Two decades of the AMOC:
Its structure, variability, and predictability

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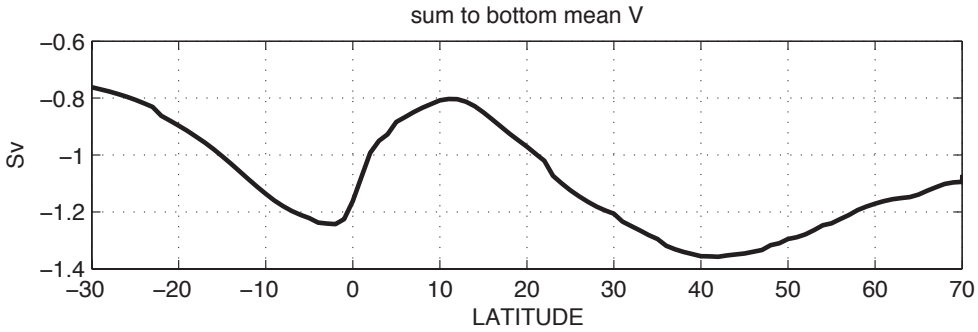
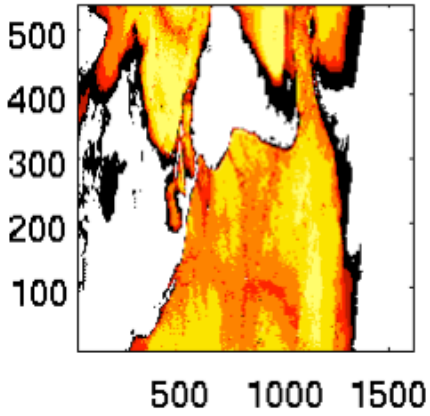
Estimating the Circulation and Climate of the Ocean
http://ecco-group.org

Outline

- Preliminary solution of new-generation decadal ocean climate state estimate – ECCO-SP (Sustained Production)
- Basic statistical properties of meridional volume transports
- Linear prediction approaches
  - AR model prediction
  - transient non-normal amplification

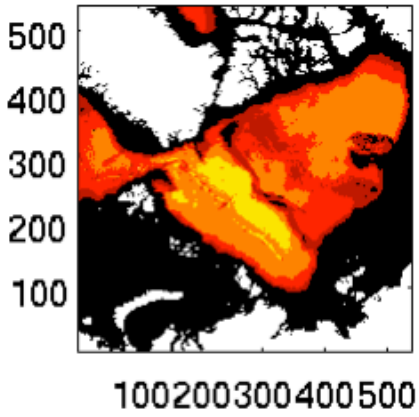
ECCO-SP version 4 grid: Lat/Lon/PolarCap (LLC_90)
Decadal ocean climate state estimate

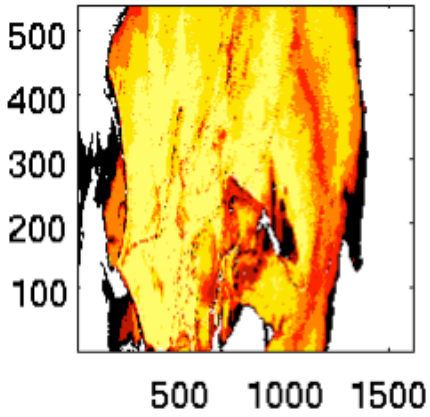


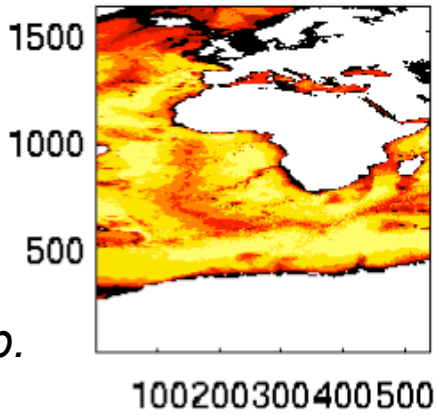


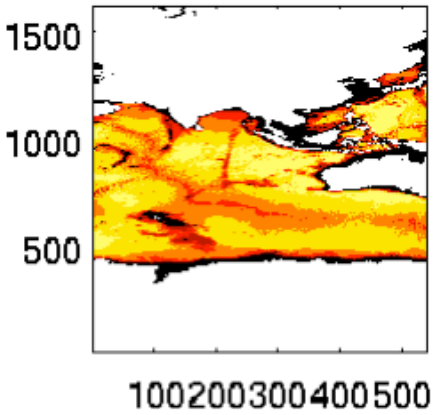
Atlantic top-bottom volume transport reflects:

