Do ocean reanalysis products agree on the historical representation of the AMOC?

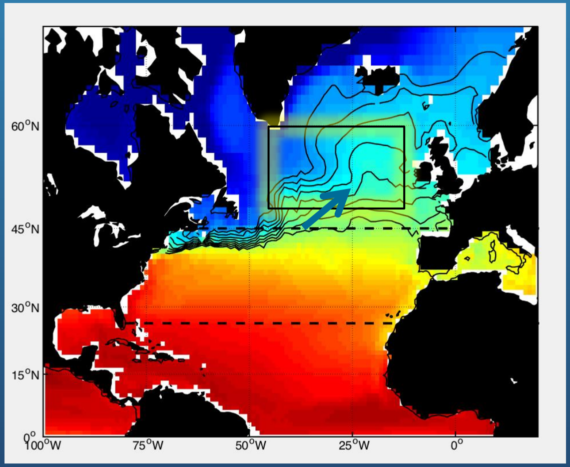
Alicia R. Karspeck

Detlef Stammer, Gokhan Danabasoglu

Thanks to Magdalena Balmaseda, Doug Smith ,Tony Rosati, Shaoquing Zhang, Armin Köhl, Keith Haines, Maria Valdivieso, Yosuke Fujii , Ben Giese for making AMOC data available

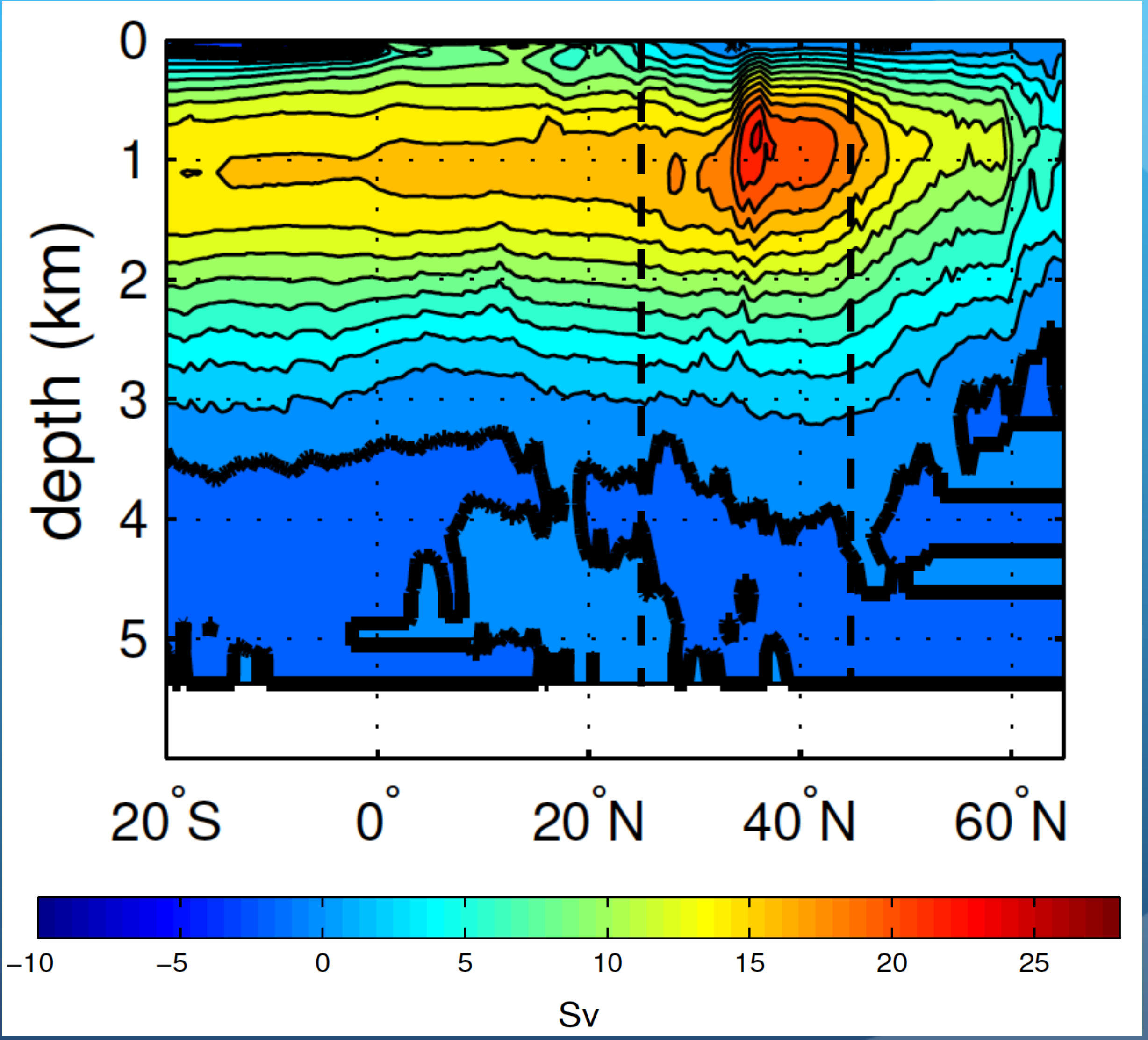
AMOC and the initialization of decadal prediction

- The AMOC state upon initialization has been cited an important influence on **decadal-scale climate prediction** in the North Atlantic (specifically the subpolar gyre).
  (Robson et al 2012; Yeager et al 2012, Matei et al 2012; Msadek et al 2014)
- In the context of decadal climate prediction --- An anomalous AMOC is invoked as a reasonable “proxy” for an anomalous net heat transport by the ocean into the subpolar gyre.



$$[vT]' = \underline{v}T' + v'\underline{T} + v'T'$$

Atlantic Meridional Overturning Circulation



Groups that have contributed* AMOC reanalyses
from 1960 – 2007 (or longer)

GROUP	METHOD	INSITU T/S	ALT	SST	NoAssim Control run?	Atm forcing	DP INIT?
GECCO2 (U. Hamburg)	4DVAR	YES	YES	YES	YES	[NCEP]*	YES
ORAS4 (ECMWF)	NEMOVAR 3DVar	YES	YES	YES	YES	ERA-40/ ERA-I	YES
MOVE-CORE (MRI)	3DVar	YES	NO	NO	YES	CORE II IAF	[NO]
SODA (U.Marylnd/ TAMU)	OI	YES	NO	YES	YES	20-CR	YES
DePreSys (UKMET)	Coupled nudging to OI product	YES	NO	YES	NO	N/A	YES
ECDA3.2 (GFDL)	coupled EaKF	YES	INDIRECTLY	YES	NO	[NCEP]*	YES

* Karspeck et al. 2013 (submitted Climate Dynamics)

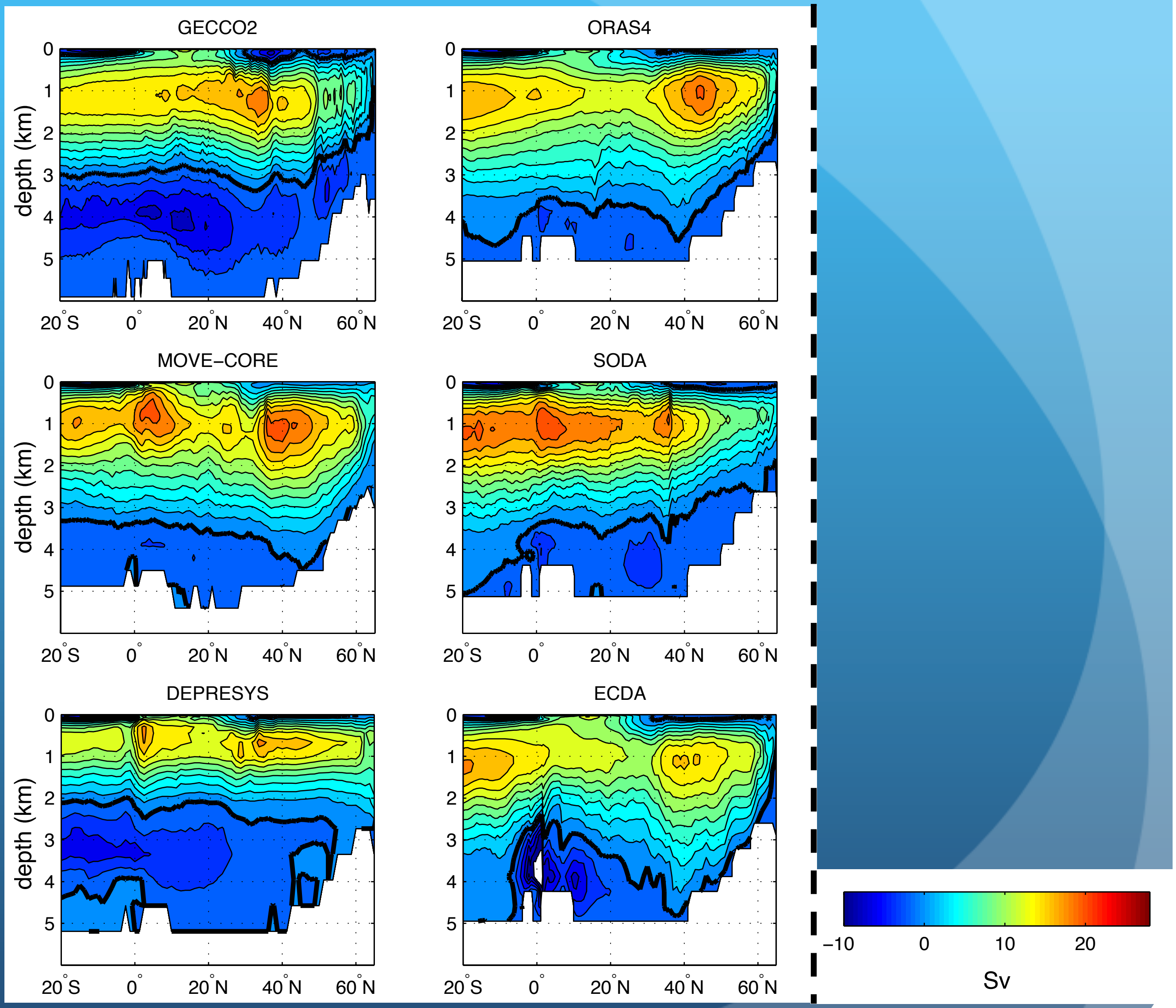
Groups that have contributed* AMOC reanalyses
from 1960 – 2007 (or longer)

GROUP	METHOD	INSITU T/S	ALT	SST	NoAssim Control run?	Atm forcing	DP INIT?
GECCO2-REF (U. Hamburg)	4DVAR	YES	YES	YES	YES	NCEP	YES
ORAS4-CNTRL (ECMWF)	NEMOVAR 3DVar	YES	YES	YES	YES	ERA-40/ ERA-I	YES
MRI-CORE (MRI)	3DVar	YES	NO	NO	YES	CORE II IAF	NO
SODA-NOASSIM (U.Marylnd/ TAMU)	OI	YES	NO	YES	YES	20-CR	YES

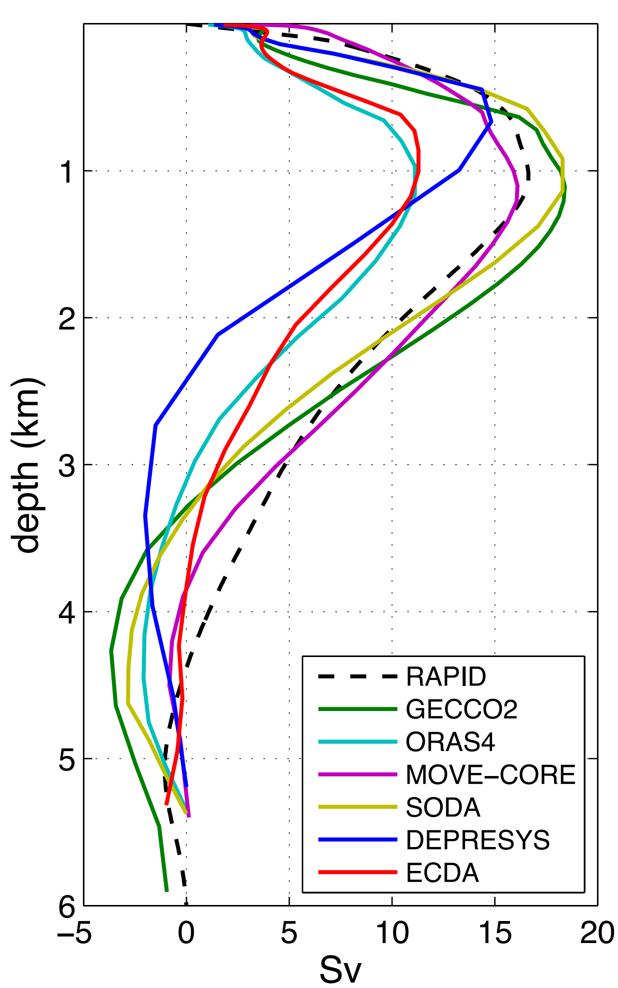
4 groups also contributed "No Assimilation" simulations to help understand the role of data constraint

*Karspeck et al. 2015 (submitted Climate Dynamics)

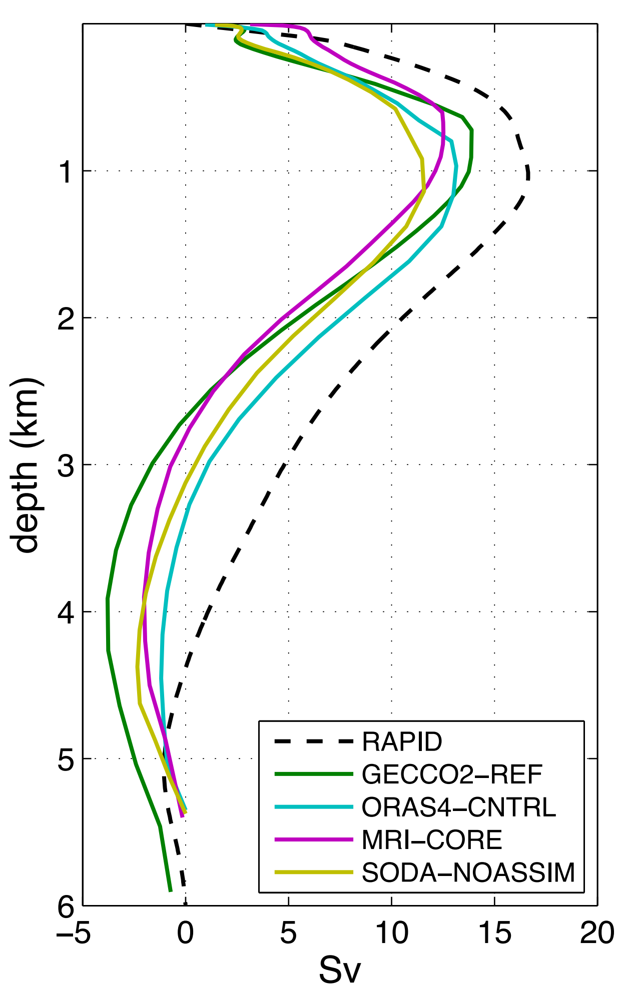
AMOC time mean (1961-2007)



Comparison to RAPID estimates @ 26.5N

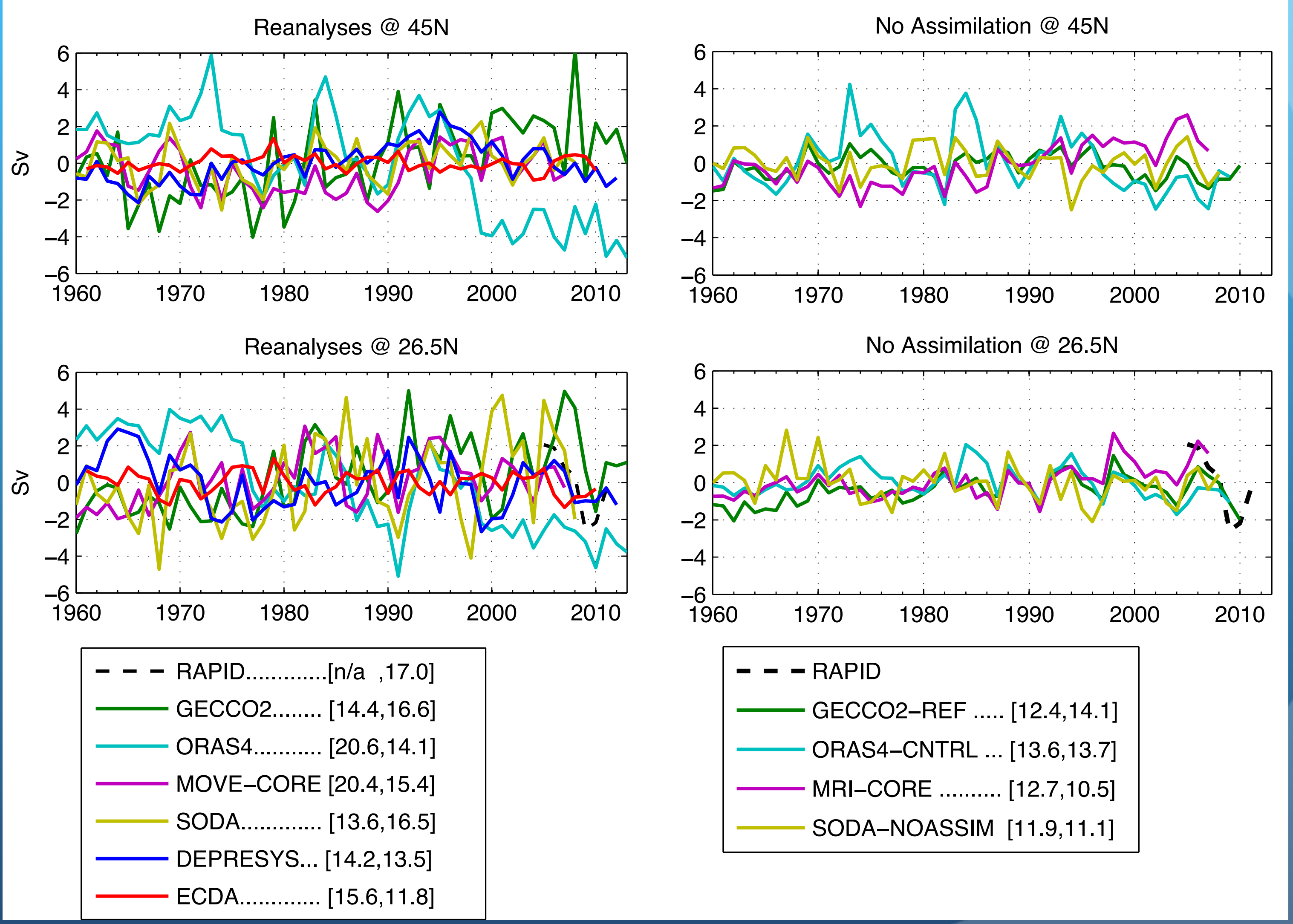


Reanalysis set

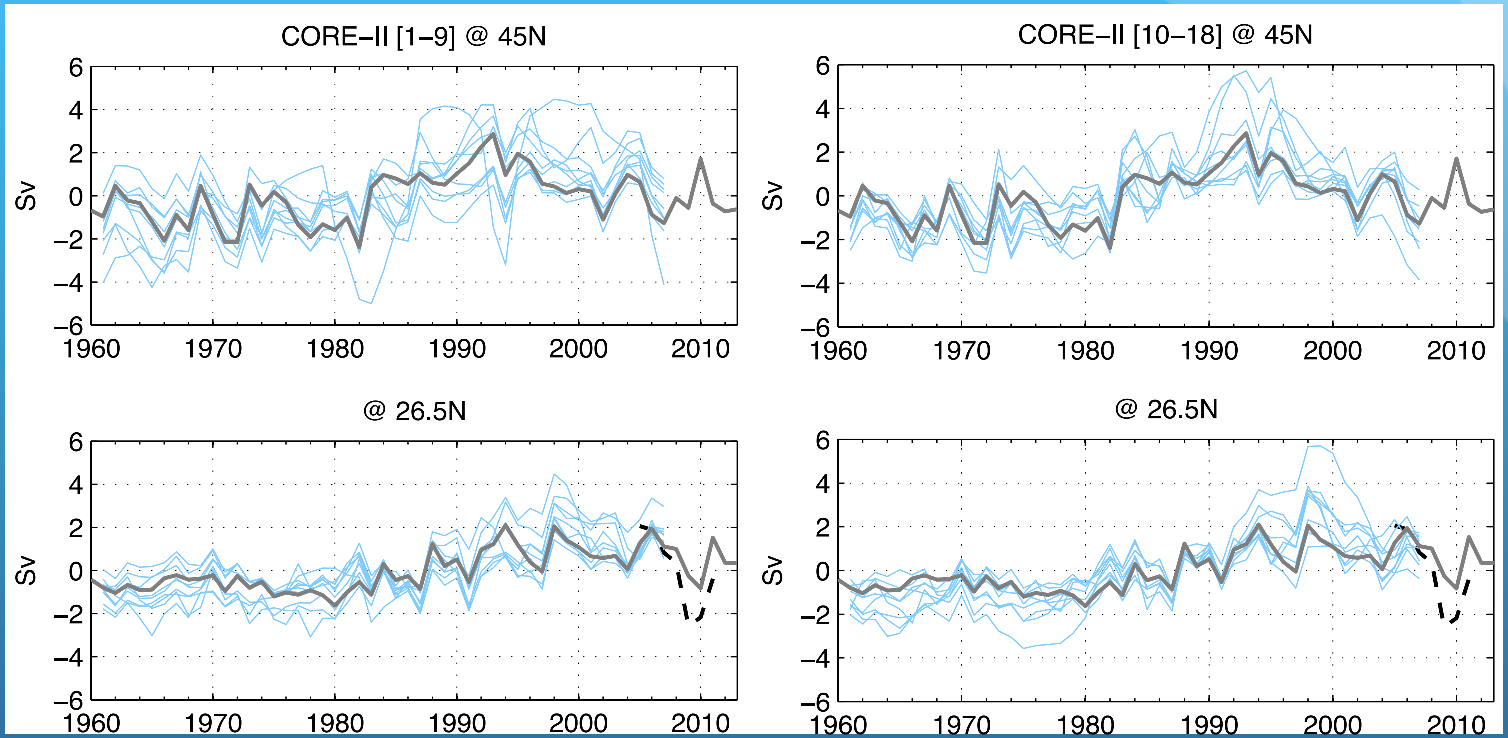


NoAssimilation set

Annual-mean AMOC variability @ 1000m

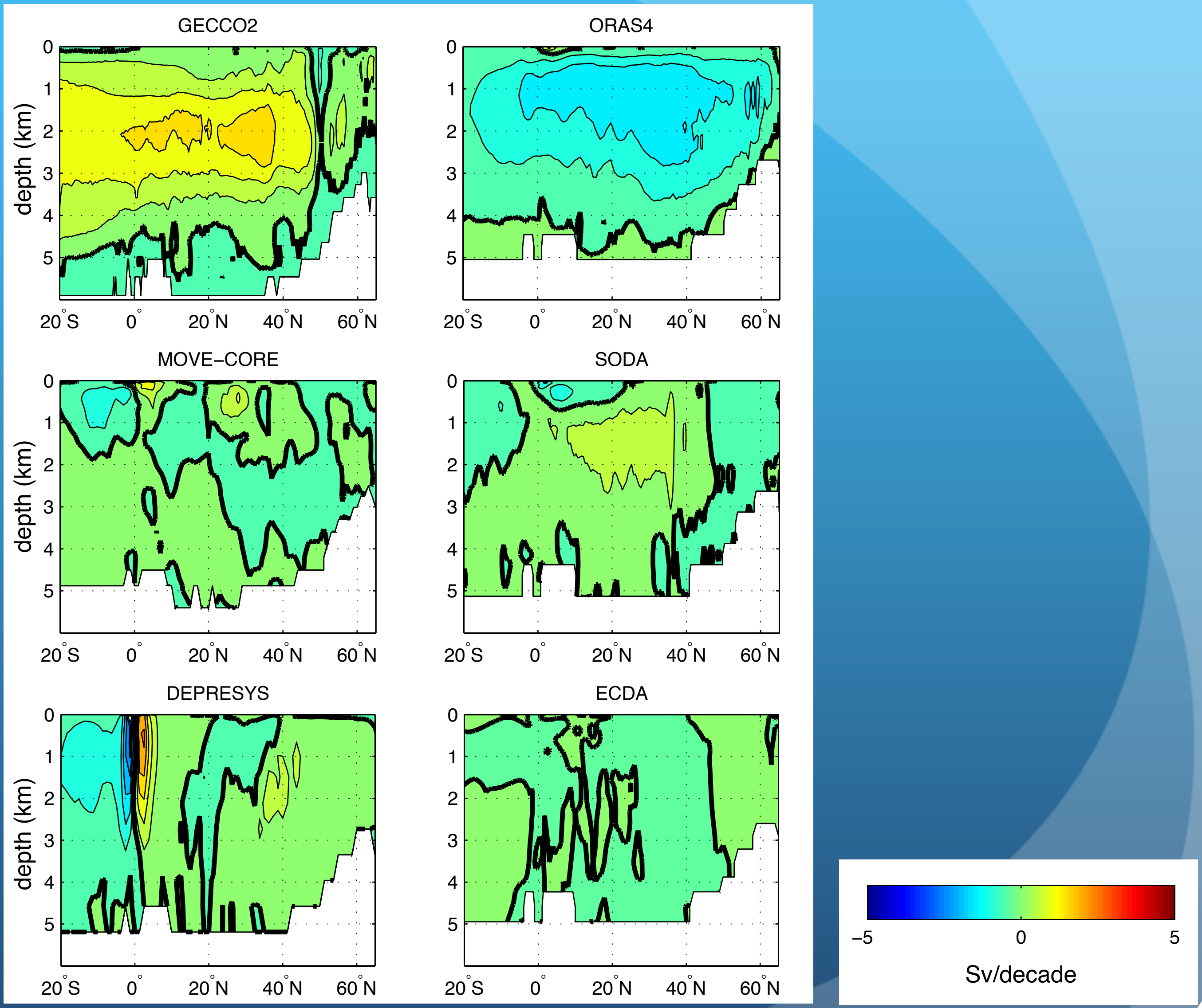


Annual-mean AMOC variability @ 1000m

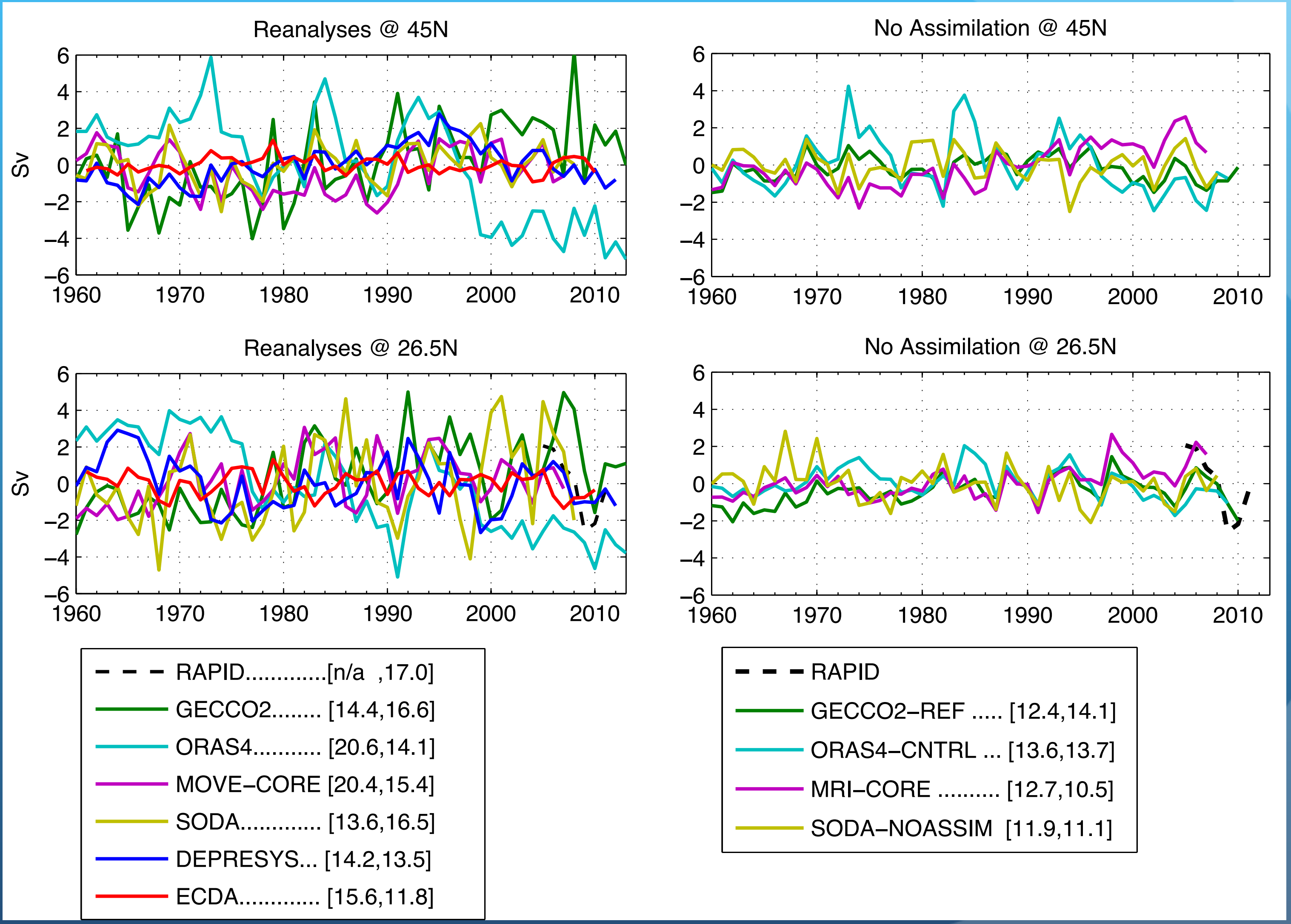


20 different models, identical CORE-IAF forcing, identical spinup procedures

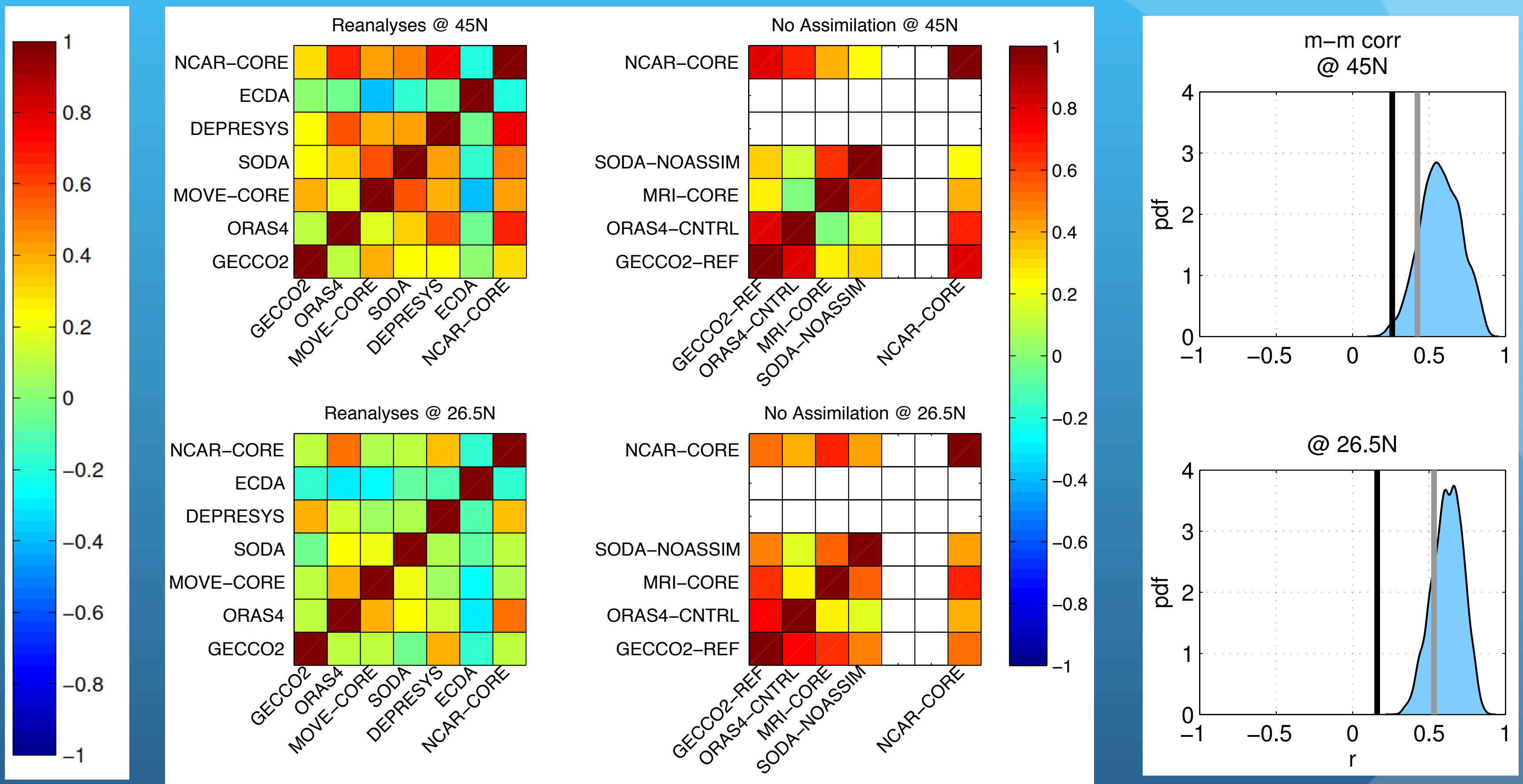
Linear trend (1961-2007)



