A CCSM4 Decadal Prediction Case Study:

Abrupt North Atlantic Ocean Heat Content Change in the 1990s

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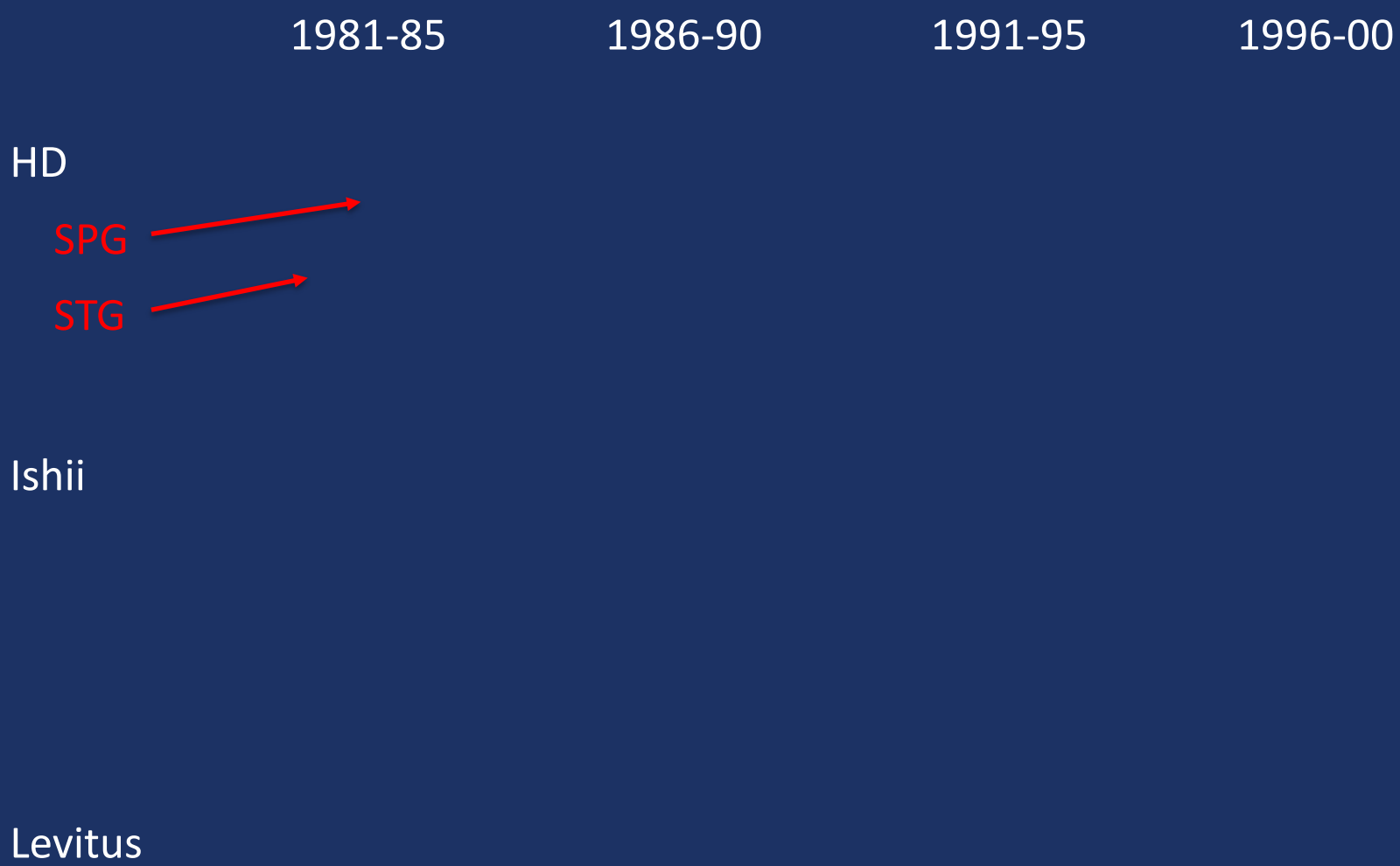
NCAR, Boulder, CO

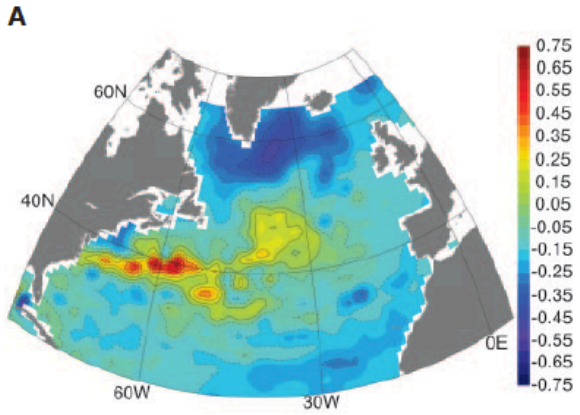
CESM Workshop, Breckenridge, June 23, 2011

275m Heat Content Anomaly (relative to 1957-1990)



Observed mid-1990's Regime Shift in the SPG

SST/SSH/BSF: Flatau et al (*J. Clim*, 2003)



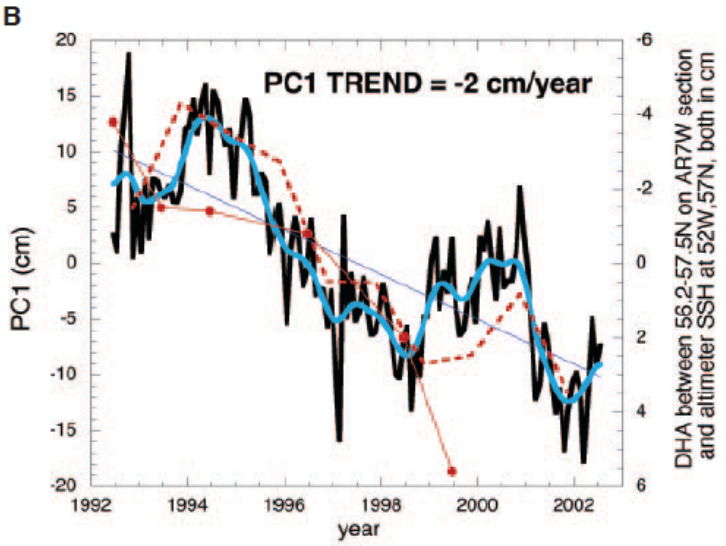


Fig. 1. (A) EOF1 of altimeter SSH and (B) its PC1 with 11.1% of the variance. EOF1 is nondimensional with contour interval of 0.05. The trend in PC1 is significantly different from zero at 95% level. The blue curve is the binomially smoothed PC1. The dynamic height anomaly (in solid red; dots denote data points of the time series) computed in the central Labrador Sea (average from 56.2° to 57.5°N along the WOCE AR7/W section across the Labrador Sea from Newfoundland to Greenland) is shown in (B) with its axis on right. The altimeter SSH anomaly at 52°W, 57°N (12-month May-to-April average; dashed red) in the central Labrador gives a similar result of about 8 cm from 1994 to 2002.

Hakkinen & Rhines (*Science*, 2004)

Marine Fauna: Hatun et al. (*Prog. Oceanogr.*, 2009)

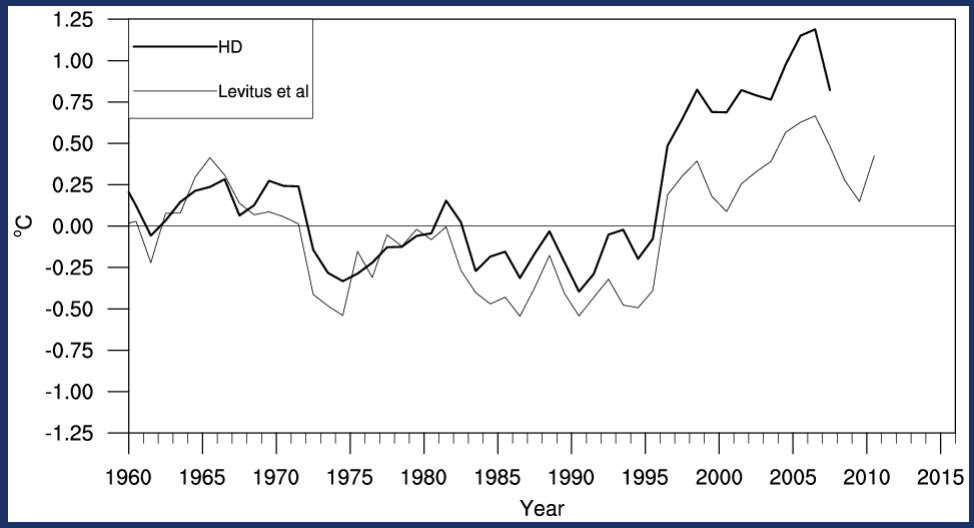
Carbon Uptake: Schuster & Watson (*JGR-Ocean*, 2007)

Greenland Glacier Melt: Holland et al. (*Nat. Geo.*, 2008)