- Bering Strait transport
- local freshwater input









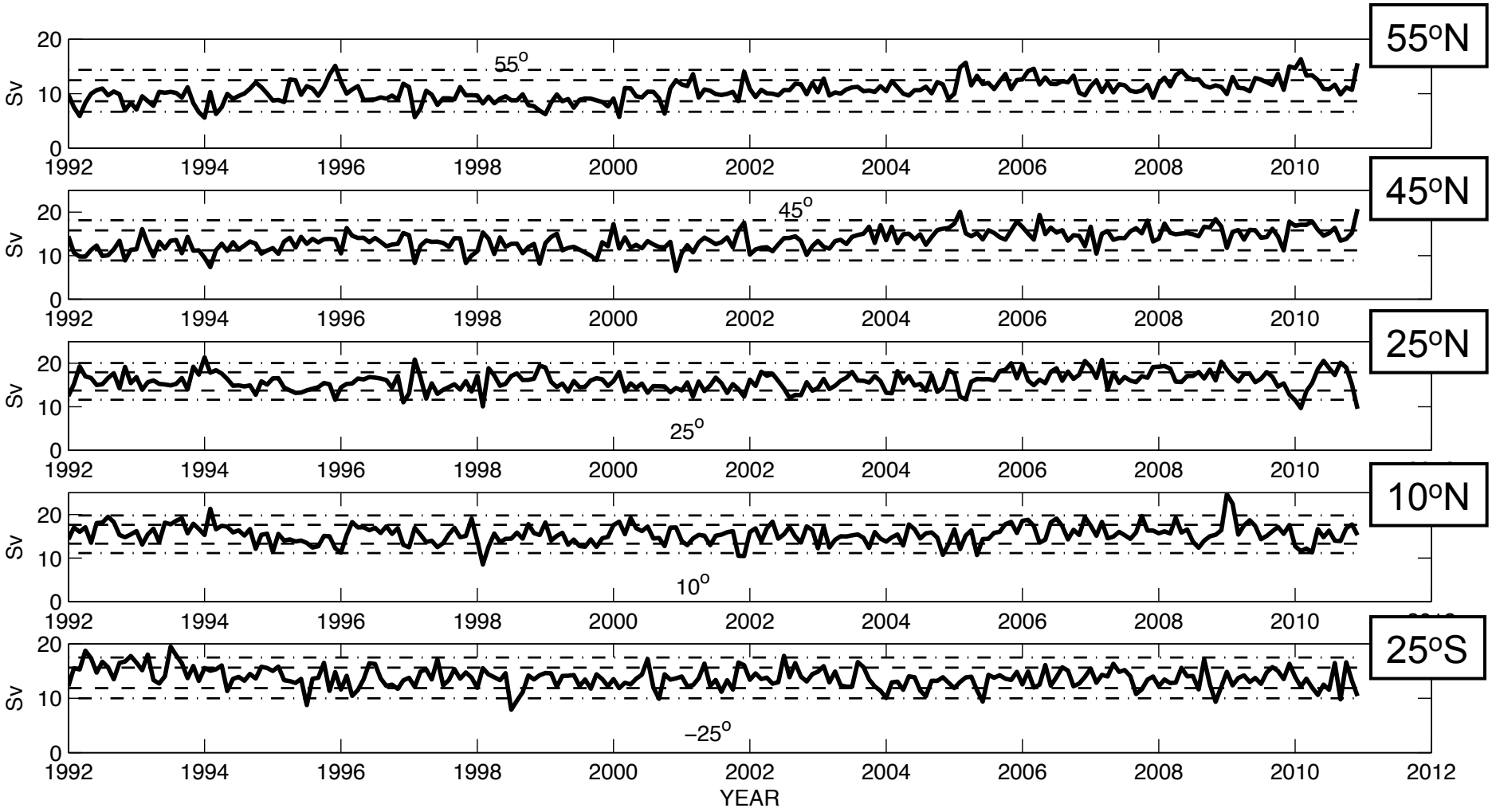
Forget et al., in prep.

New features in forthcoming ECCO-SP "version 4" (1992-2010)

- new global grid LLC_90
  - includes the Arctic
  - telescopic resolution to 1/3° near the Equator
  - meridionally isotropic in mid-latitudes
- shift from 23 to 50 vertical levels with partial cells
- forcing using ERA-Interim
- state-of-the-art dynamic/thermodynamic sea ice model
- nonlinear free surface + real freshwater flux B.C.s
- third-order advection scheme
- removal of C-D scheme for Coriolis terms
- use of diffusion operator (Weaver & Courtier, 2001) for in-situ obs.
- all satellite data are daily along-track
- internal model parameters are part of the control space

