A CCSM4 Decadal Prediction Case Study:

Abrupt North Atlantic Ocean Heat Content Change in the 1990s

Steve Yeager, Alicia Karspeck, Gokhan Danabasoglu,
Joe Tribbia, Haiyan Teng, Jerry Meehl
NCAR, Boulder, CO

AGCI Meeting, Aspen, June 29, 2011

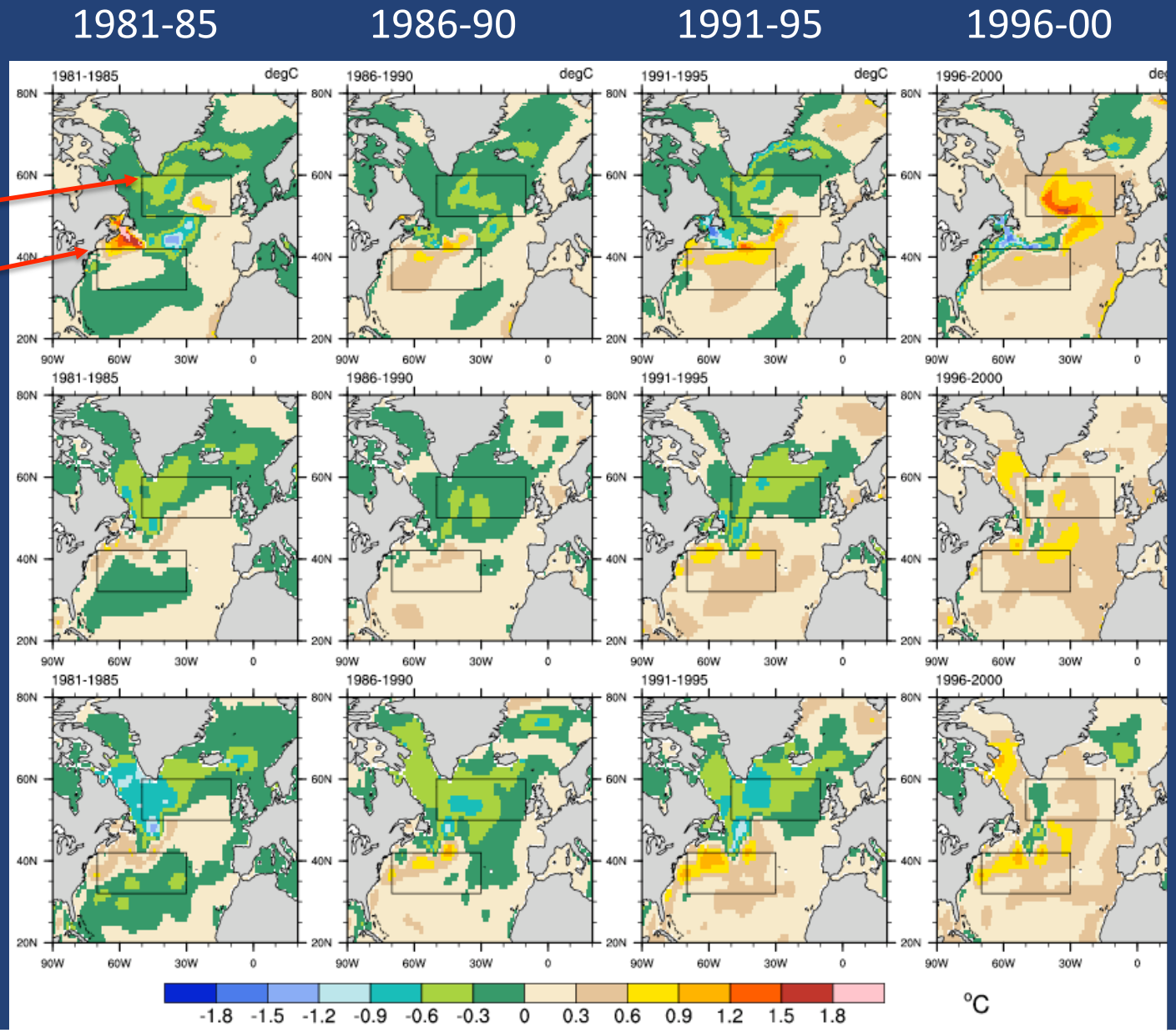
OUTLINE

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

II. 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 (10-member ensembles)
   - full-field initialization & bias-correct