275m Heat Content Anomaly

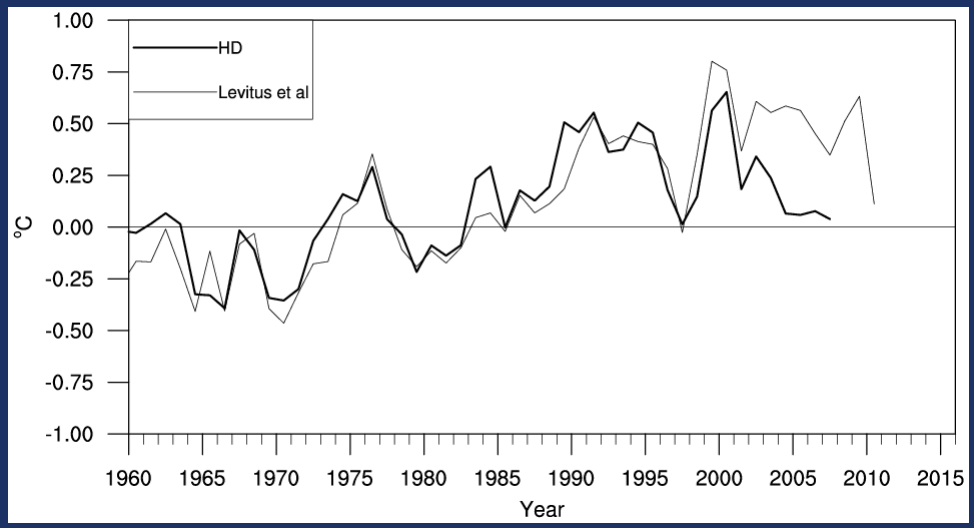
SPG

1960-2007 correlation is 0.9



STG

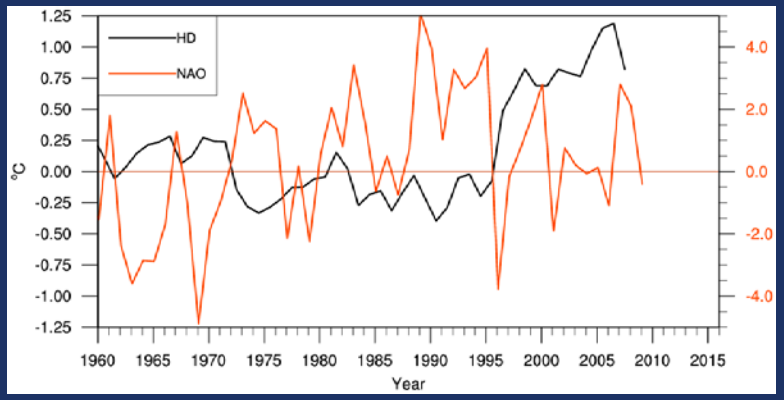
1960-2007 correlation is 0.83



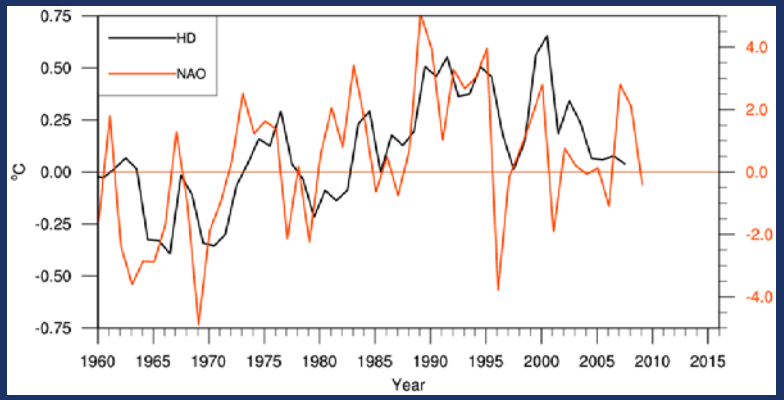
*1957-90 climatology

HD response to observed NAO

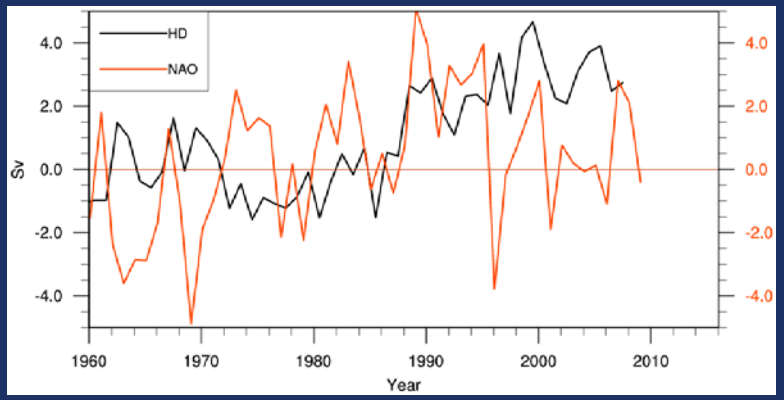
SPG HC



STG HC



AMOC at 37°N



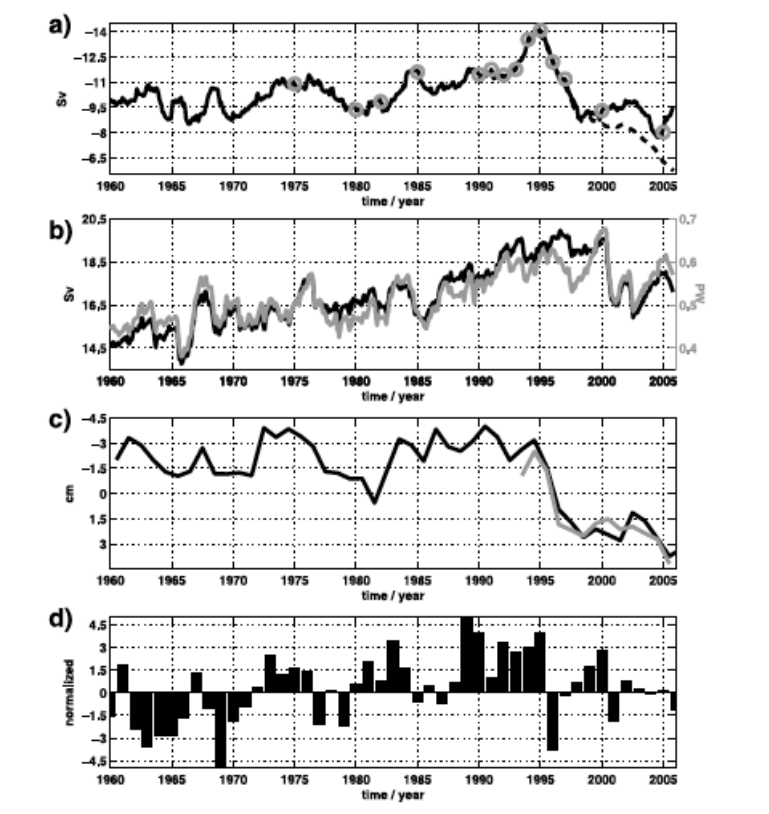
Ocean Preconditioning by persistent NAO$^+$

SPG BSF

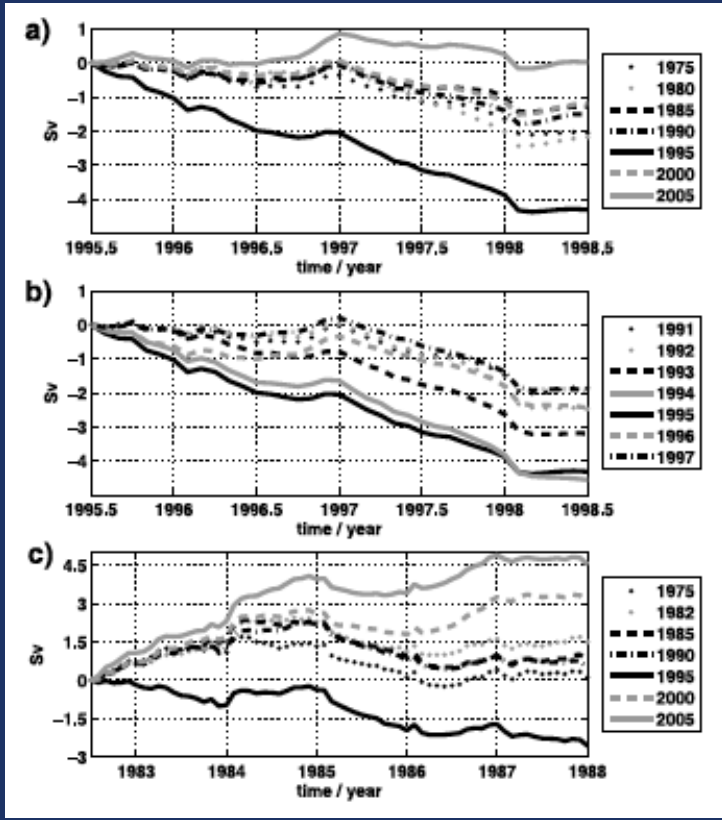
AMOC

SSH

NAO

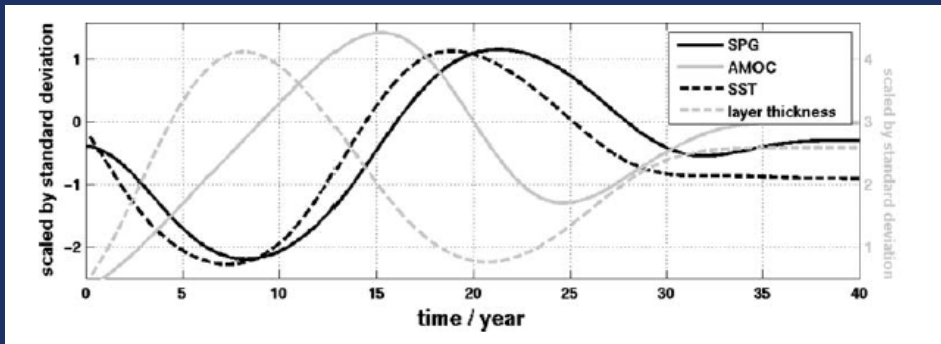


SPG BSF dependence on i.c./forcing

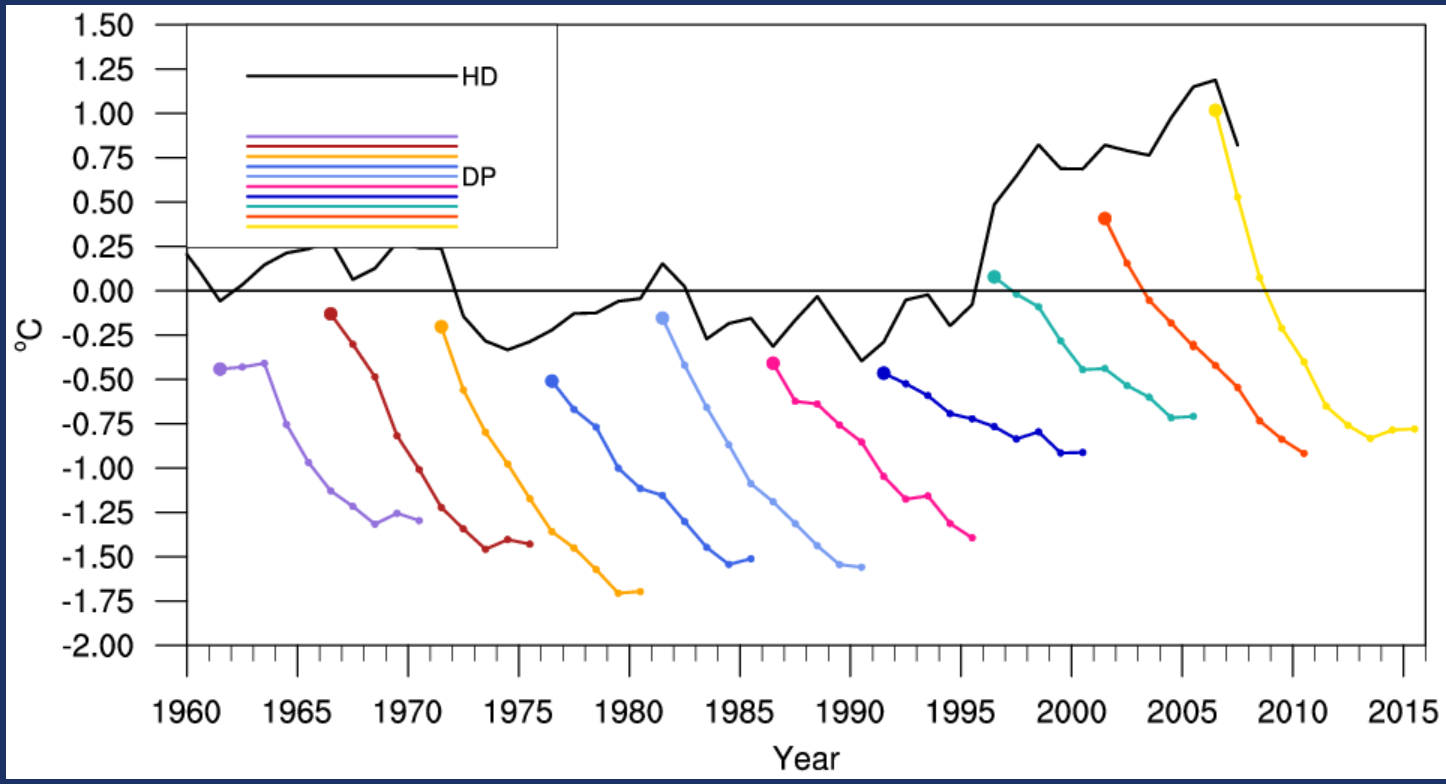


Lohmann et al (*Clim Dyn*, 2009)
Lohmann et al (*GRL*, 2009)

NAO$^+$ - NAO^n

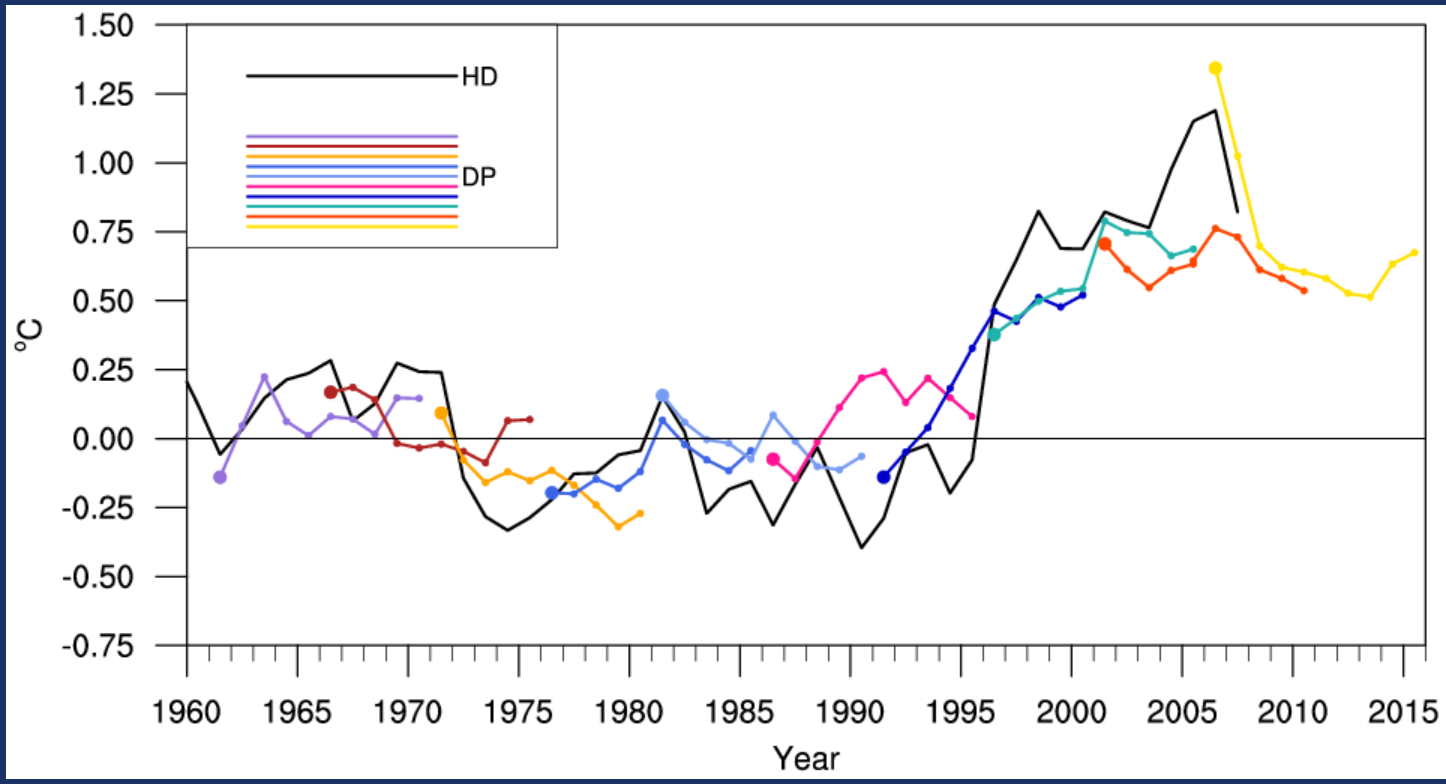


275m Heat Content Anomaly in SPG box



- 10-yr DP experiments initialized from HD on January 1 1961, 1966, ..., 2006
- Colored curves are 10-member ensemble means