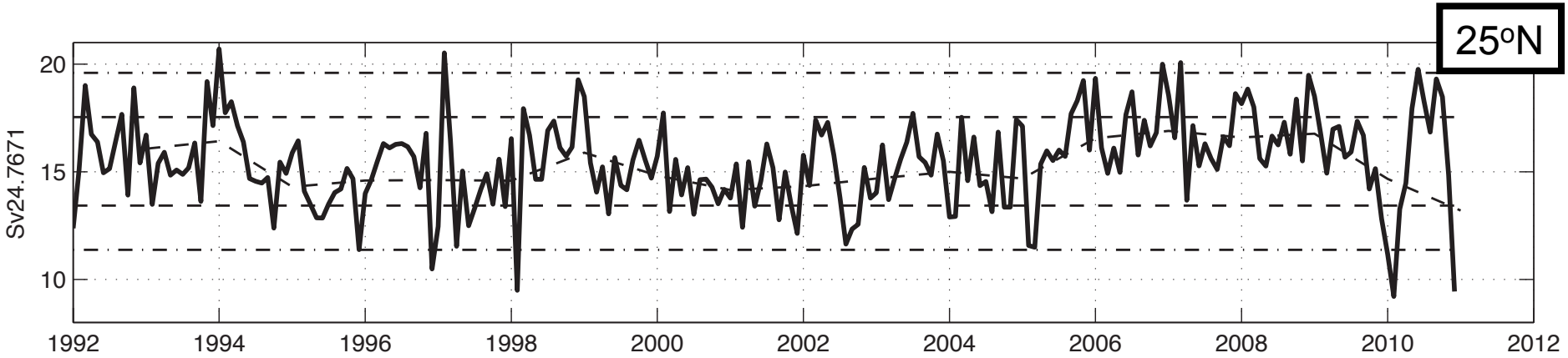
observation	instrument	product/source	area	period	dT
Mean dynamic topography (MDT)	• GRACE SM004-GRACE3 • GRACE GGM02 • EGM2008/DNSC07	CLS/GFZ (A.M. Rio) CSR/U. Texas (B. Tapley) N. Pavlis	global	time-mean	mean
Sea level anomaly (SLA)	• TOPEX/POSEIDON • Jason-1/2 • ERS-1/2, ENVISAT • GFO	NOAA/RADS & PO.DAAC NOAA/RADS & PO.DAAC NOAA/RADS & PO.DAAC NOAA/RADS & PO.DAAC	65°N/S 65°N/S 82°N/S 65°N/S	1993 – 2002 2002 – 2011 1992 – 2011 2001 - 2008	daily daily daily daily
bottom pressure	• EIGEN-GRACE05	GFZ Potsdam	global	2002 – 2011	weekly
SST	• blended, AVHRR (O/I) • TRMM/TMI • AMSR-E (MODIS/Aqua)	Reynolds & Smith GHRSST GHRSST	Global 40°N/S Global	1992 - 2011 1998 - 2004 2001 - 2011	monthly daily daily
SSS	Various in-situ	WOA09 surface	Global	climatology	monthly
In-situ T, S (floats, sections,…)	• Argo, P-Alace • XBT • CTD • SEaOS	Ifremer M. Baringer (NCEP) various SMRU & BAS (UK)	“global” “gobal” sections SO	1992 – 2011 1992 – 2011 1992 – 2011 2004 – 2010	daily daily daily daily
Mooring arrays	•TOGA/TAO, Pirata • Florida Straits [WITHELD]	PMEL/NOAA NOAA/AOML	Tropics N. Atl.	1992 – 2011 1992 – 2011	daily daily
Climatological T,S	• WOA09 • OCCA	WOA09 Forget, 2010	“global” “global”	1950 - 2008 1950 - 2002	mean mean
sea ice cover	• satellite brightness temp. (passive microwave)	• NSIDC-0079 (Bootstrap) • NSIDC-0051 (NASA Team)	Arctic, SO	1992 - 2011	daily
Wind stress	QuickSCAT	• NASA (Bourassa) • SCOW (Risien & Chelton)	global	1999 – 2009 climatology	daily monthly
Tide gauge SSH	Tide gauges	NBDC/NOAA	sparse	1992 - 2006	monthly
Flux constraints	from ERA-Interim, JRA-25, NCEP, CORE-2 variances	Various	global	1992 - 2011	2-day to 14-day
Balance constraints	heat & freshwater (E-P-R)		global	1992 - 2011	mean
bathymetry		Smith & Sandwell, ETOPO5	global	-	-