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

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)

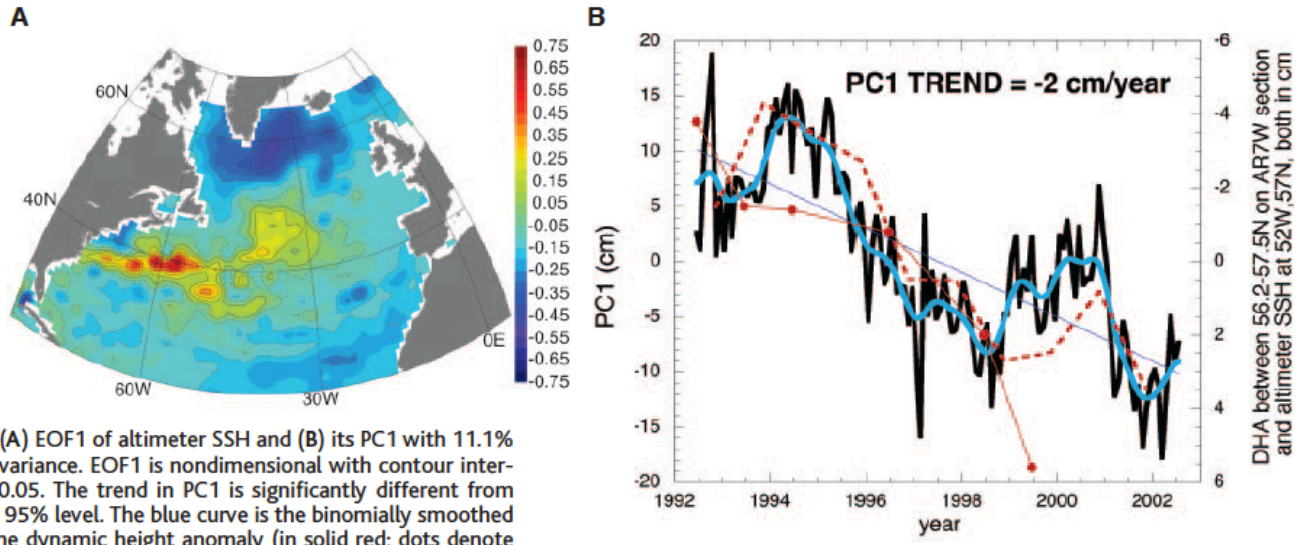


Fig. 1. (A) EOF1 of altimeter SSH and (B) its PC1 with 11.1% of the variance. EOF1 is nondimensional with contour interval of 0.05. The trend in PC1 is significantly different from zero at 95% level. The blue curve is the binomially smoothed PC1. The dynamic height anomaly (in solid red; dots denote 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.