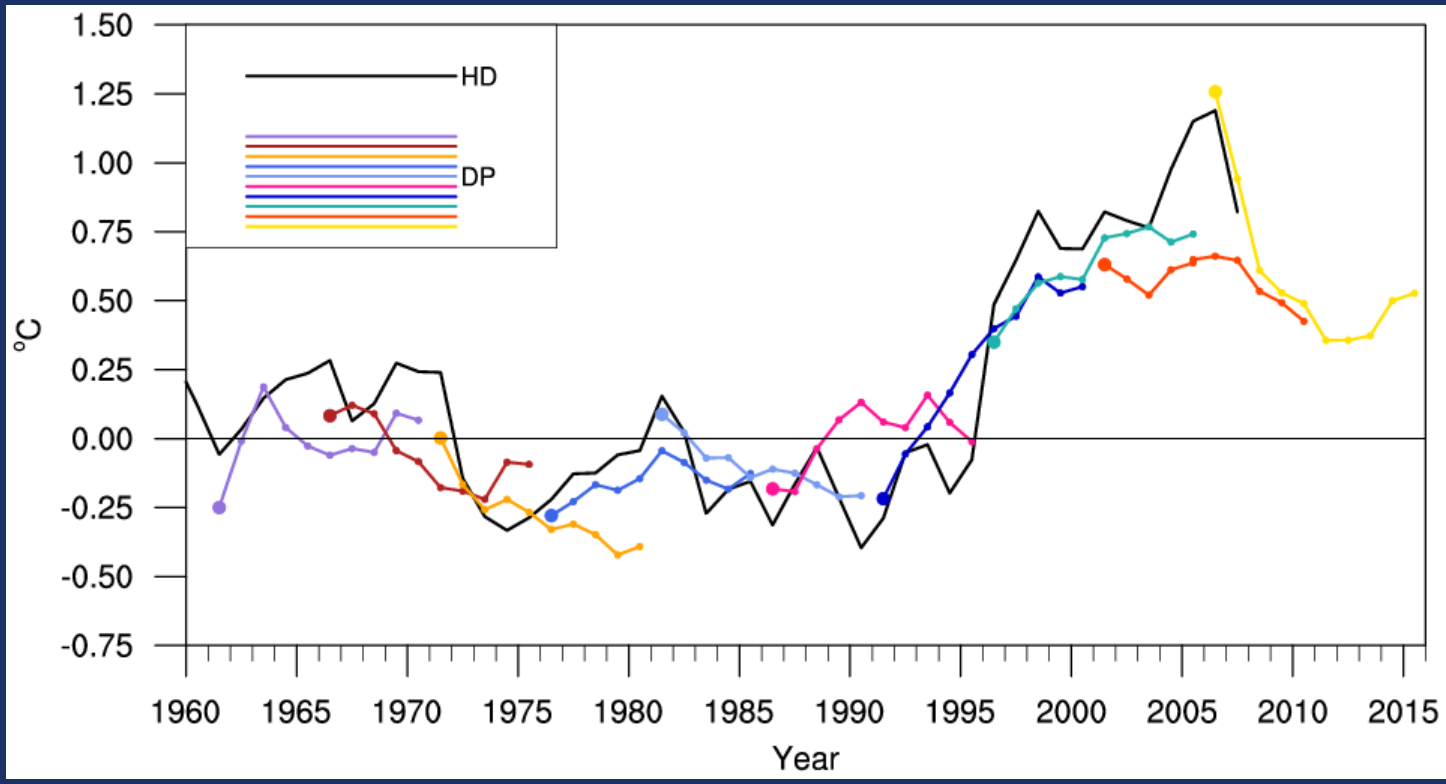
275m Heat Content Anomaly in SPG box



Bias-corrected DP experiments (Method 1)

HD/DP correlation of lag1-5 pentads (N=9): 0.94 (>99% signif)
HD/DP correlation of lag6-10 pentads (N=8): 0.92 (>99% signif)

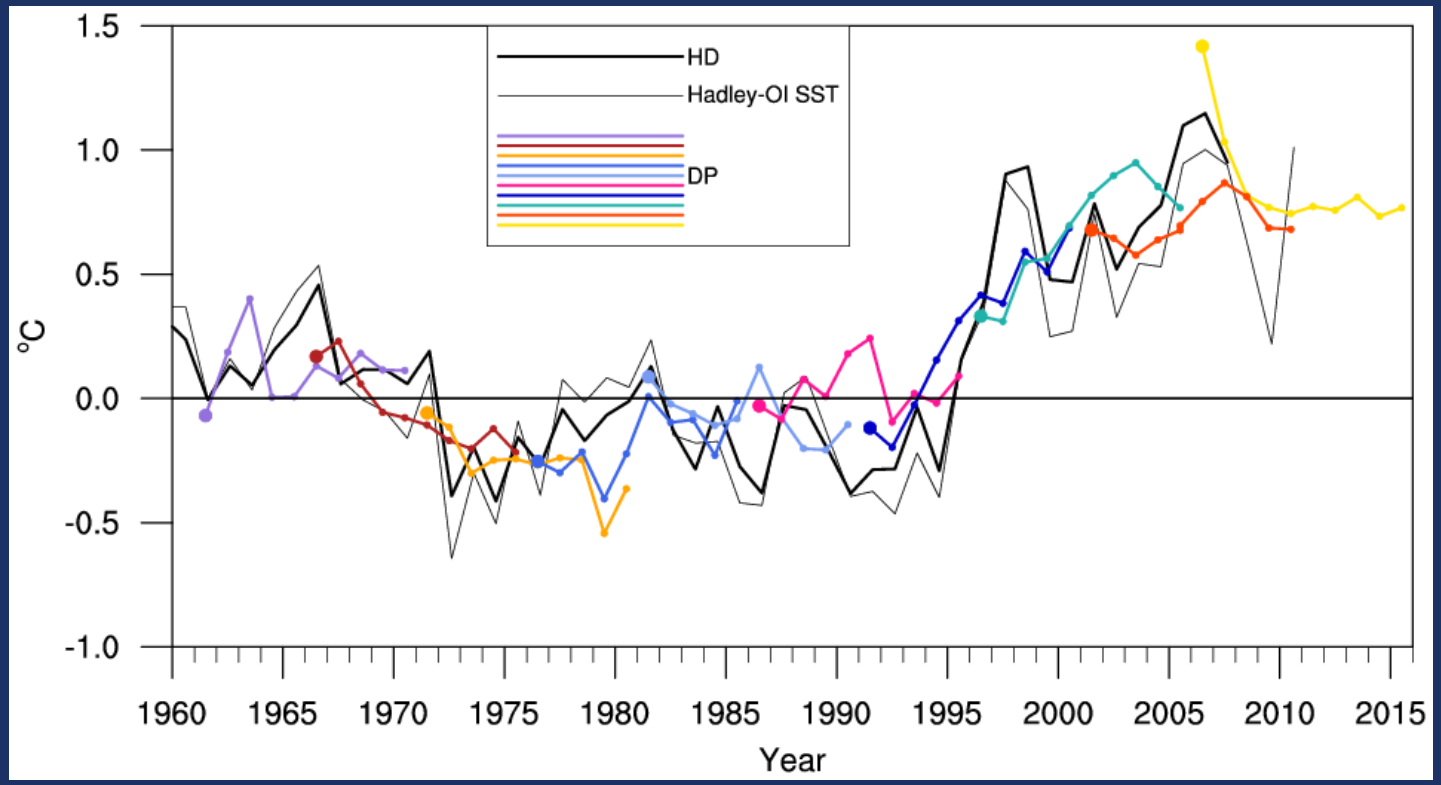
275m Heat Content Anomaly in SPG box



Bias-corrected DP experiments (Method 2)

HD/DP correlation of lag1-5 pentads (N=9): 0.94 (>99% signif)
HD/DP correlation of lag6-10 pentads (N=8): 0.94 (>99% signif)

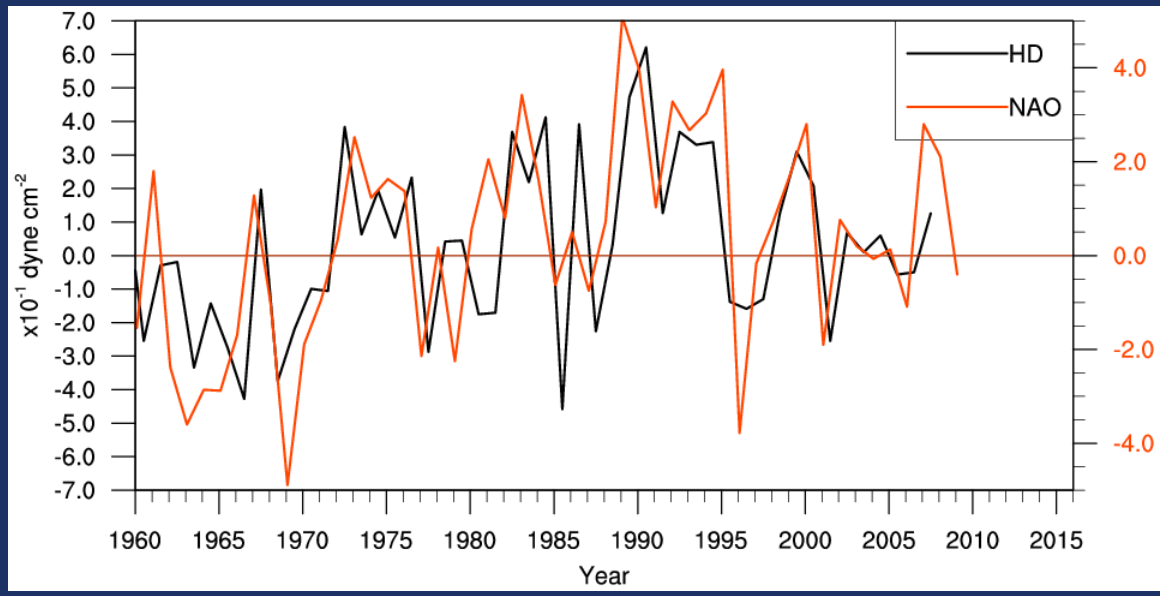
SST Anomaly in SPG box



HD/DP correlation of lag1-5 pentads (N=9): 0.93 (>99% signif)
HD/DP correlation of lag6-10 pentads (N=8): 0.94 (>99% signif)

Zonal Wind Stress Anomaly in SPG box

Correlation = 0.7 implies SPG TAUX is reasonable proxy for NAO

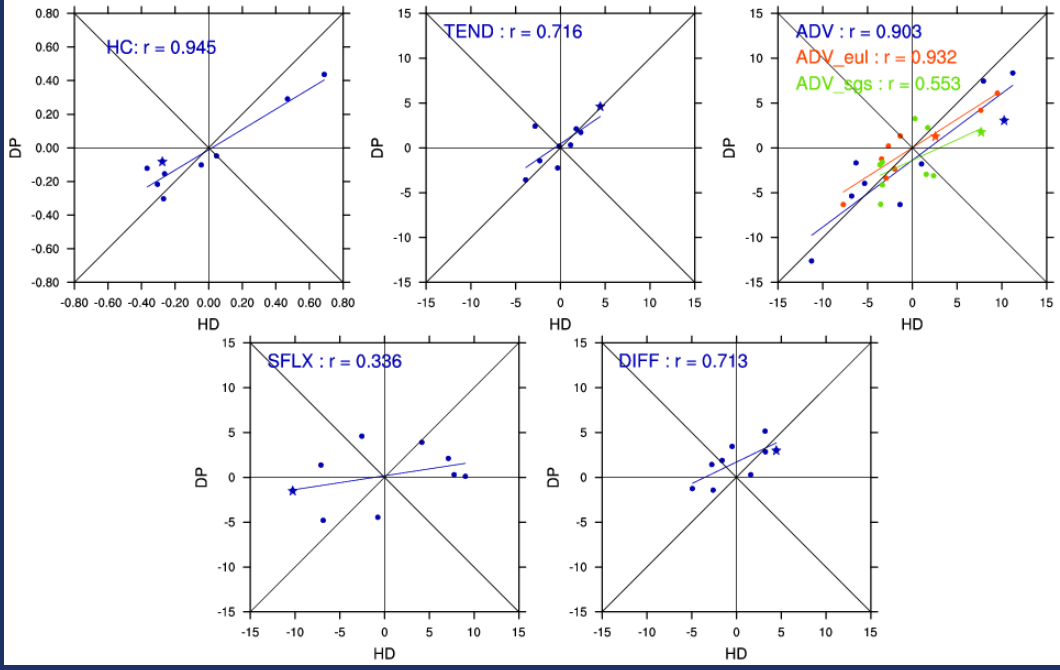


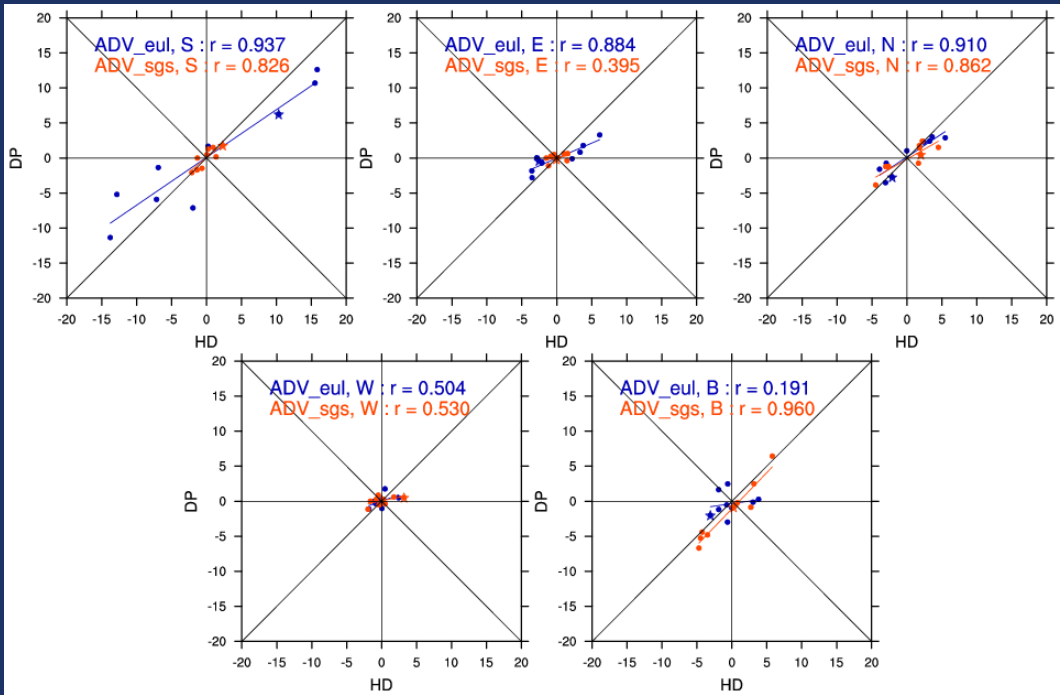
➔ DP's show low skill at predicting TAUX (NAO) variations

Comparison of pentadal mean Heat Budget terms: lags 1-5

- High tendency correlation attributable to skillful prediction of 1) advective and 2) diffusive heat flux anomalies.