Annual-mean AMOC variability @ 1000m

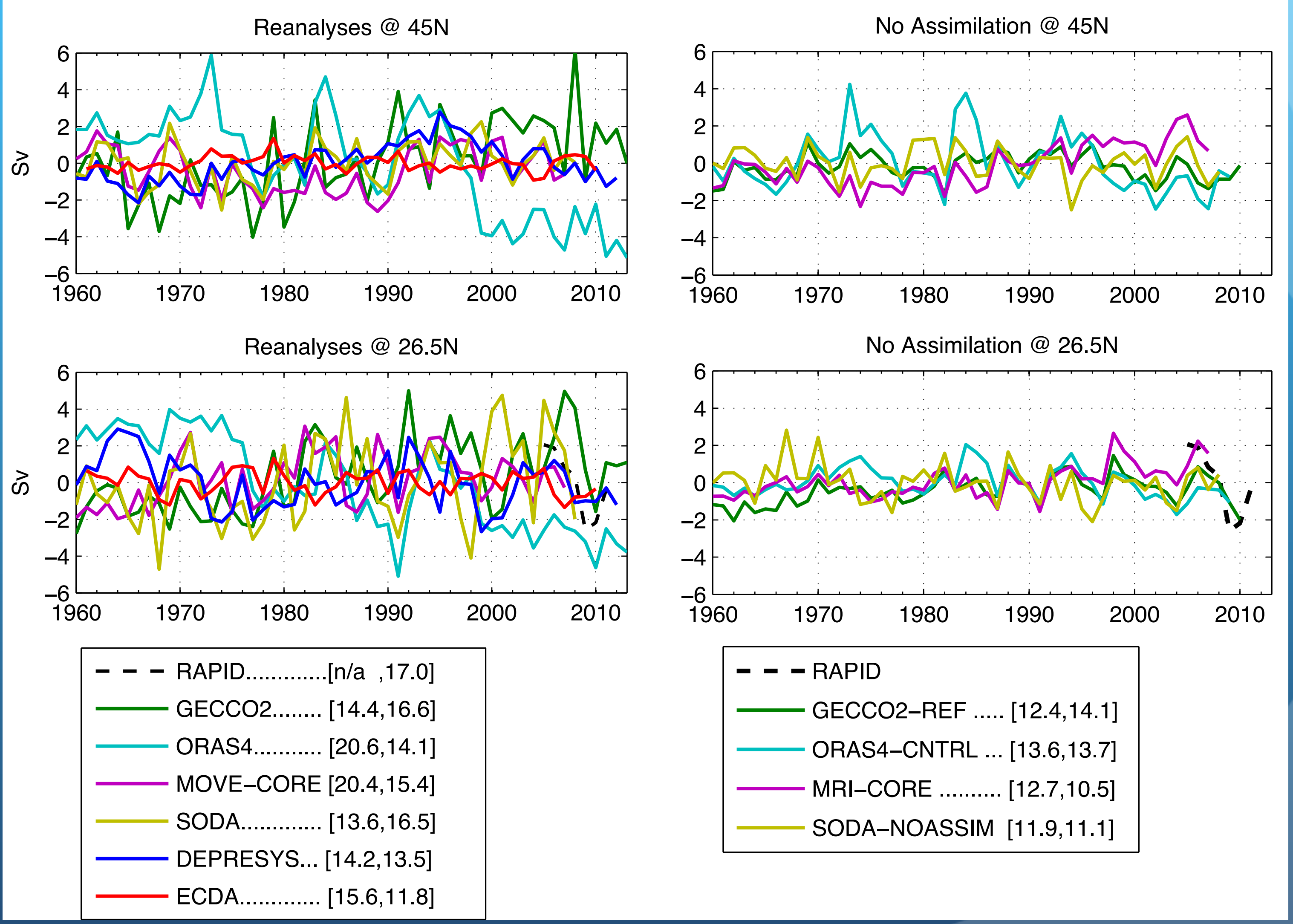


Within-group similarity: "model-model correlation"

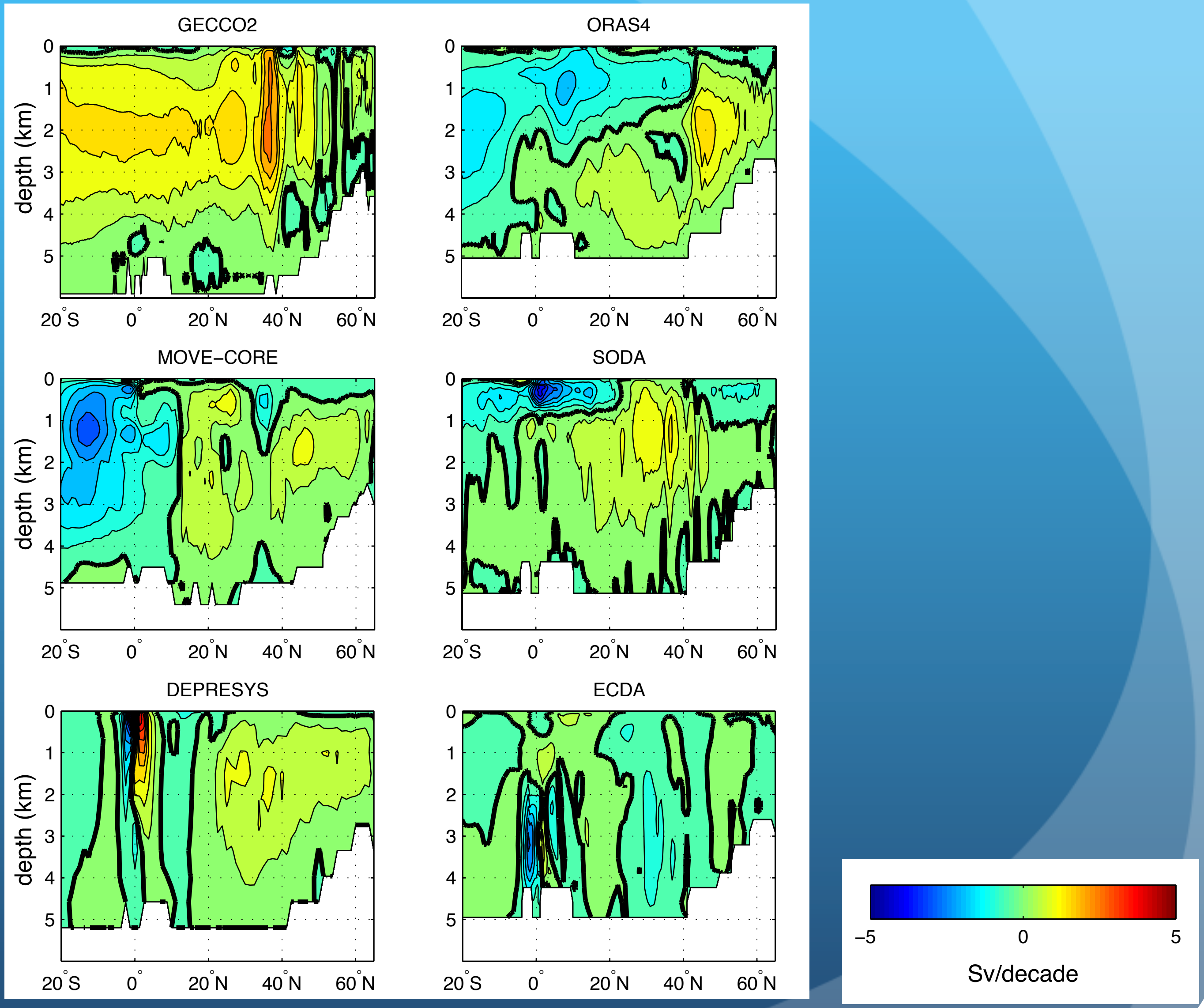


The assimilation process tends to ***reduce within group*** *consistency*

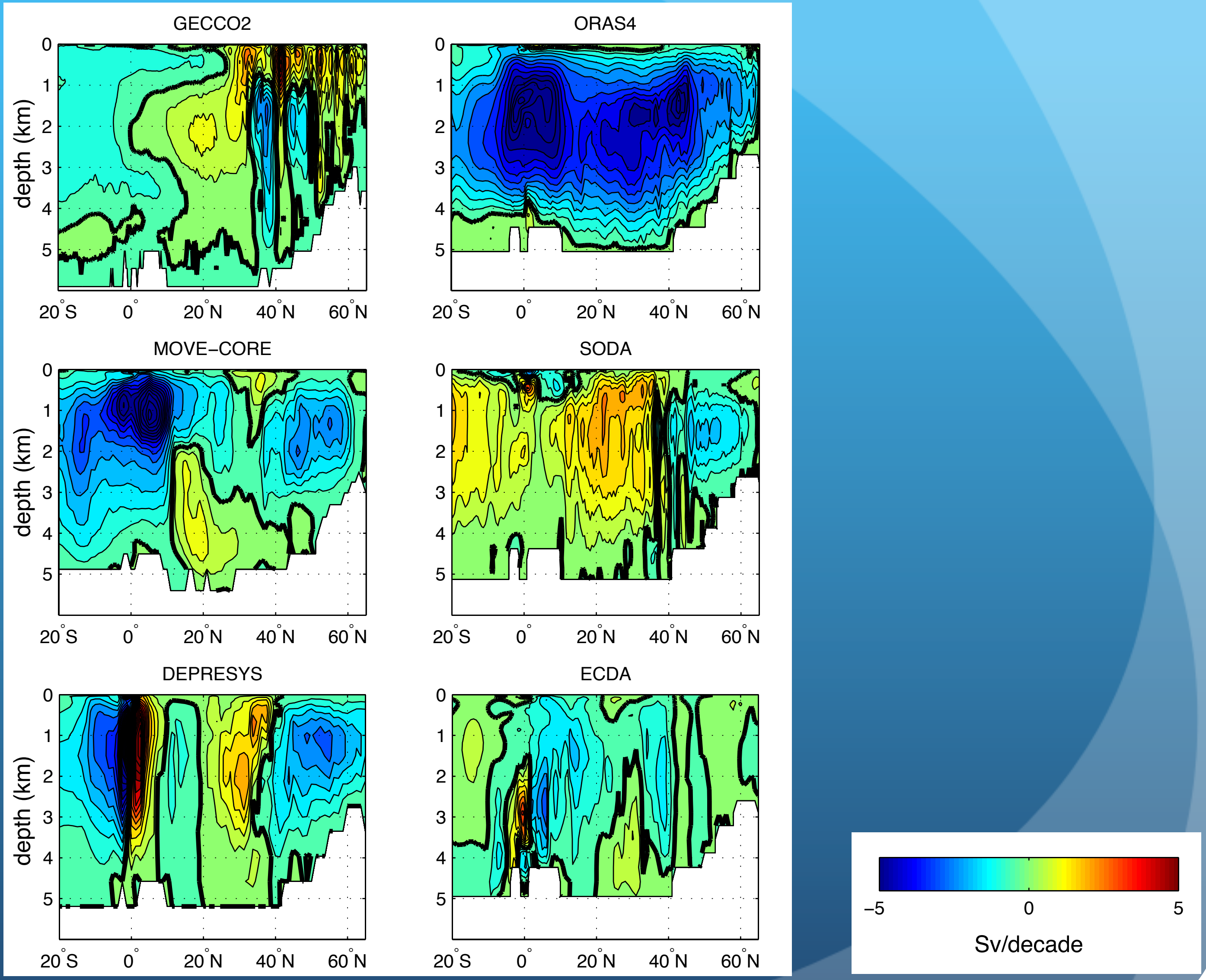
Annual-mean AMOC variability @ 1000m

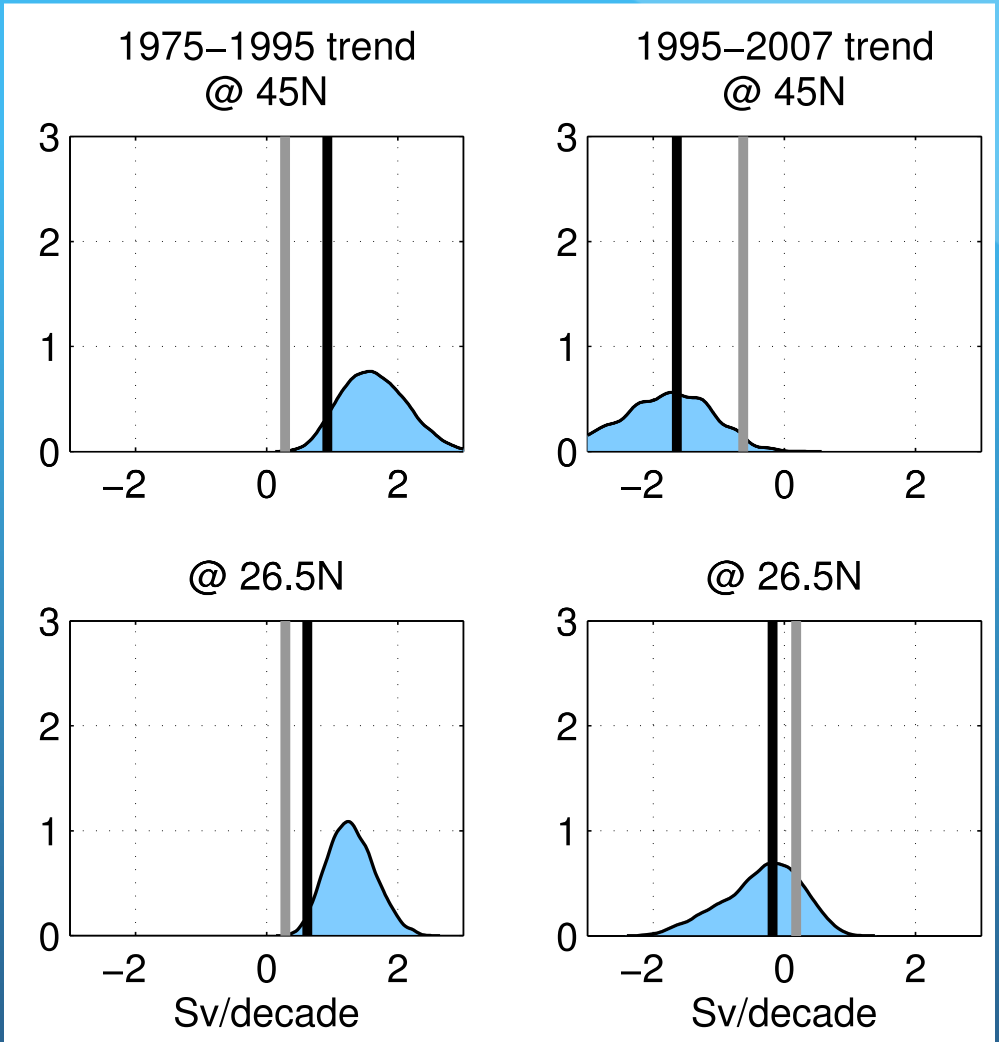


Linear trend (1975-1995)

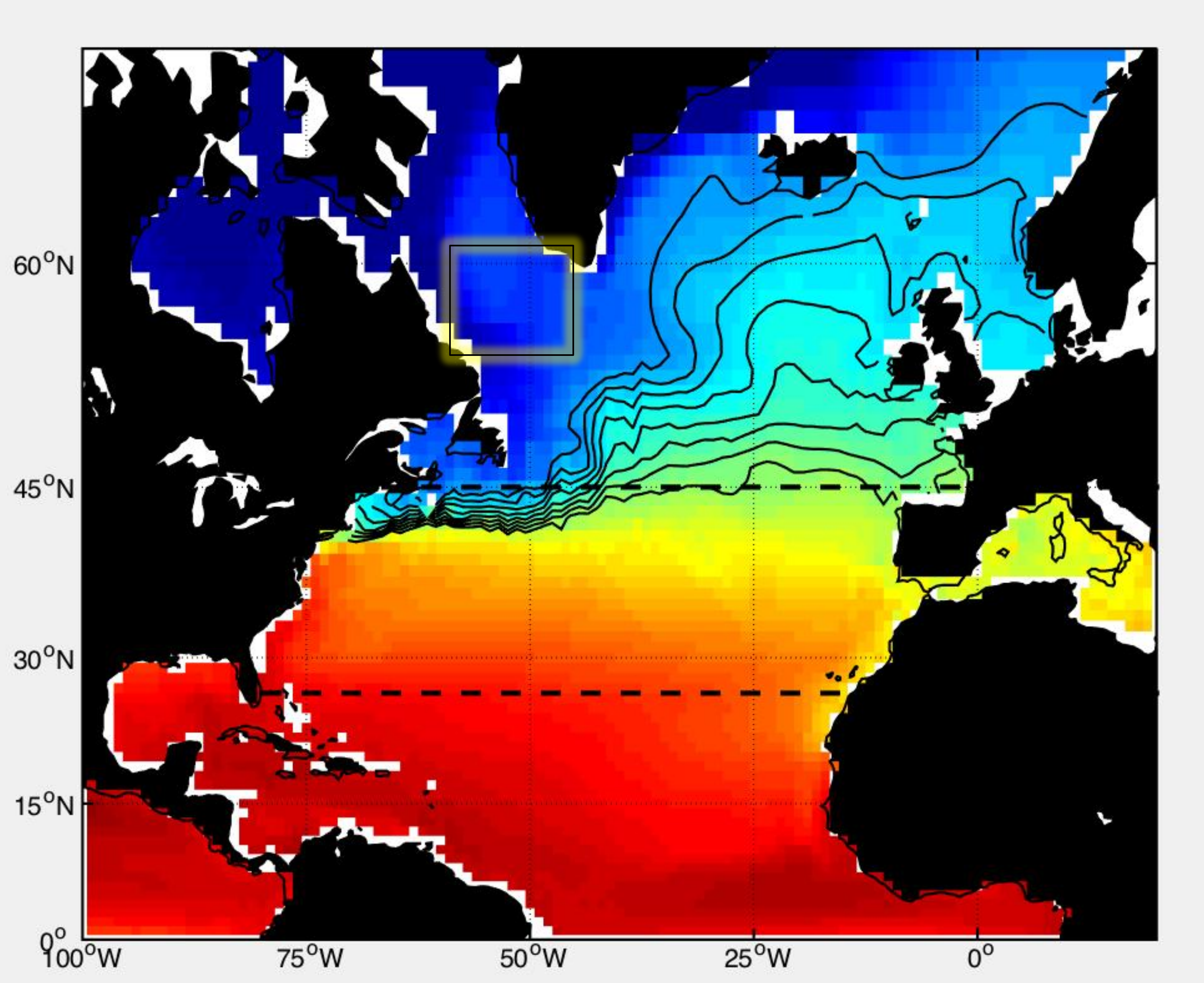


Linear trend (1995-2007)



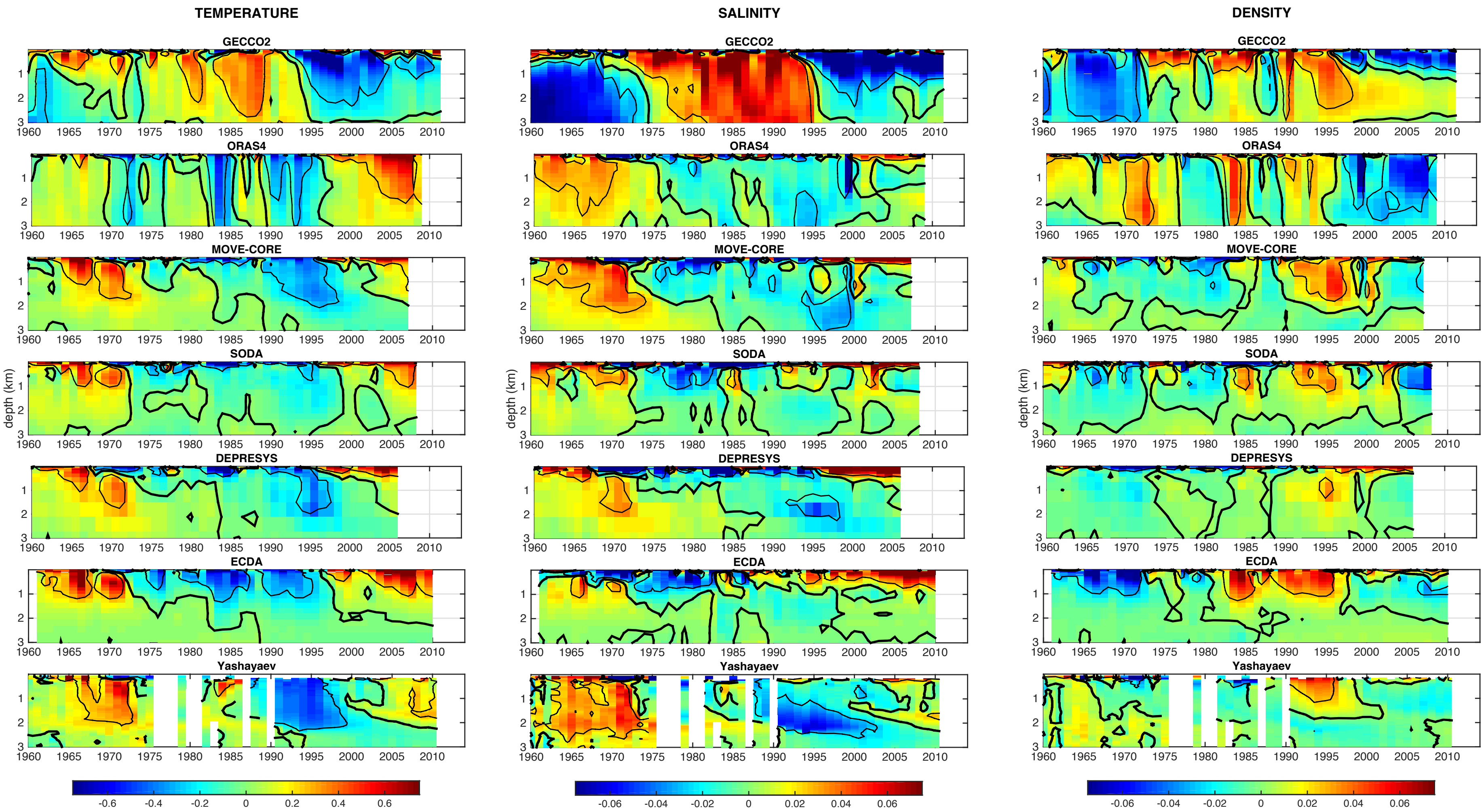


Some indications that DA contributes to the* upward trend in AMOC from 1975 to 1995 and a downward trend at 45N in the 2000's

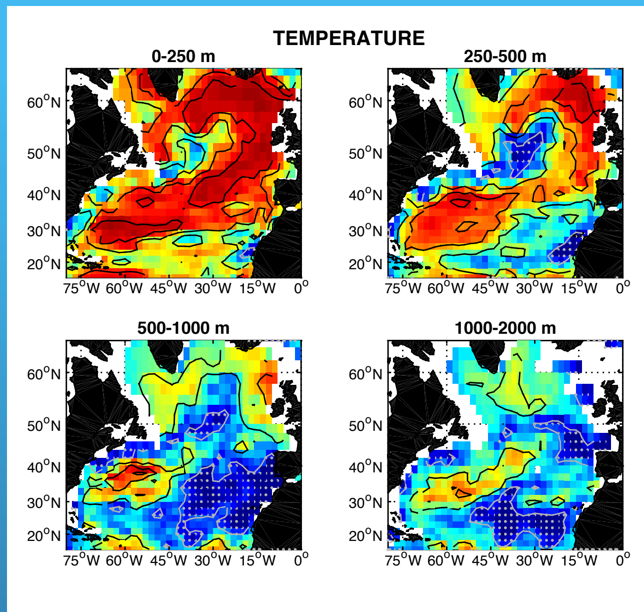


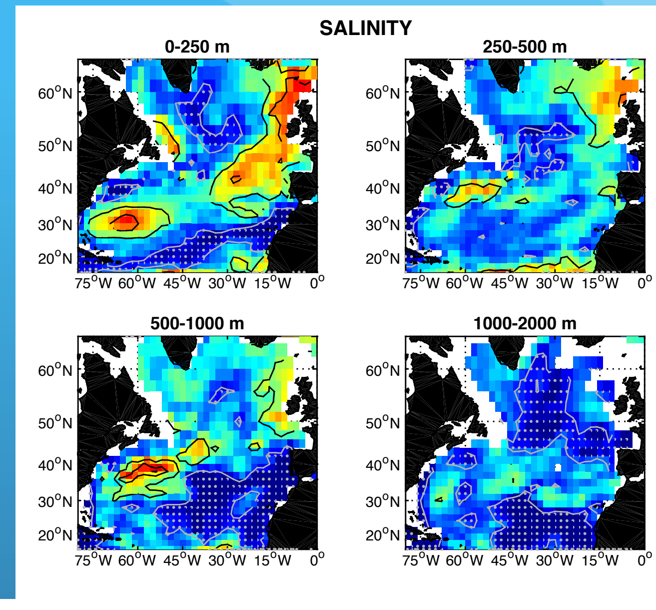
60°N
45°N
30°N
15°N
0°
100°W
75°W
50°W
25°W
0°

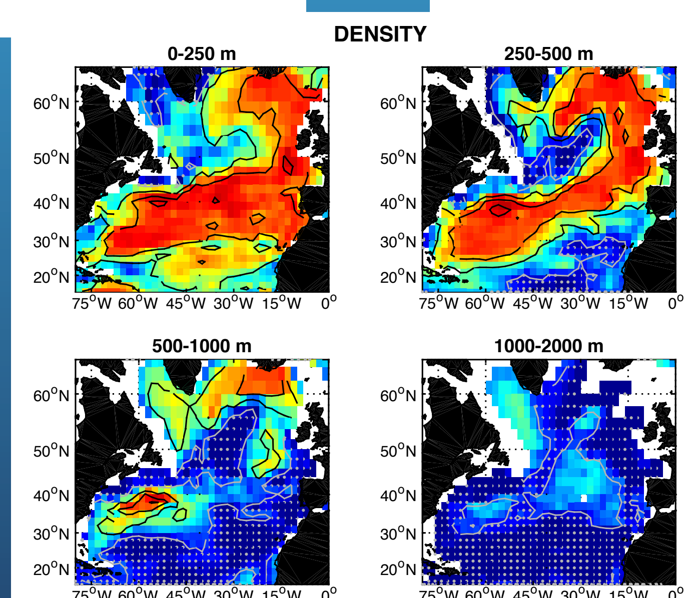
Hydrography in the Labrador Sea



Hydrographic similarities*







*measured by average model-model correlation

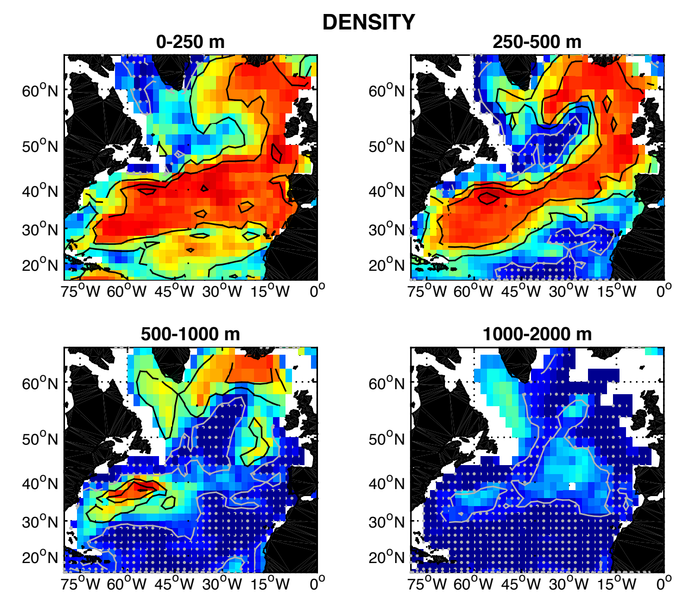
Transport variability computed from end-point density geostrophic shear

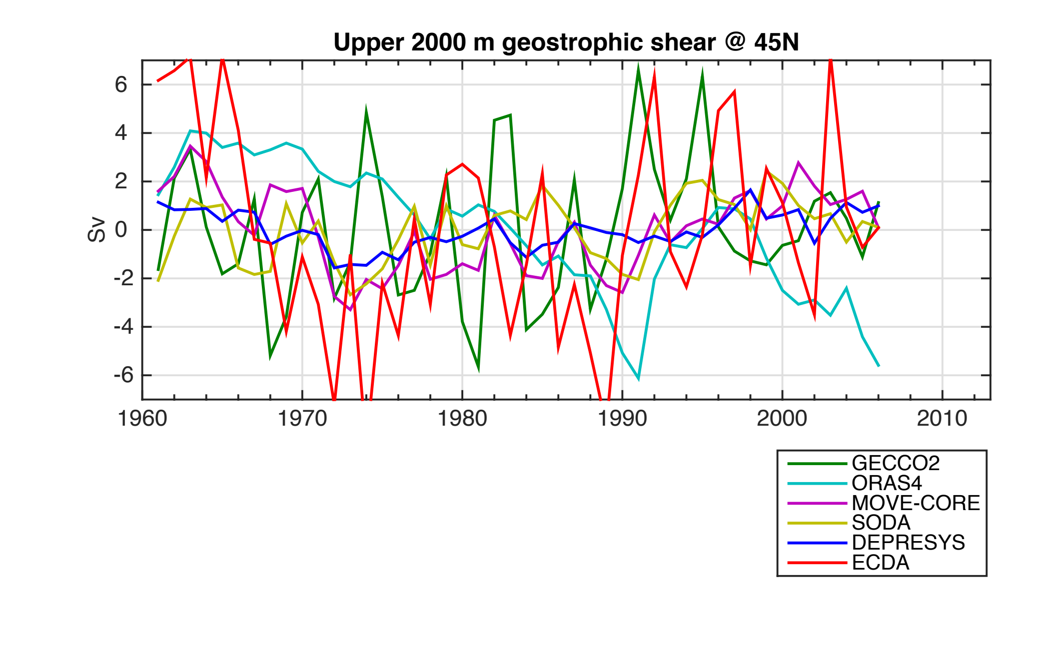
$$\Psi_{total} \approx \Psi_{Ekman} + \Psi_{geostrophic}$$

$$\Psi_{geostrophic} = \int_{-H}^{0} \frac{g}{f\rho_o} \int_{-H}^{z} \rho_w(z') - \rho_e(z')\,dz'\,dz \quad + \quad H\overline{v}^{x}_{-H}$$

Geostrophic shear

Velocity at reference level
(includes bottom pressure effects)





Some summary points :

- Ocean data constraints tend to increase mean AMOC strength (closer to RAPID observations)
- Ocean data constraints tend to increase trends and variability strength but...
- Long-term AMOC variability/trends are *less* consistent within ocean reanalysis products than in forced-ocean runs but…
- … show some agreement over the periods 1975-1995 and 1995 to present (likely associated with low-frequency density variations in the Lab sea)
- Disagreement in boundary density and density at depth in the subtropical gyre contribute to AMOC dissimilarity

Some questions:

If the AMOC state is important for prediction, can these products be used indiscriminately for initialization and verification?