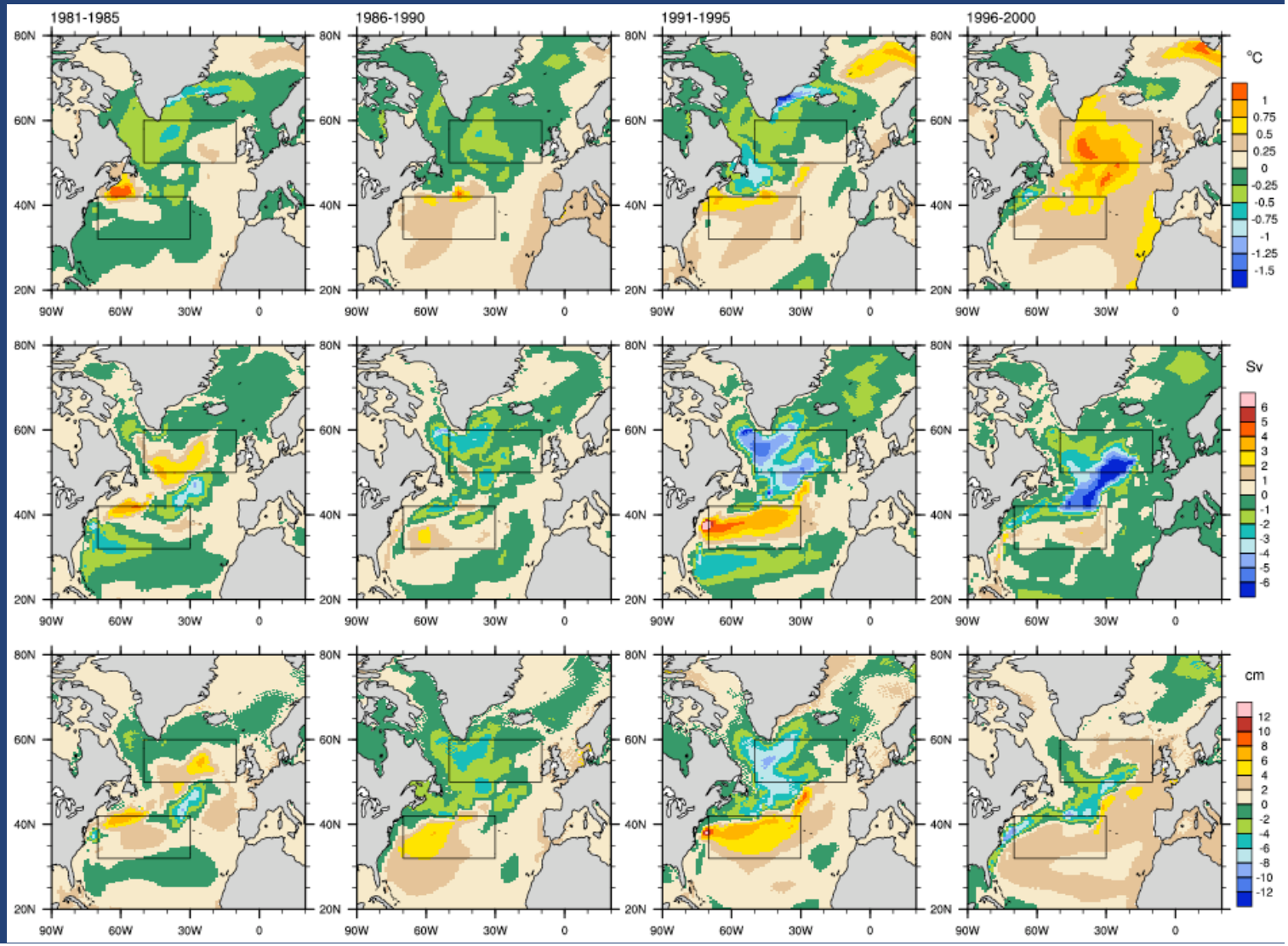
Hakkinen & Rhines (*Science*, 2004)