- Surface heat flux anomalies (NAO) are poorly predicted

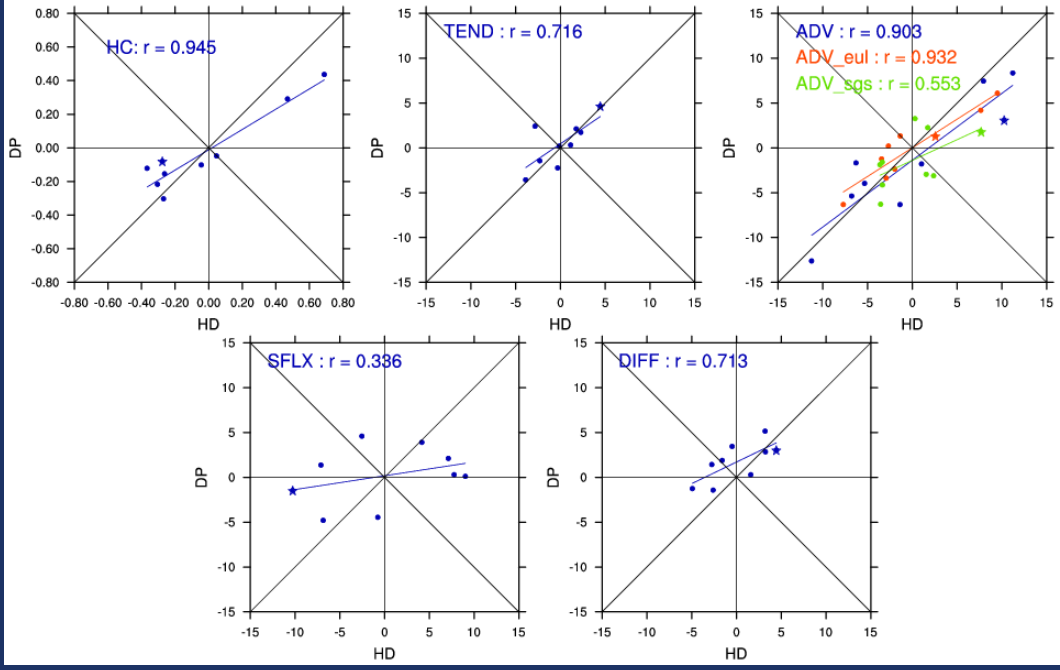


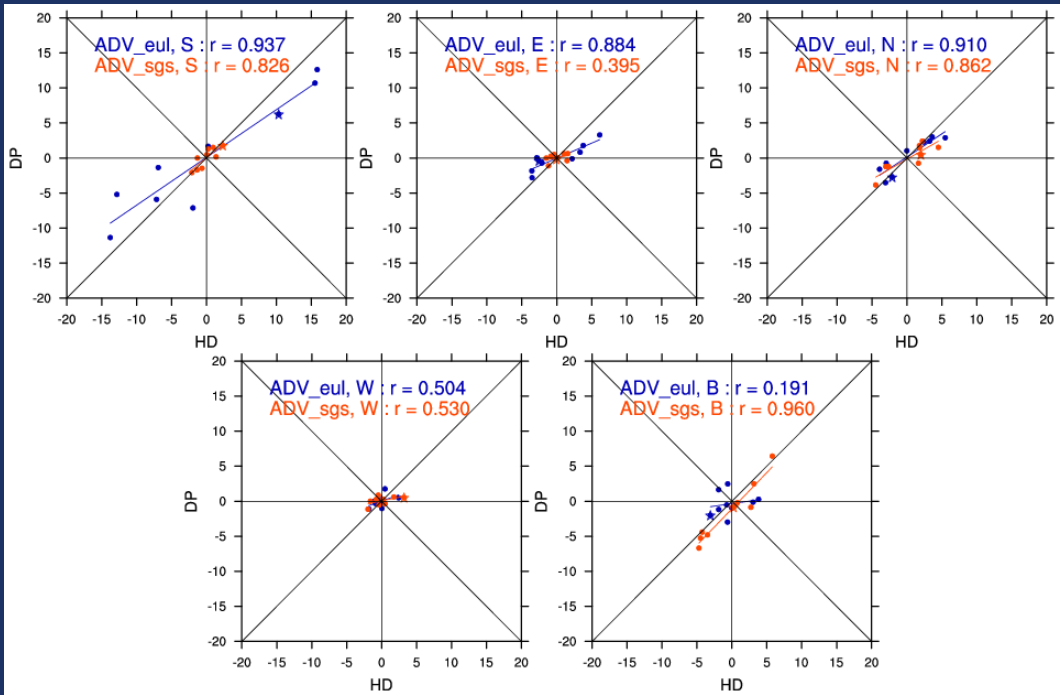


Comparison of pentadal mean Heat Budget terms: lags 1-5

- Eulerian (eul) advective heat flux better predicted than sub-gridscale (sgs) advective heat flux, except vertical component

- Highly-correlated eulerian advection through the south face (due to AMOC initialization) appears to be the dominant contributor to tendency skill



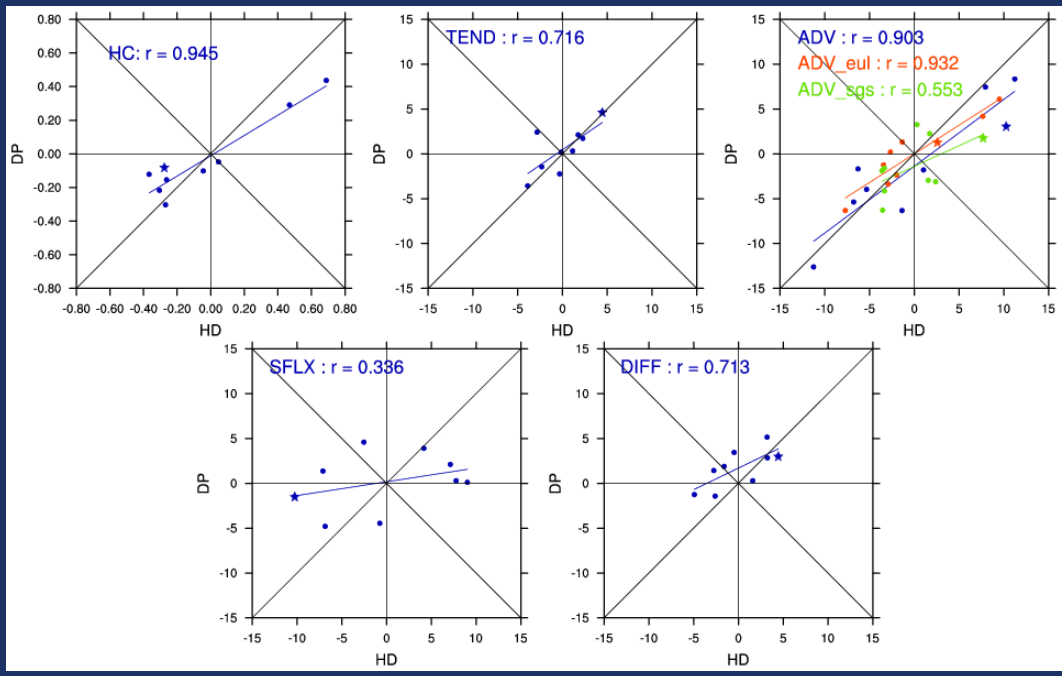


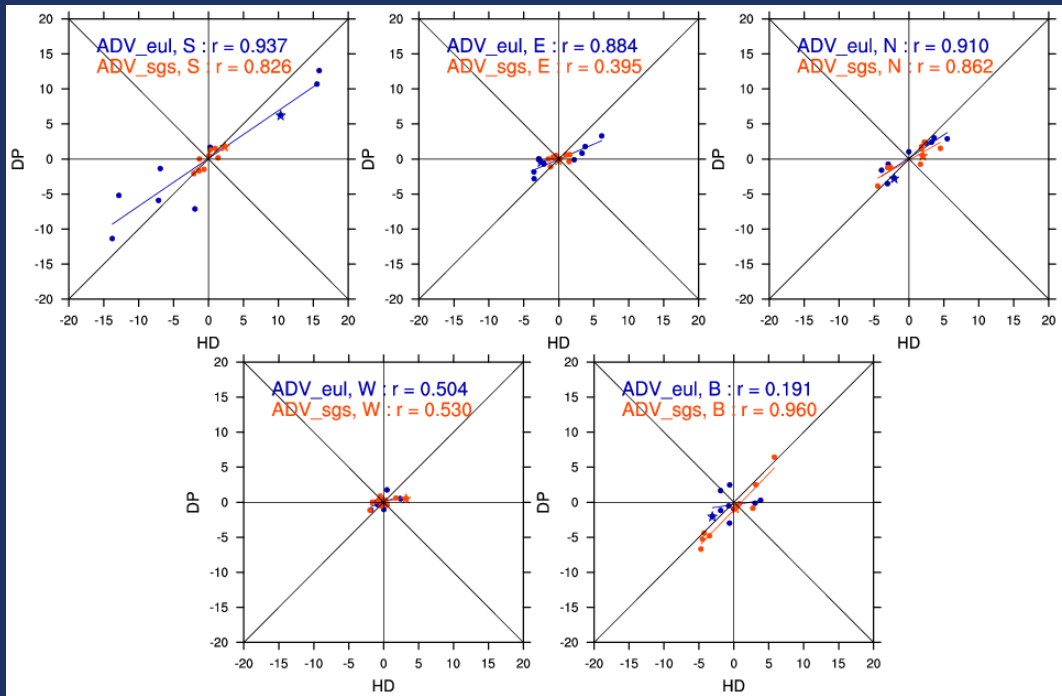
Comparison of pentadal mean Heat Budget terms: lags 1-5