Is high latitude AMOC really the most important metric for prediction in the subpolar gyre given that ocean heat transport is dominated the gyre circulation?

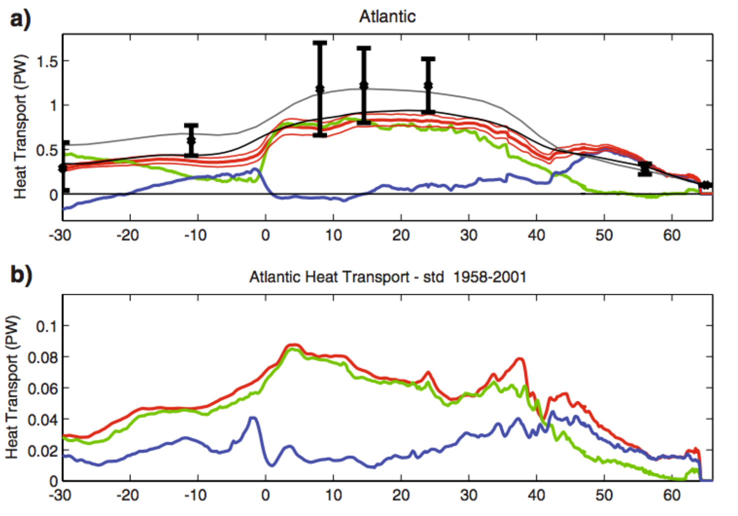
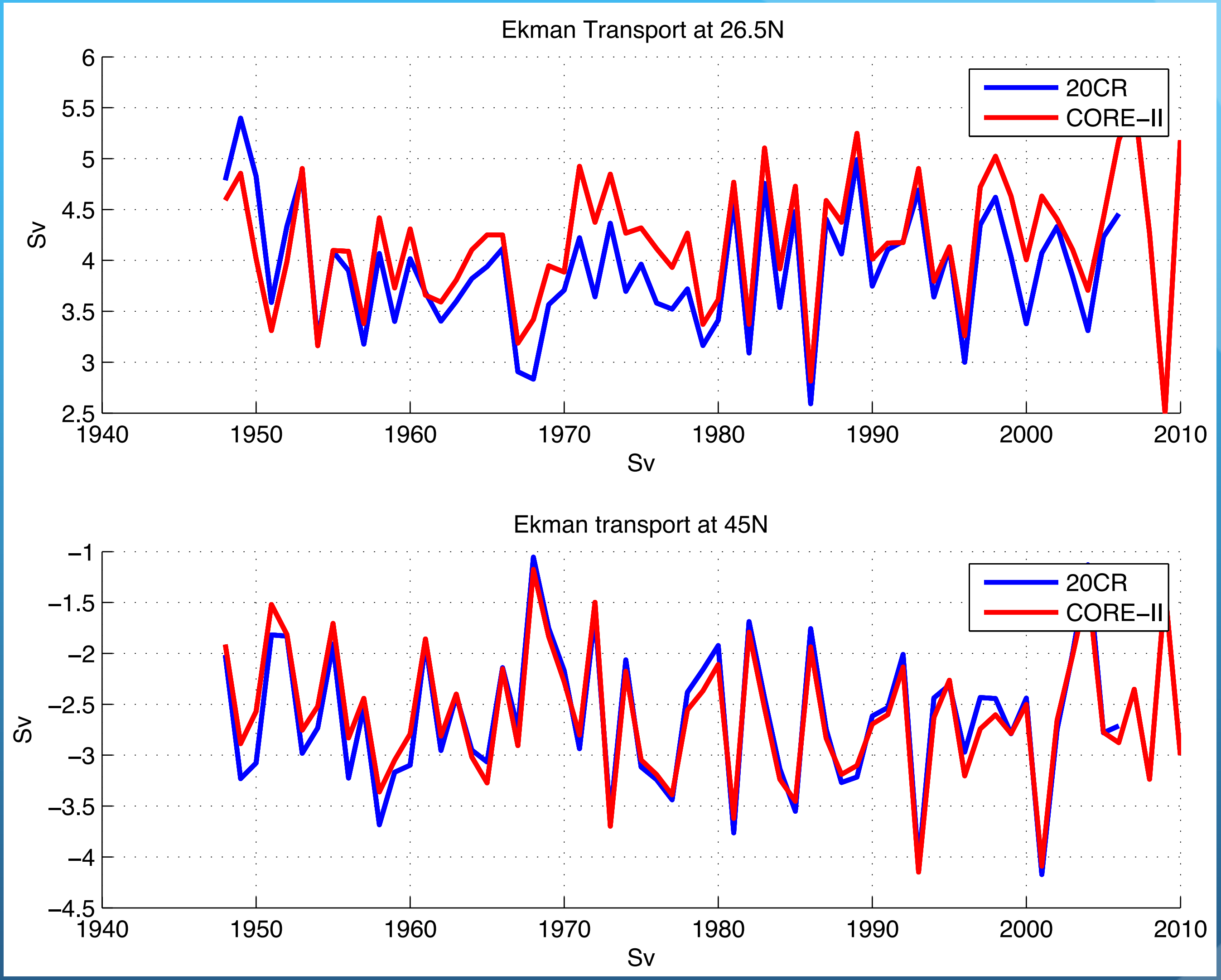
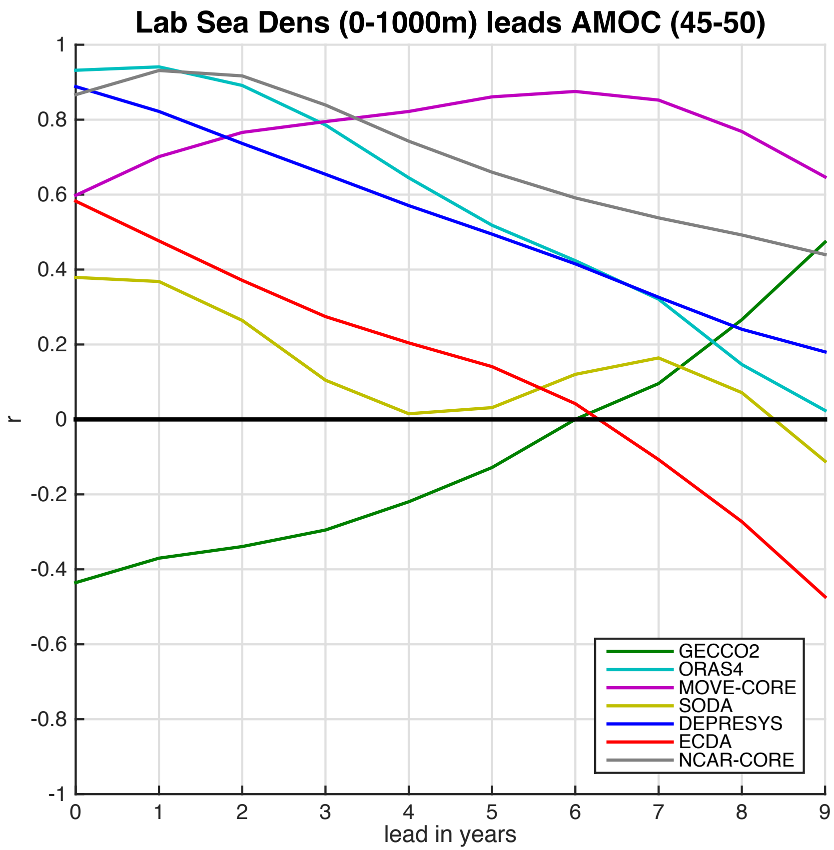


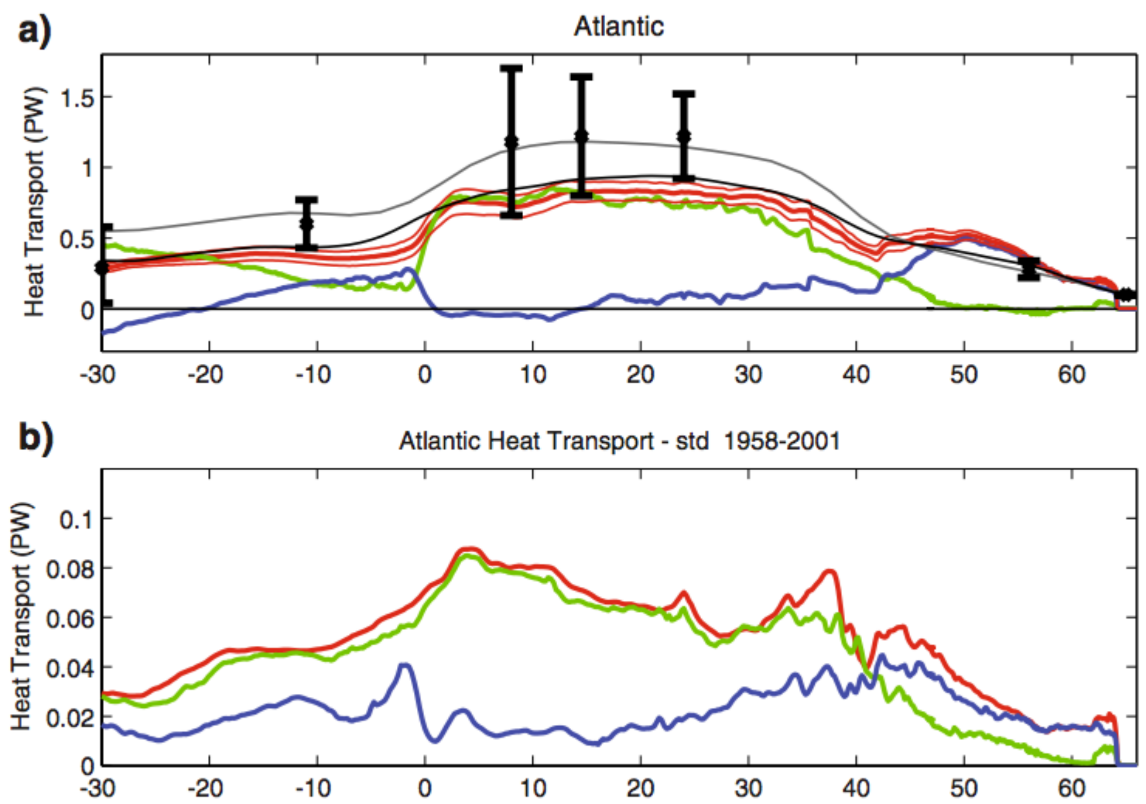
Fig. 6 Atlantic Meridional Ocean Heat Transport (*OHT*) from the model hindcast 1958–2001 as a function of latitude: mean (**a**) and standard deviation (**b**). *Red line* is the total transport, *green line* is the MOC component and *blue line* is the gyre component. **a** Also includes estimates of mean Atlantic transport from Trenberth and Caron (2001) (*grey line*), Grist and Josey (2003) (*black line*) and hydrographic sections (*black crosses*, see Table 1 for details). *Thin red lines* are ±1 standard deviation of the total heat transport

Grist et al. (2010)

Extra slides…


Ekman Transport at 26.5N
Sv
6
5.5
5
4.5
4
3.5
3
2.5
1940
1950
1960
1970
1980
1990
2000
2010
Sv
20CR
CORE−II
Ekman transport at 45N
Sv
−1
−1.5
−2
−2.5
−3
−3.5
−4
−4.5
1940
1950
1960
1970
1980
1990
2000
2010
Sv
20CR
CORE−II


Lab Sea Dens (0-1000m) leads AMOC (45-50)
r
lead in years
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
1
2
3
4
5
6
7
8
9
GECCO2
ORAS4
MOVE-CORE
SODA
DEPRESYS
ECDA
NCAR-CORE



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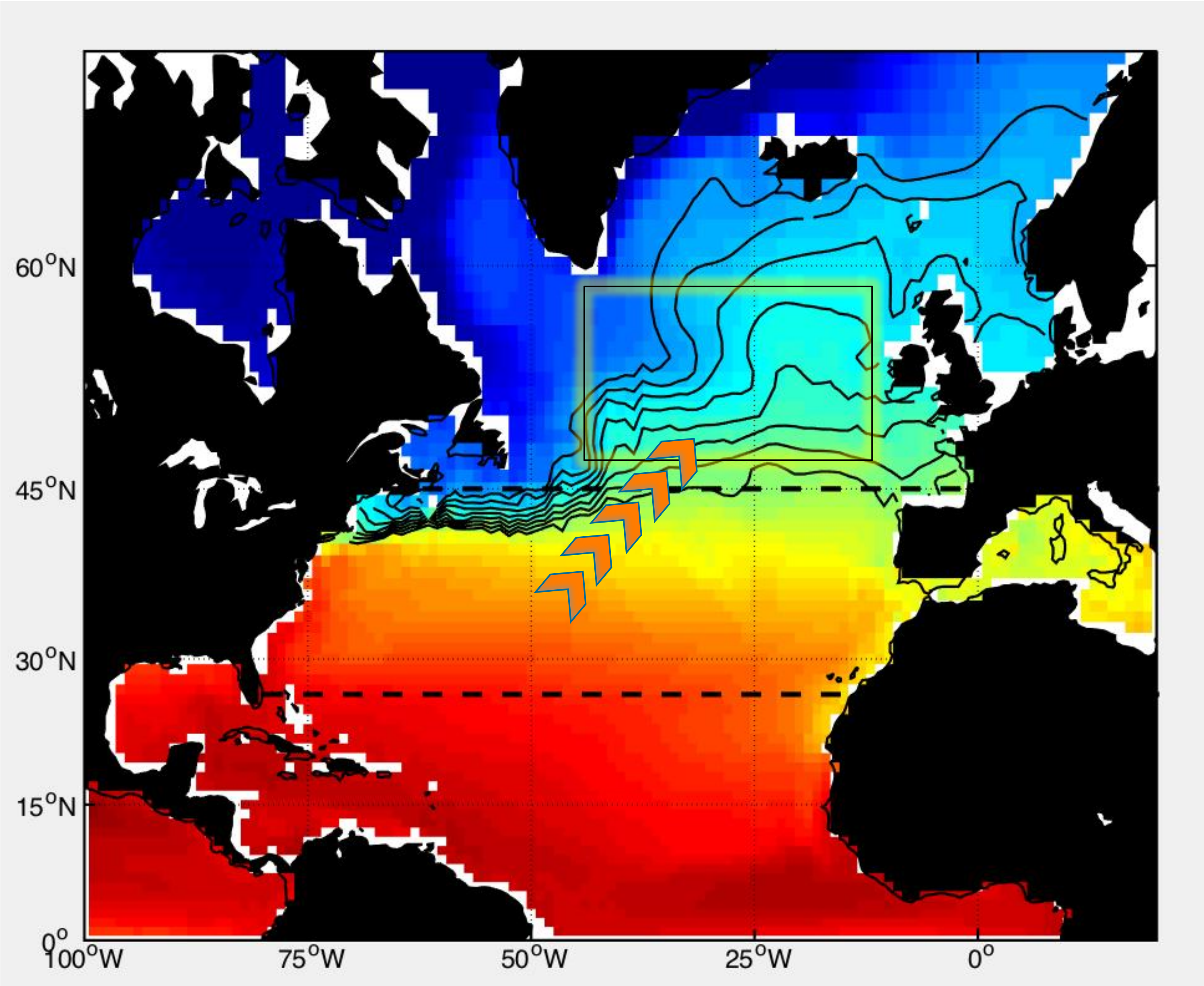
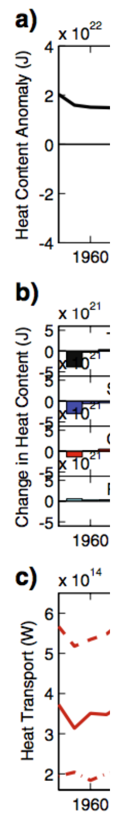
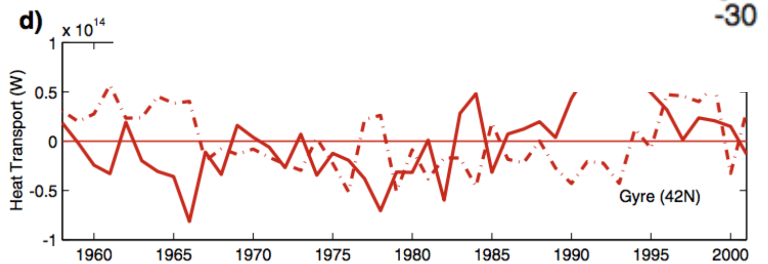


$$[vT]' = \underline{v}T' + v'\underline{T} + v'T'$$

Fig. 7 **a** Time series of full-depth ocean heat content anomaly, OHC* (J), in the North Atlantic subpolar gyre. **b** Anomalous annual change in heat content, ΔOHC* (J, *black bars*), and the contribution to this change from anomalous surface heat flux (*blue bars*), anomalous ocean heat transport convergence (*red bars*) and residual terms (*cyan bars*). **c** Ocean heat convergence for the North Atlantic Subpolar Gyre region (*solid red line*) and corresponding heat transports at the southern (*dashed*) and northern (*dot-dashed*) boundaries of the domain (W). **d** Anomalies of the MOC (*solid*) and gyre (*dot-dashed*) components of heat transport (W) at the southern boundary





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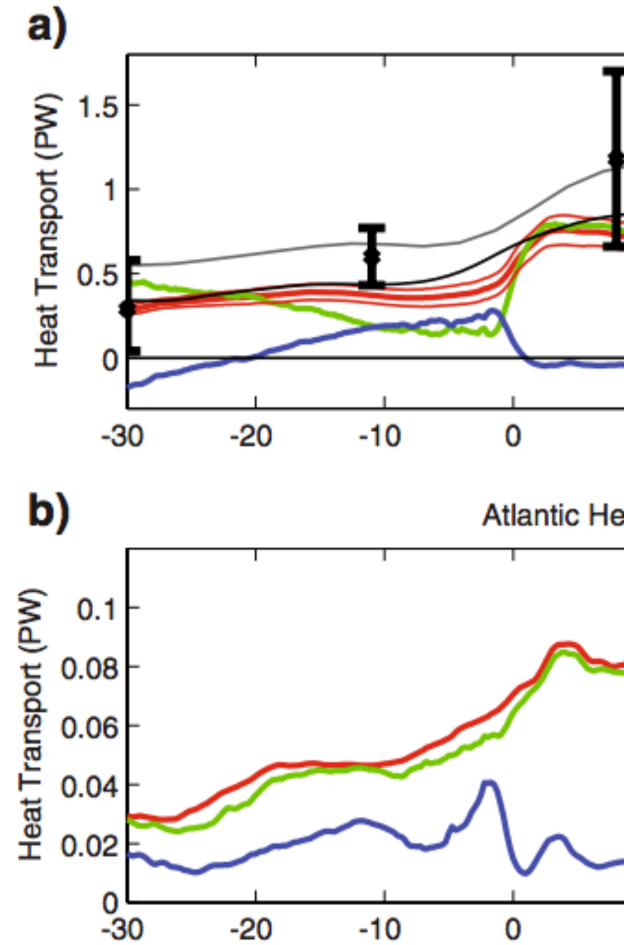
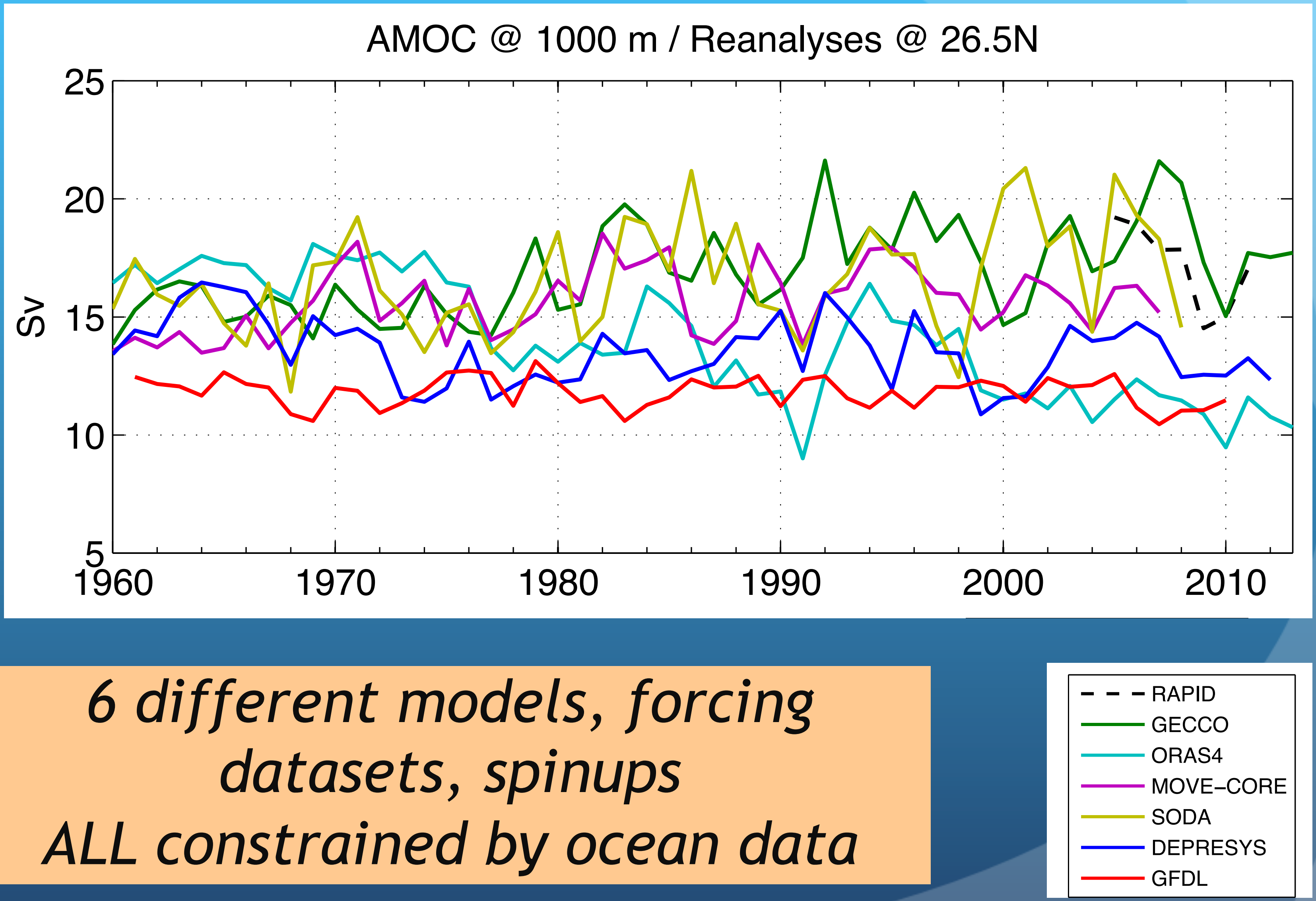
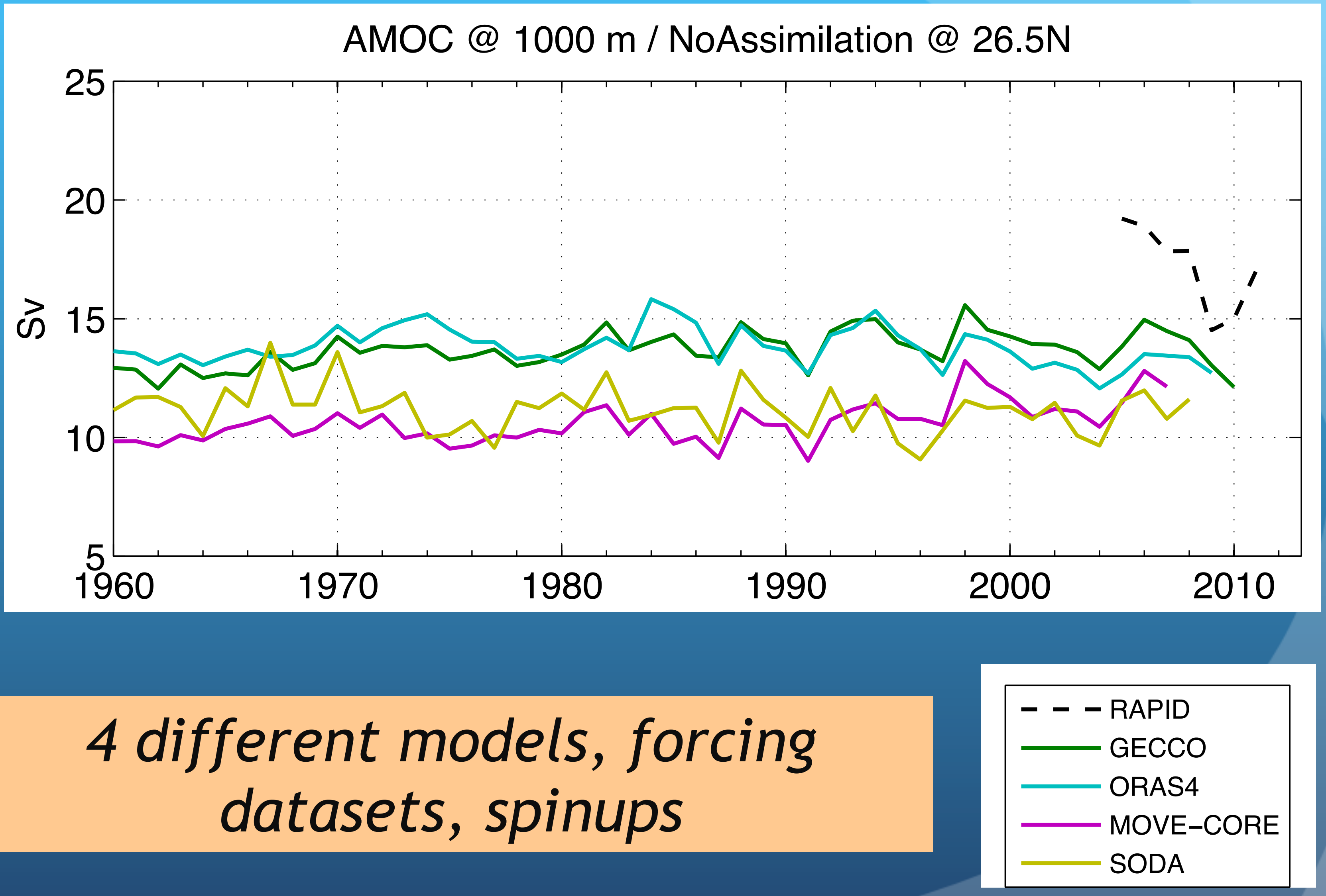


Reanalyses set



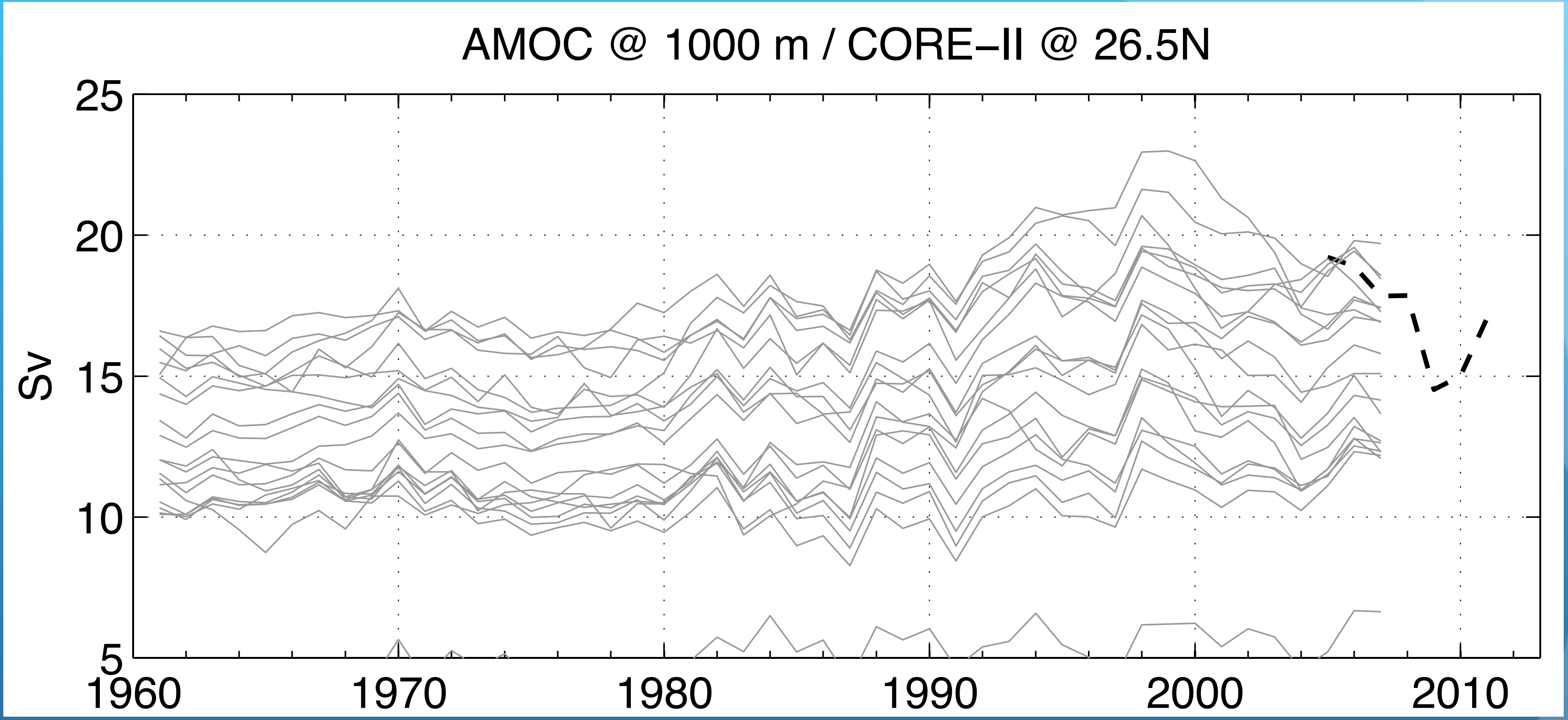
6 different models, forcing datasets, spinups
ALL constrained by ocean data