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

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

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

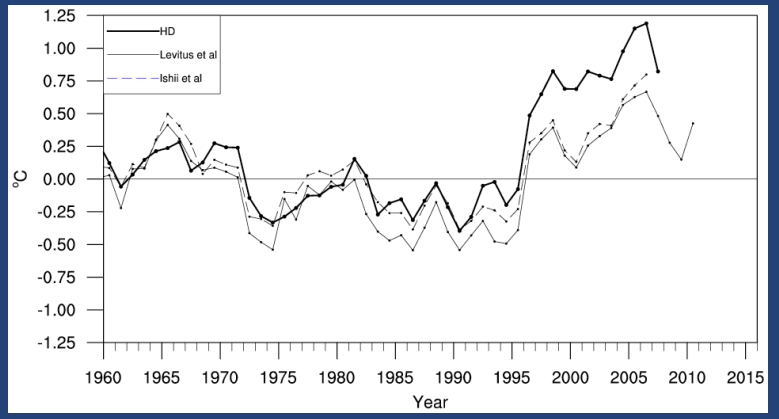
N Atlantic Pentadal Anomalies



275m Heat Content Anomaly

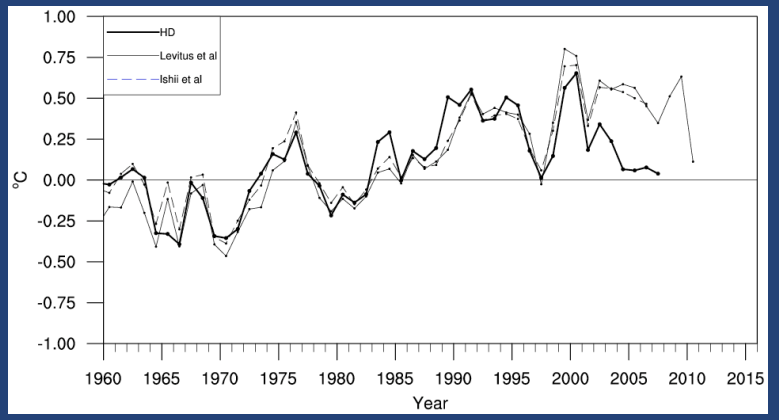
SPG

1960-2007 correlation with Levitus is 0.9



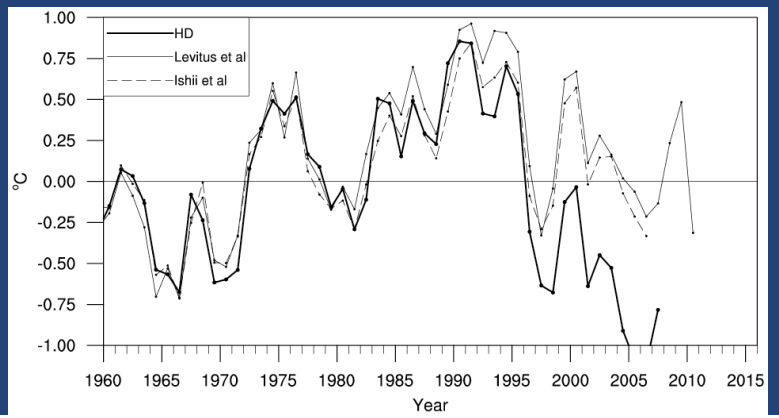
STG

1960-2007 correlation with Levitus is 0.83



STG-SPG

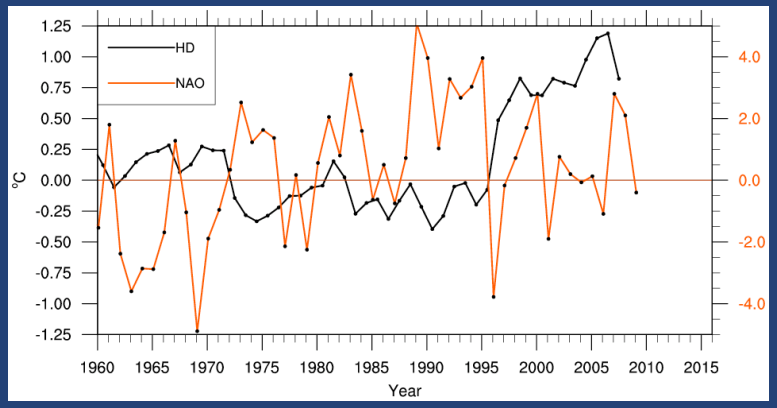
1960-2007 correlation with Levitus is 0.8