★ = 1991 DP

• 1991 DP regime shift due to large positive <1991-1995> tendency

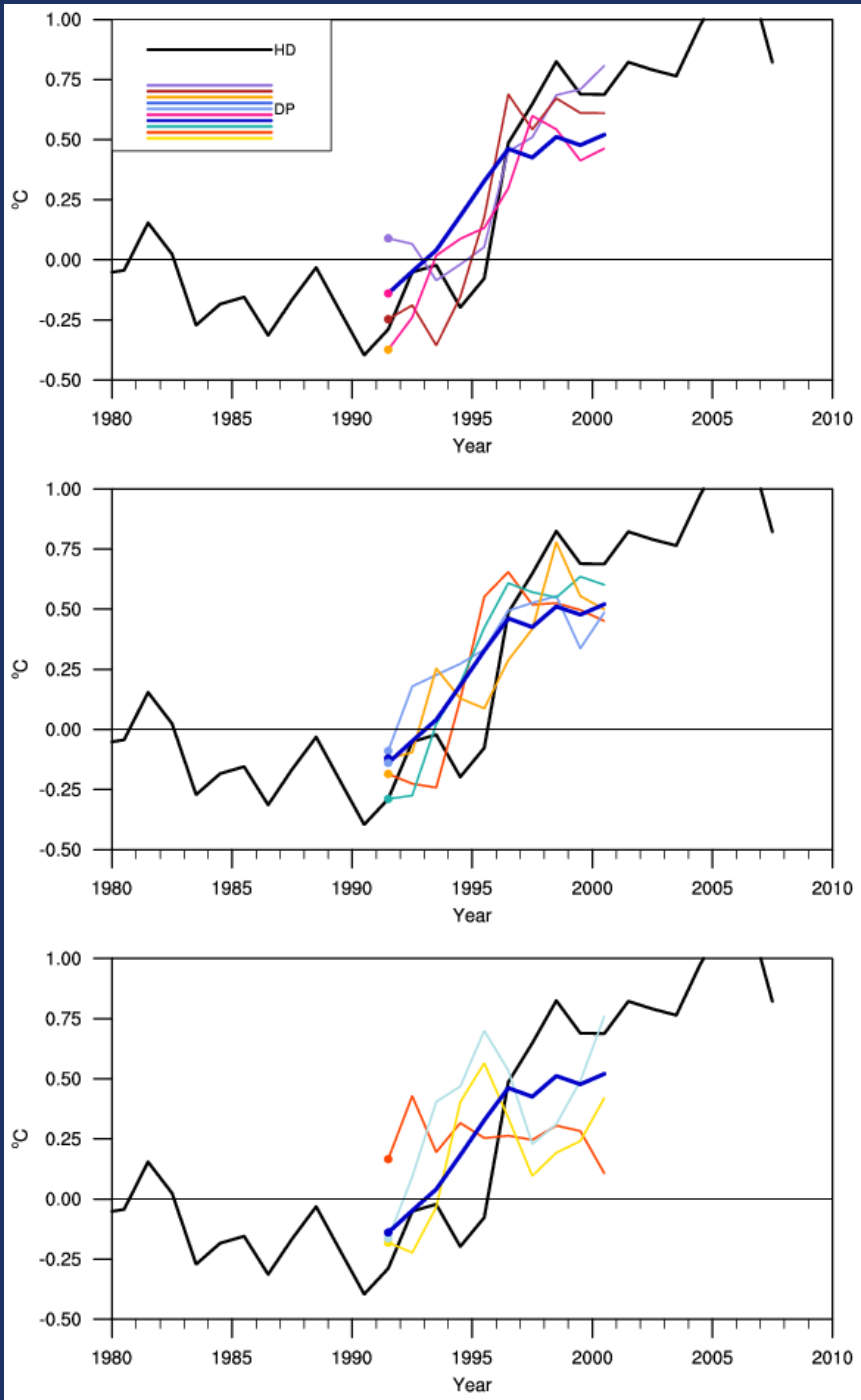
•1991 DP ensemble gets tendency correct despite too weak cooling and too little ADV heating. These (nearly compensating) flux biases are associated with poor prediction of the observed NAO+ between 1991-1995. This explains the early timing of predicted regime shift.



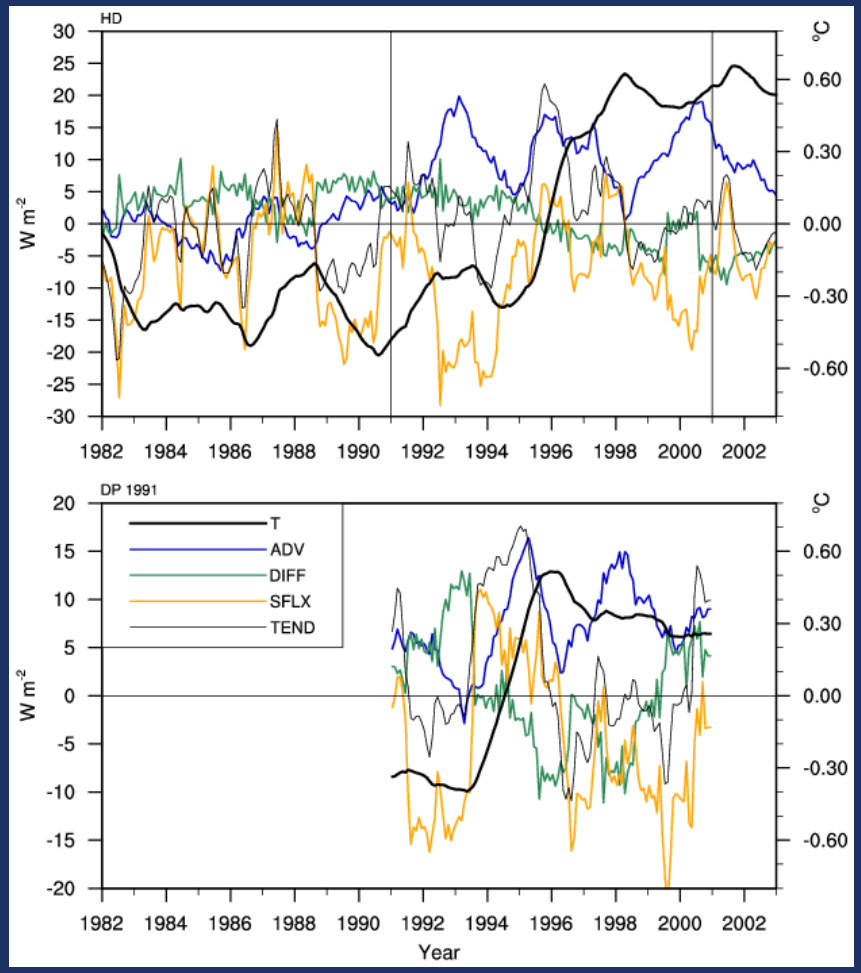


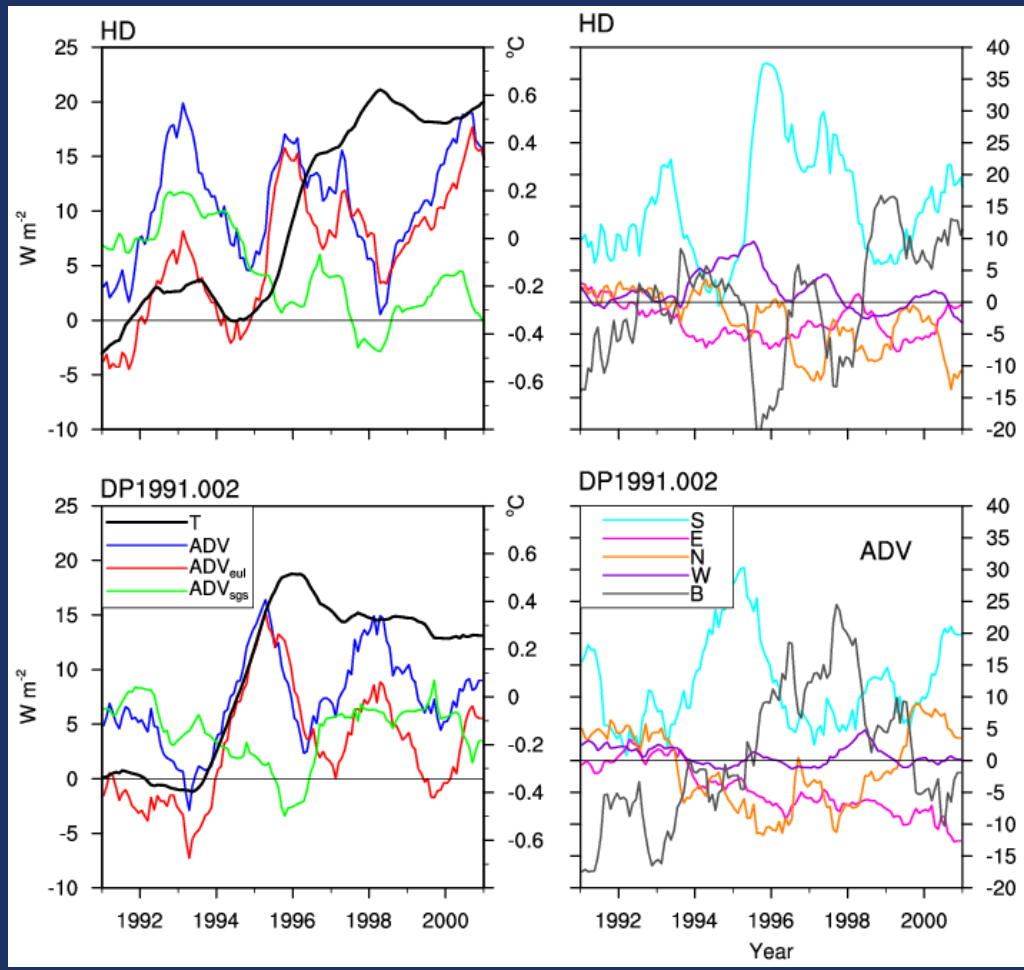
1991 DP ensemble

Some ensemble members get the timing & magnitude of 95/96 warming correct, but most predict an earlier rise.



Heat Budget of SPG box





Monthly budget terms from HD (top panels) and DP1991 member #2 (bottom panels).

Conclusions

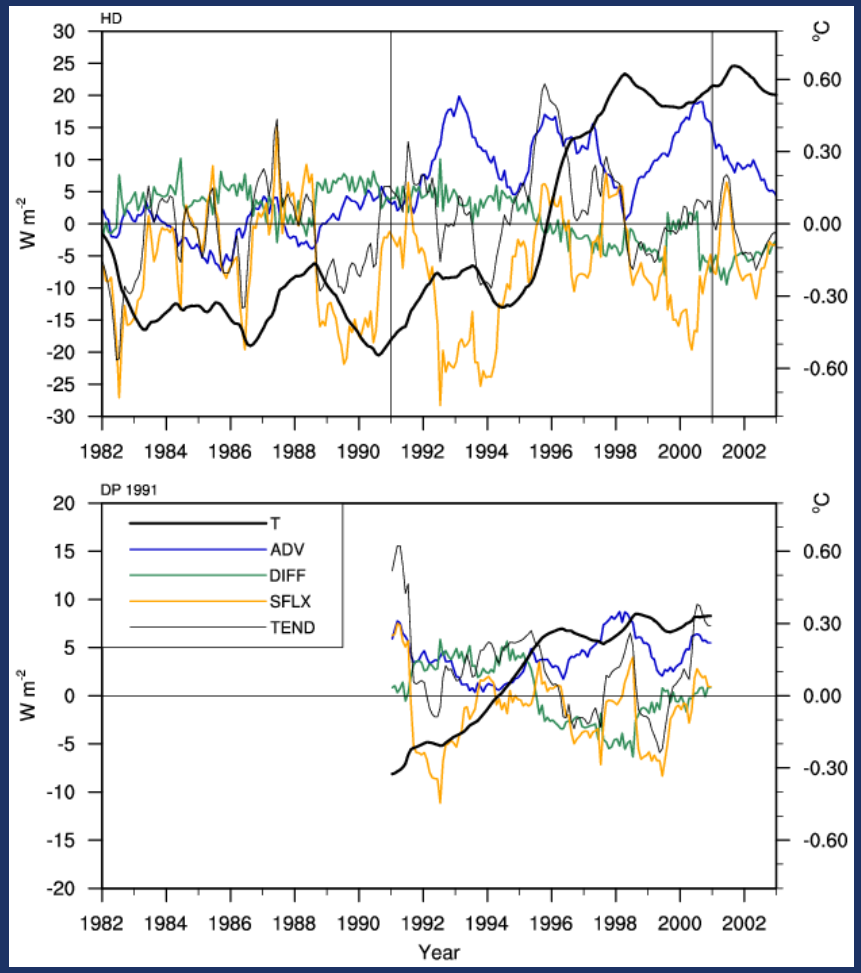
- The CCSM4 CMIP5 DP runs show skill at predicting North Atlantic SPG heat content & SST changes up to a decade in advance.

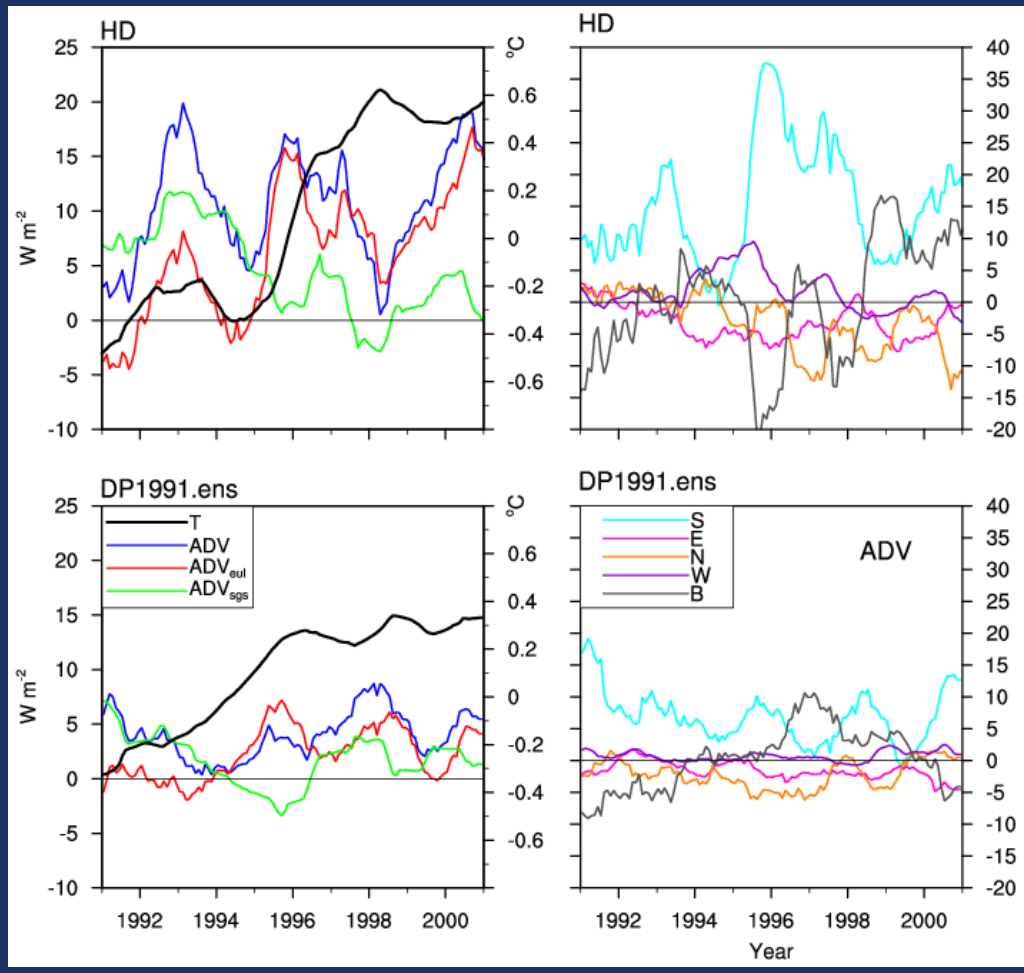
- Most of the skill in predicting high latitude HC tendency derives from the correct initialization of the magnitude of eulerian heat advection from the south (ie, AMOC strength). However, there is also considerable skill at predicting large, anomalous diffusive and vertical eddy fluxes even out to lag 10. DP skill is degraded by poor prediction of surface heat flux tendency (NAO).