No Assimilation



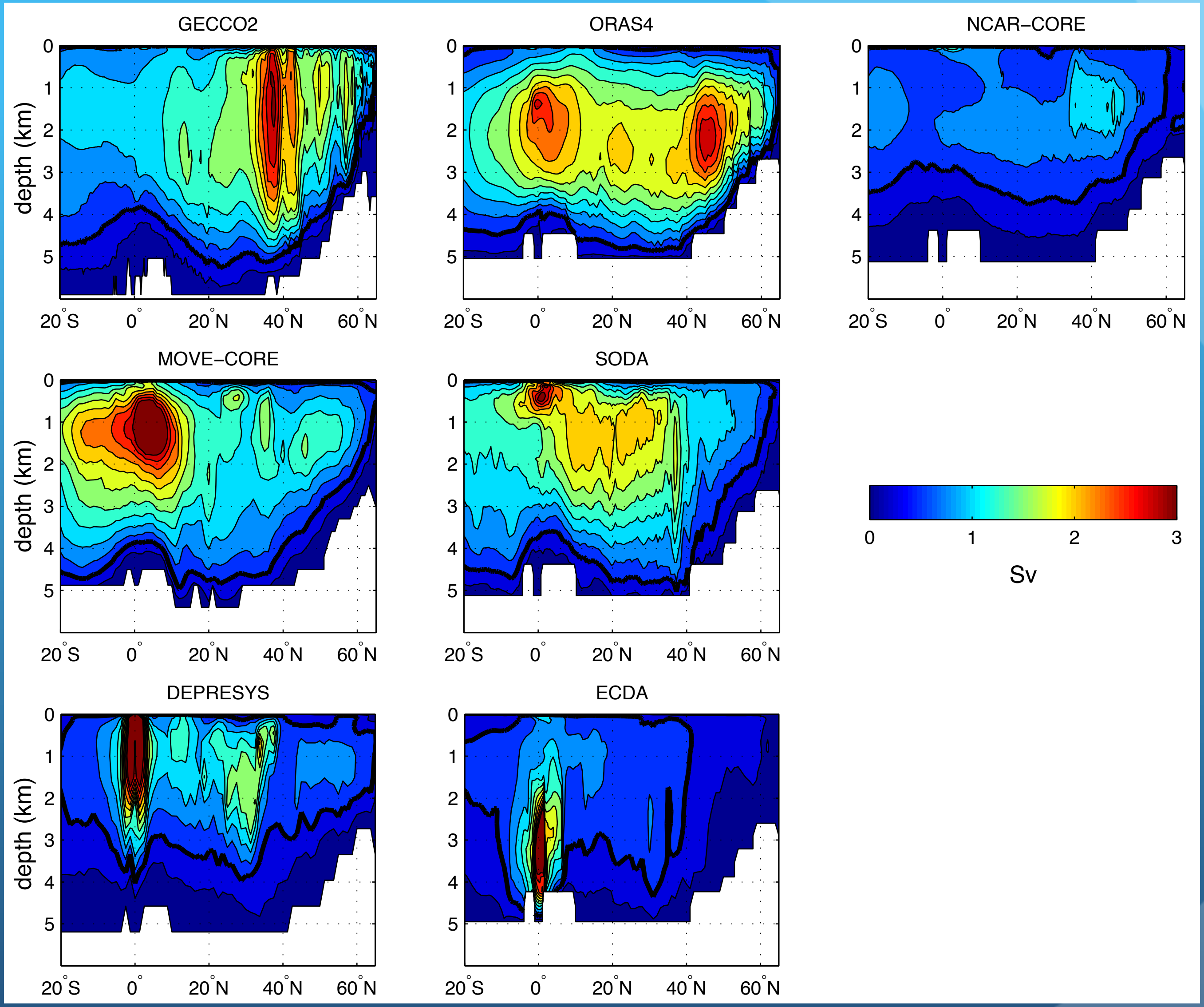
4 different models, forcing datasets, spinups

CORE-II

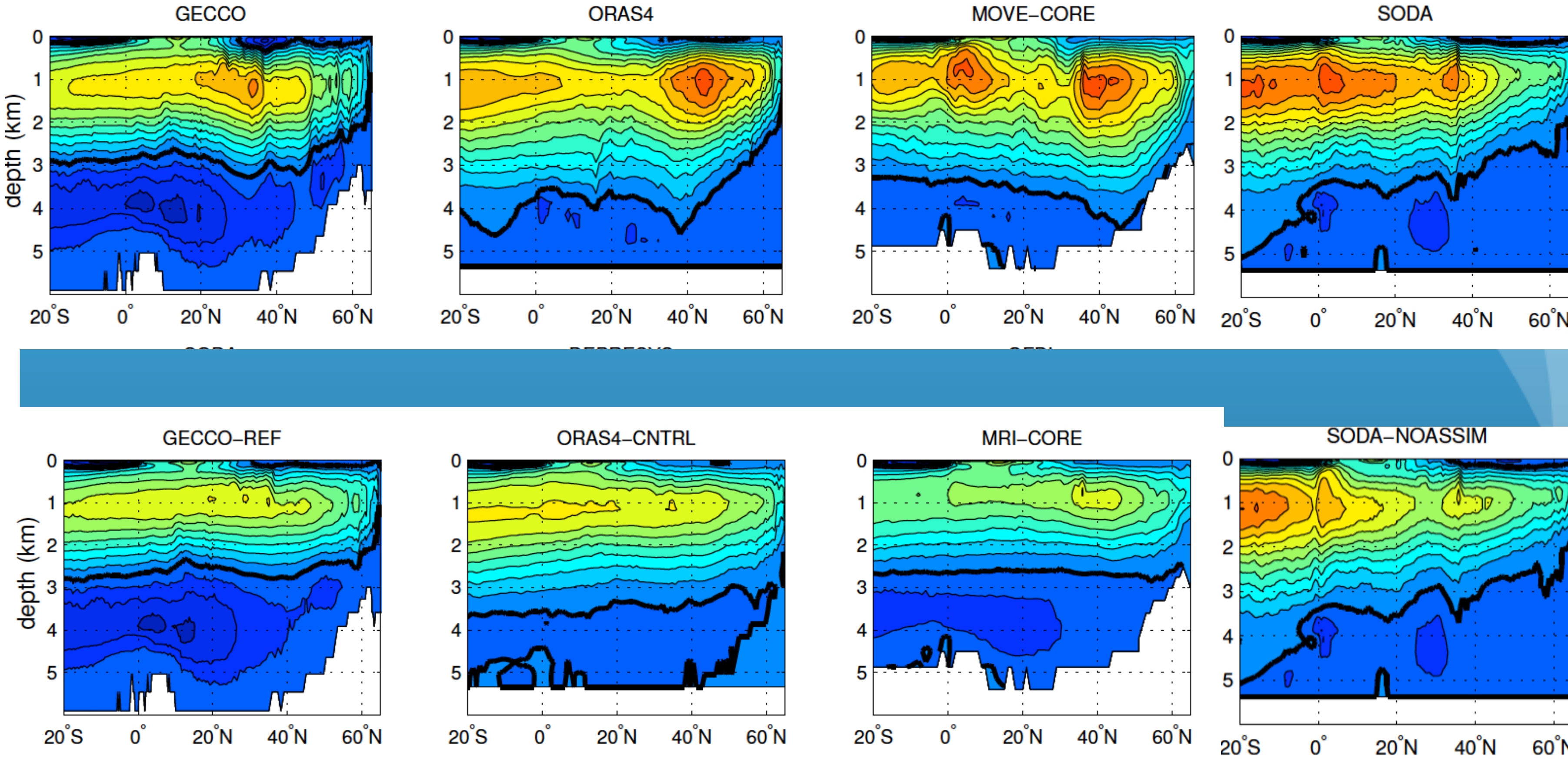


20 different models, identical CORE-IAF forcing, identical spinup procedures

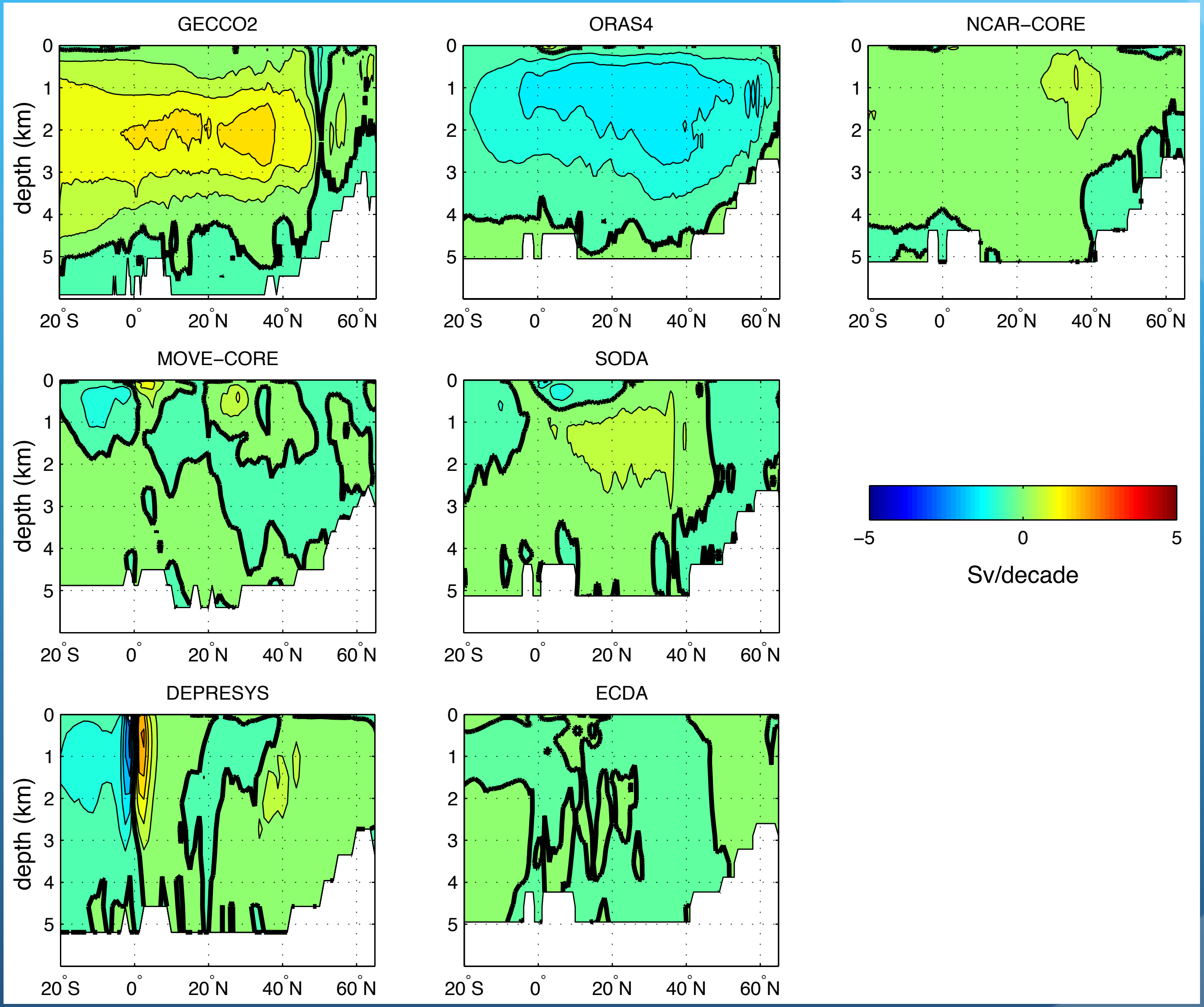
AMOC Variability (all groups)



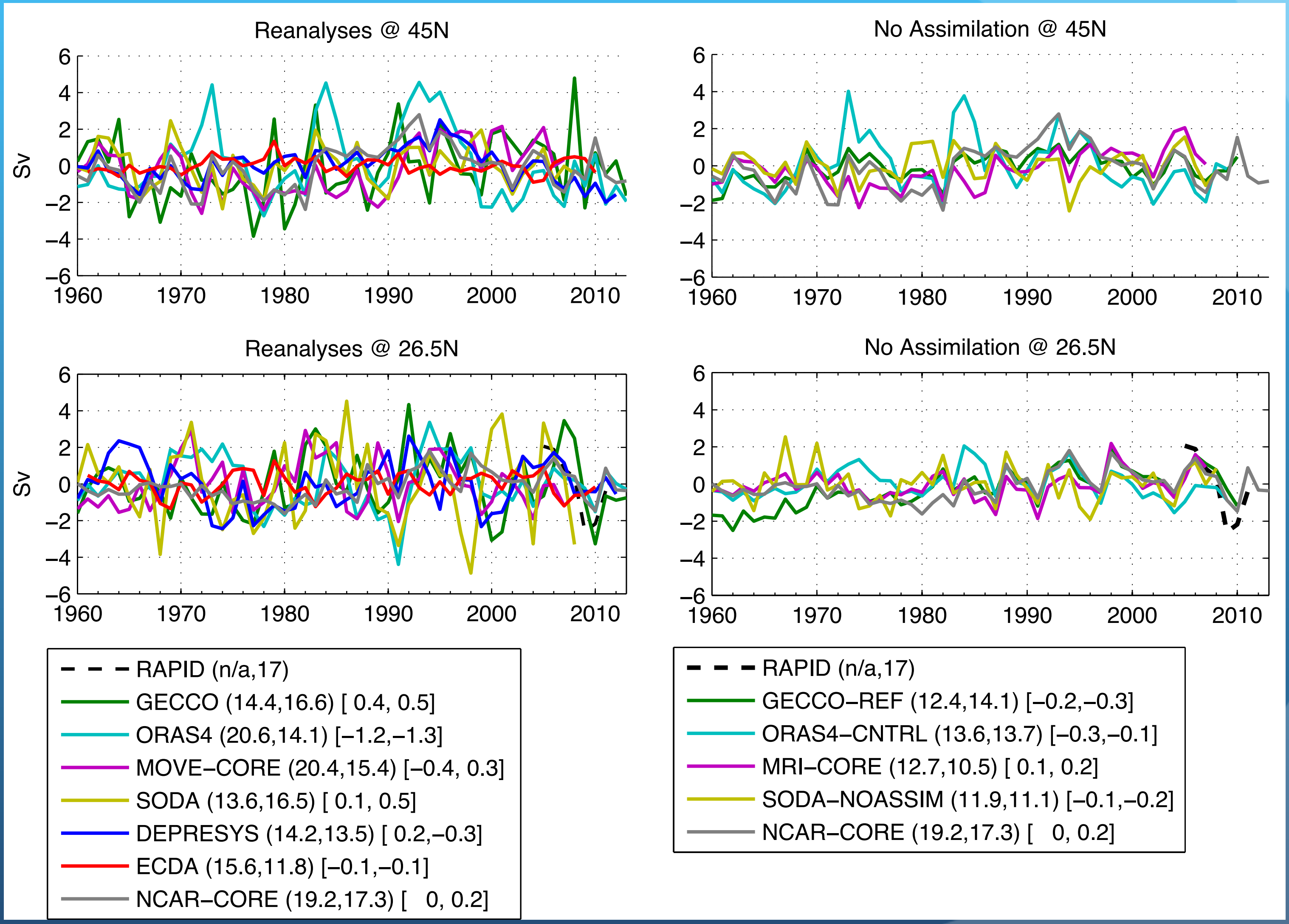
Time-Mean AMOC



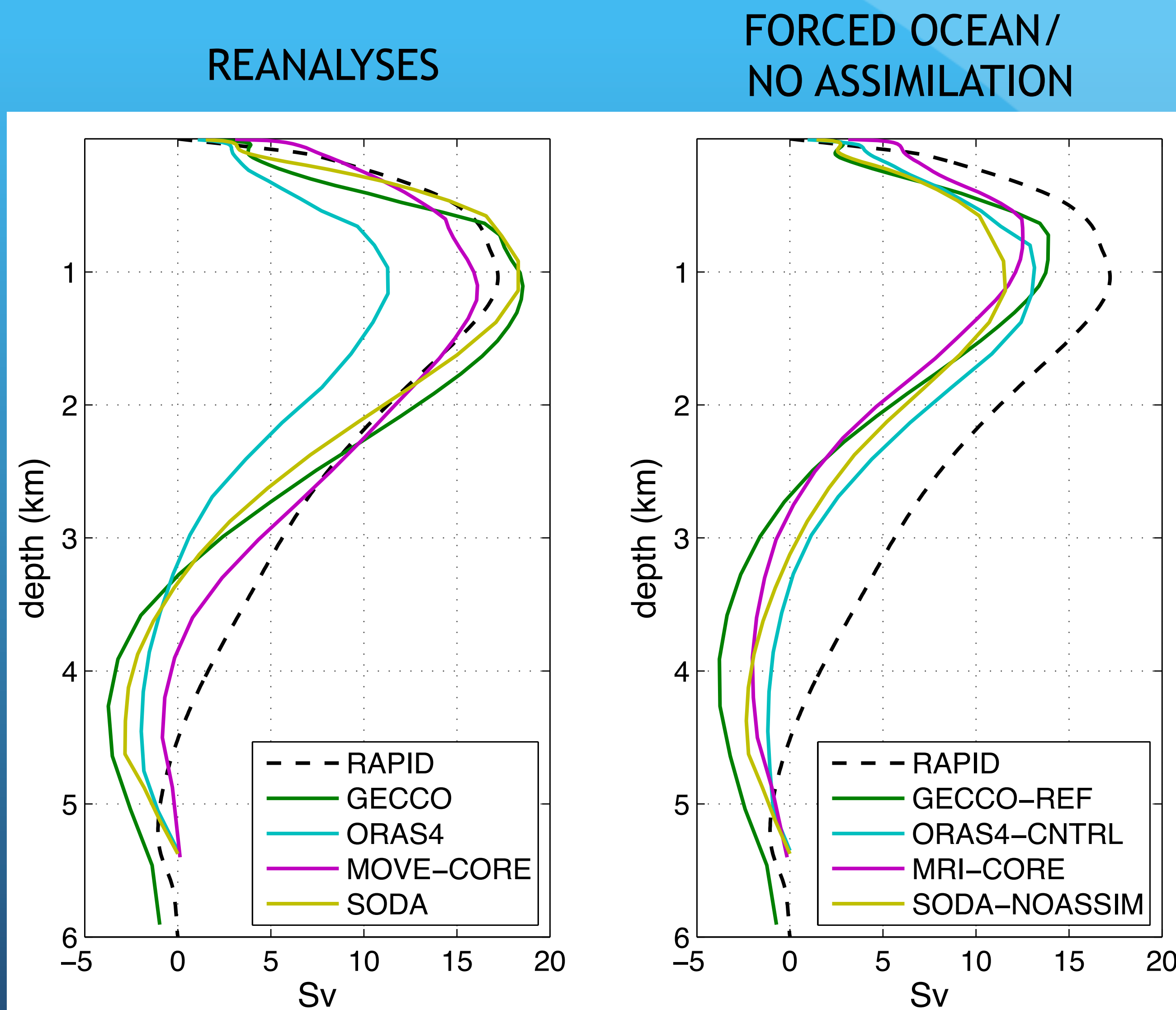
AMOC Trend (1960-2007)



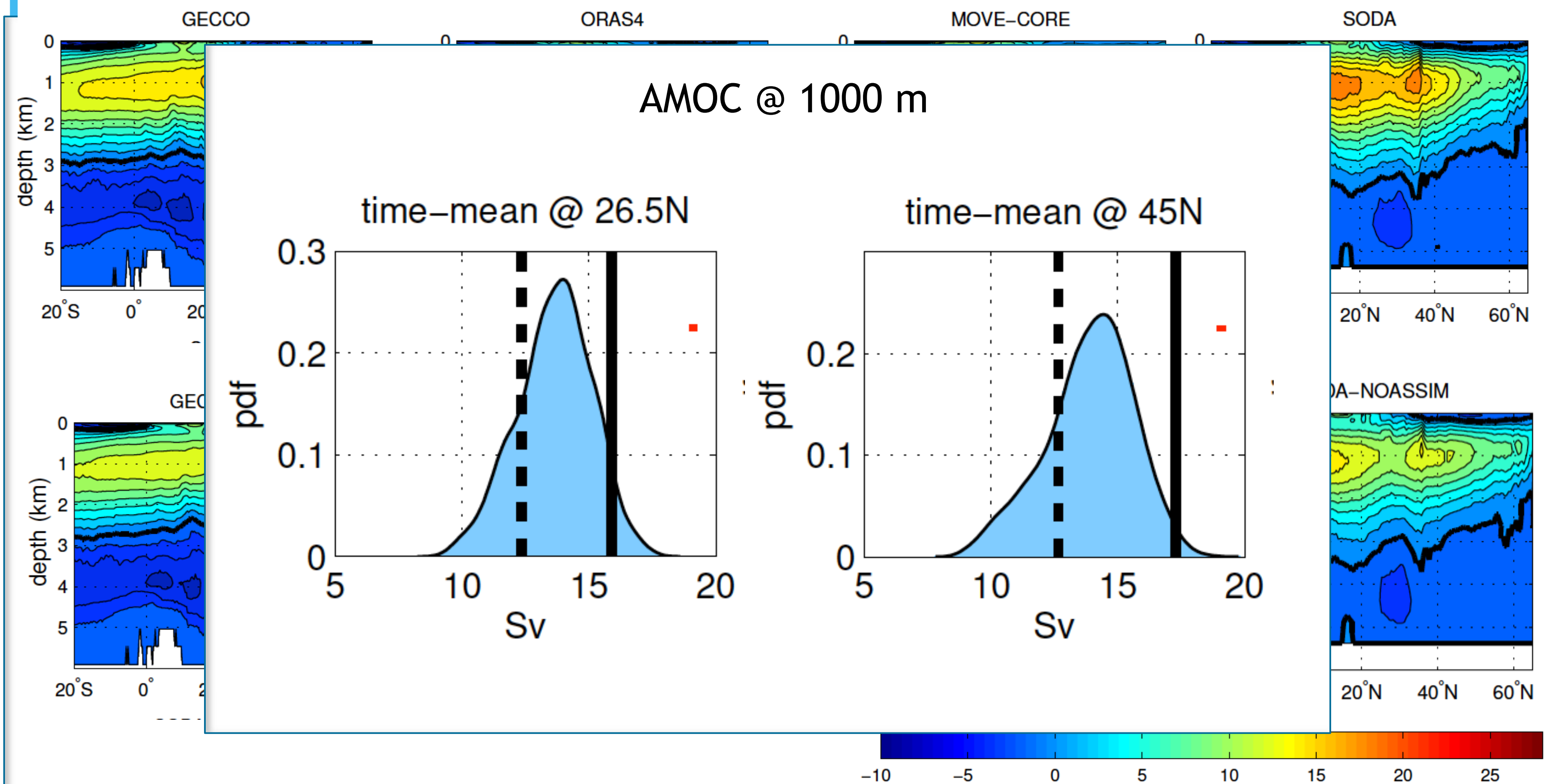
Agreement in year-to year signal? (all groups)



Comparison to RAPID estimates @ 26.5N

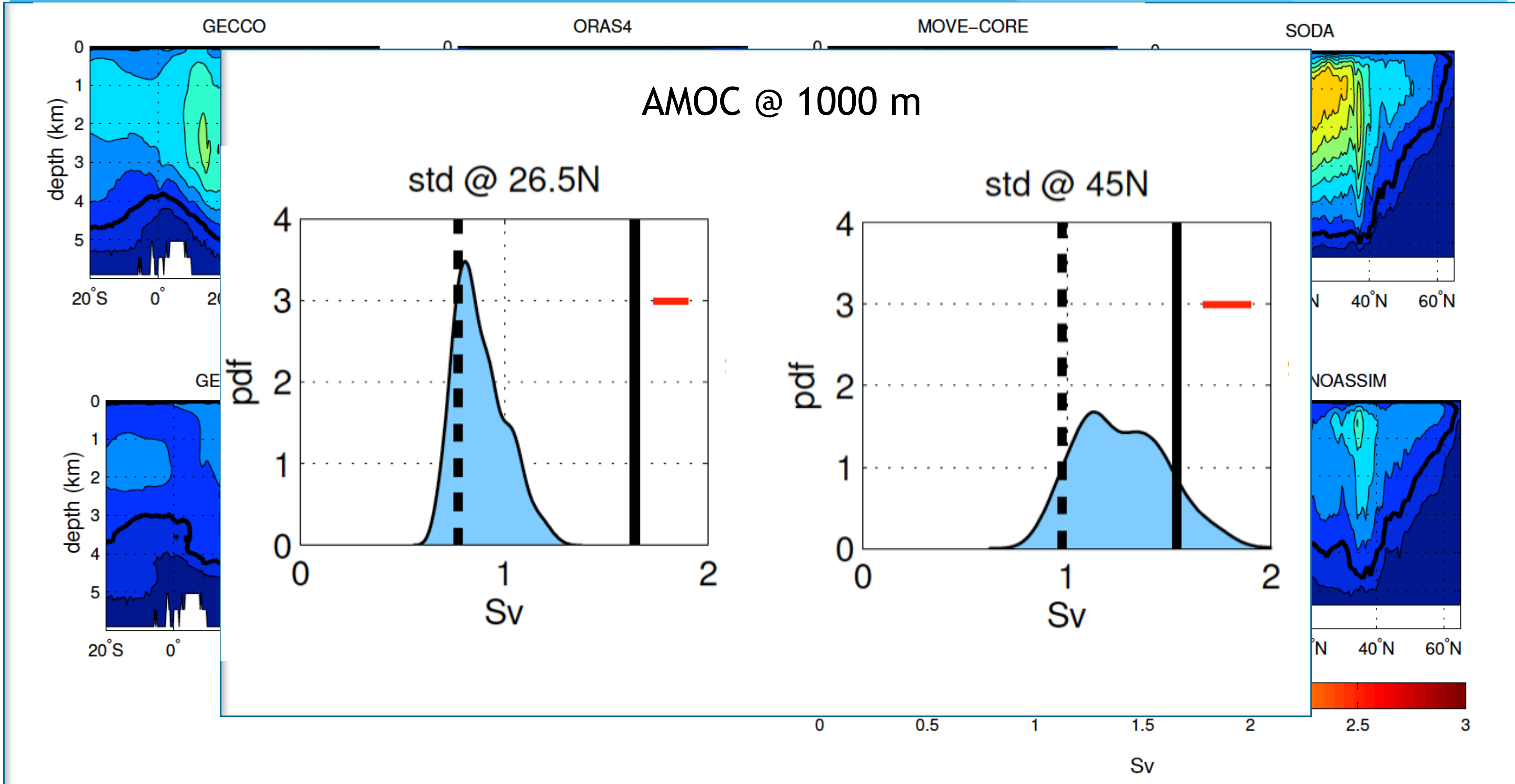


AMOC Time Mean



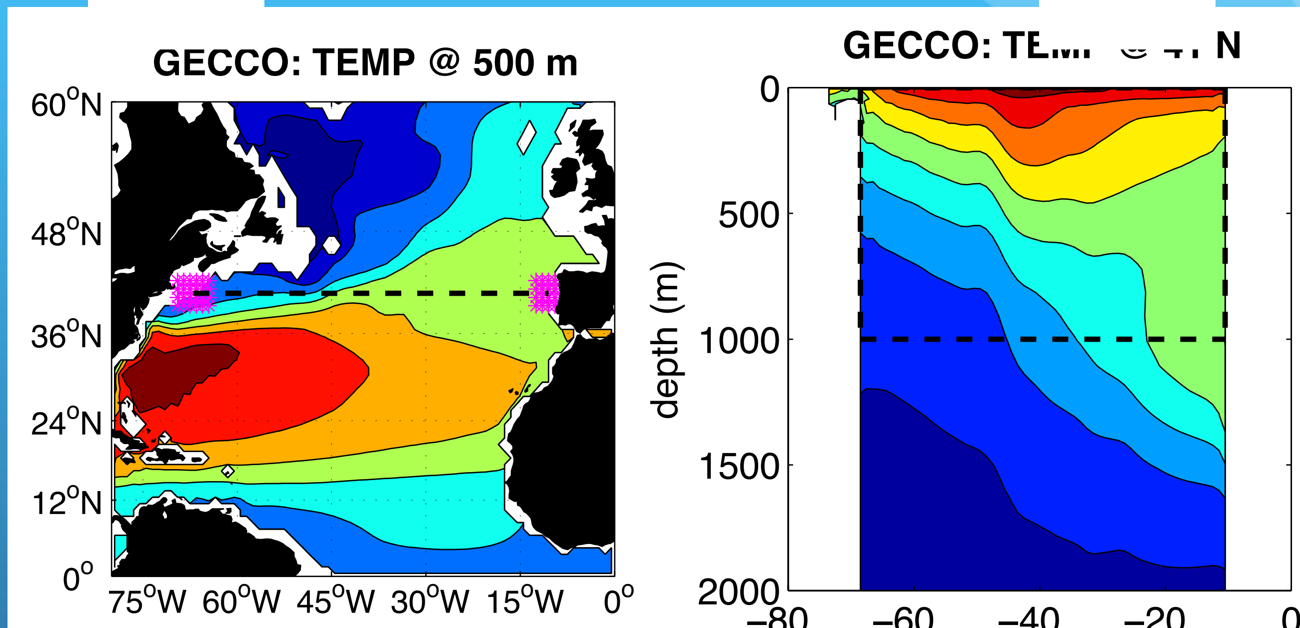
Data constraints lead to stronger mean AMOC, more consistent with RAPID