ECCO-SP v4:
Preliminary AMOC transport estimates at selected latitudes

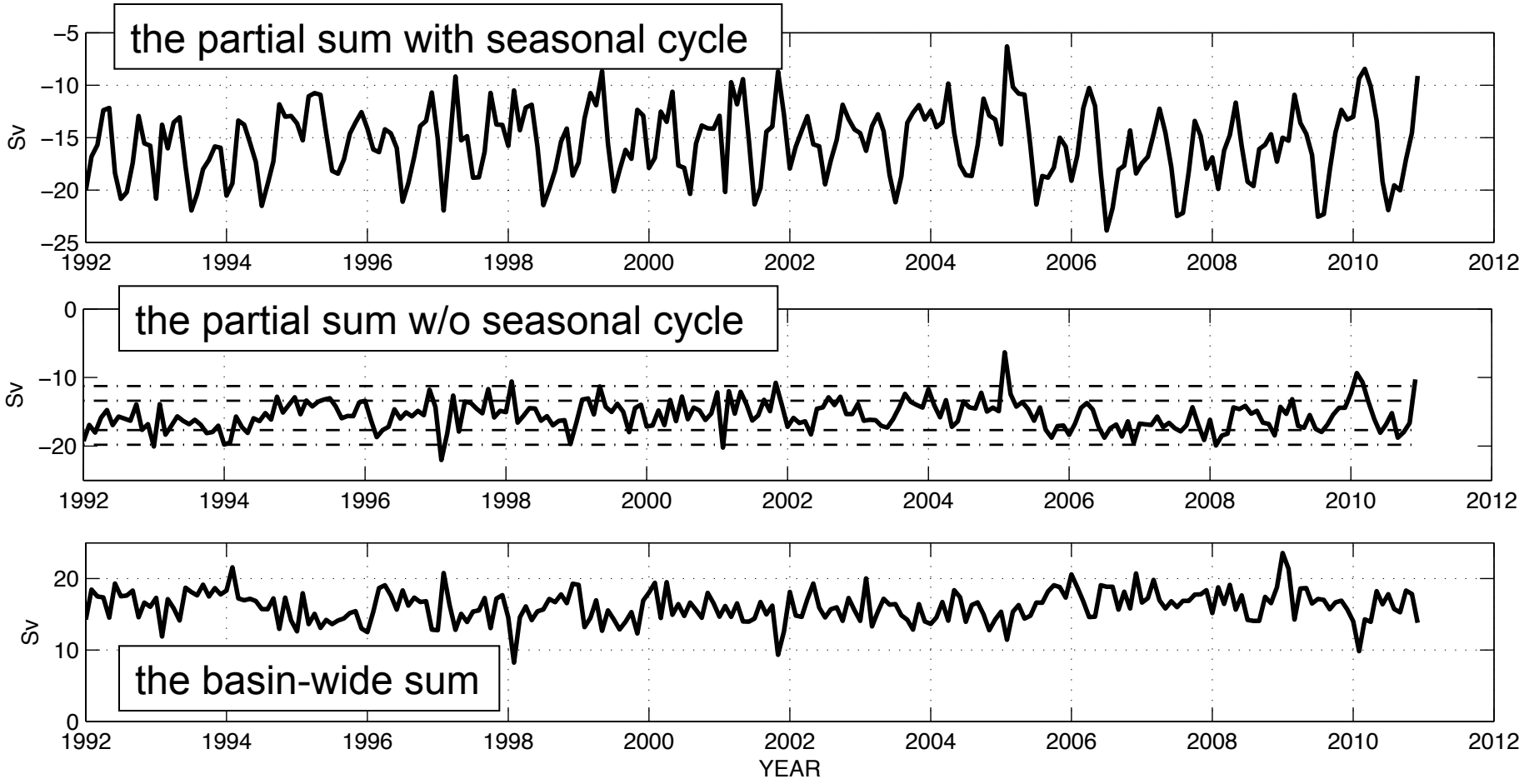


ECCO-SP v4:
Preliminary AMOC transport estimates at selected latitudes

- ECCO-SP, using global observing system:
  - provides a basin-wide or global perspective
  - perspective back to 1992 (beginning of satellite altimetry)
  - considerable interannual variability
  - no discernable trends
  - 2010 transport minimum not unprecedented in 20-year context ?

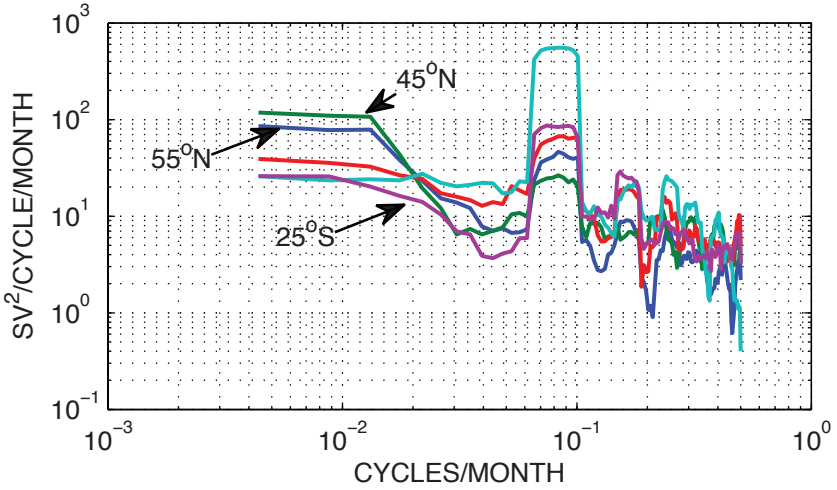


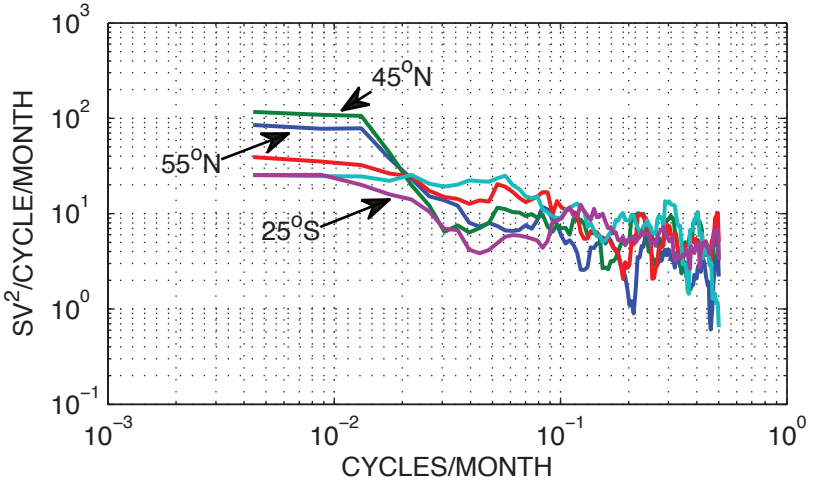
ECCO-SP v4:
Perspective at 16N – partial vs. basin-wide sums



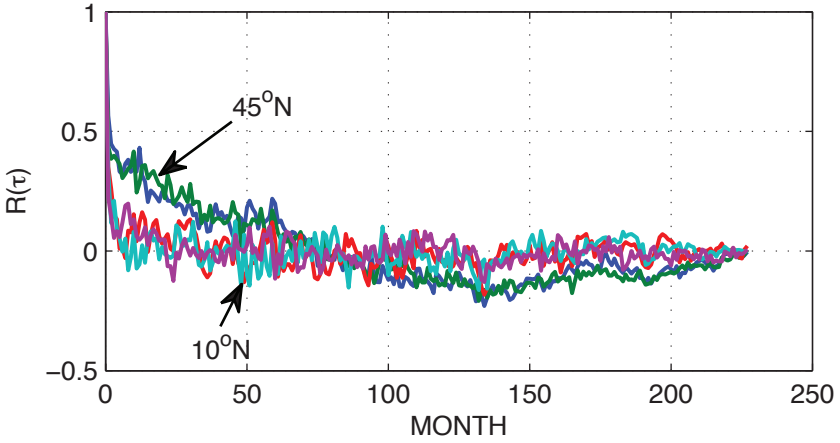
Partial sums are hard to interpret

AMOC as Gaussian red noise process: Power spectra & autocorrelation at five latitudes