- The mid-90's regime shift is captured despite poor NAO prediction because of strong preconditioning of the 1991-initialized DP run for large advective & diffusive fluxes into the SPG.

- These results supports the idea of ocean preconditioning by persistent NAO^{+} advanced by Lohmann et al. and imply that a SPG regime shift would in general be predicted by DP experiments initialized between 1989-1995, because of strong NAO+ preceding those years.

Heat Budget of SPG box





Monthly budget terms from HD (top panels) and DP1991 ensemble mean (bottom panels).

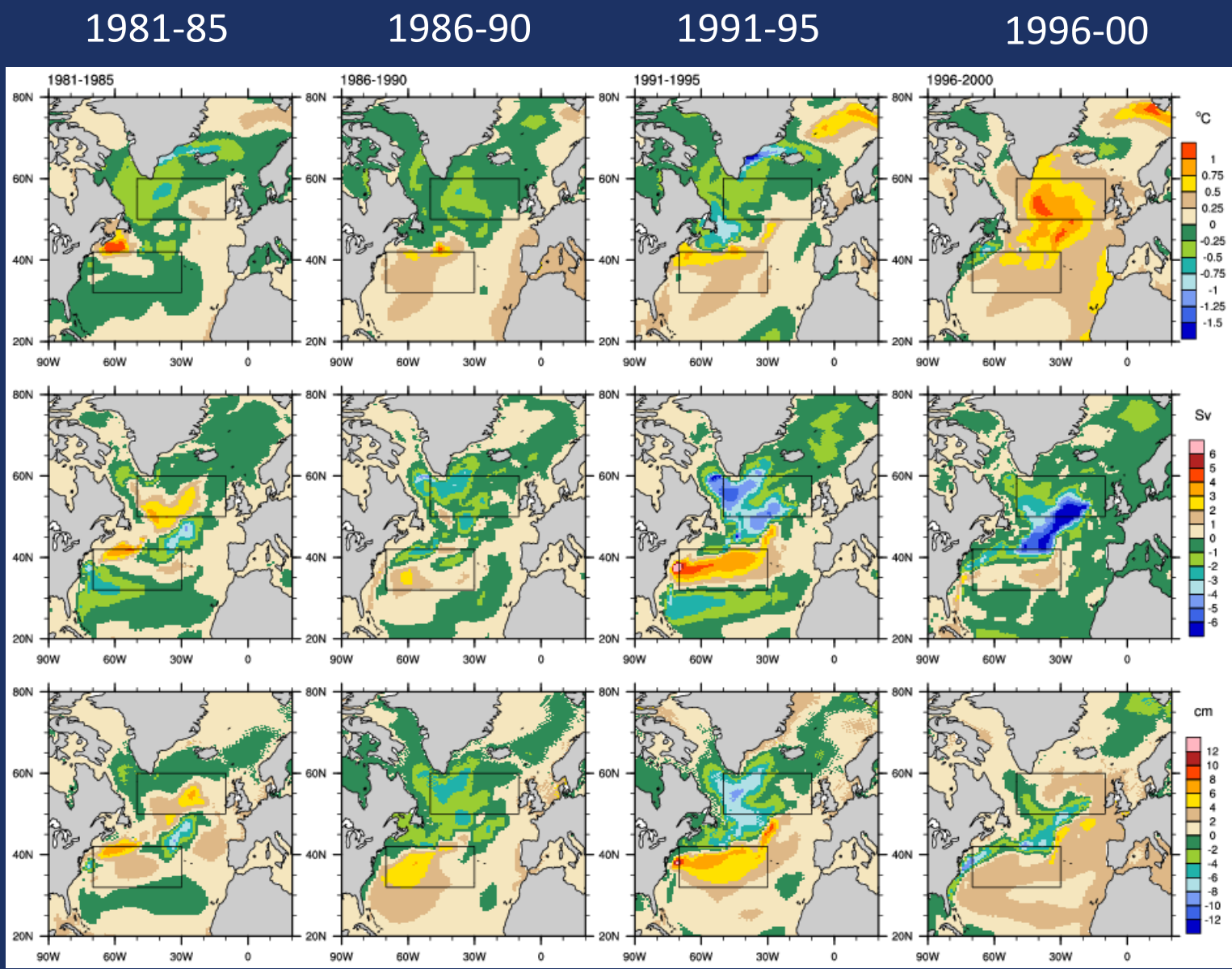
OUTLINE

I. Late 20th century changes in N. Atlantic Heat Content (HC) and related fields from observations & CCSM4 ocean-ice hindcast (HD) simulation

I. Results from 10-yr CMIP5 decadal prediction (DP) experiments run over the historical period
   - fully-coupled CCSM4 20C runs initialized at 5-yr intervals from ocean/ice states obtained from HD simulation
   - full-field initialization & bias-corrected

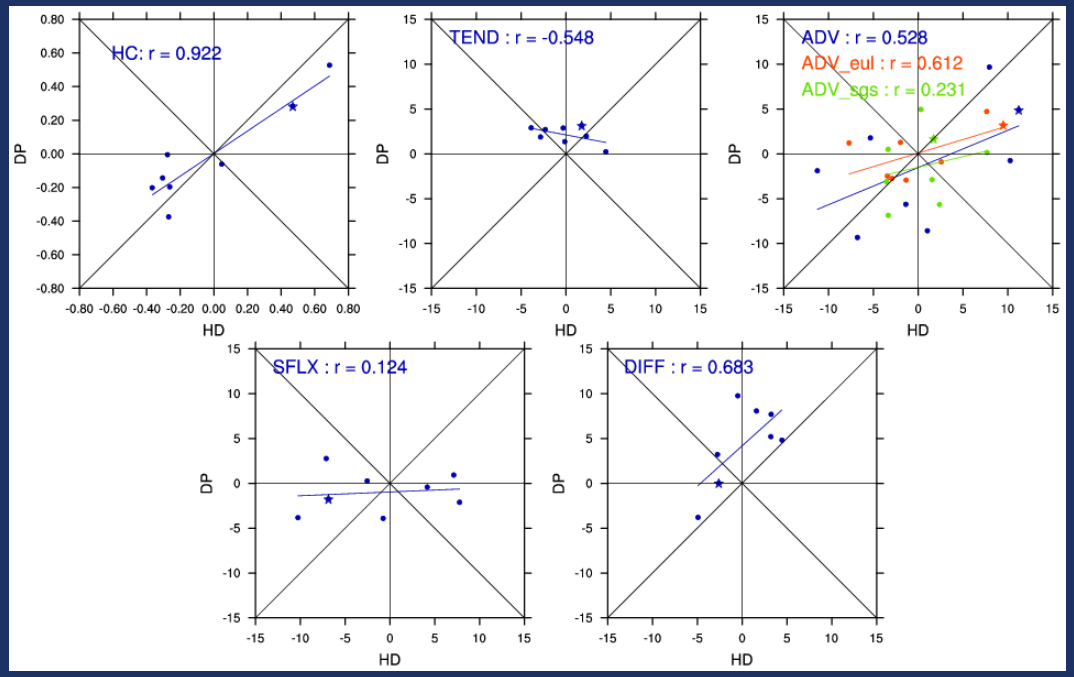
II. What mechanisms(s) explain the success of DP experiments in reproducing subpolar gyre changes between 1961-2007, and in particular the large mid-1990's shift?