AMOC Variability



Data constraints increase variability, especially at lower-latitudes

The geostrophic shear @ 41N



$$\Psi_{total} \approx \Psi$$

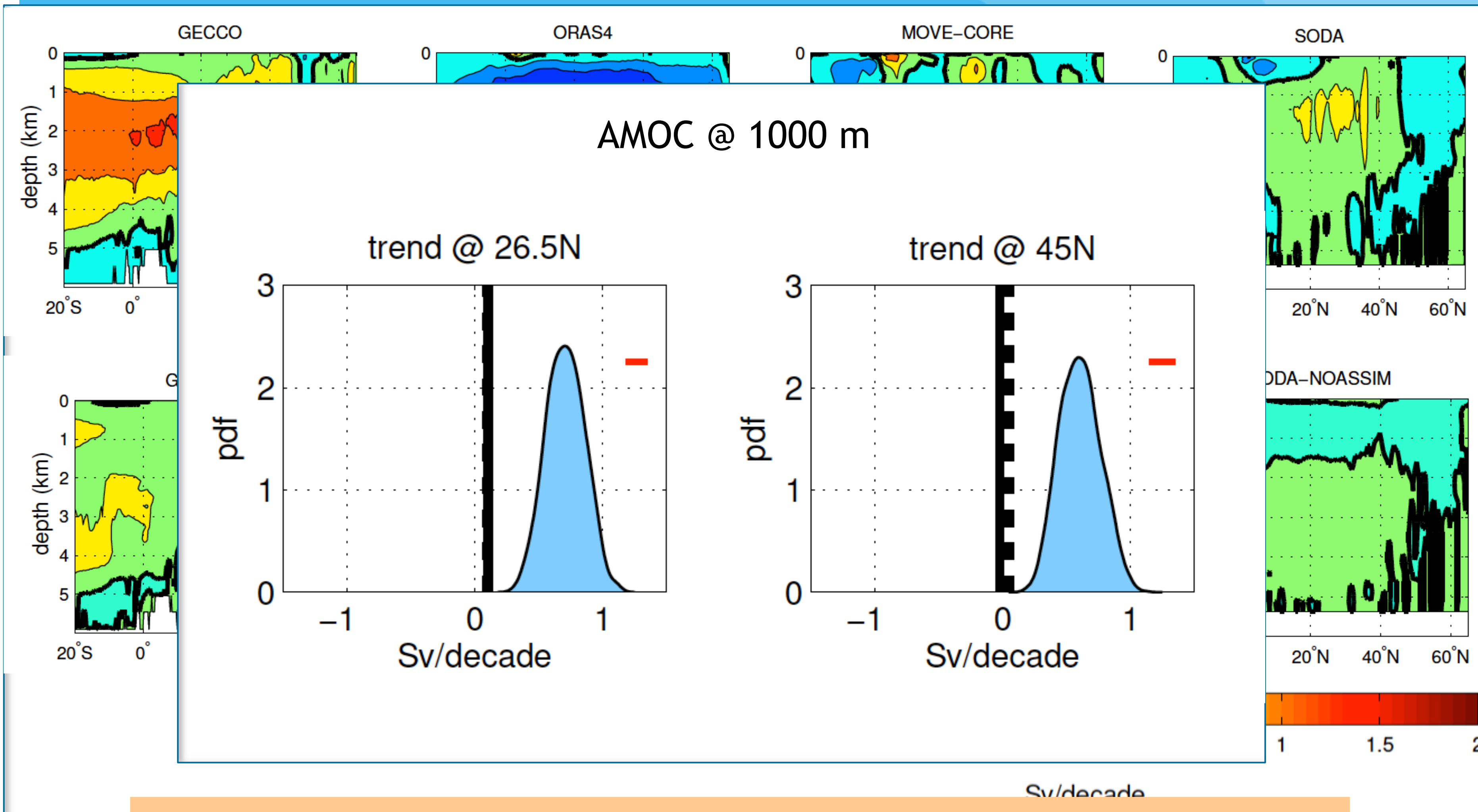
$$_{phic} = \int_{-H}^{0} \overline{v}_g^{\,x} dz$$

$$= \int_{-H}^{0} \frac{g}{f\rho_o} \int_{-H}^{z} \rho_w(z') - \rho_e(z') dz' dz \quad + \quad H\overline{v}_{-H}^{\,x}$$

$$\rho_w = f(T_w$$
$$= f(\overline{T}_w$$

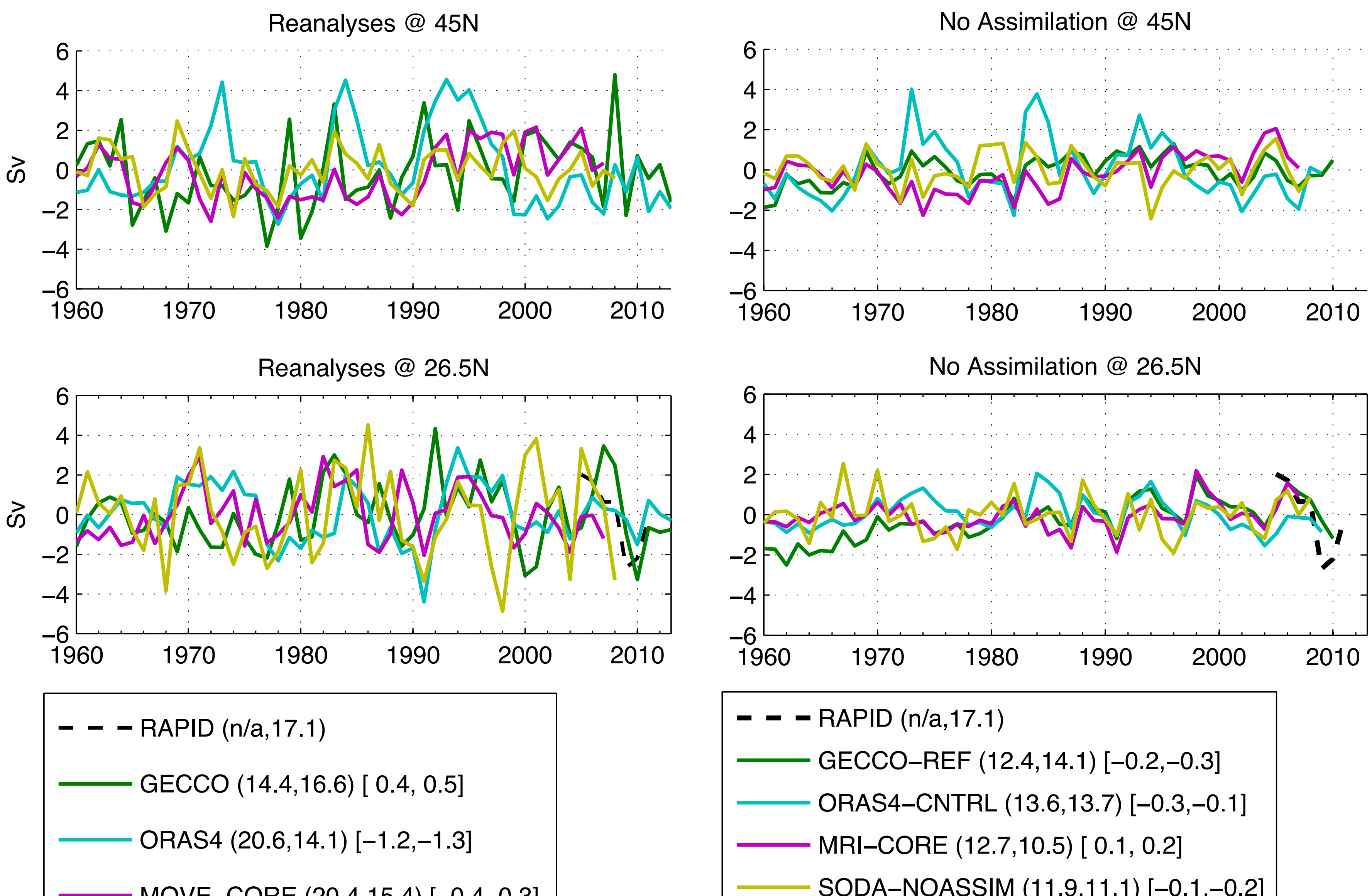
$$\rho_e = f(T_e$$
$$= f(\overline{T}_e$$

AMOC Trend (1960-2007)

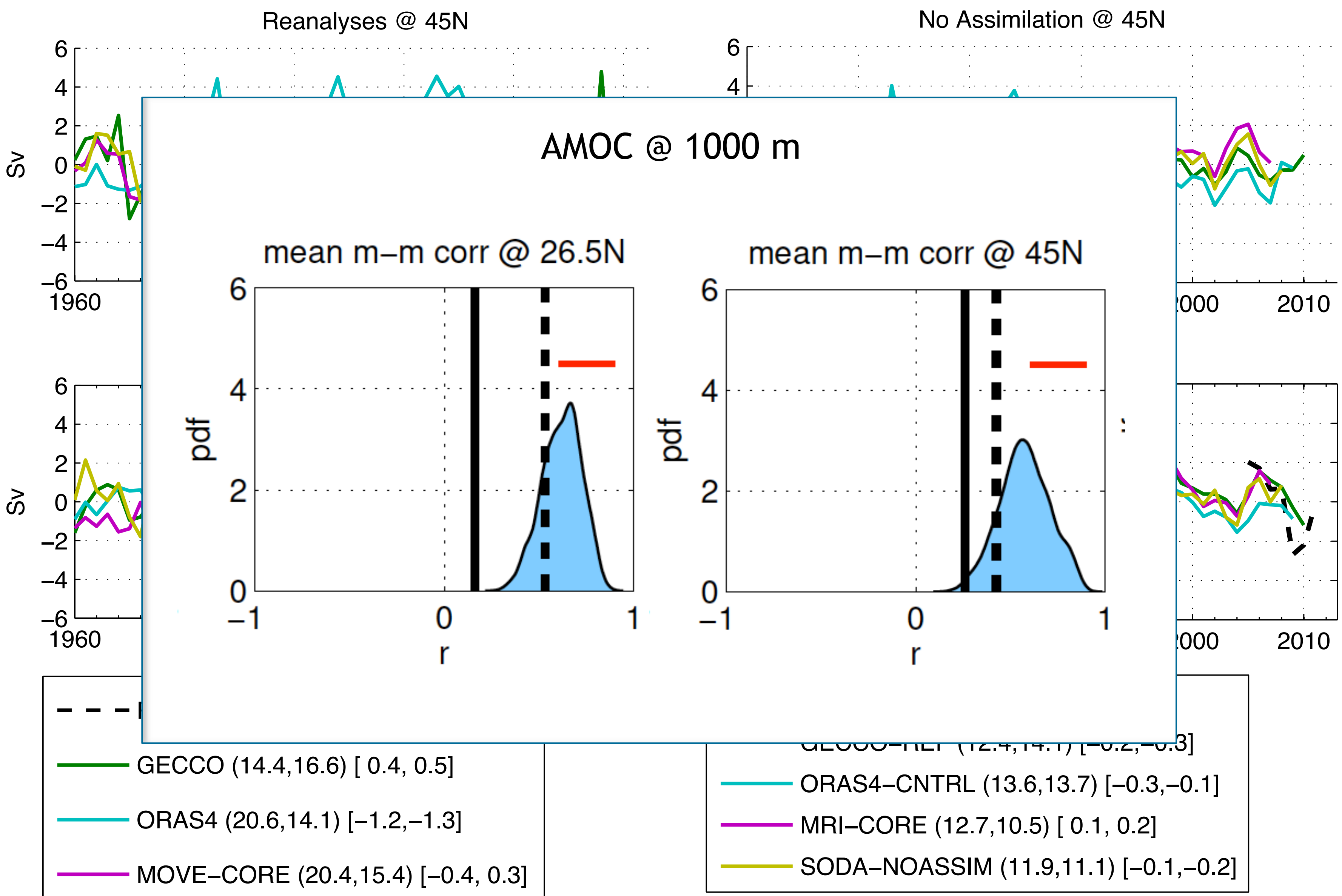


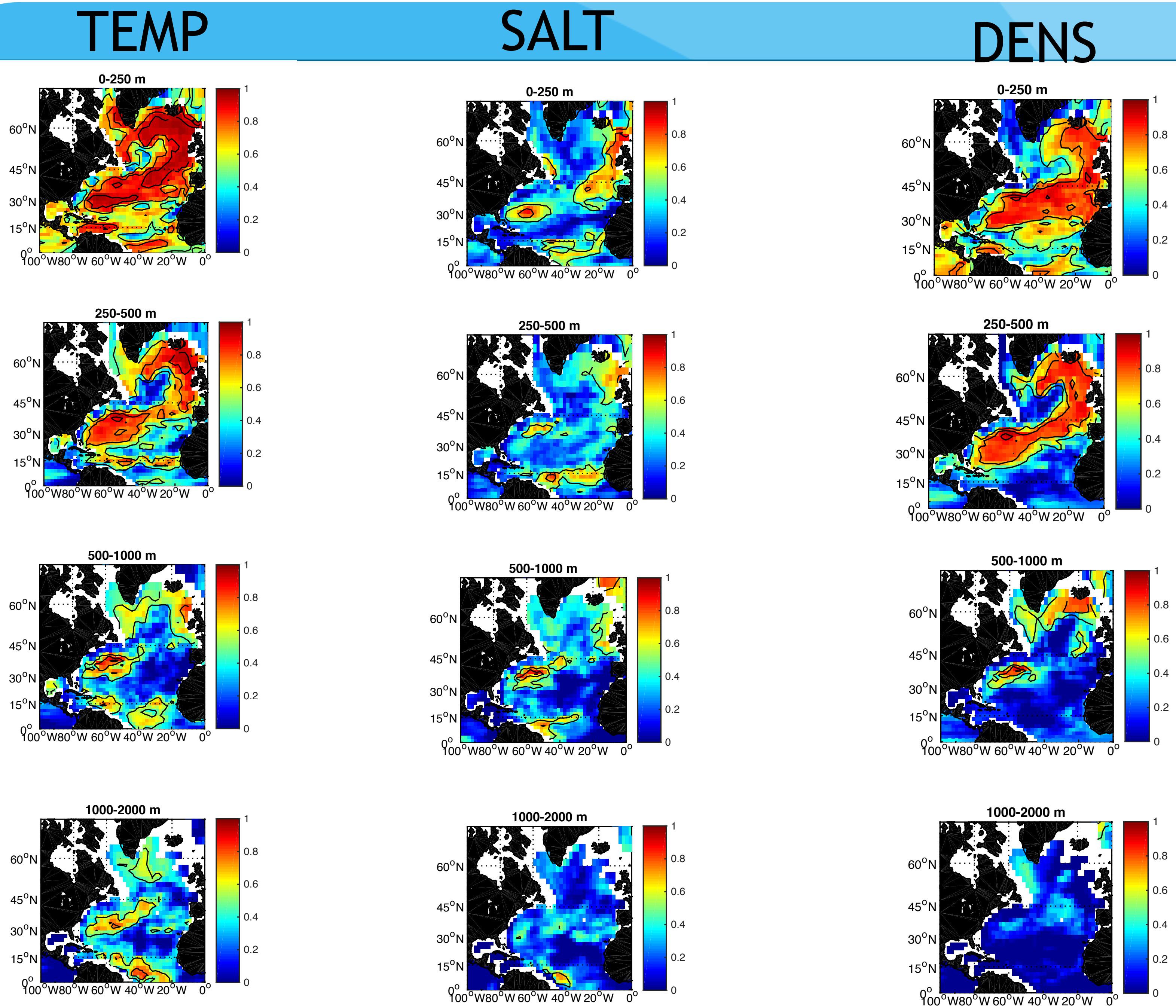
Data constraints increase trends
- and not consistently

Agreement in year-to year signal?

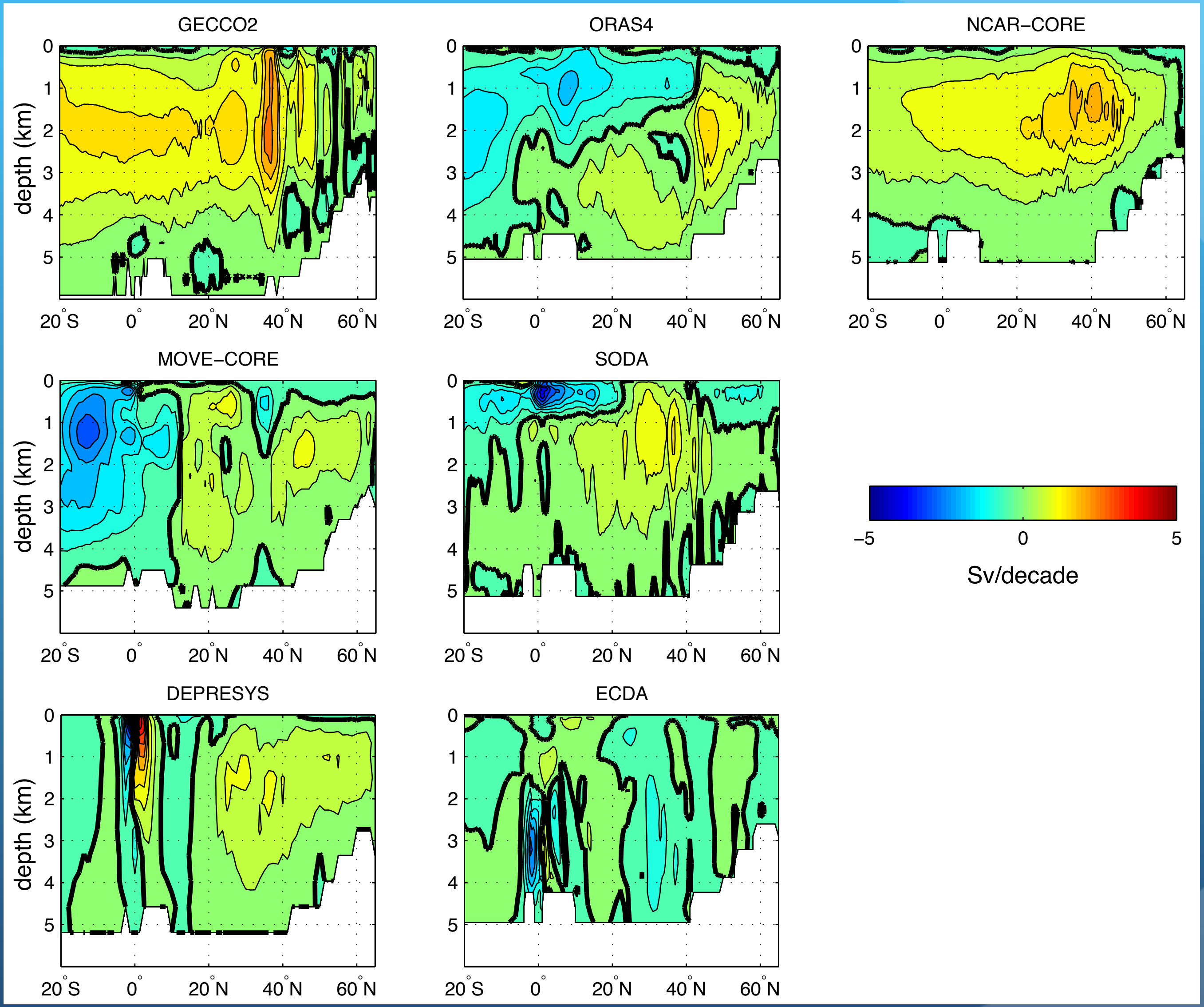


Agreement in year-to year signal?

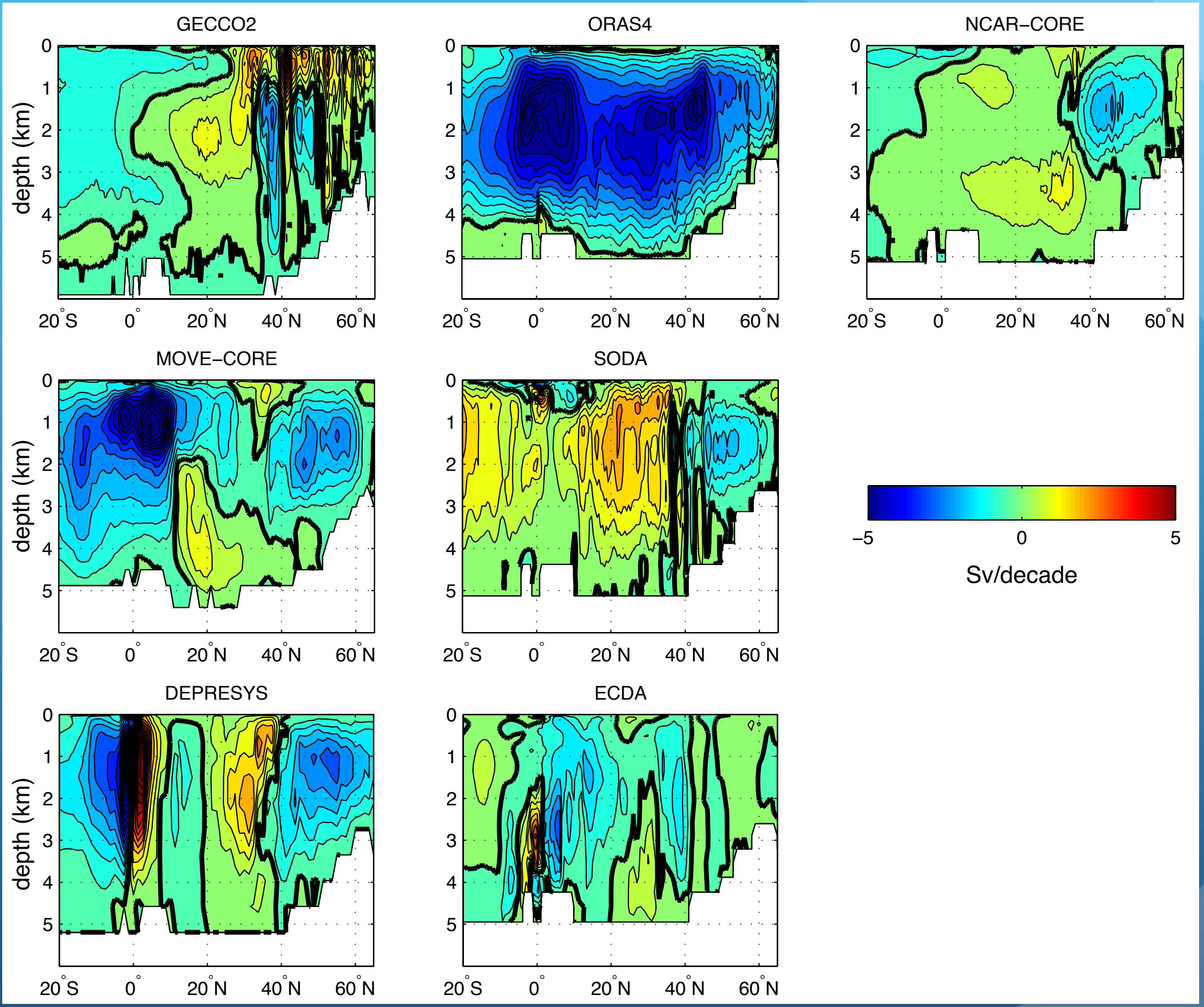


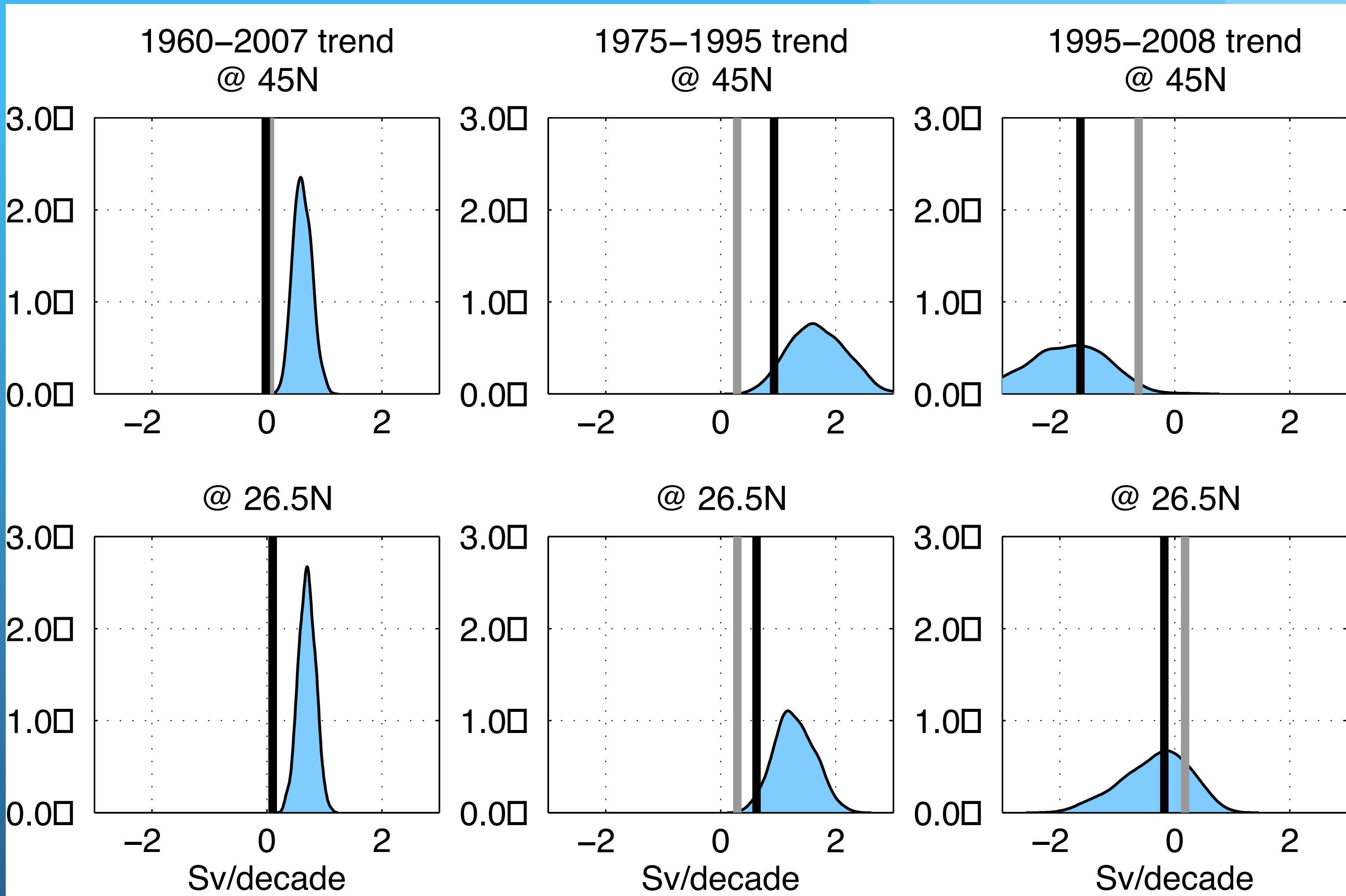

TEMP
SALT
DENS
0-250 m
250-500 m
500-1000 m
1000-2000 m
60°N
45°N
30°N
15°N
0°
100°W 80°W 60°W 40°W 20°W 0°

AMOC Trend (1975-1995)

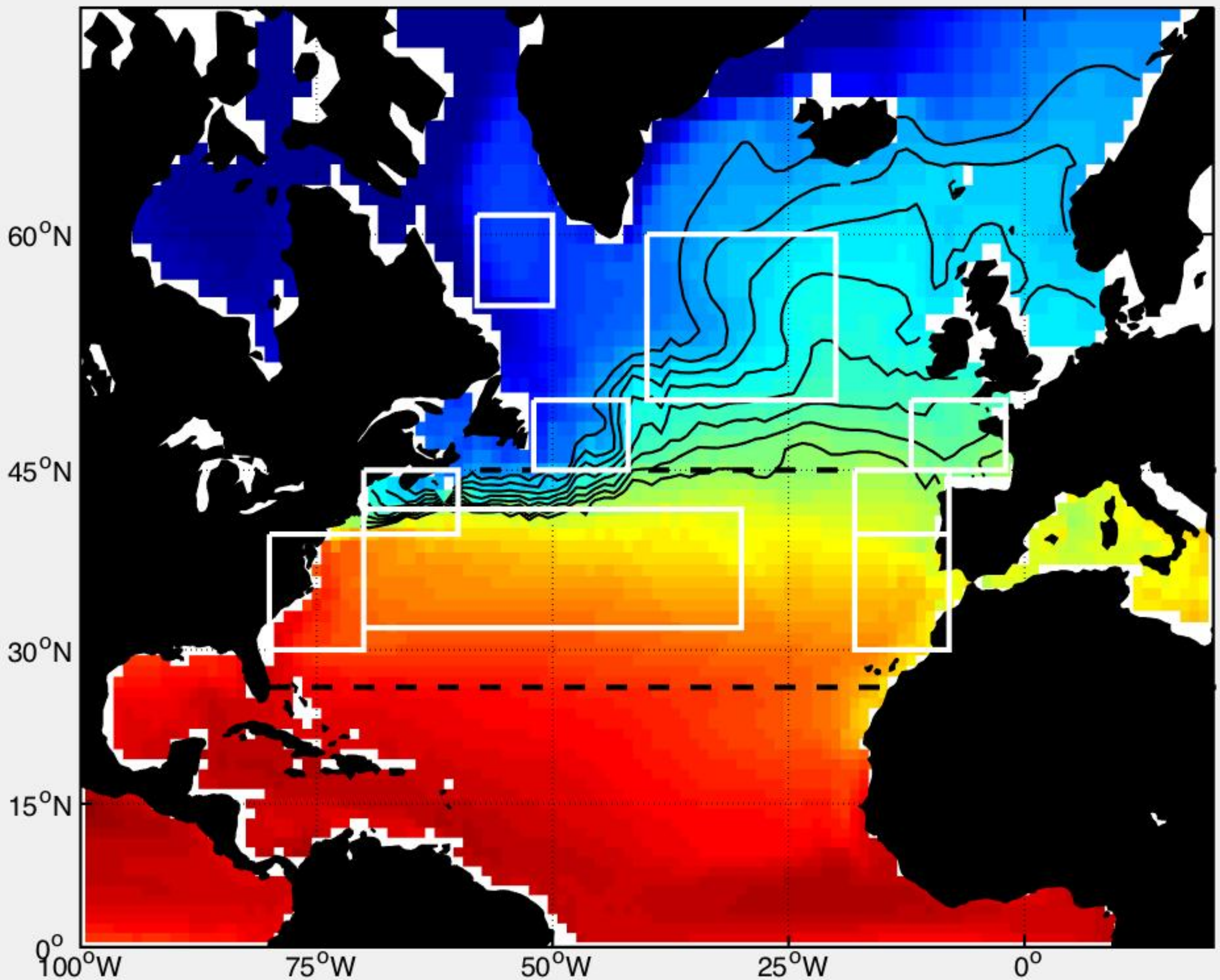


AMOC Trend (1995-2007)