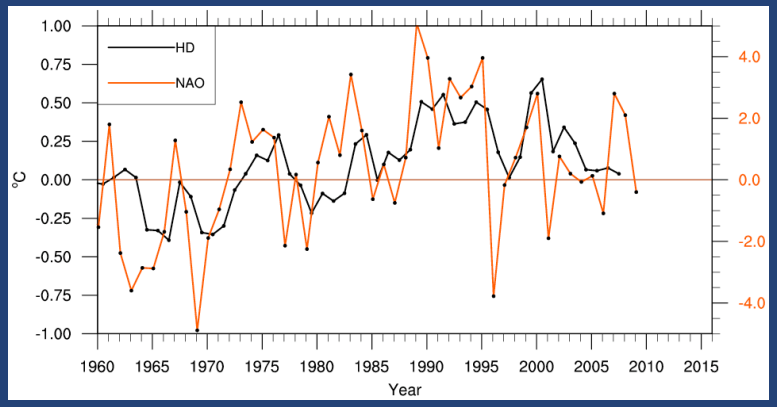
*1957-90 climatology

HD response to observed NAO

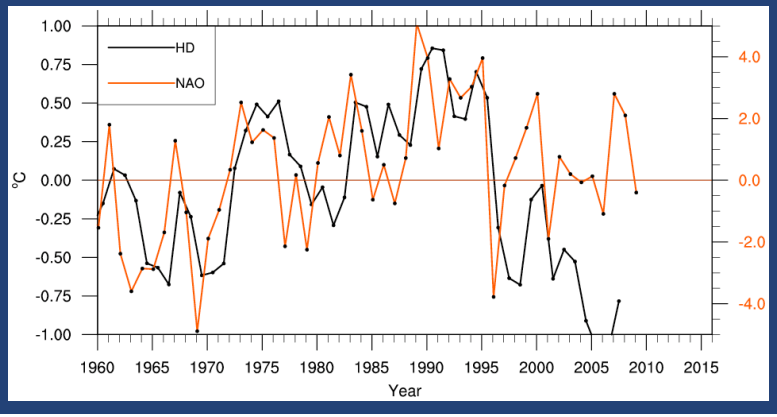
SPG HC



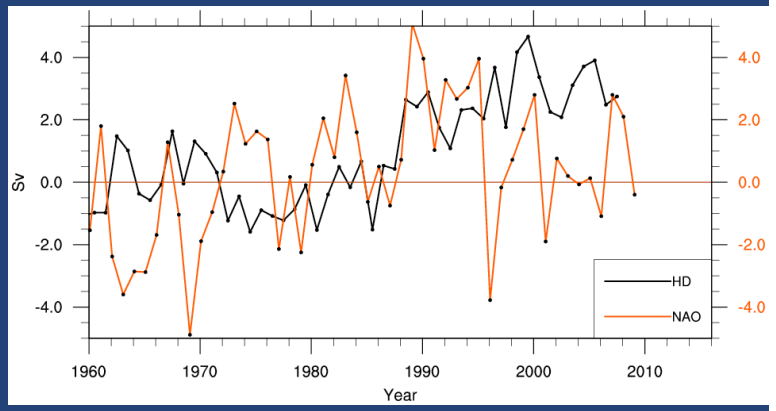
STG HC



STG-SPG HC



AMOC at 37ºN



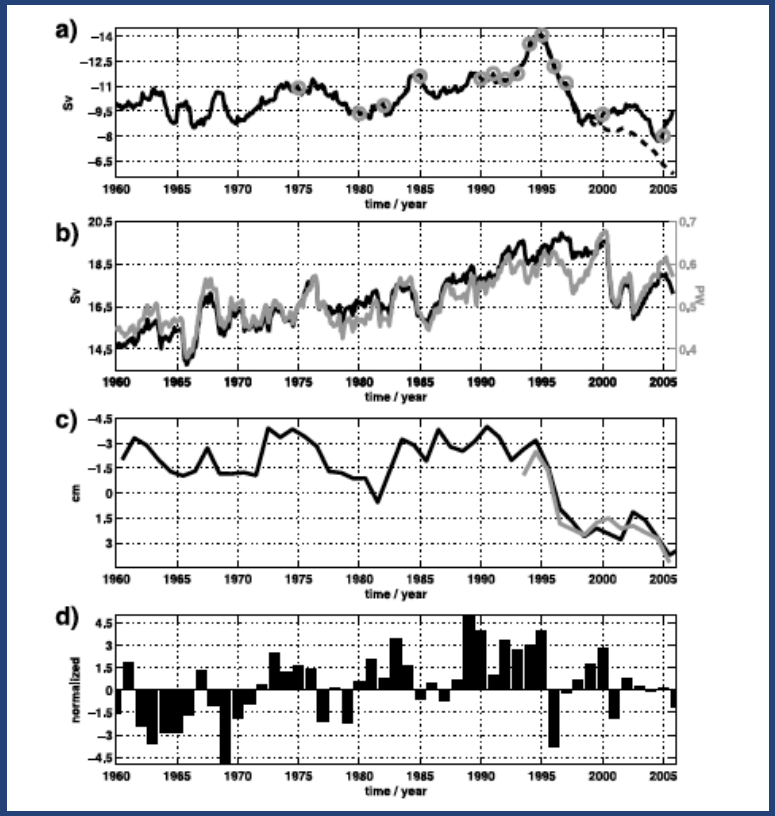
Ocean Preconditioning by persistent NAO$^+$