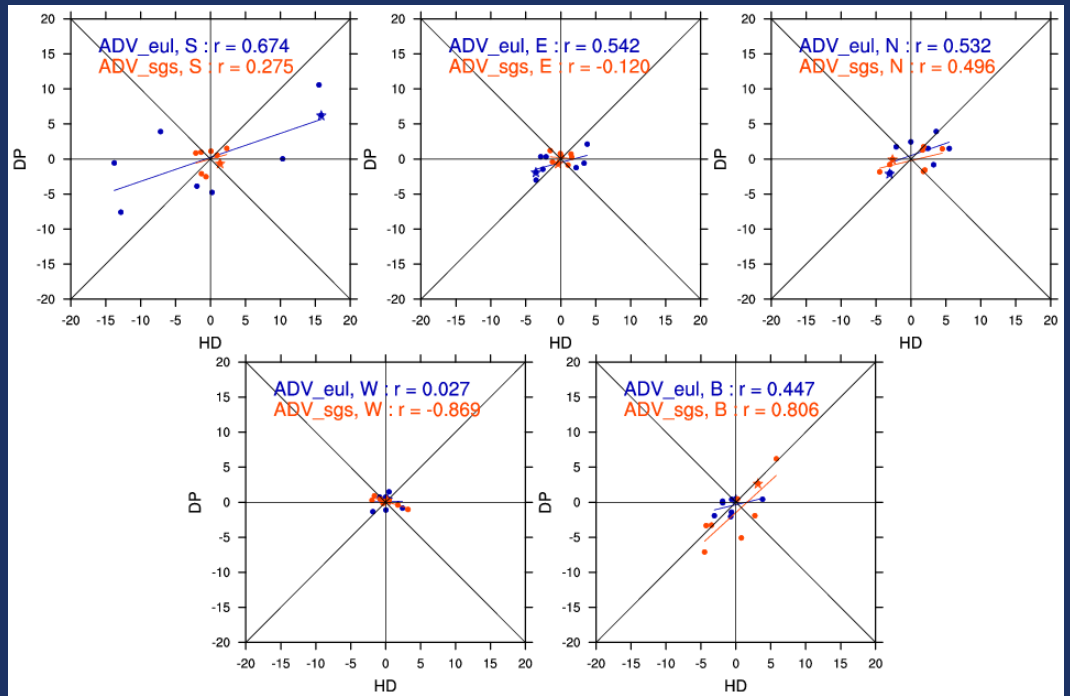
N Atlantic Pentadal Anomalies



Comparison of pentadal mean Heat Budget terms: lags 6-10

★ = 1991 DP



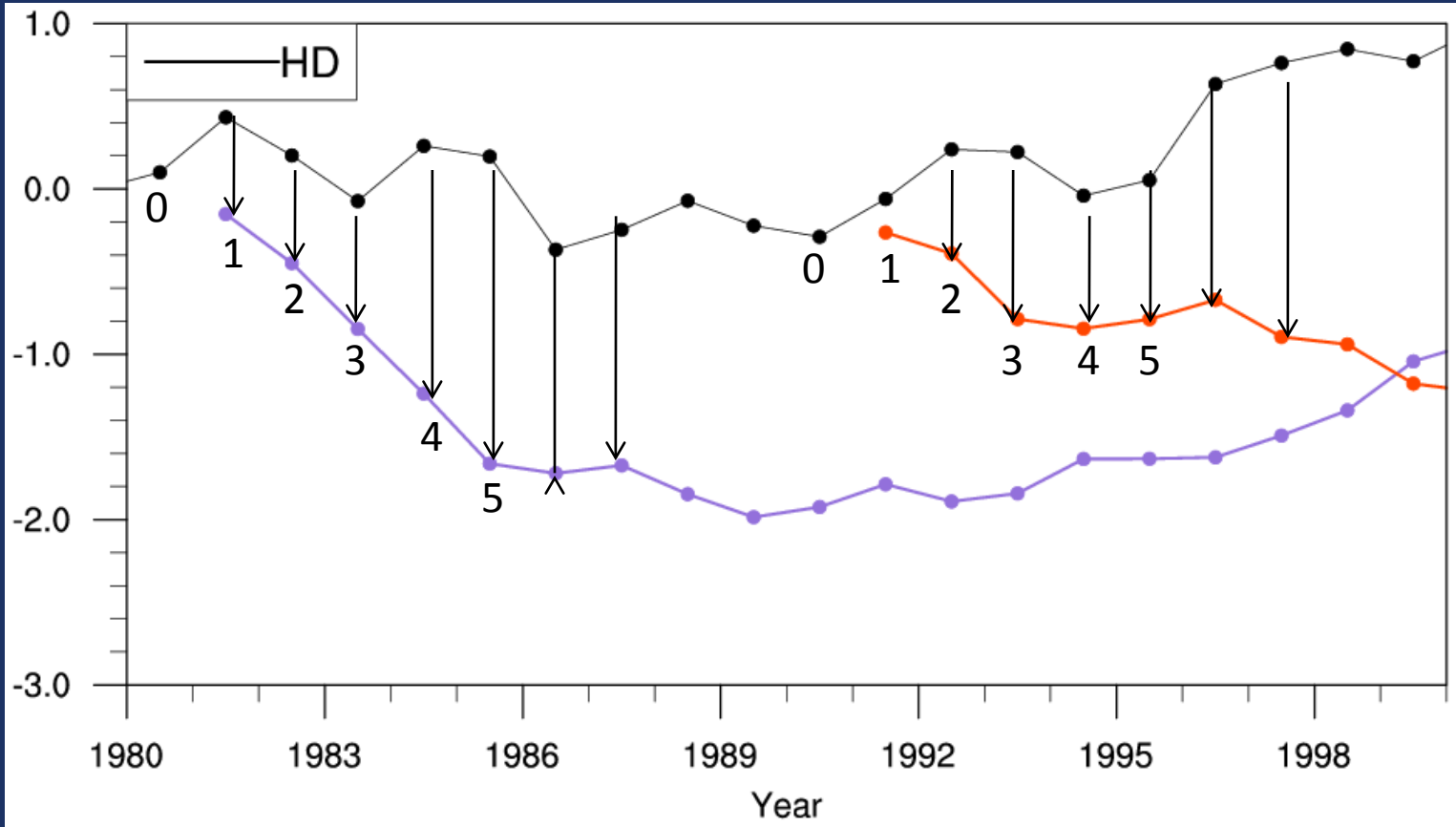


Bias Correction: Method 1

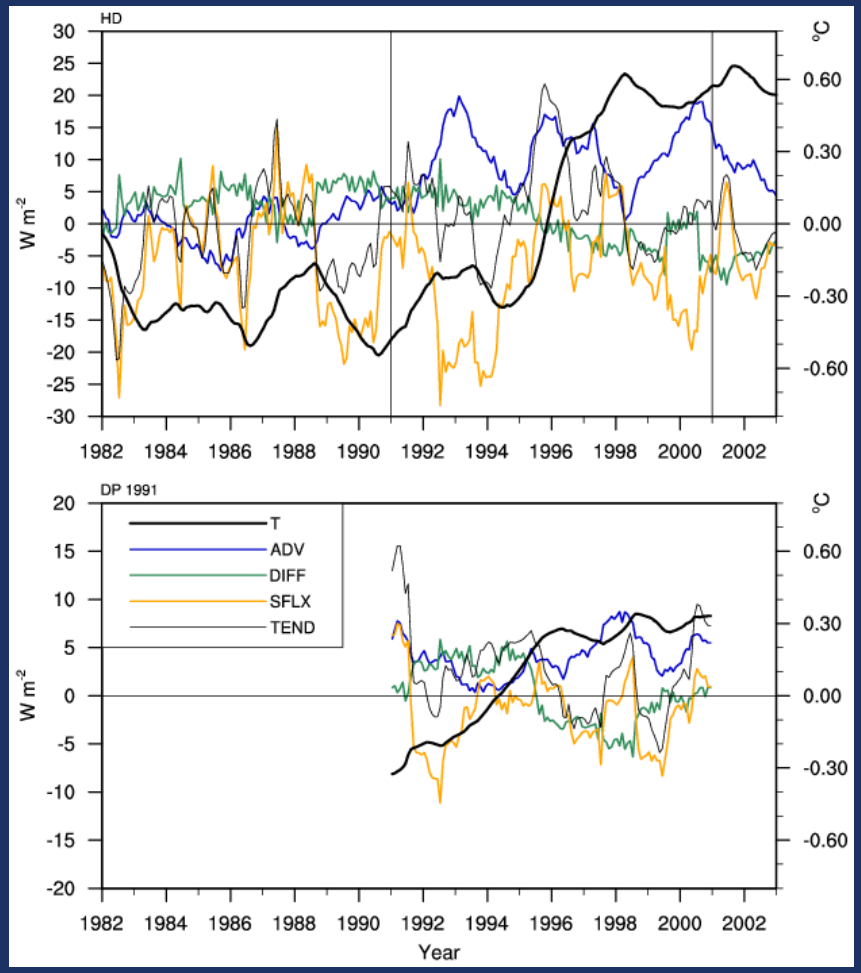
• For each field and spatial location (x,y,z), define the (10-member) ensemble-mean DP evolution away from the HD ocean state:

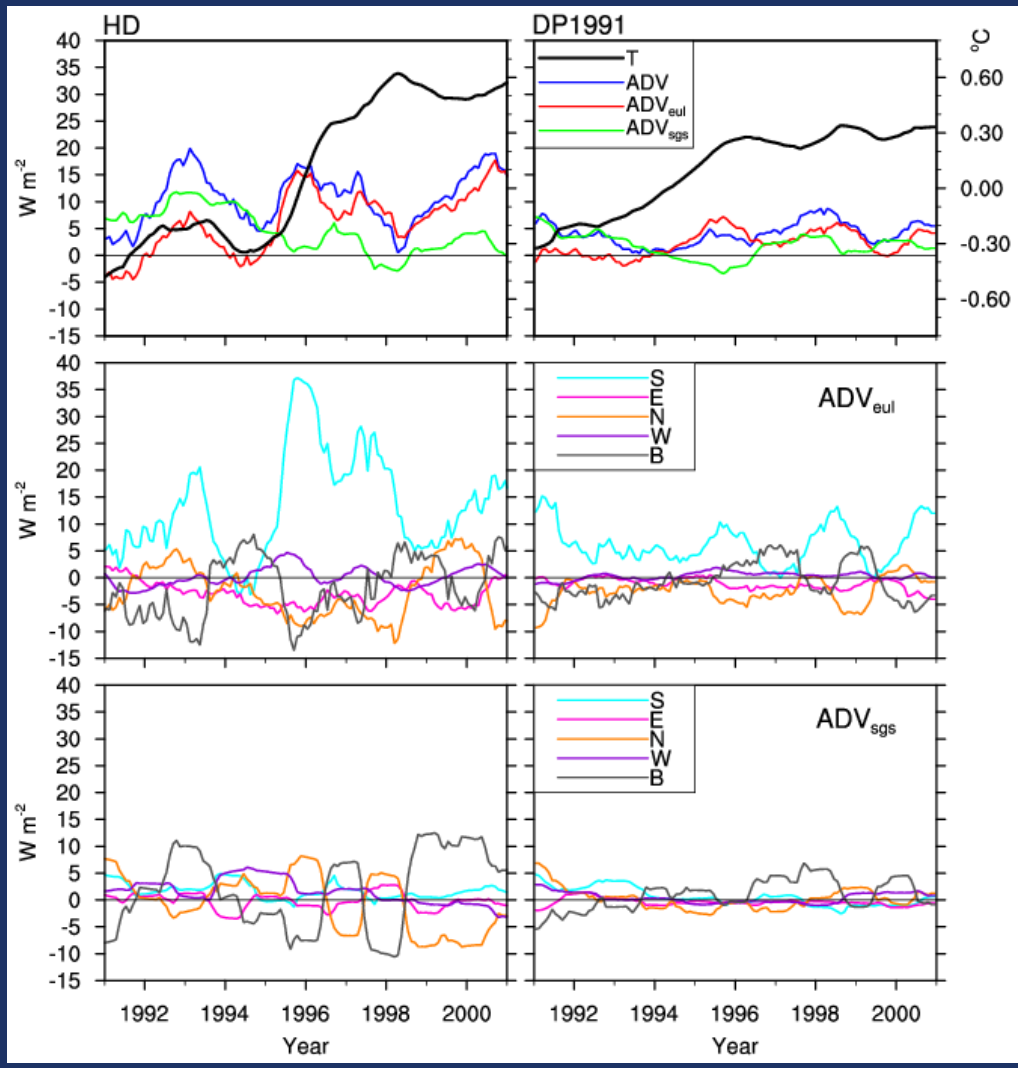
$$d(t) = DP(t) - HD(0), \quad t == \text{forecast year } (1,2,3,...)$$

• Average over all start years (10 from HD-ic's) to get the common evolution (mean drift) as a function of forecast year.