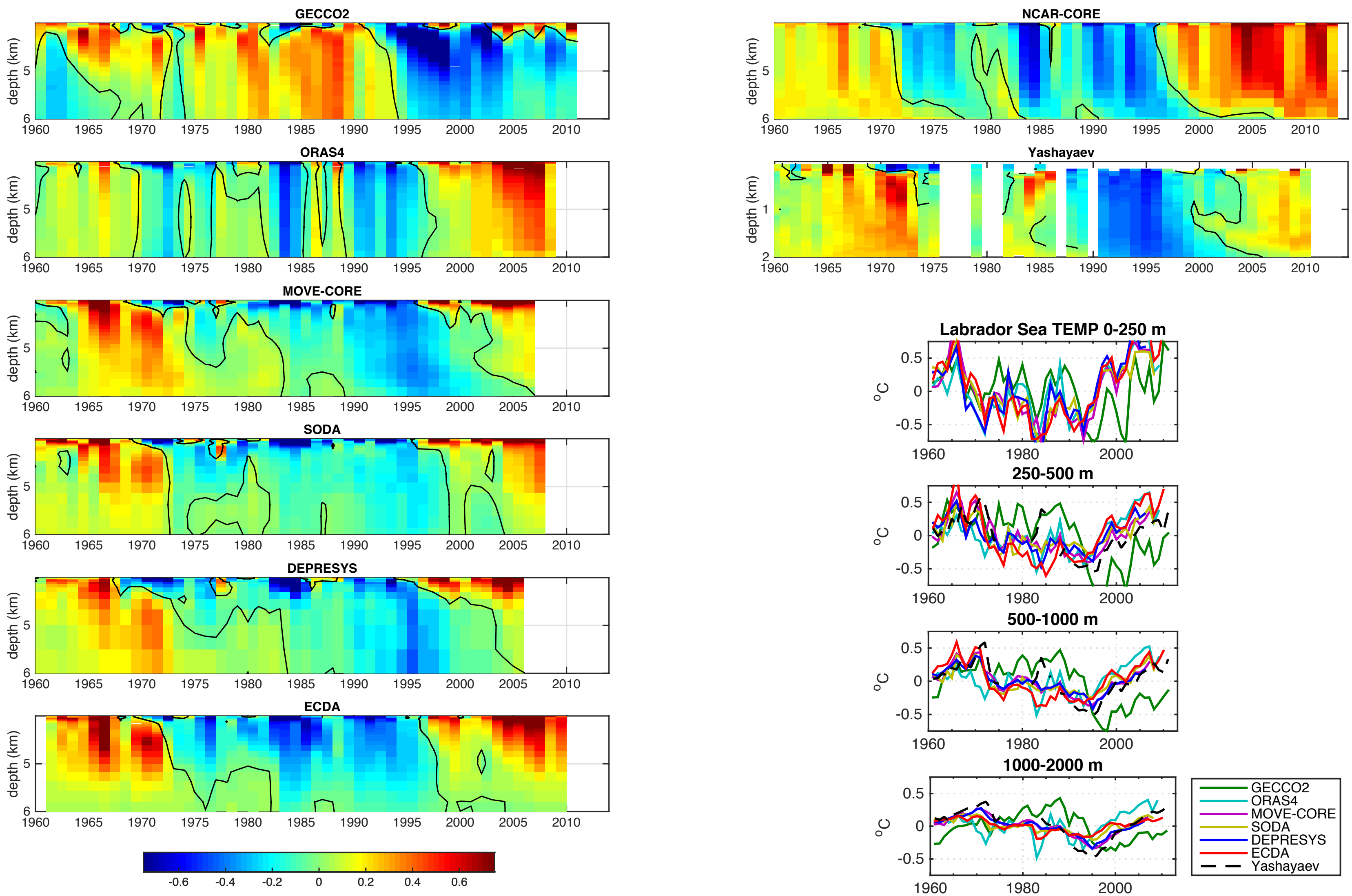


1960–2007 trend
@ 45N
1975–1995 trend
@ 45N
1995–2008 trend
@ 45N
@ 26.5N
@ 26.5N
@ 26.5N
3.0
2.0
1.0
0.0
−2
0
2
Sv/decade

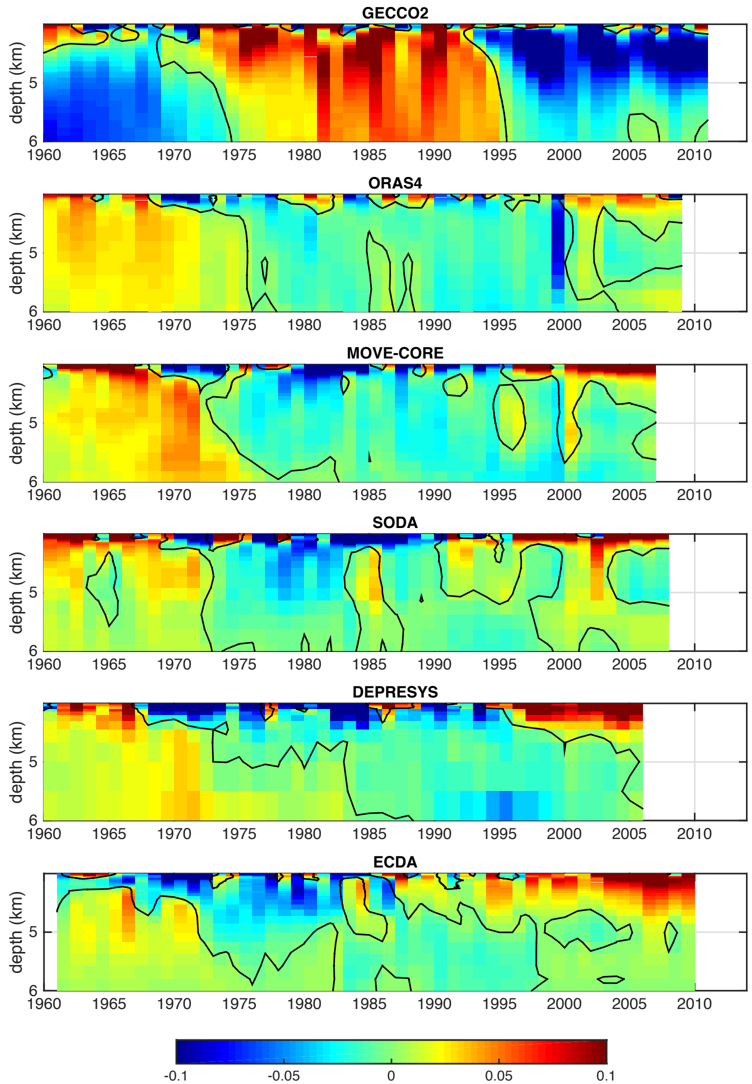


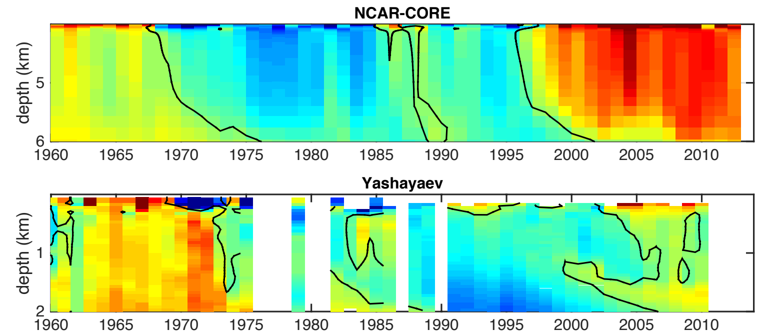
60°N
45°N
30°N
15°N
0°
100°W
75°W
50°W
25°W
0°

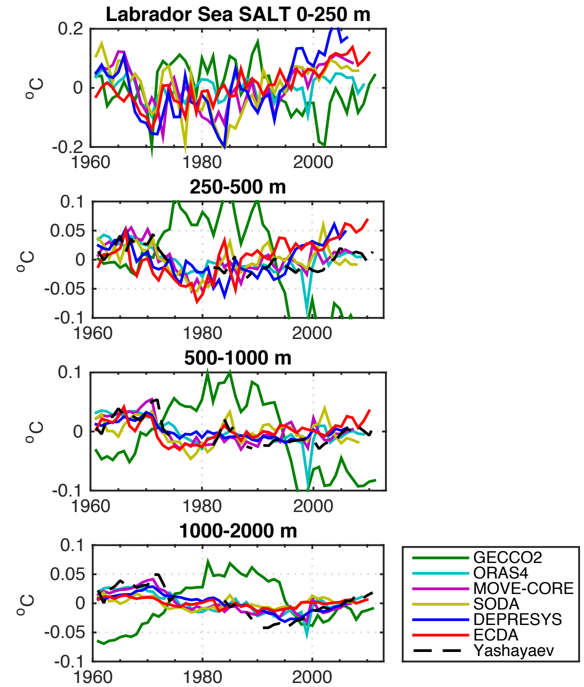
TEMP in Labrador Sea



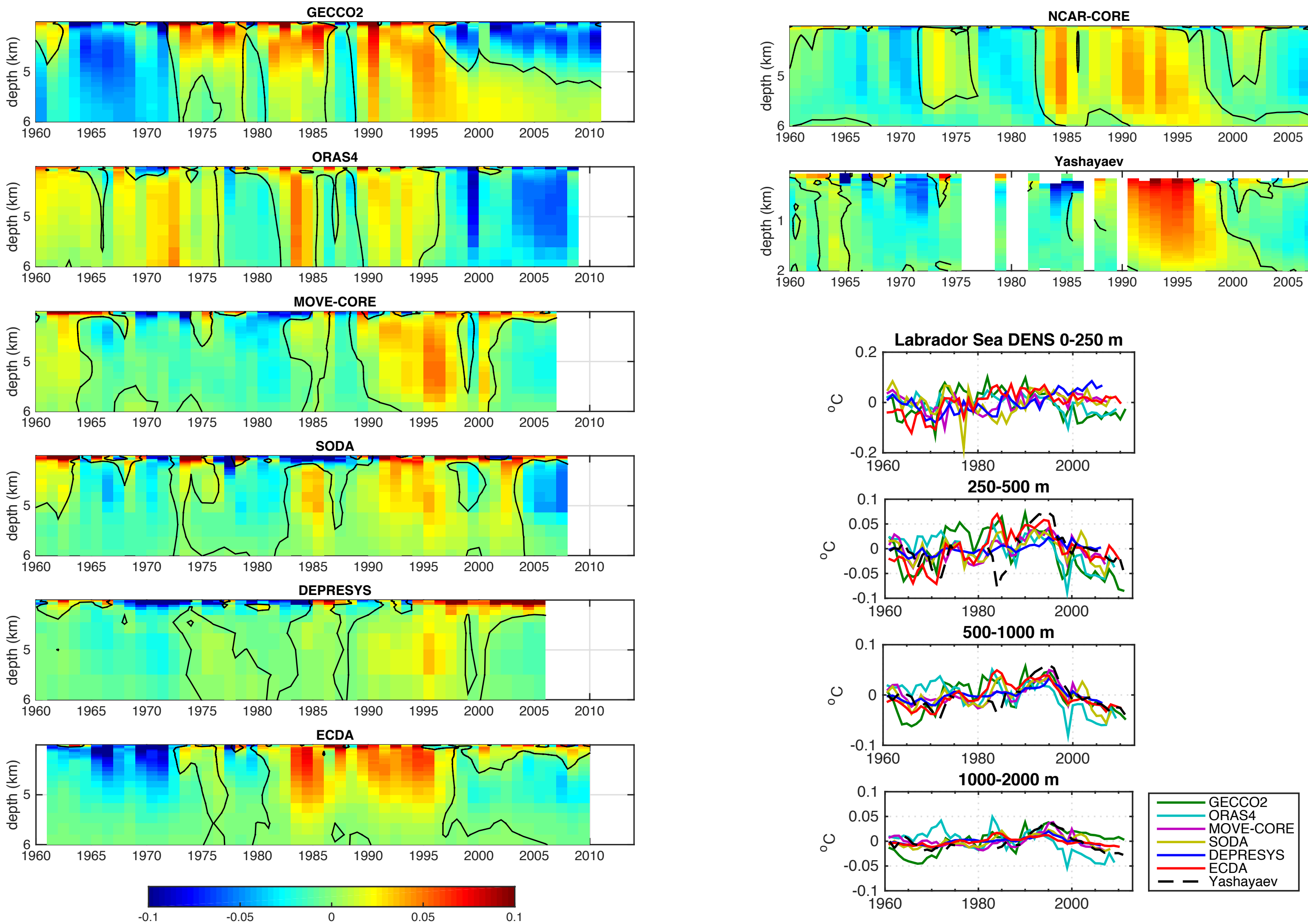
Salinity in Labrador Sea



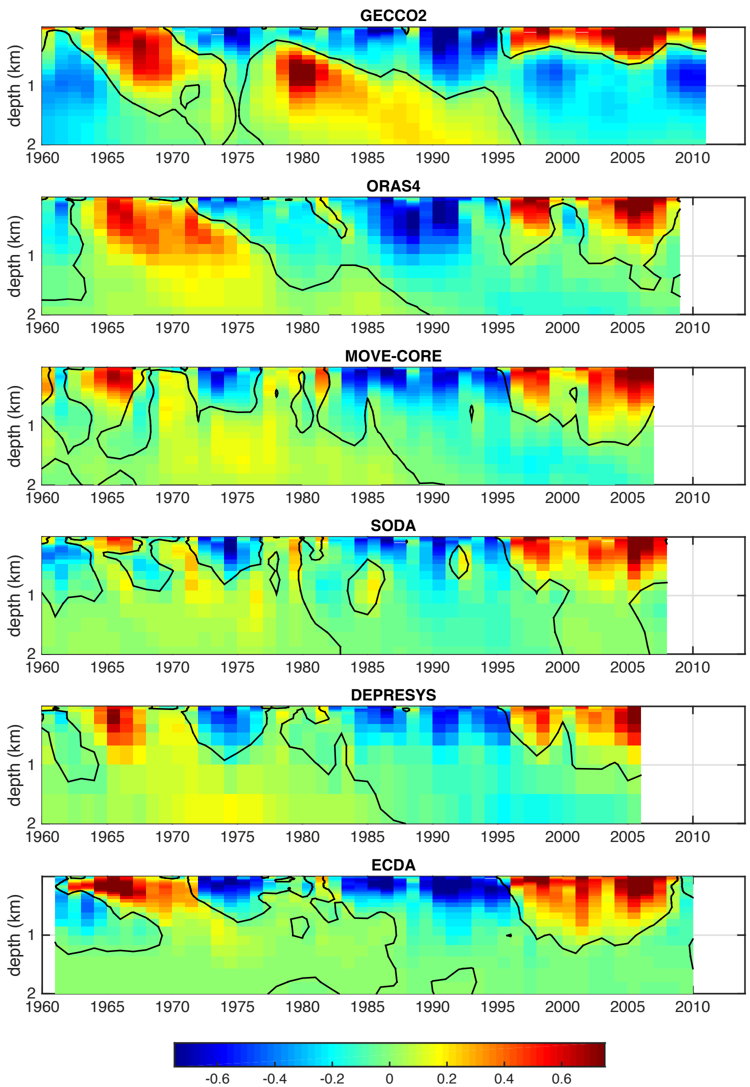


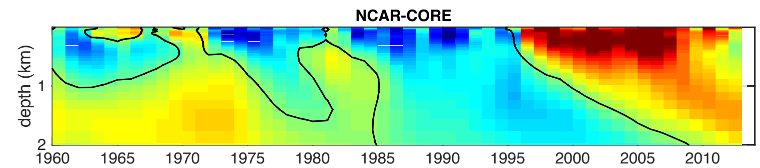


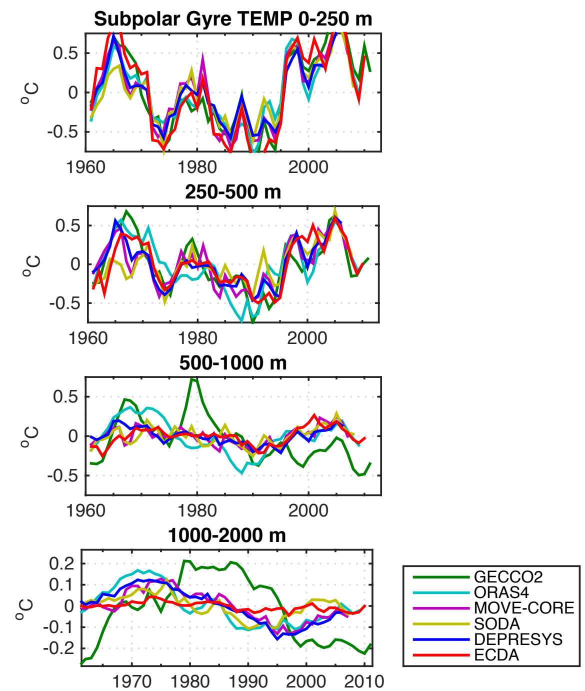
Density in Labrador Sea

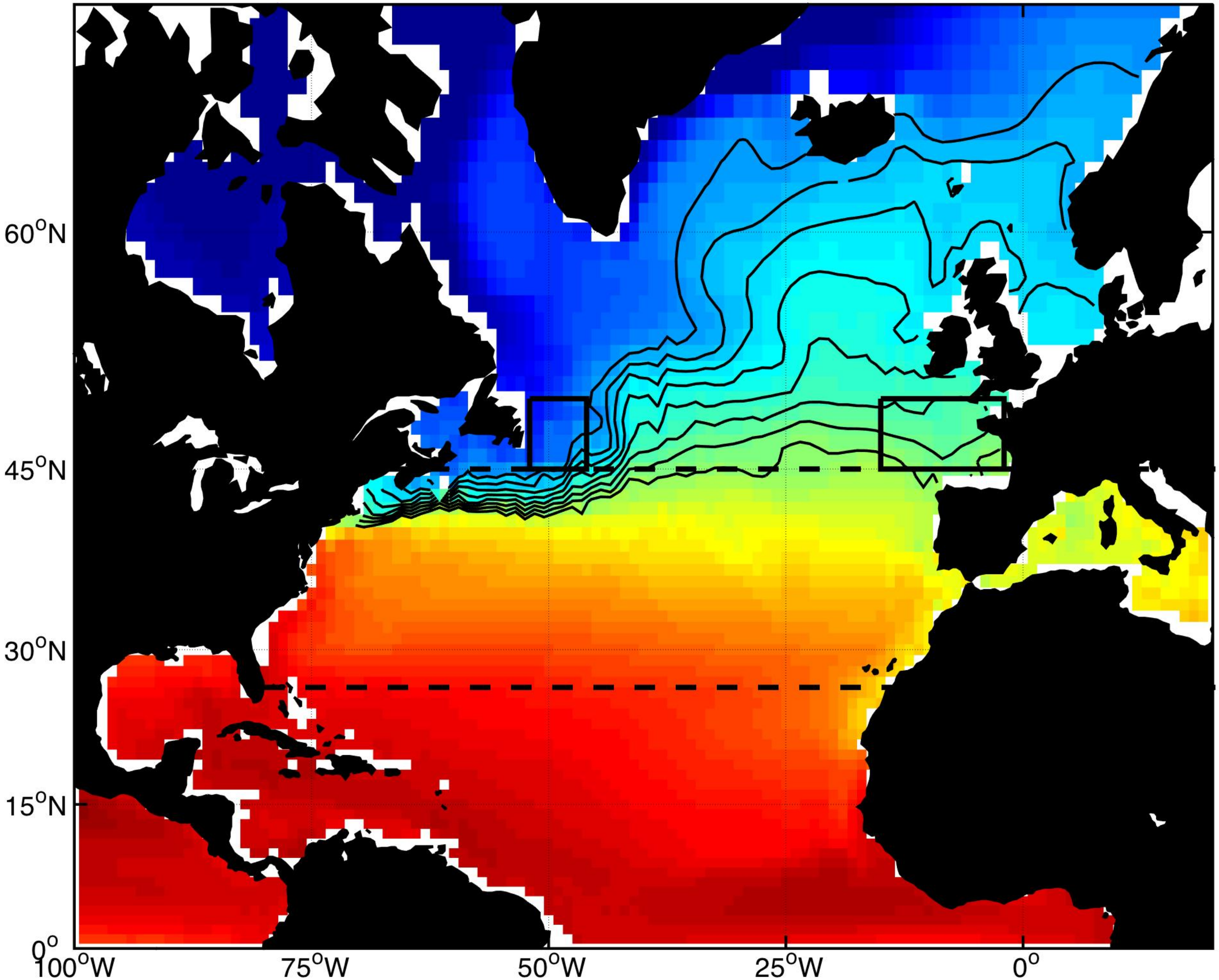


TEMP in subpolar gyre

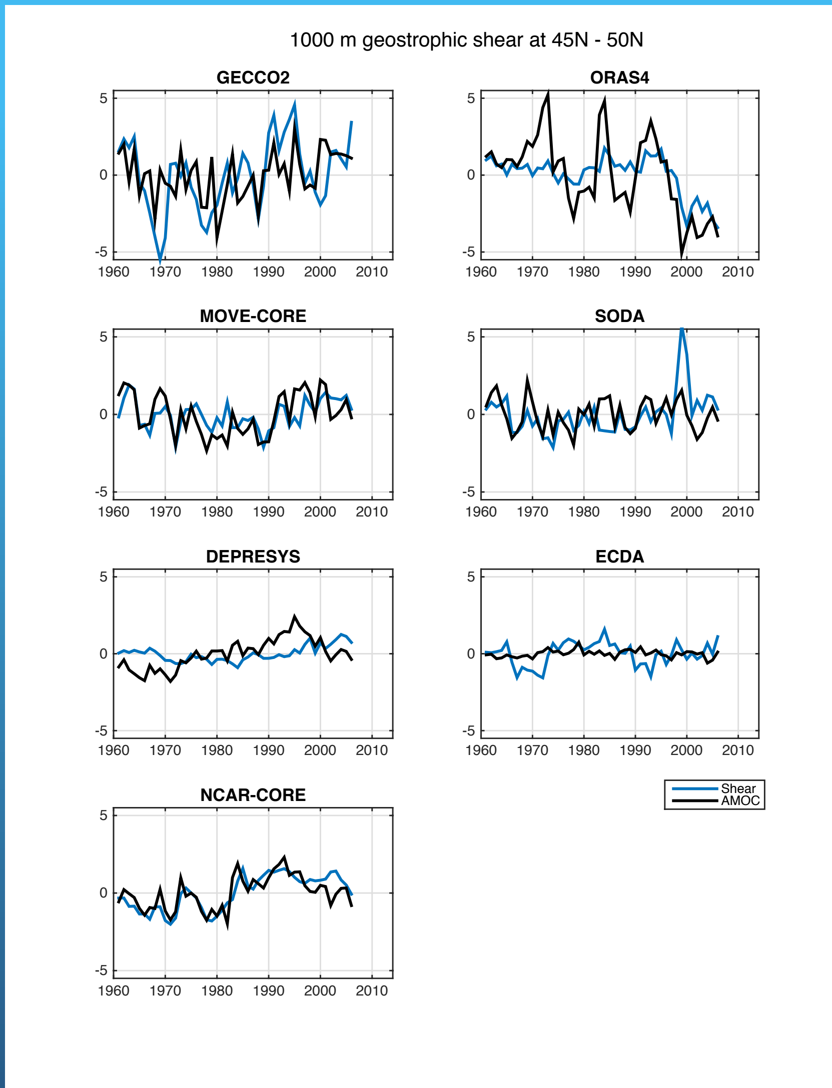


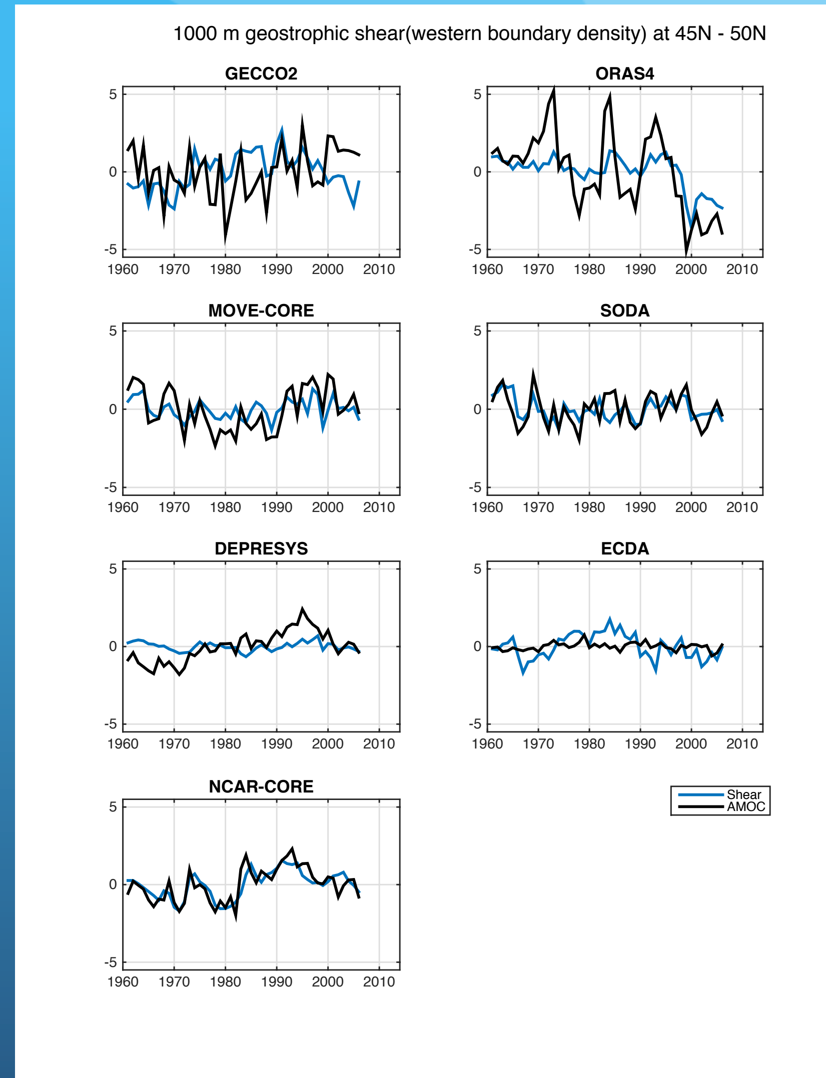




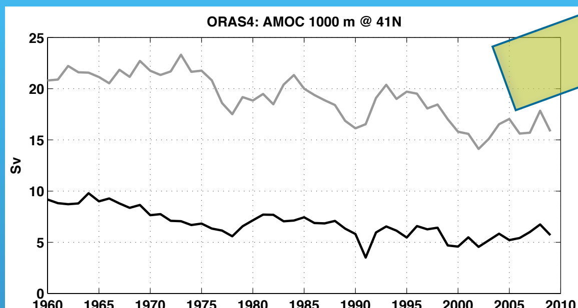


60°N
45°N
30°N
15°N
0°
100°W
75°W
50°W
25°W
0°

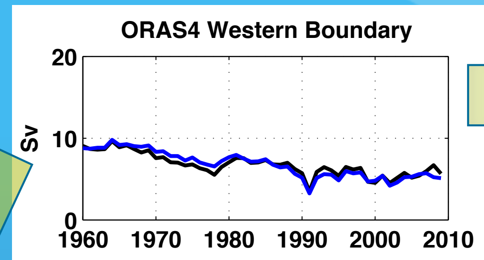

1000 m geostrophic shear at 45N - 50N
GECCO2
ORAS4
MOVE-CORE
SODA
DEPRESYS
ECDA
NCAR-CORE
Shear
AMOC


1000 m geostrophic shear(western boundary density) at 45N - 50N
GECCO2
ORAS4
MOVE-CORE
SODA
DEPRESYS
ECDA
NCAR-CORE
Shear
AMOC

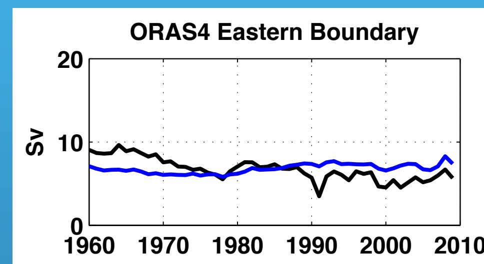
ORAS4



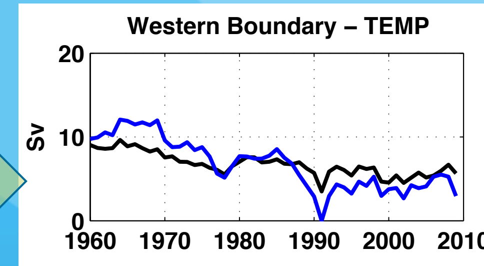
ORAS4: AMOC 1000 m @ 41N
Sv
0 5 10 15 20 25
1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010



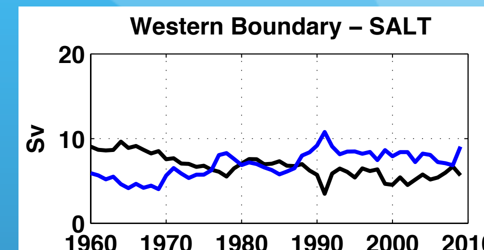
ORAS4 Western Boundary
Sv
0 10 20
1960 1970 1980 1990 2000 2010



ORAS4 Eastern Boundary
Sv
0 10 20
1960 1970 1980 1990 2000 2010

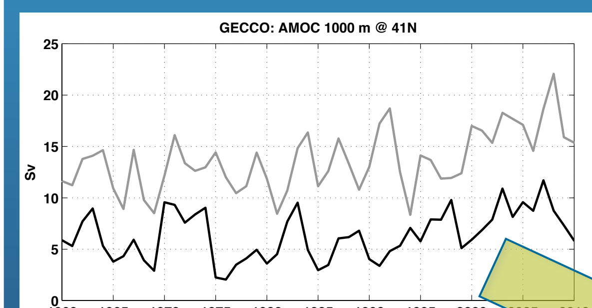


Western Boundary – TEMP
Sv
0 10 20
1960 1970 1980 1990 2000 2010

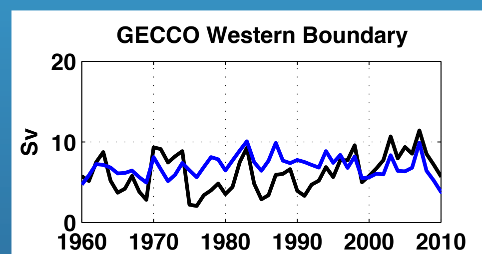


Western Boundary – SALT
Sv
0 10 20
1960 1970 1980 1990 2000 2010

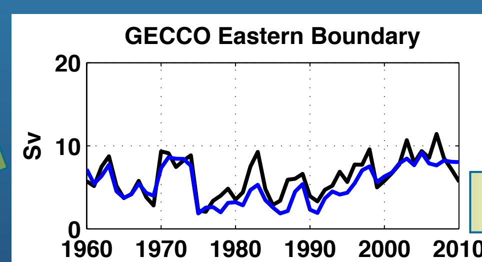
GECCO



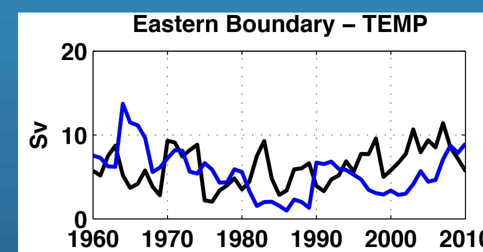
GECCO: AMOC 1000 m @ 41N
Sv
0 5 10 15 20 25
1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010



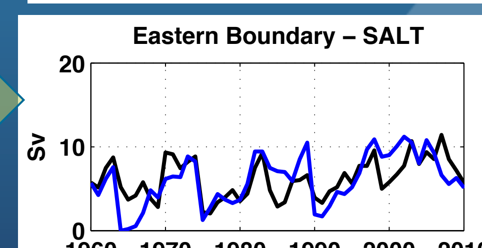
GECCO Western Boundary
Sv
0 10 20
1960 1970 1980 1990 2000 2010



GECCO Eastern Boundary
Sv
0 10 20
1960 1970 1980 1990 2000 2010



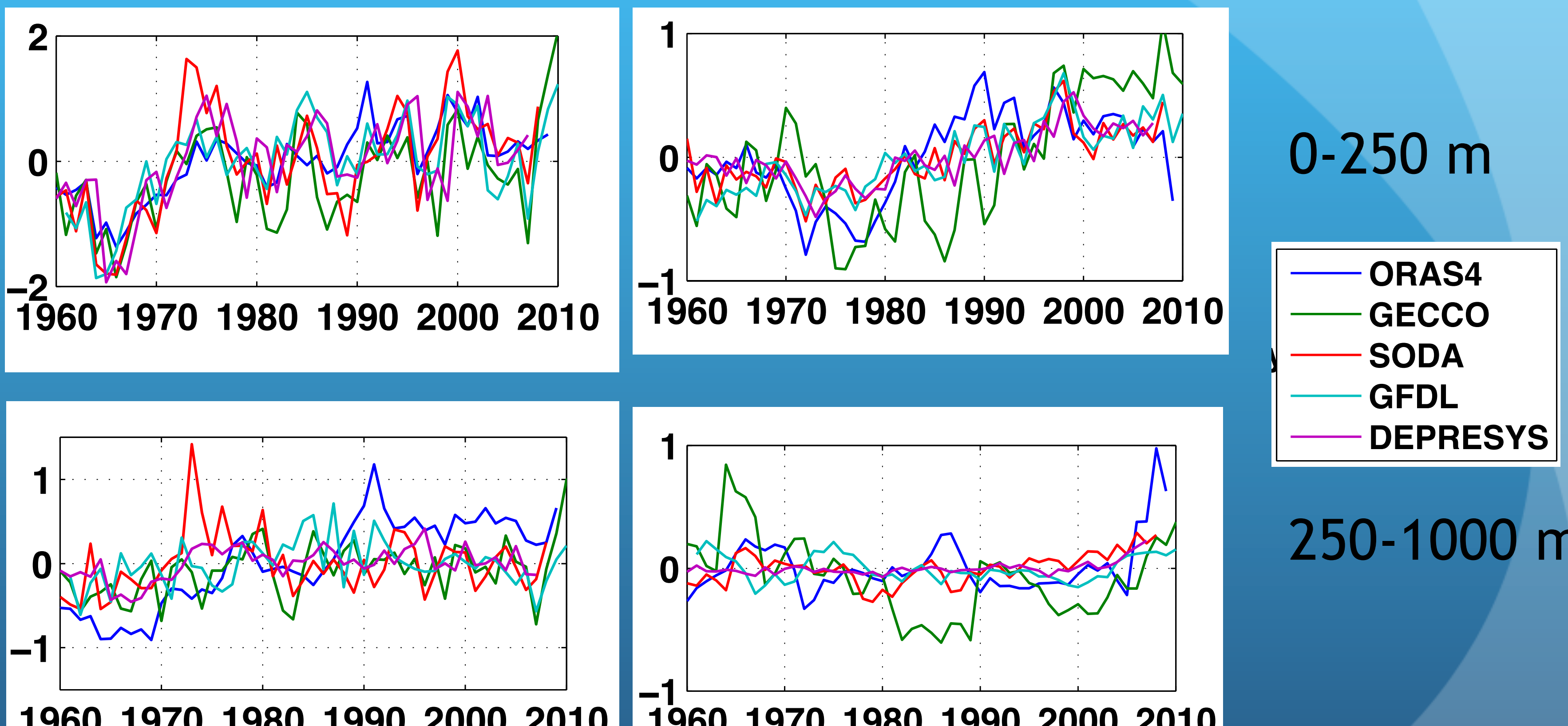
Eastern Boundary – TEMP
Sv
0 10 20
1960 1970 1980 1990 2000 2010



Eastern Boundary – SALT
Sv
0 10 20
1960 1970 1980 1990 2000 2010

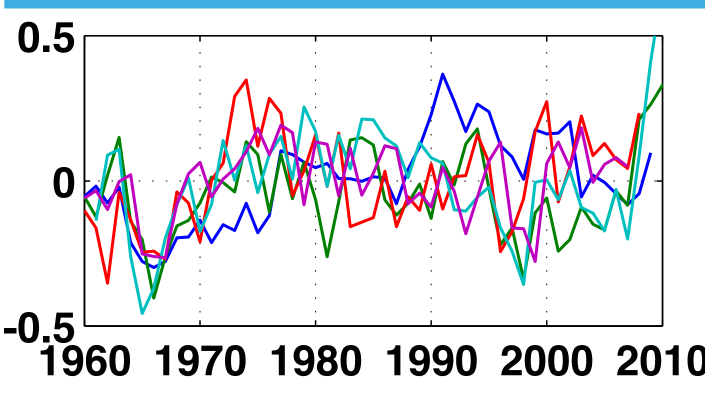
Is the temperature at the eastern/western boundary in agreement?