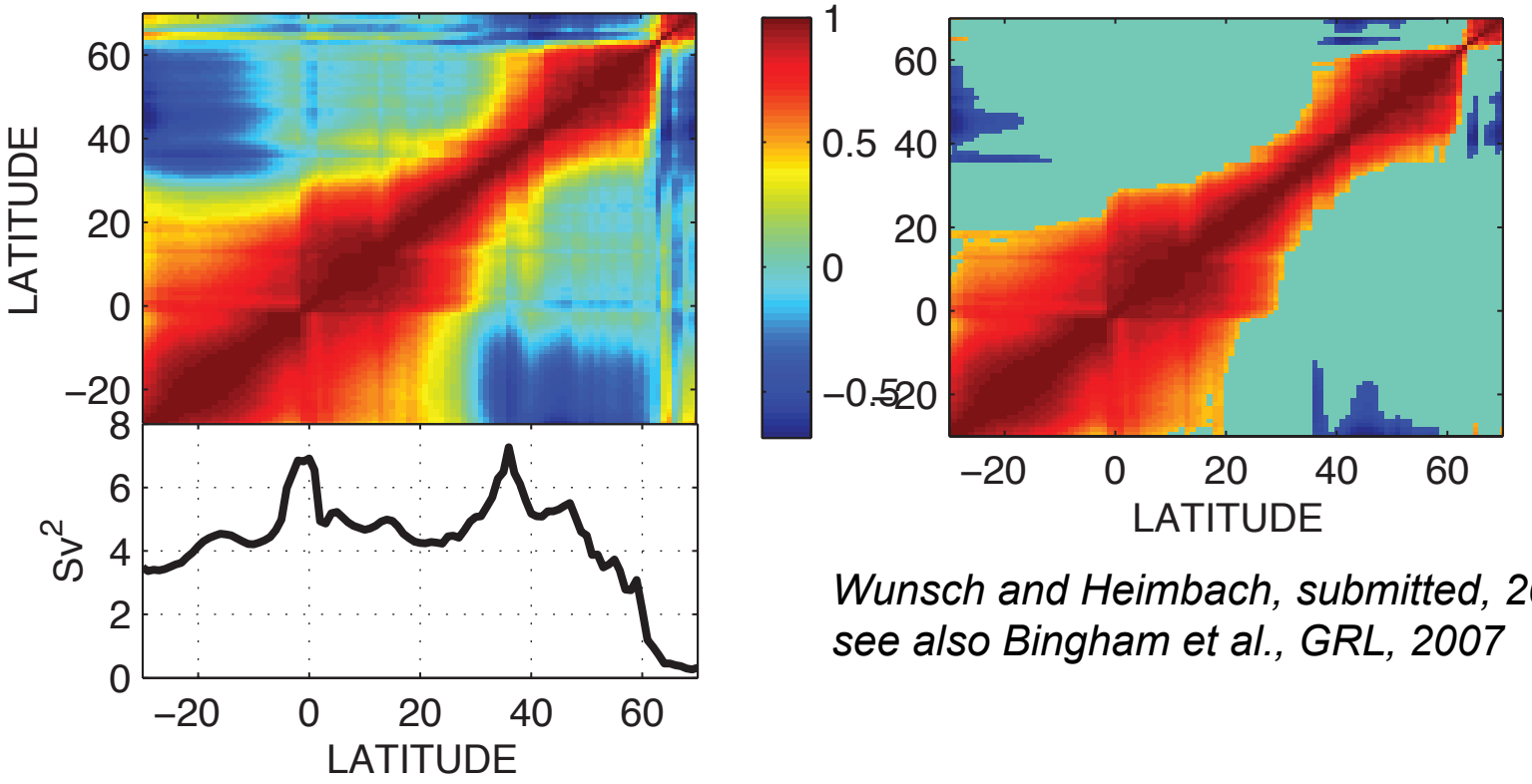
Wunsch and Heimbach, submitted, 2012



Autocorrelation function suggests

- essentially white-noise, with slight reddening toward higher latitudes
- but too short time series to resolve multi-decadal adjustment timescales)