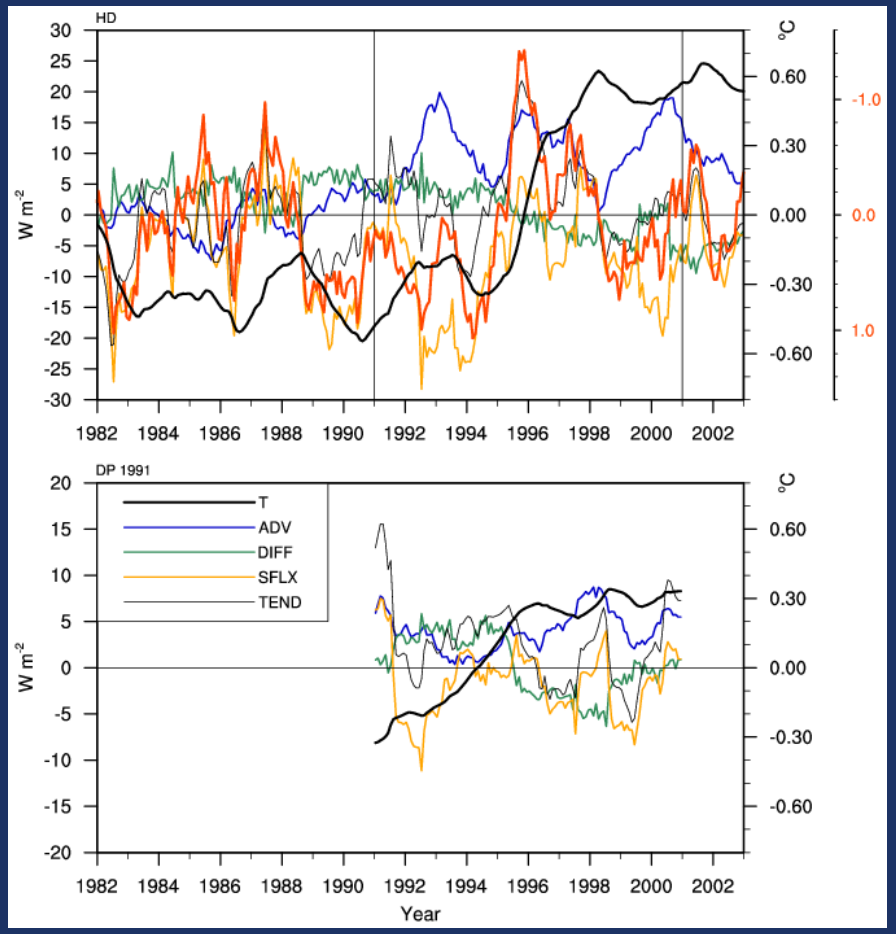


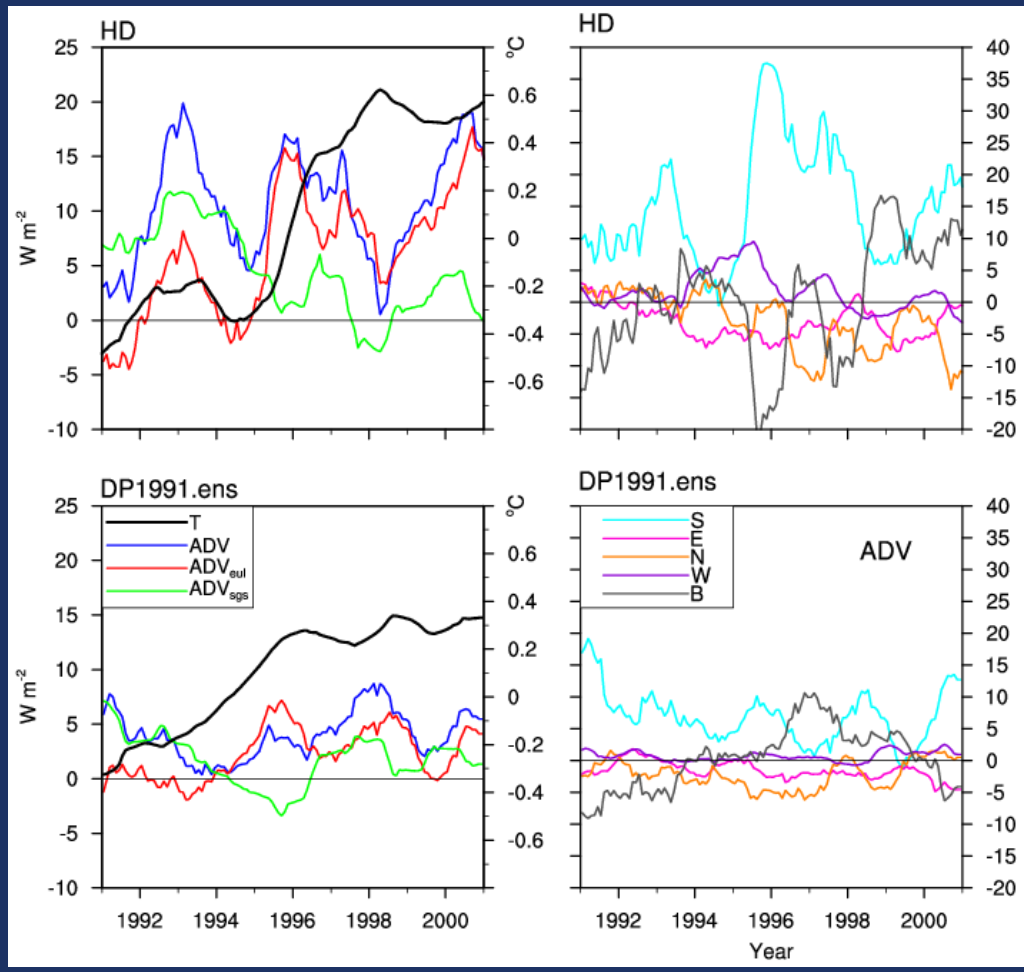
Heat Budget of SPG box





Heat Budget of SPG box





Bias Correction: Method 2

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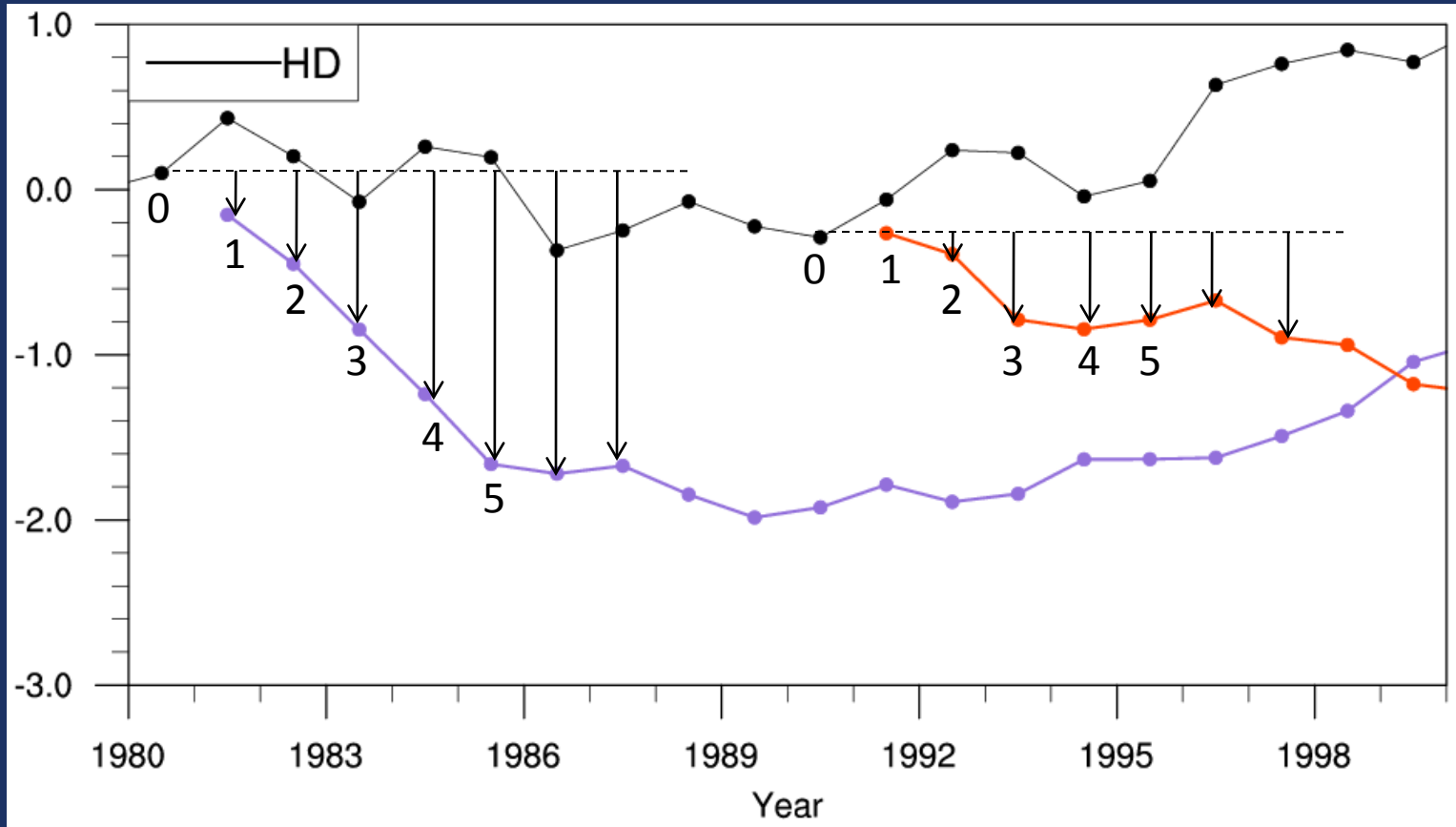


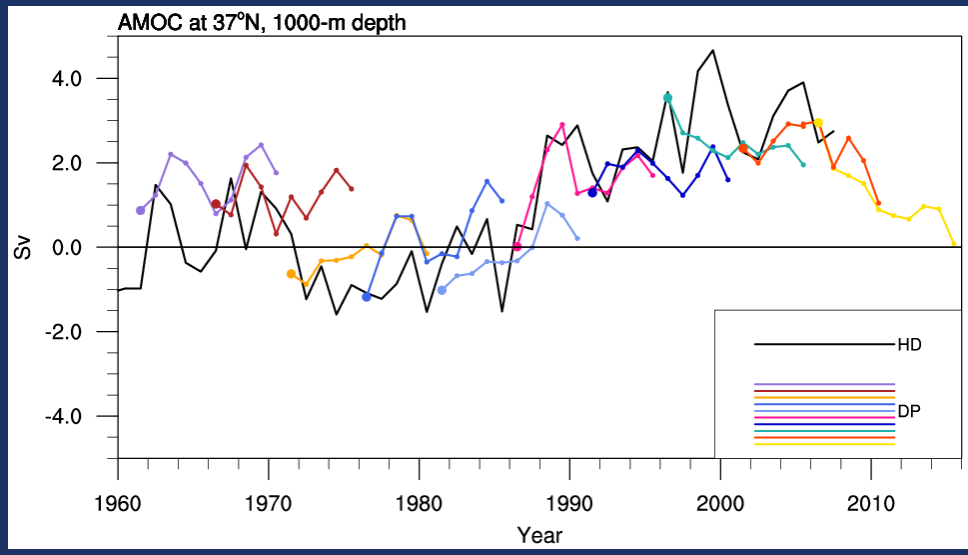
SPG Box Heat Budget

	HD (W/m^2)	DP (W/m^2)
ADV	47	46
ADV: eul,sgs	18,29	18,28
ADV: S,E,N,W,B	149,-65,-98,9,50	149,-65,-97,10,49
ADV$_{eul}$: S,E,N,W,B	138,-53,-58,11,-20	138,-53,-58,11,-20
ADV$_{sgs}$: S,E,N,W,B	11,-12,-40,-1,70	11,-12,-40,-1,69
SFLX	-60	-60
DIFF	14	17
TEND	1	2

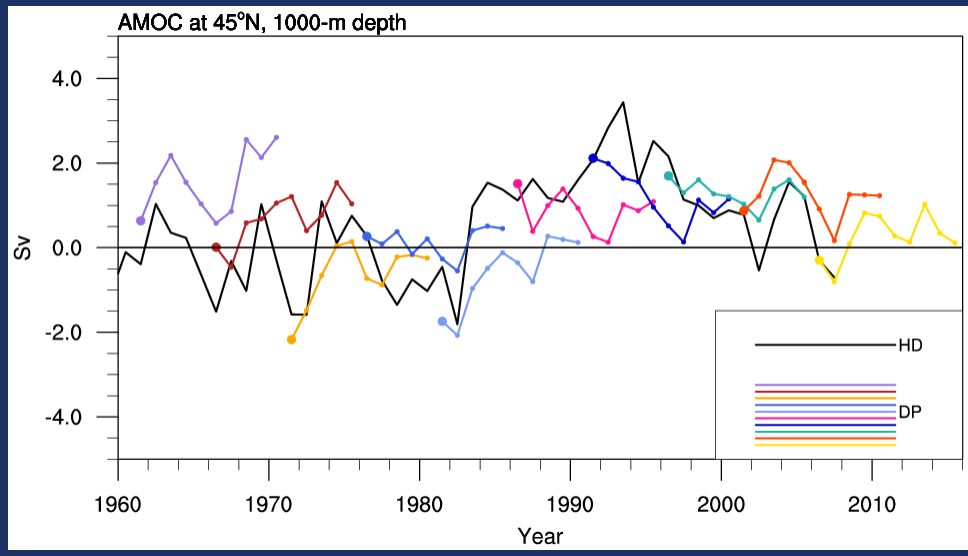
- 1961-2007 climatology

AMOC Predictions

37°N

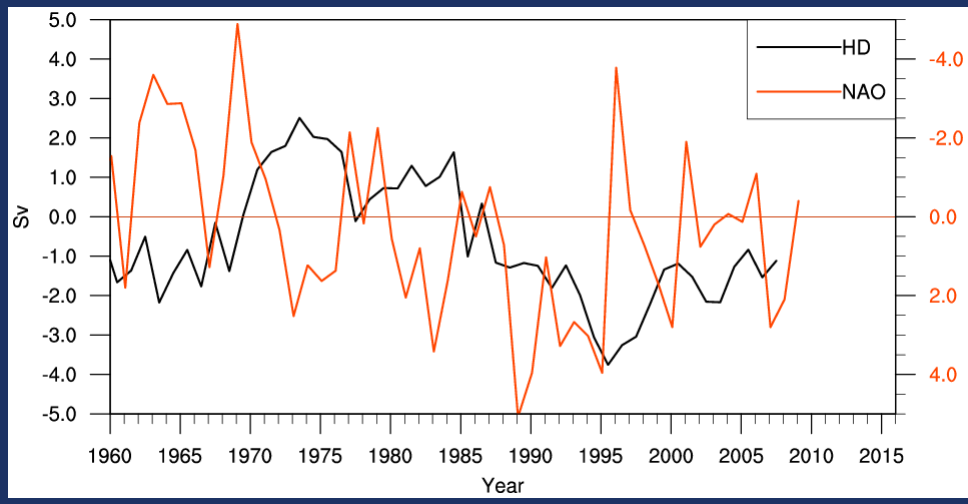


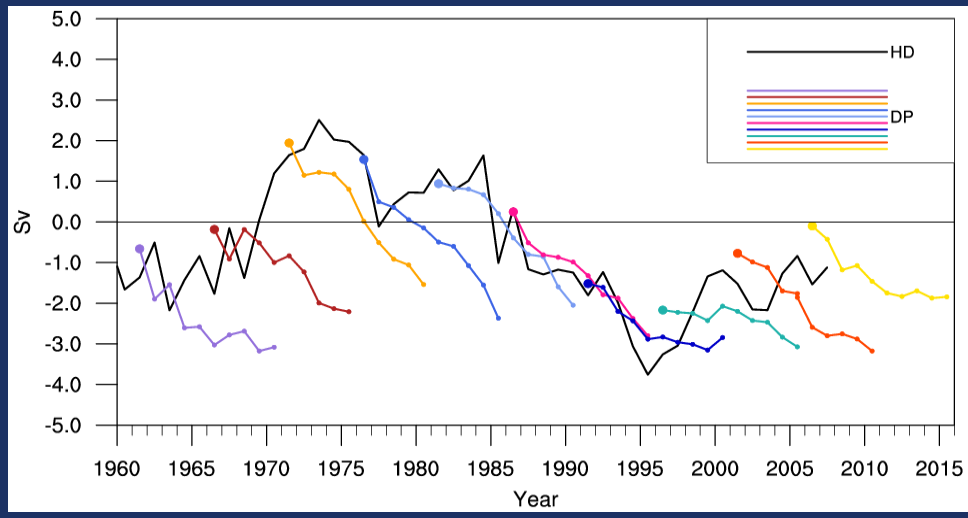
45°N



Barotropic Streamfunction (BSF) predictions

raw





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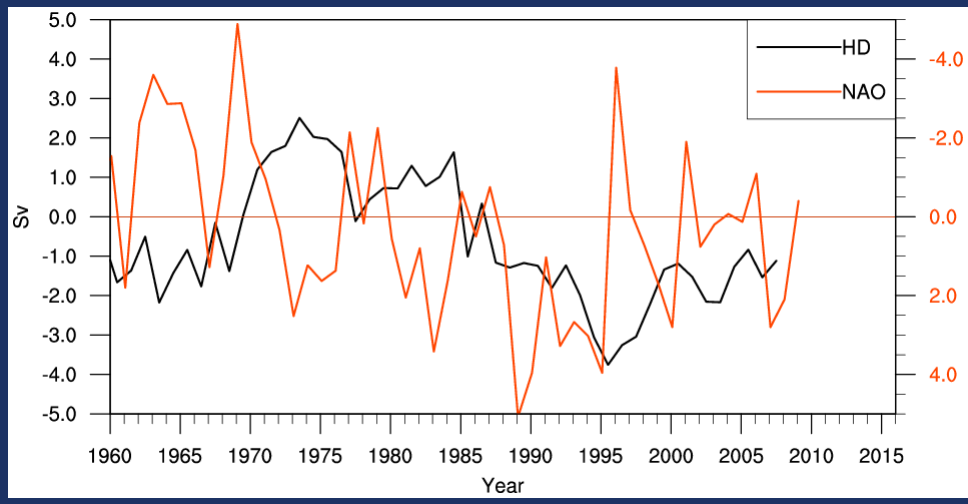

bias-corrected