WESTERN BOUNDARY EASTERN BOUNDARY

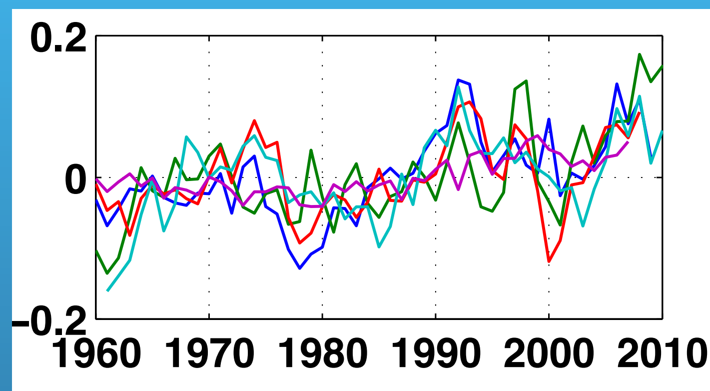


Is the salinity at the eastern/western boundary in agreement?

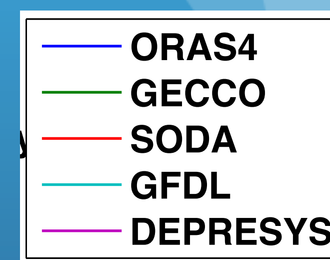
WESTERN BOUNDARY

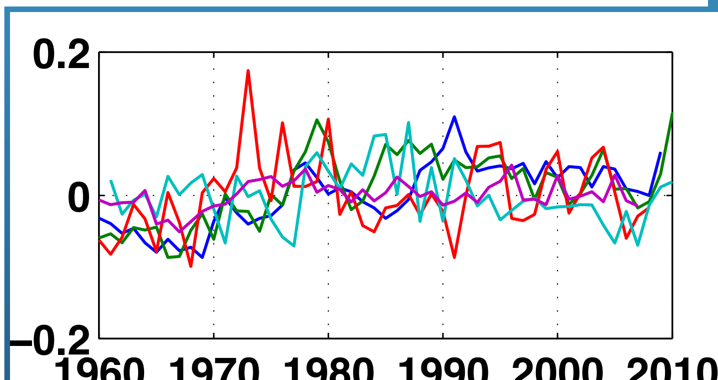


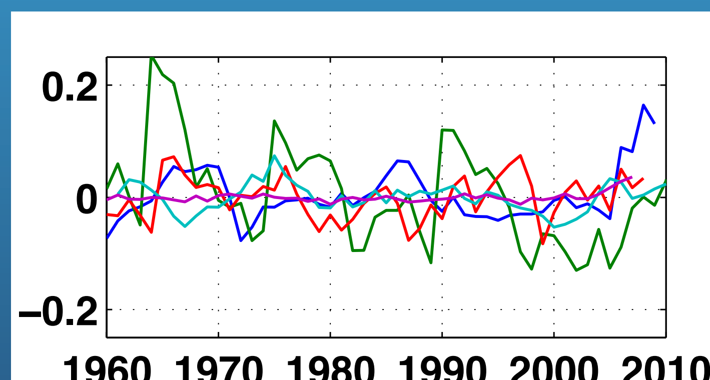
EASTERN BOUNDARY



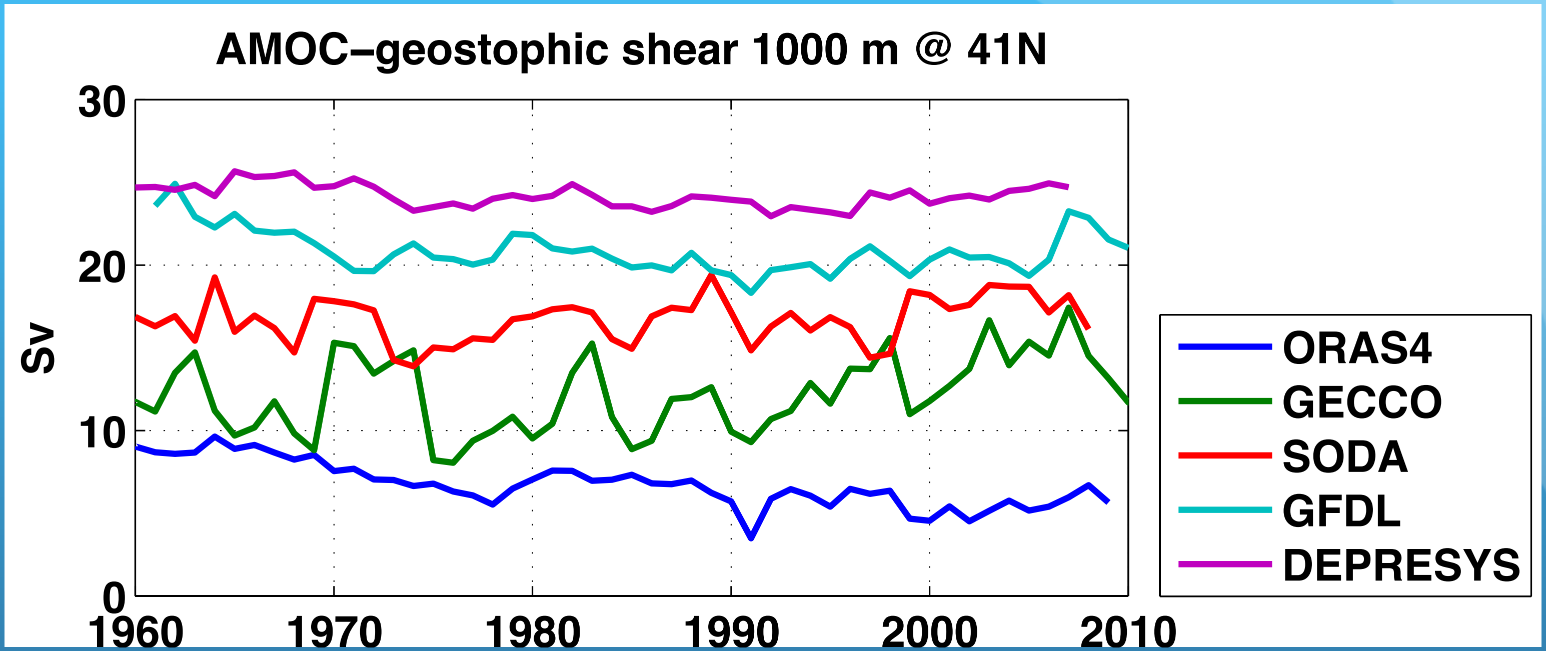
0-250 m







250-1000 m



Trends in the
geostrophic shear component of AMOC
in the upper ocean are inconsistent

What do we know so far about why?

In a preliminary analysis at 41N we found disagreement that

- 1) whether density variations on the east or west boundary were dominating the trends
- 2) whether density variations were primarily driven by temperature or salinity.
- 3) temp/salinity variability on the boundaries, especially below 250m

End

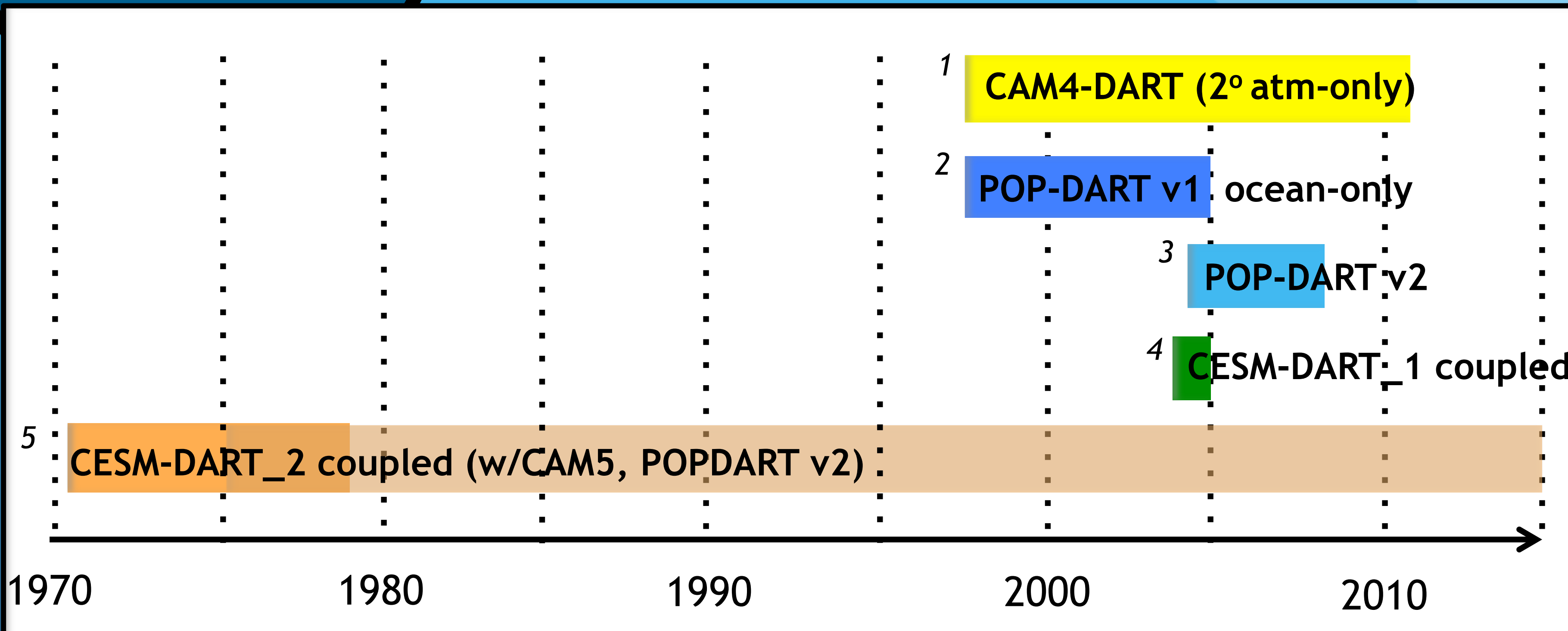
An overview of experimental reanalysis efforts at NCAR

Alicia R. Karspeck, Abhishek Chatterjee

Data assimilation key personnel:
Jeff Anderson, Nancy Collins, Tim Hoar, Helen Kershaw, Kevin Raeder
Climate modeling key personnel:
Gokhan Danabasoglu, Joe Tribbia, Steve Yeager, Svetlana Karol

Formal
Data Assimilation
activites
led by CGD scientists

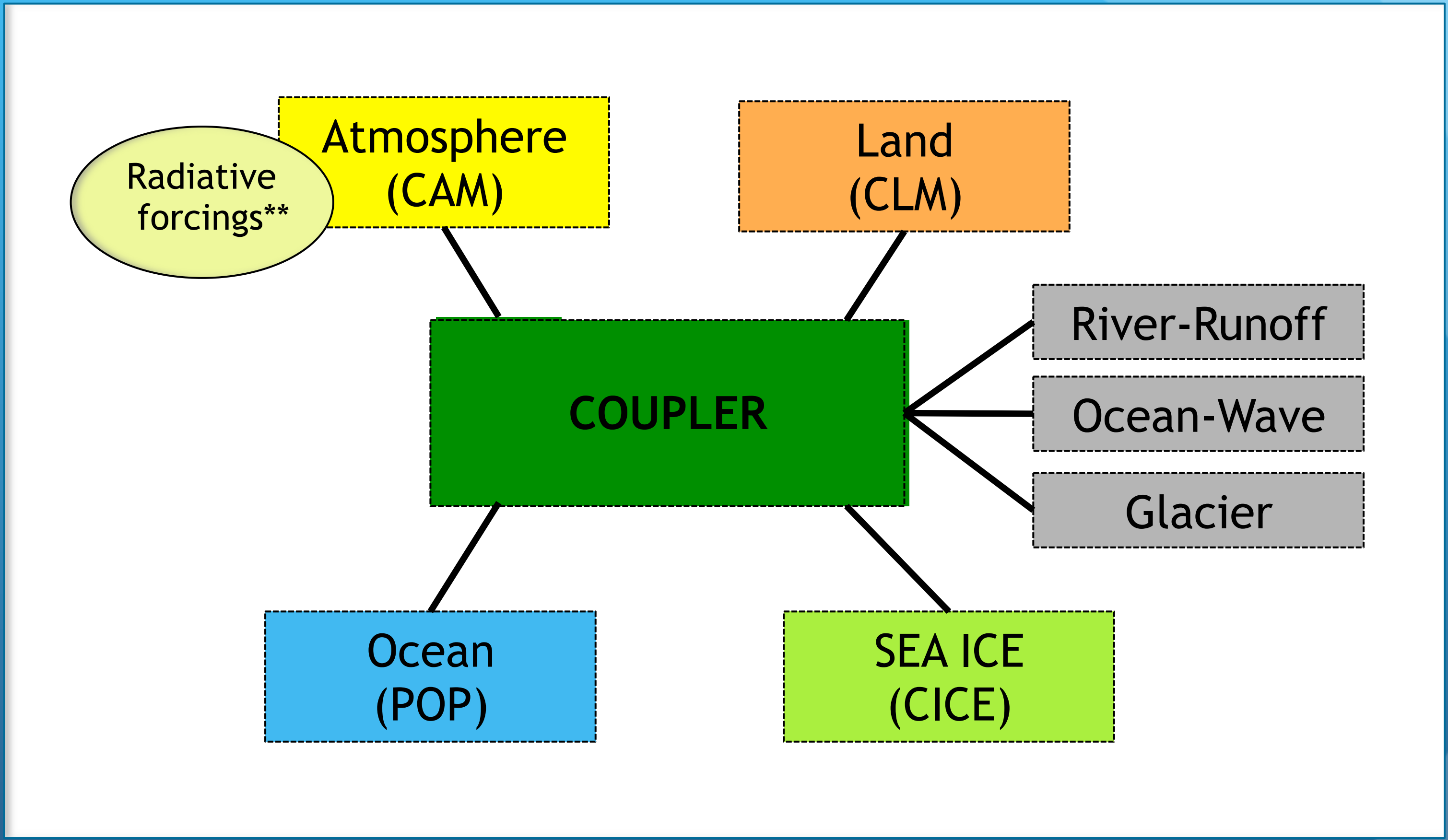
POP/CAM/CESM DART: experimental climate reanalyses



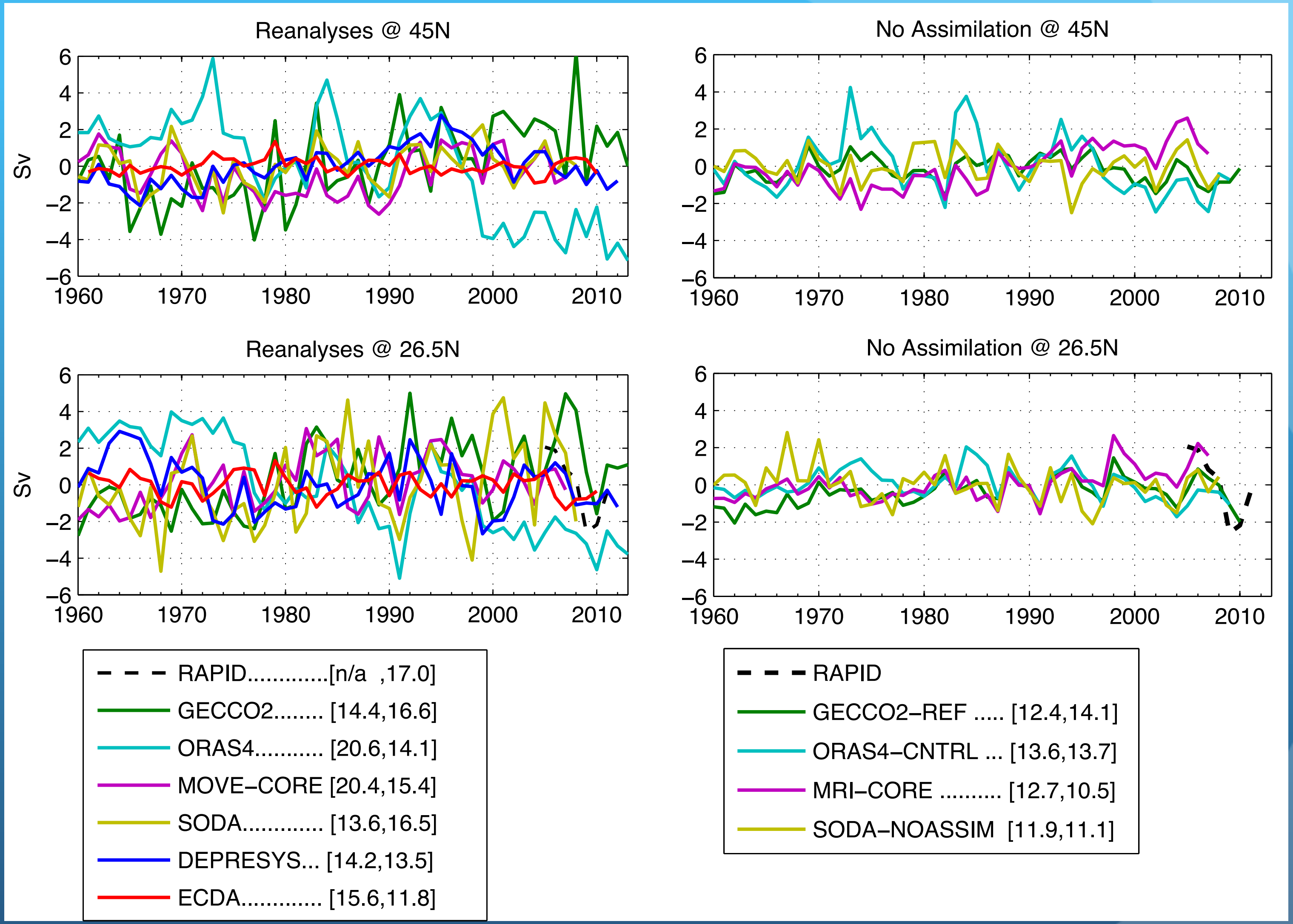
[1] Kevin Raeder (DAReS-CISl)
[2] Alicia Karspeck (Ocean-CGD)
[3] Alicia Karspeck (Ocean-CGD)
[4] Abhishek Chatterjee(CGD/DAReS-CISL)
[5] Alicia Karspeck (Ocean-CGD)

All methods use the DART implementation of the Ensemble Adjustment Kalman Filter

Community Earth System Model

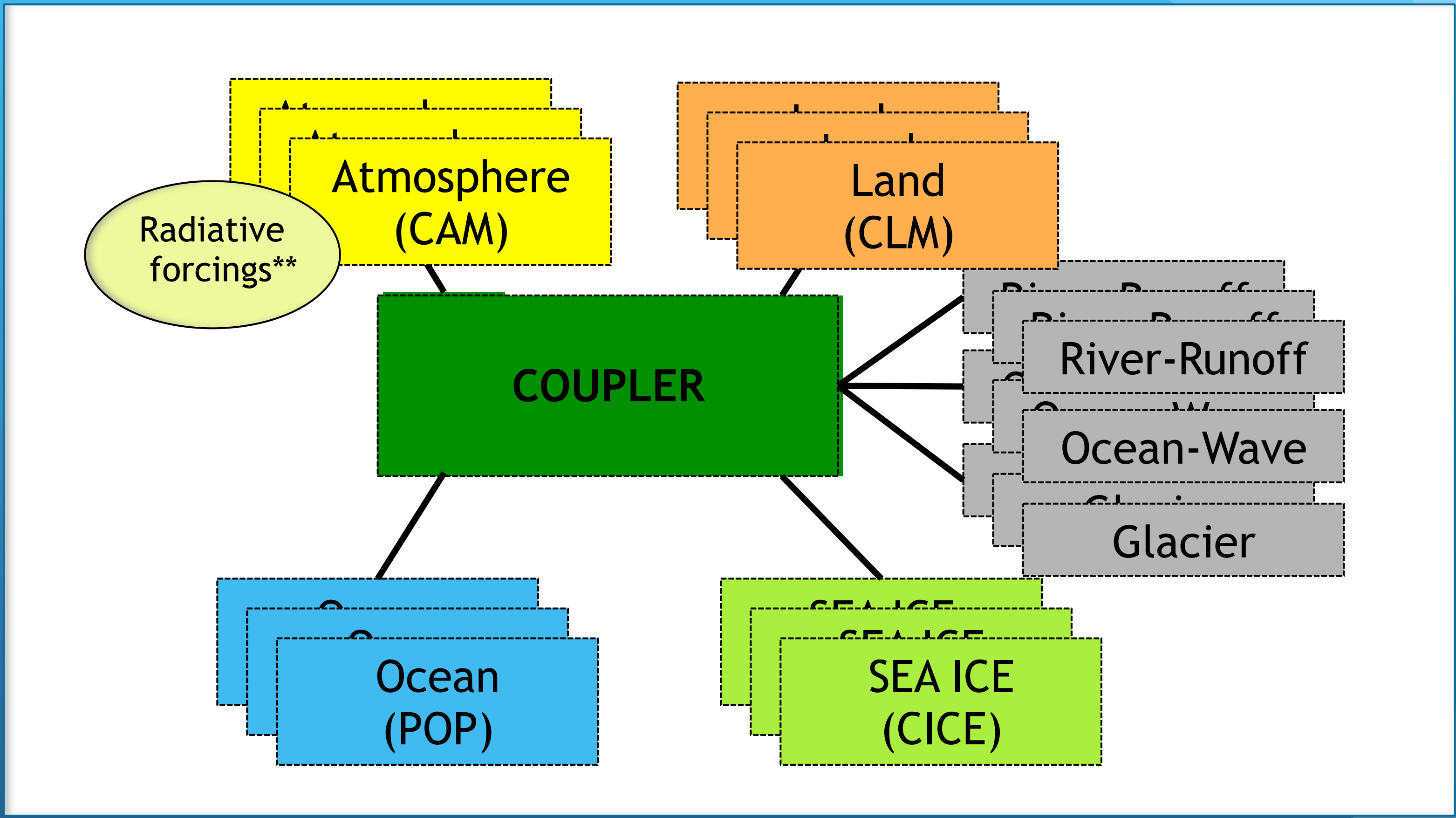


** Greenhouse gases, manmade aerosols, volcanic eruptions, solar variability



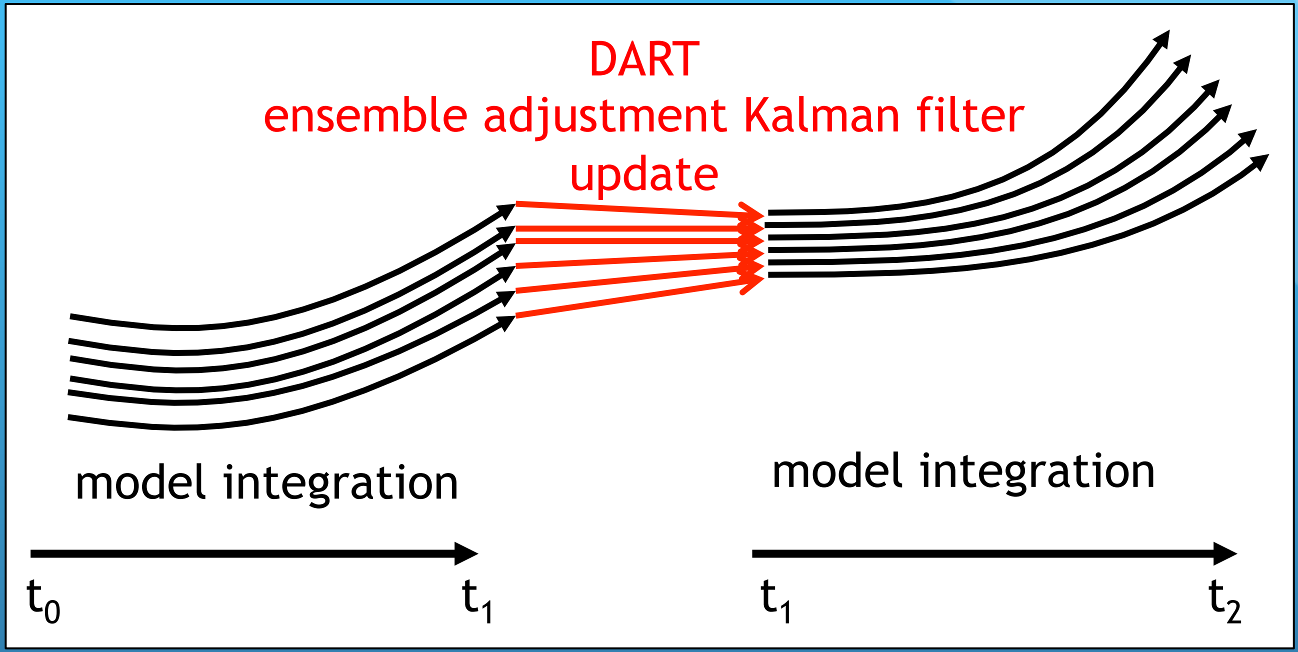
Reanalyses @ 45N
No Assimilation @ 45N
Reanalyses @ 26.5N
No Assimilation @ 26.5N
Sv
6
4
2
0
−2
−4
−6
1960
1970
1980
1990
2000
2010
RAPID............[n/a ,17.0]
GECCO2........ [14.4,16.6]
ORAS4........... [20.6,14.1]
MOVE−CORE [20.4,15.4]
SODA............. [13.6,16.5]
DEPRESYS... [14.2,13.5]
ECDA............. [15.6,11.8]
RAPID
GECCO2−REF ..... [12.4,14.1]
ORAS4−CNTRL ... [13.6,13.7]
MRI−CORE .... [12.7,10.5]
SODA−NOASSIM [11.9,11.1]

Community Earth System Model "multi-instance"