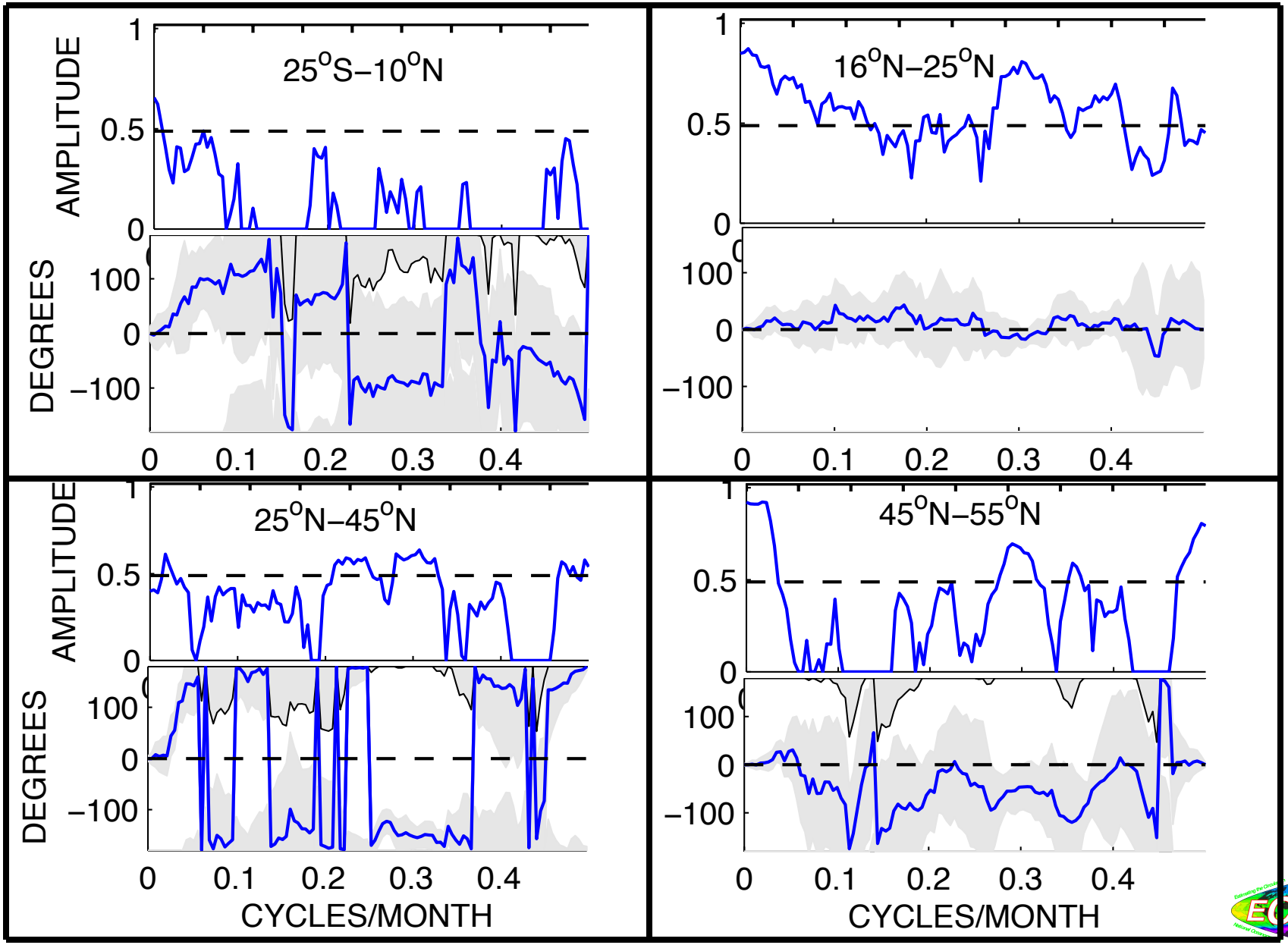
Meridional AMOC correlation matrix



Wunsch and Heimbach, submitted, 2012
see also Bingham et al., GRL, 2007

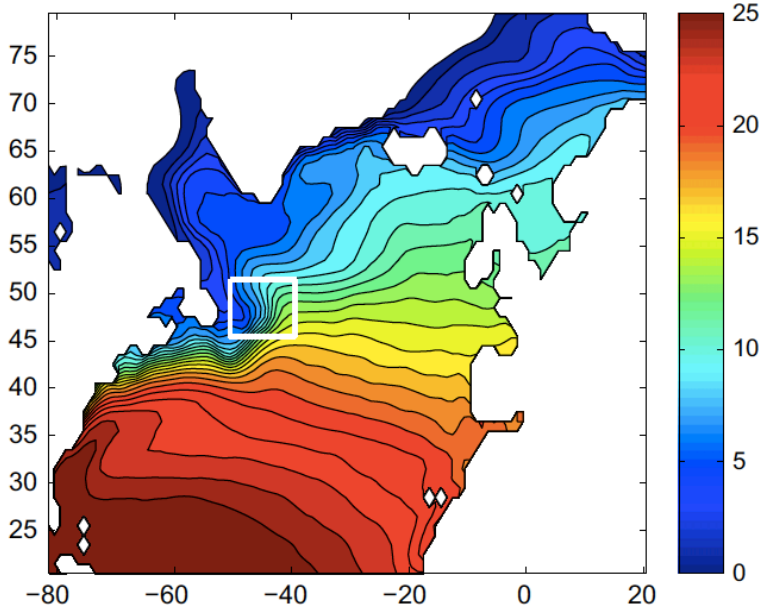
- Confirms findings of meridional decorrelation across ~40°N
  - different circulation regimes vs. masking by noise
  - issues of lumping together of dynamical regimes into zonal integrals
  - a limitation: no separation of time scales of variability

ECCO-SP v4:
Coherence amplitude & phase between neighboring latitudes



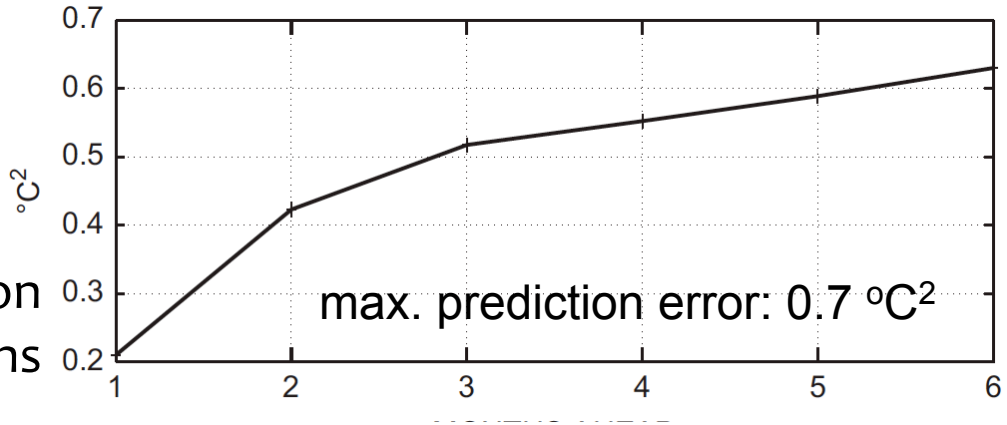
Exploring linear predictability via autoregressive (AR) models