SPG BSF

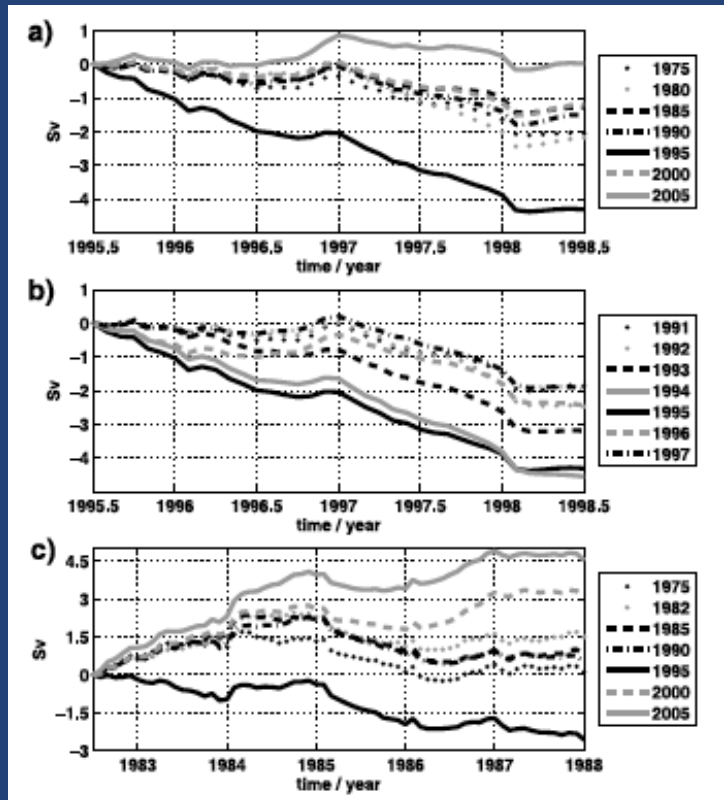
AMOC

SSH

NAO

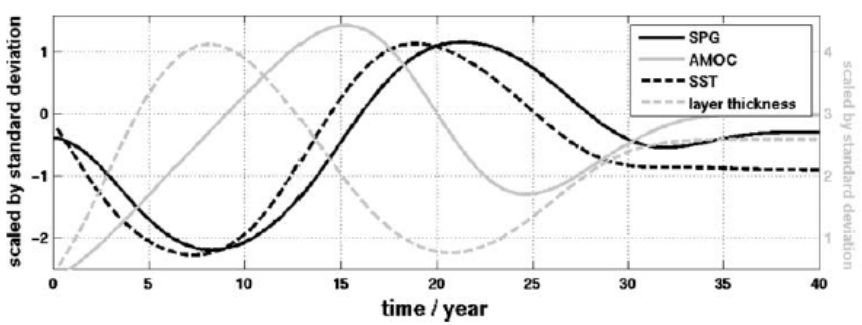


SPG BSF dependence on i.c./forcing



Lohmann et al (*Clim Dyn*, 2009)
Lohmann et al (*GRL*, 2009)
Robson et al (2011)