** Greenhouse gases, manmade aerosols, volcanic eruptions, solar variability

Data Assimilation Research Testbed

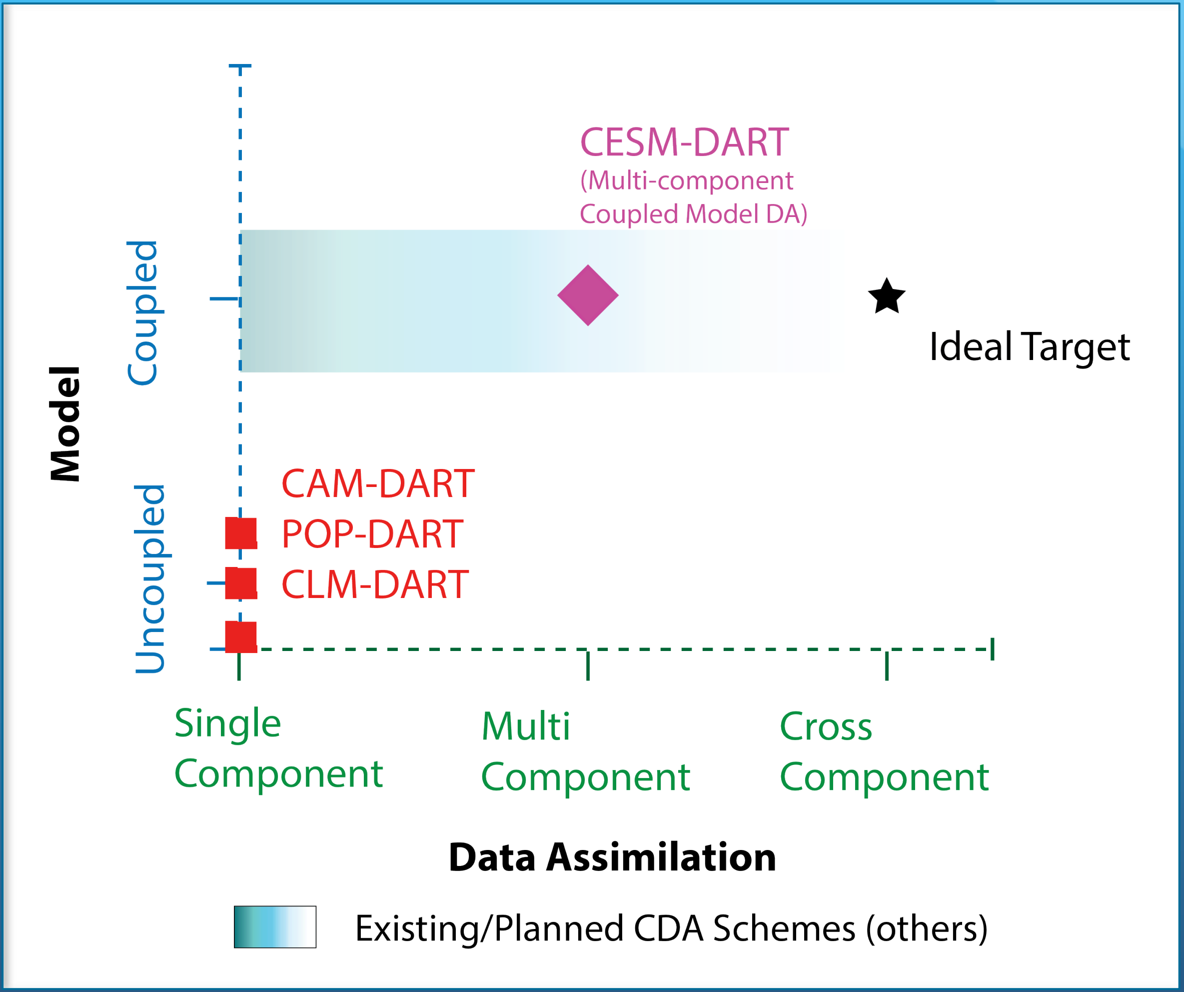


DART is a generic ensemble filter; necessary ingredients:

- ***Model forecasts***
  - In a coupled framework -- model state can be defined independently for each component or jointly across components.
- ***Forward operators*** to map from the model state vector to the observation space
- ***Observations***

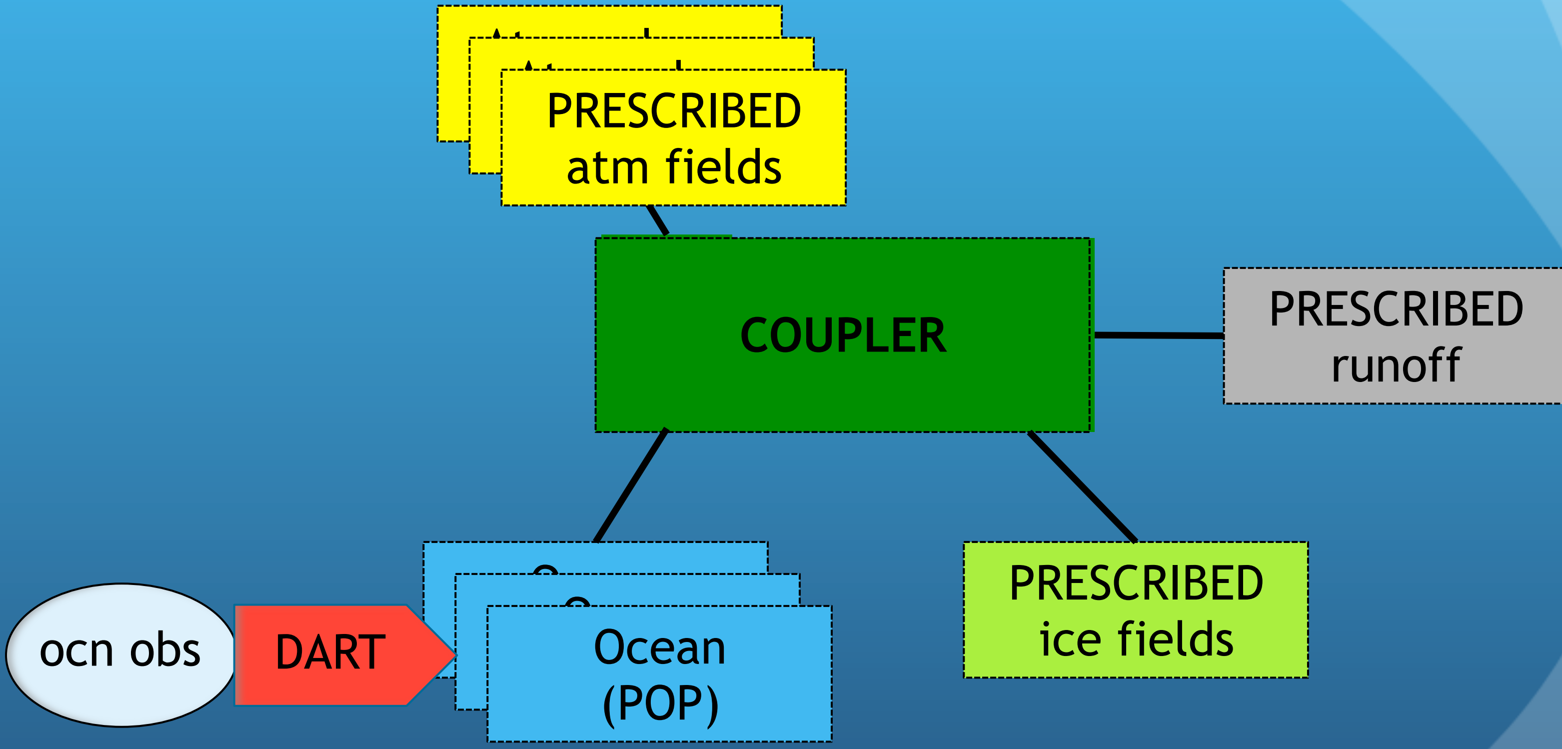
(http://www.image.ucar.edu/DAReS/DART)

Frameworks for data assimilation

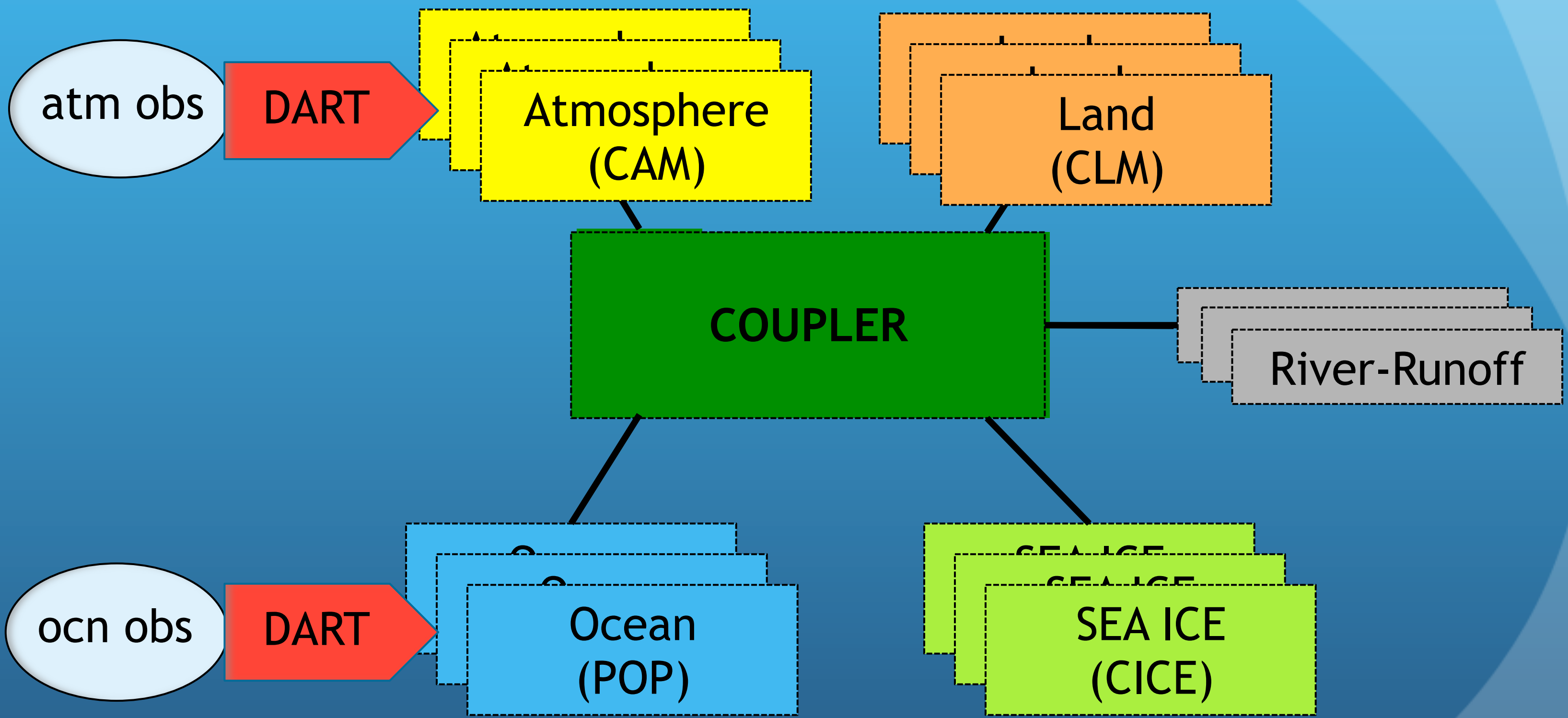


Schematic courtesy of A. Chatterjee

Community Earth System Model interfacing with DART in a "single-component" DA uncoupled framework



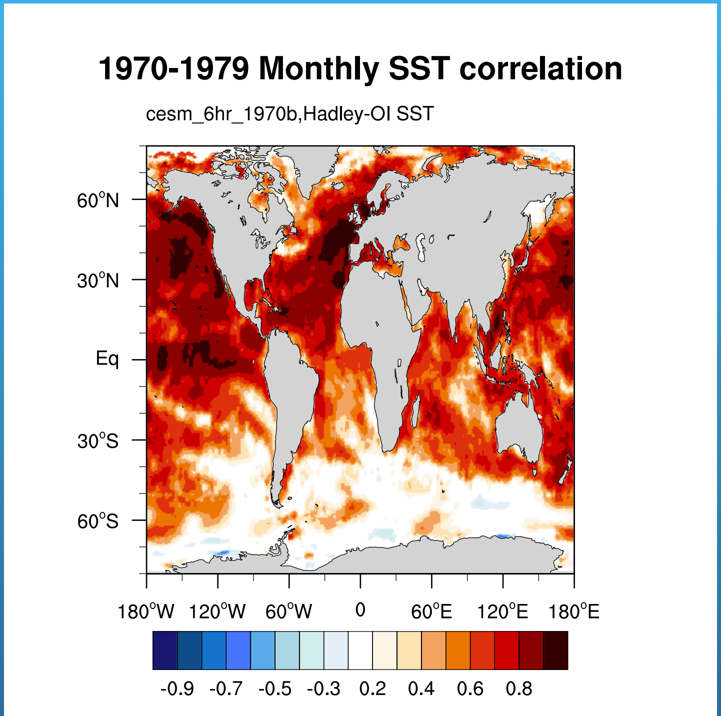
Community Earth System Model interfacing with DART in a "multi-component" DA coupled framework

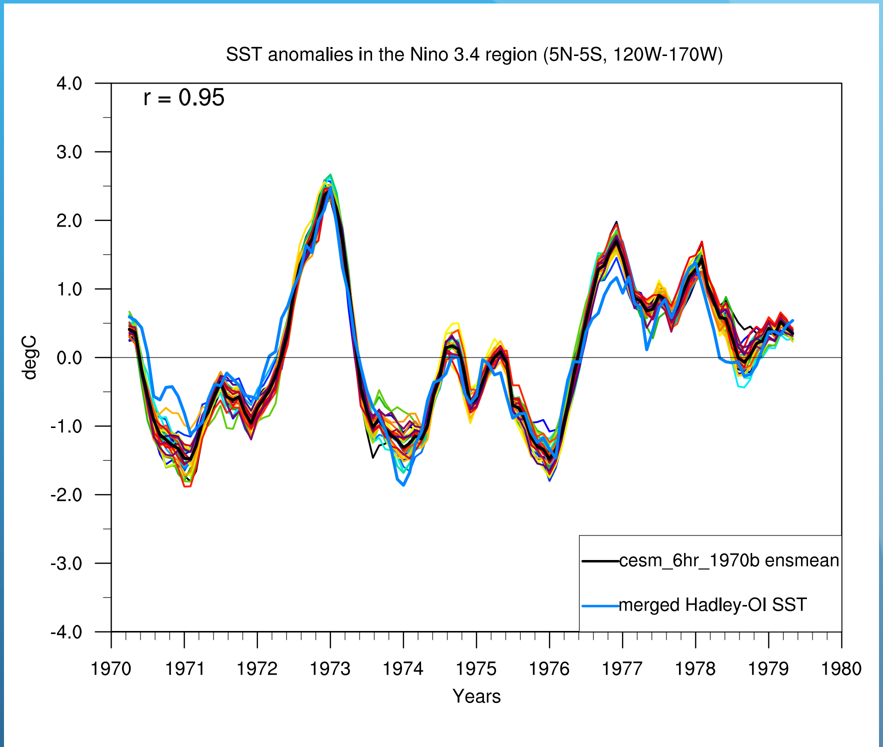


Summary info on the CESM-DART coupled assimilation system

Model:	CESM global coupled ocean/atm/ice/land Horizontal resolution: nominal 1º Vertical resolution: CAM5 30 levels (~2hPa) POP 60 levels (10 m upper to ~250m deep)
DA method:	30 member DART ensemble adjustment Kalman filter (EAKF)
Ocean obs:	In-situ temp and salinity (XBT, MBT, CTD, drifters, floats, moorings, ARGO floats, ocean station; **no SST, no altimetry**)
Atm obs:	temp and winds (radiosondes, aircraft, satellite drift winds, GPSRO-COSMIC, ACARS; currently no moisture, surface pressure, or radiometer retrievals)

Early results from the CESM-DART coupled assimilation



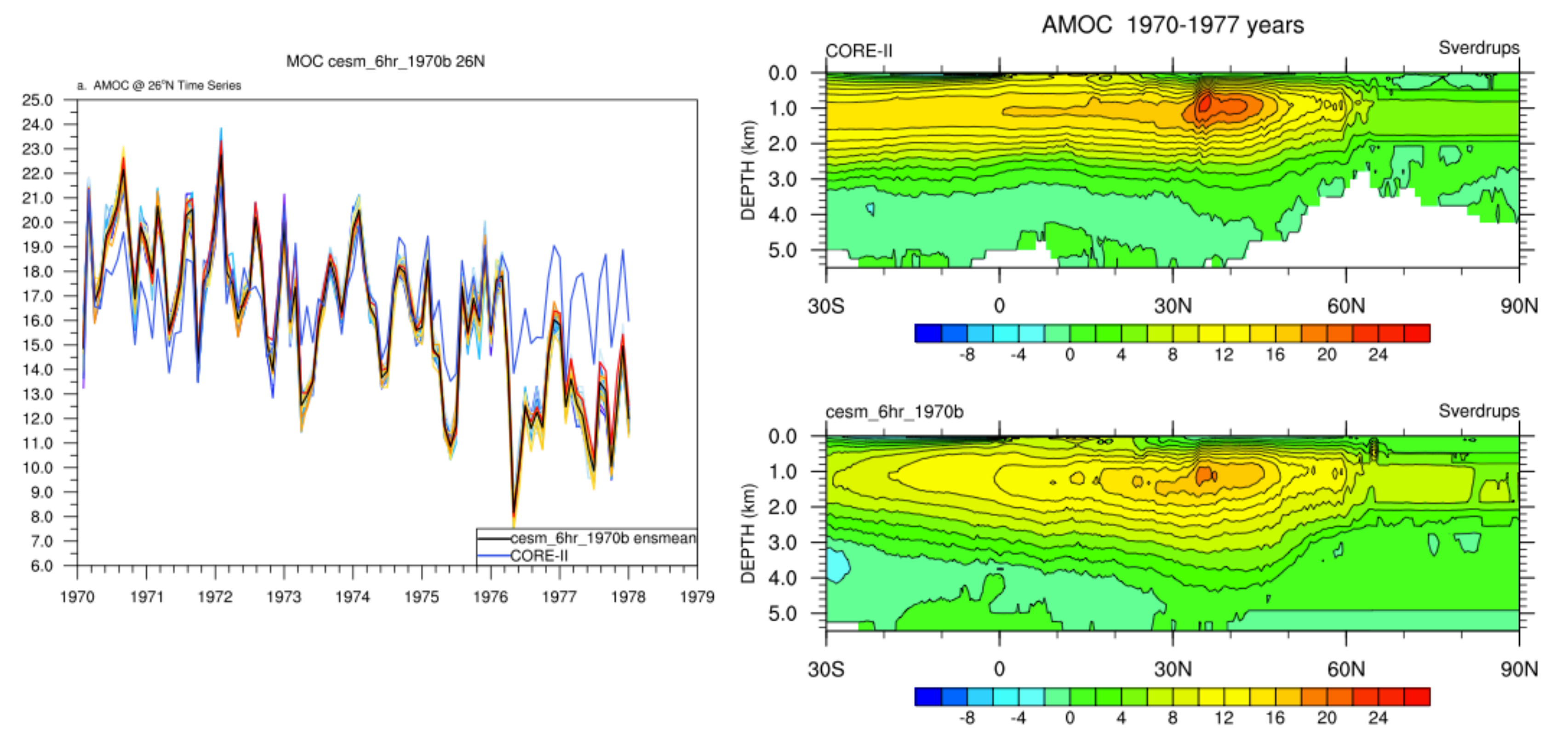


Generally high correlation with HADISST

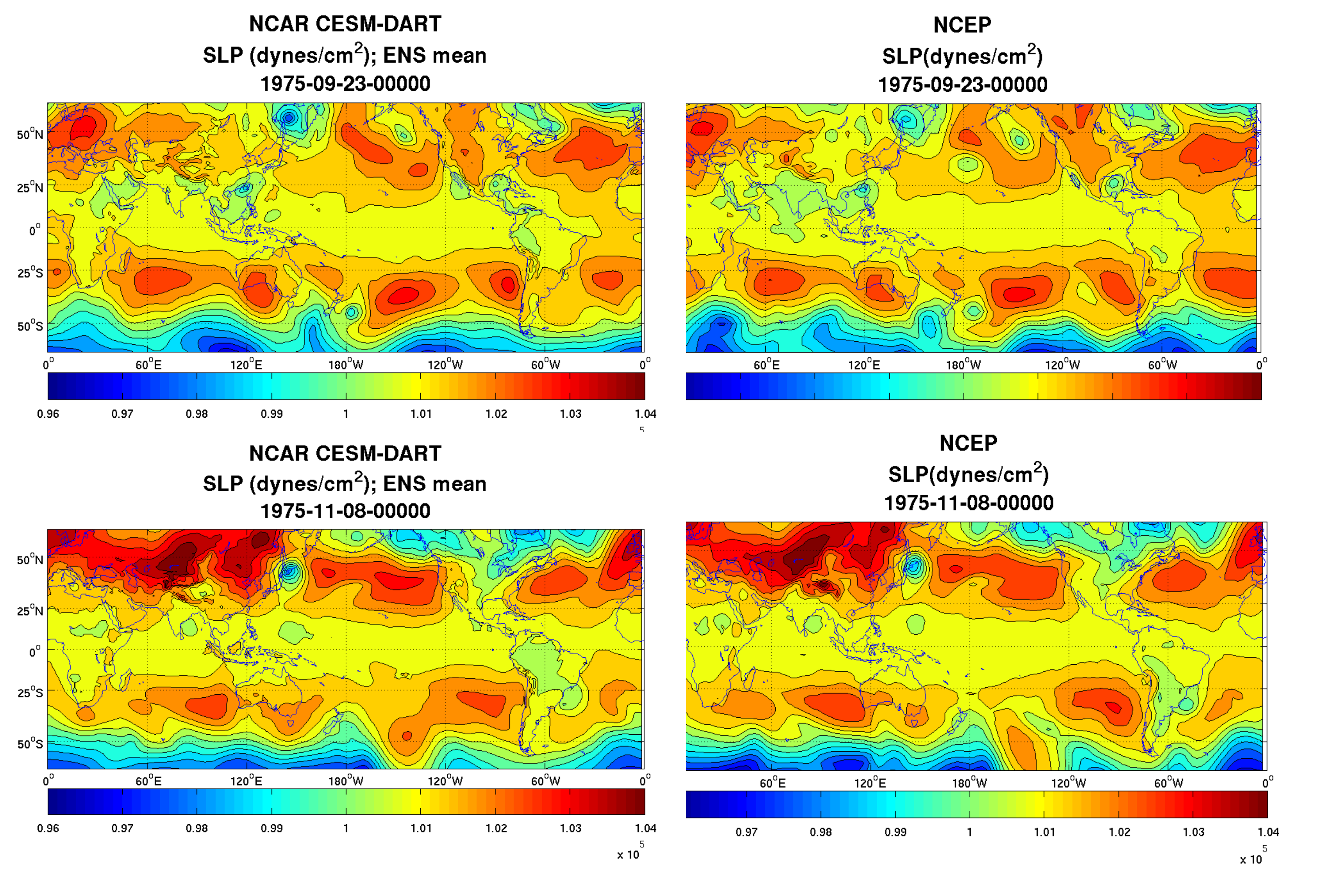
1972-73 El Nino event simulated

Plots courtesy of S. Karol

AMOC


MOC cesm_6hr_1970b 26N
a. AMOC @ 26°N Time Series
cesm_6hr_1970b ensmean
CORE-II
AMOC 1970-1977 years
CORE-II
Sverdrups
DEPTH (km)
30S
0
30N
60N
90N
cesm_6hr_1970b
Sverdrups
DEPTH (km)
30S
0
30N
60N
90N

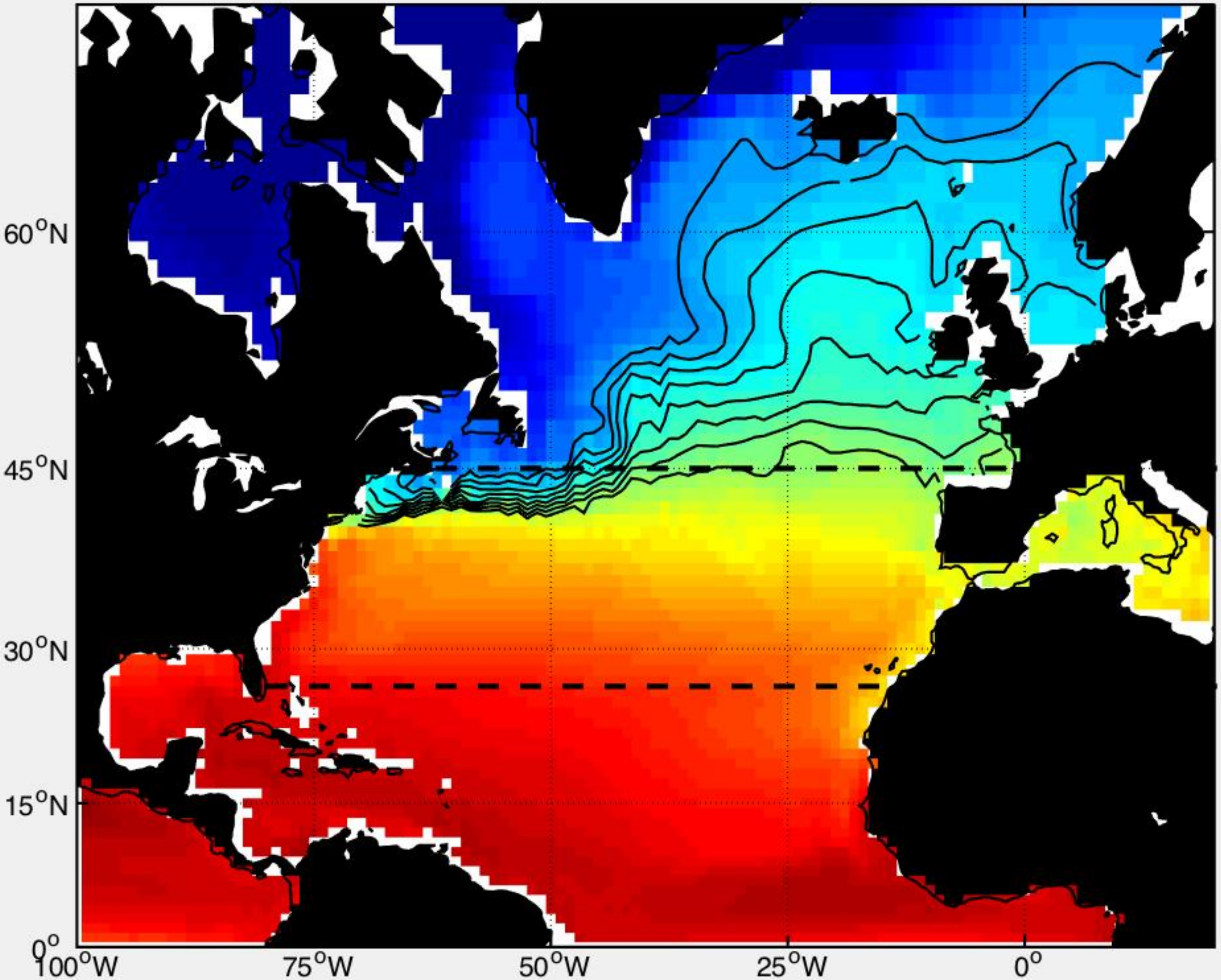
Ski-hourly snapshot of SLP from CAM5

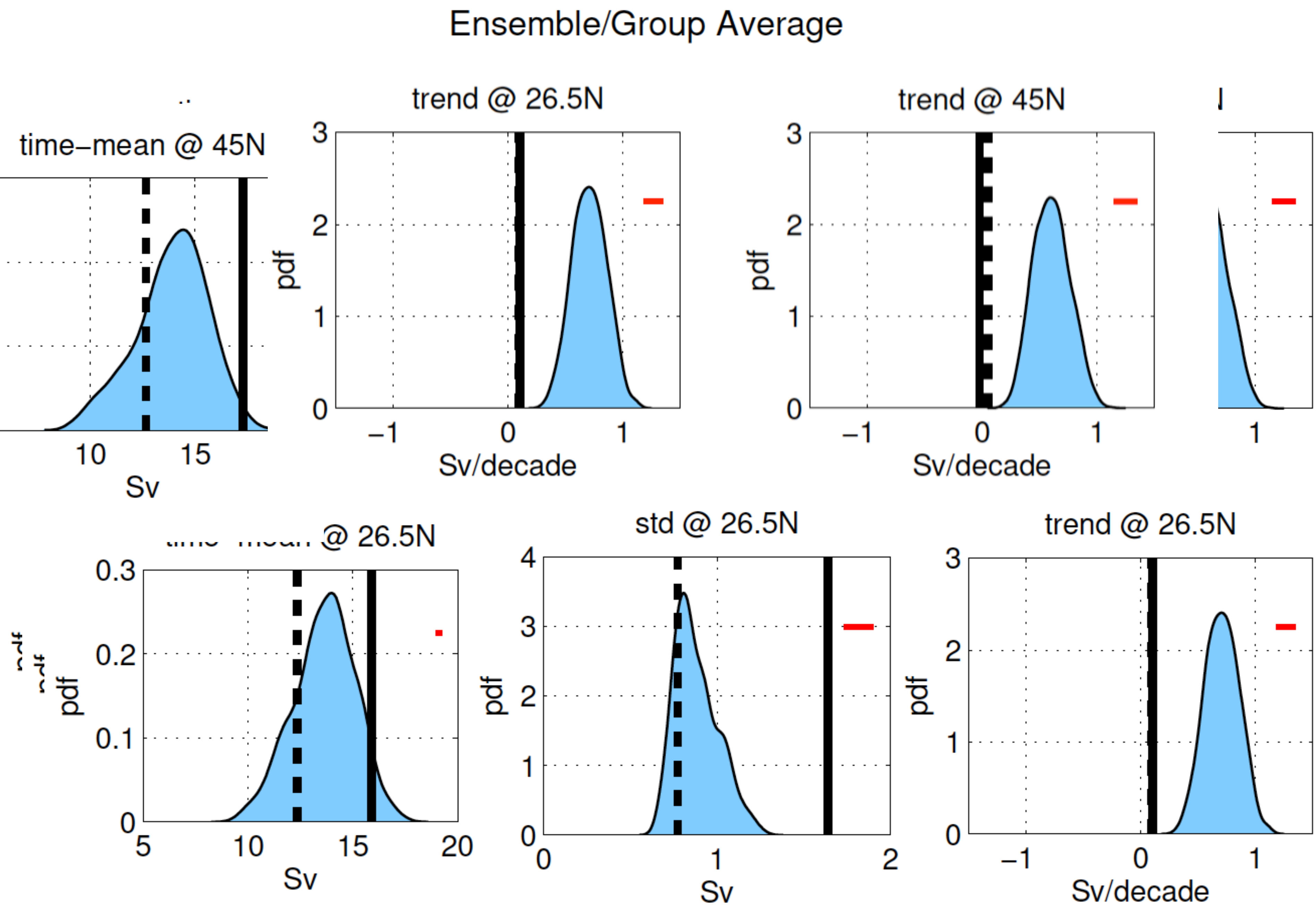


- Reasonable AMOC/variability (albeit with a drfit)
- Skill in 6 hourly forecast in atmosphere comparable to the stats published by NCEP
- Reasonable SST variability

Plans in the next 5 years:

- Complete coupled-model, multi-component assimilation
- Develop coupled-model cross-component assimilation (cross component covariances / increments)
- Software advances for speeding-up the assimilation
- Include altimetry in ocean assimilation
- Global ocean assimilation with eddy-resolving model
- **Investigate the ways that coupled assimilation may be advantageous for state estimation and prediction**


60°N
45°N
30°N
15°N
0°
100°W
75°W
50°W
25°W
0°



Ensemble/Group Average
time−mean @ 45N
trend @ 26.5N
trend @ 45N
time−mean @ 26.5N
std @ 26.5N
trend @ 26.5N
pdf
Sv
Sv/decade