Wunsch, DSR, 2012

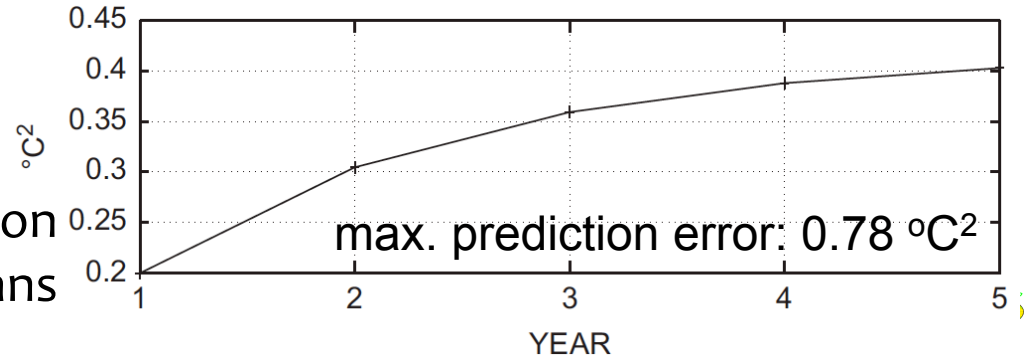


- Assume system to be linear
- Represent SST (w/o annual seasonal cycle) as AR(N) process
- Separately consider seasonal and interannual prediction

month-ahead prediction from monthly means



year-ahead prediction from yearly means

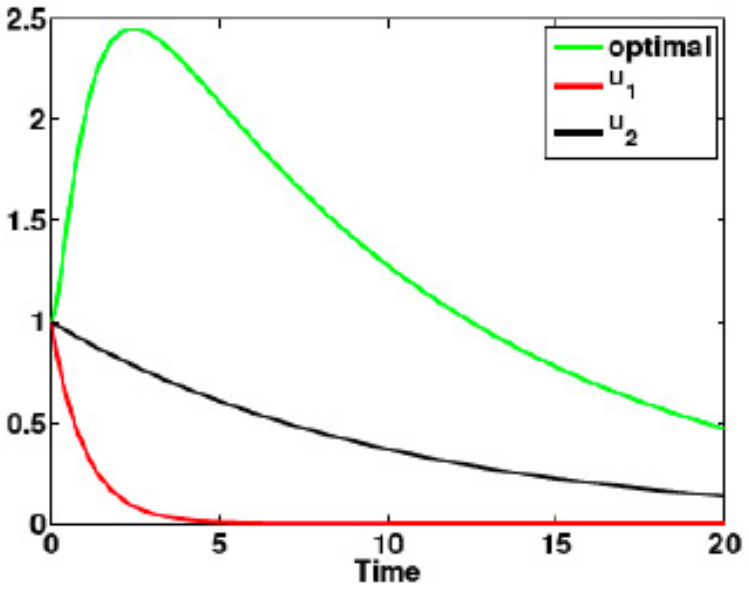


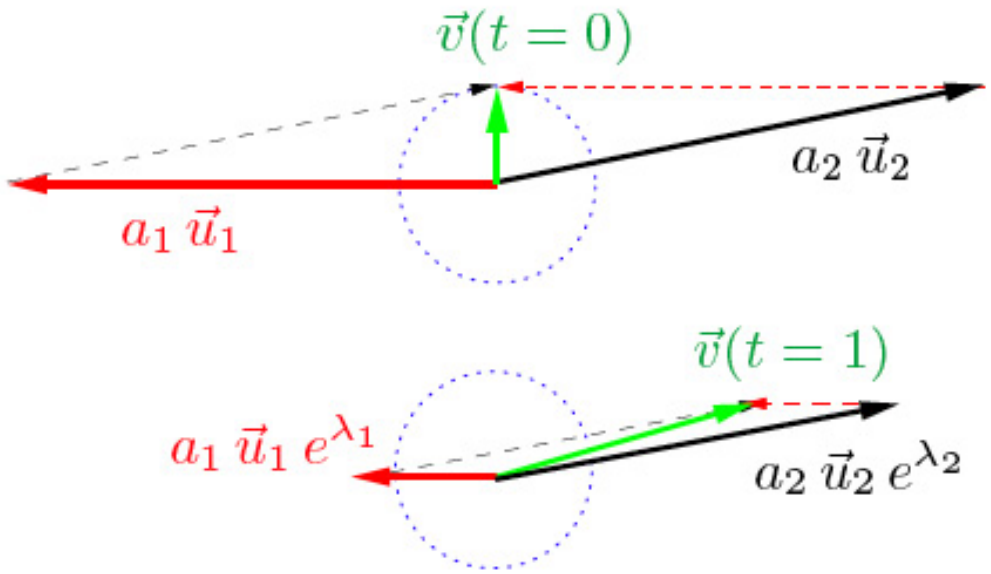
Transient growth & non-normal amplification of linear decaying modes

Zanna et al., 2011/12

- Singular vectors (SVs): fastest (or optimal) growing perturbations for a chosen norm (Lorenz, 1965), e.g. AMOC anomalies

  - Non-orthogonal superposition of modes, both of which decay, but with very different time scales
  - Leads to transient amplification on the fast decaying time scale Farrell (1988, 1989), Trefethen et al. (1993), Trefethen (1997)





