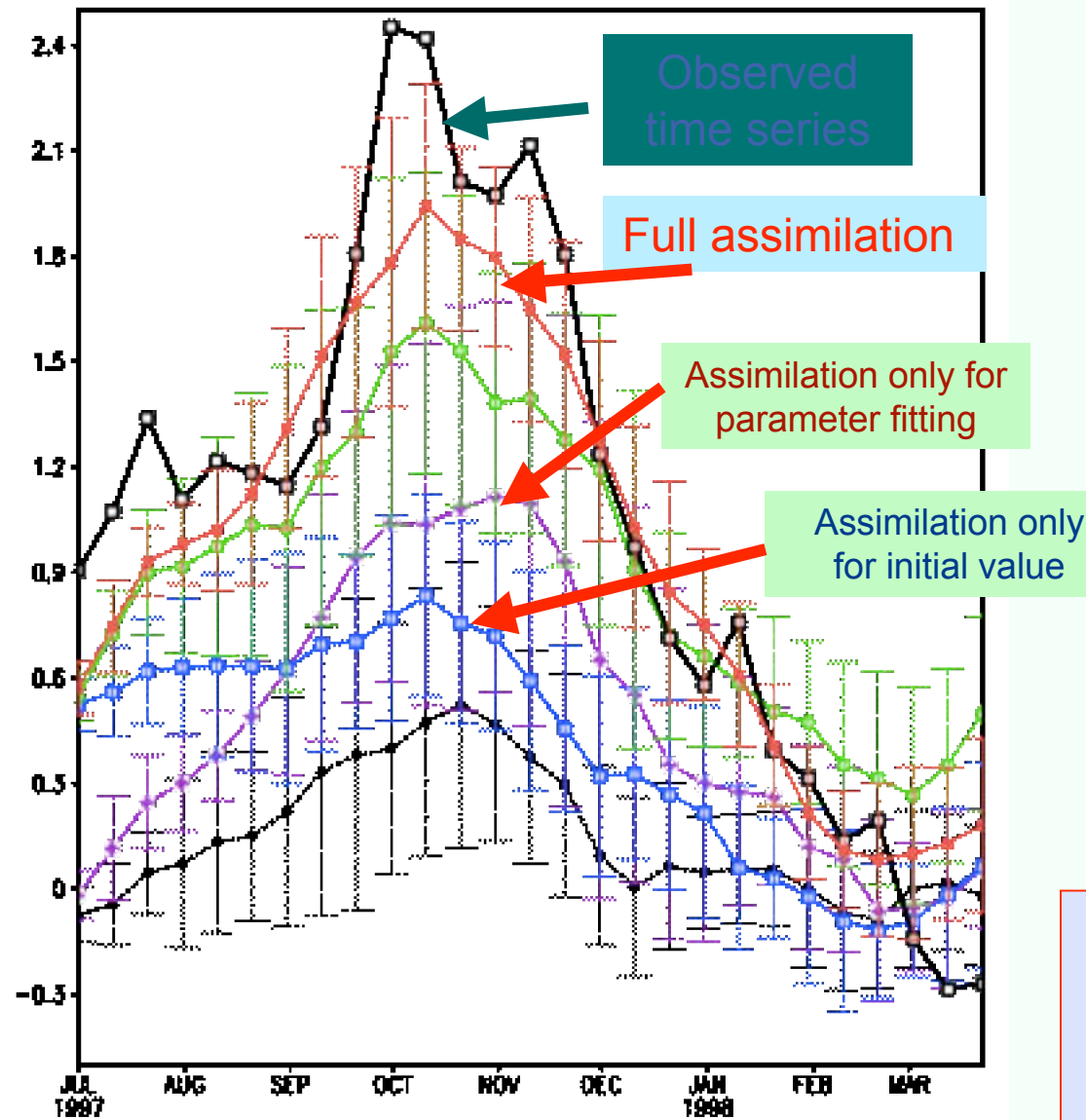
$$F_\theta = \rho c_p \alpha_H C_H |\mathbf{v}|(\theta_g - \theta)$$

Latent heat

$$F_q = \rho\alpha_E C_E |\mathbf{v}|(q_g - q)$$

For Smaller-scale Parameterization: pre-optimization using the Green function approach.

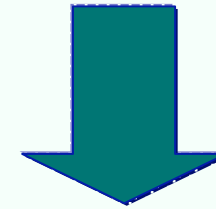
Indian Dipole Mode Index (DMI)



1997

1998

**4DVAR CDA
improved DMI
index**



**Correction by both
oceanic initial
conditions and
parameters plays an
important role**

**4D-VAR approach allows
to make initial conditions
as close as possible to
the observed climate
attractors for a target
phenomenon**

Remarks

- Initializing short-term climate forecasts with climate data sets appears necessary.
- This implies that a **climate observing system** needs to be maintained (in situ, satellites) and data are part of the climate modeling enterprise.
- Reducing significant model biases is critical and here a unified approach is promising. **Is not just resolution!**
- To reduce model errors and initialization shock **assimilation in coupled models is** necessary (ocean, ice, atmosphere, land).
- First results are promising, much improvement can be expected, **but we are just at the beginning.**

Prospects of Decadal Predictions

- Various time horizons involved.
- Short term: If AR 5 runs need to be finished in two years, existing initial conditions and existing initialization methods need to be used.
- To provide appropriate IC, GSOP can help, if this group specified requirements.

Ocean Syntheses

- All ocean syntheses will be made available over the next few month on the CLISAP Climate Data Center Web page together with documentation and possibly input data sets.

Initialization

- **Several efforts for improving model initialization are spinning up.**

WCRP: Short-term climate /decadal prediction proposal

In Europe: ENSEMBLES, UKMetOffice, THOR, ...

In Germany: CLISAP, CSC,

In the US: GFDL, others?

Coupled Data Assimilation

- **Longer term: Assimilation needs to play an important role for climate model improvements.**
- **Several efforts for coupled assimilation are spinning up.**
 - In Germany: THOR, CLISAP
 - In the US: GFDL, others?