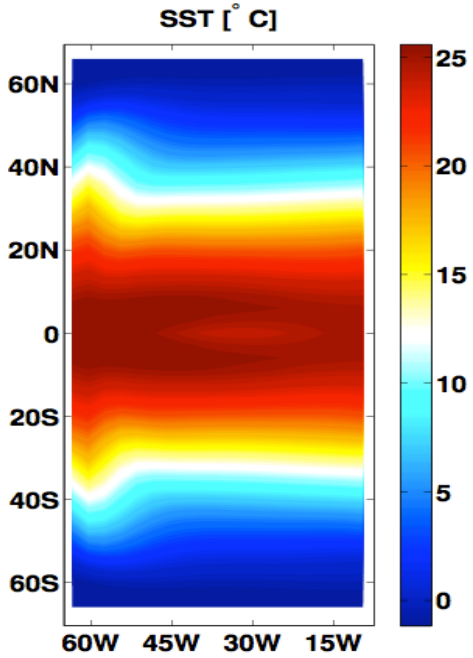
How to calculate SVs in an ocean general circulation model (GCM)?

Zanna et al., 2011/12

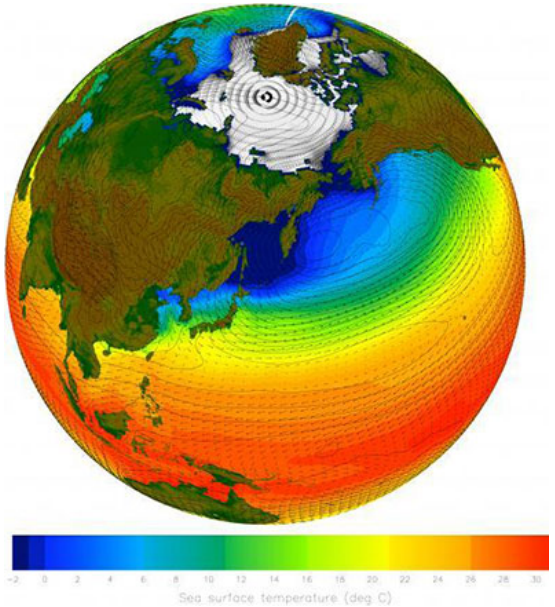
Here we consider an idealized basin configuration:

- the MIT general circulation model @ 1° horizontal resolution
- with tangent linear and adjoint model capabilities

MITgcm ocean basin
(Marshall et al., 1997)
http://mitgcm.org



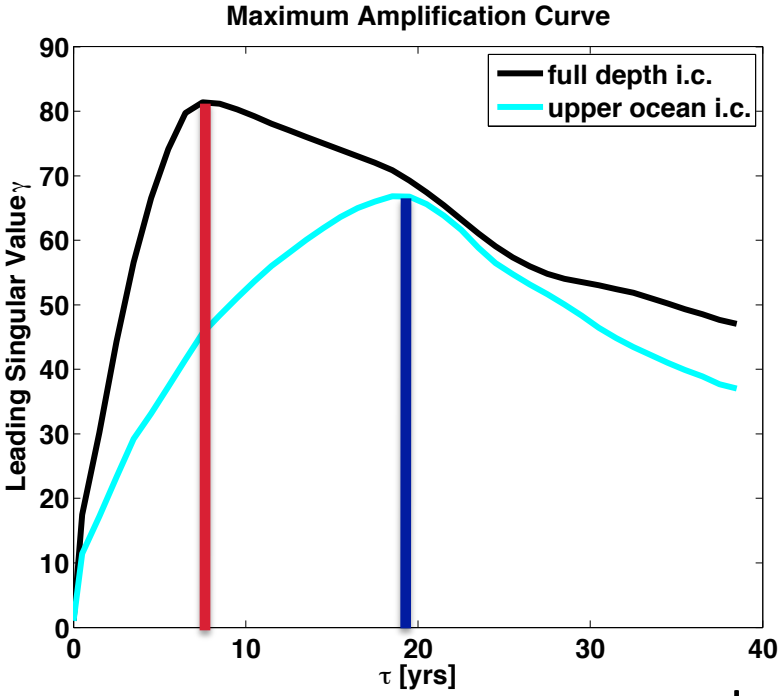
An IPCC AR4 model: GFDL CM2.1
@ 1° horizontal resolution
(Delworth et al. 2006)



Results: SV's for upper-ocean vs. full-depth perturbations

Zanna et al., 2011/12

- Singular vectors constrained to upper 300 m (SST / mixed-layer) vs. full depth 3D perturbations



7 yr **19 yr**

predictability horizon (uncertainty growth)

Time scales & amplitudes:

Full 3D singular vectors:

$$\vec{P}_0' = 0.1C \rightarrow \; MOC'(7.5yrs) = 2.4Sv \;\; (12\% \;\; mean)$$

Upper 300 m singular vectors:

$$\vec{P}_0' = 0.1C \rightarrow \; MOC'(19yrs) = 1.8Sv \;\; (9\% \;\; mean)$$

Impact of upper ocean perturbations on MOC:

1. not as efficient
2. not as fast as the deep perturbations

→ an overestimate predictability time

Conclusions

- State estimation indispensible for
  - data synthesis (see *R. Ponte* talk on Thu.)
  - obtaining basin-wide (& global) perspective
  - process partitioning/budgets (see *M. Buckley* talk; *C. Piecuch* poster)

- Preliminary solution from new-generation ECCO-SP estimate suggests little discernable AMOC trends at various latitudes for 1992-2010

- white to weakly red spectral character suggests that AMOC index
  - integrates various (high-frequency) processes
  - perhaps of limited use for deeper understanding

- Predictability horizon, applying several linear methods, appears to be limited; much less than a decade

- For some of these analyses, available time series remain too short to provide robust results