NAO$^+$ - NAO^n



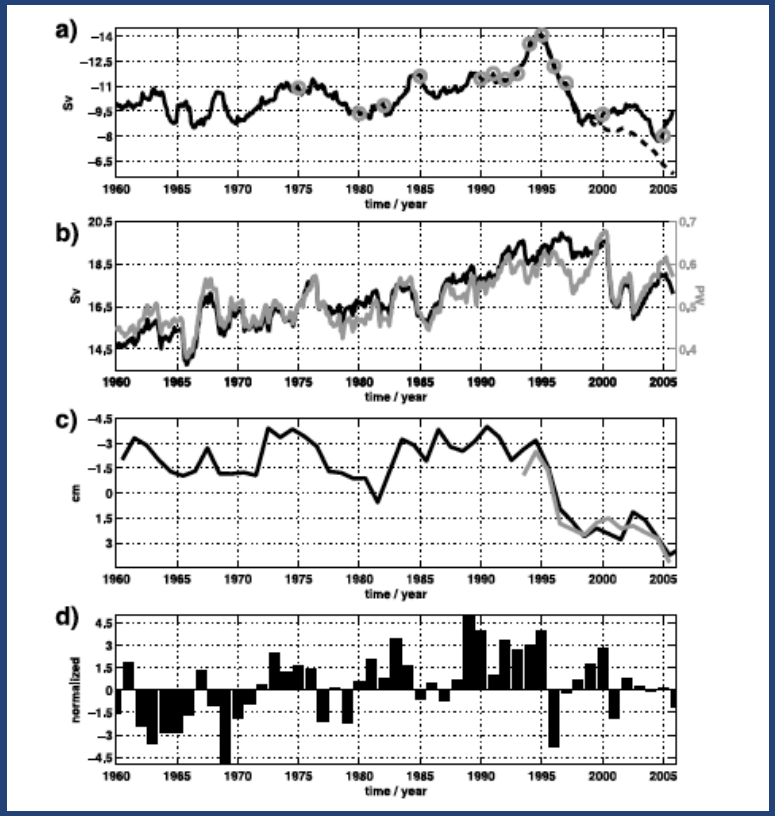
Ocean Preconditioning by persistent NAO$^+$

SPG BSF

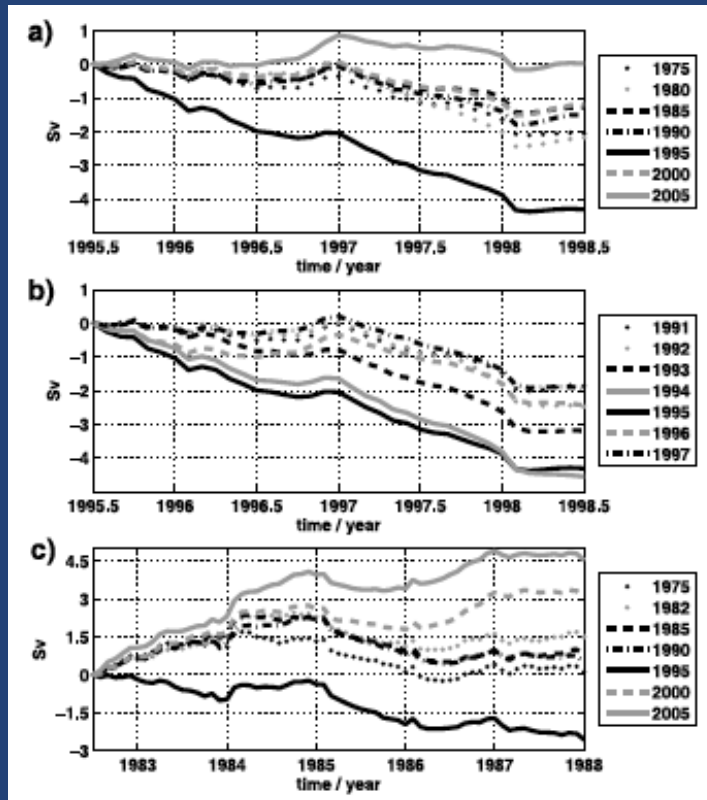
AMOC

SSH

NAO

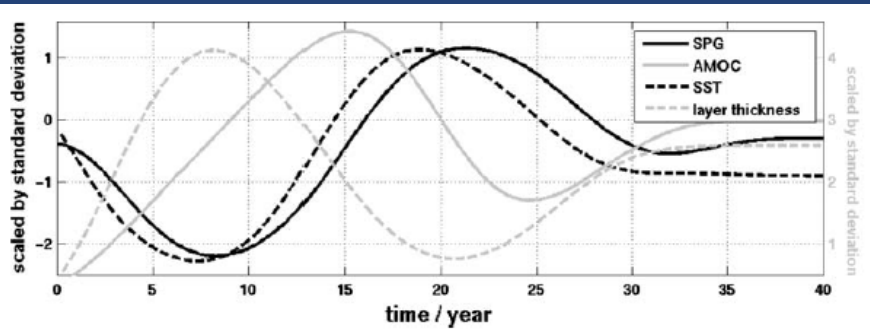


SPG BSF dependence on i.c./forcing

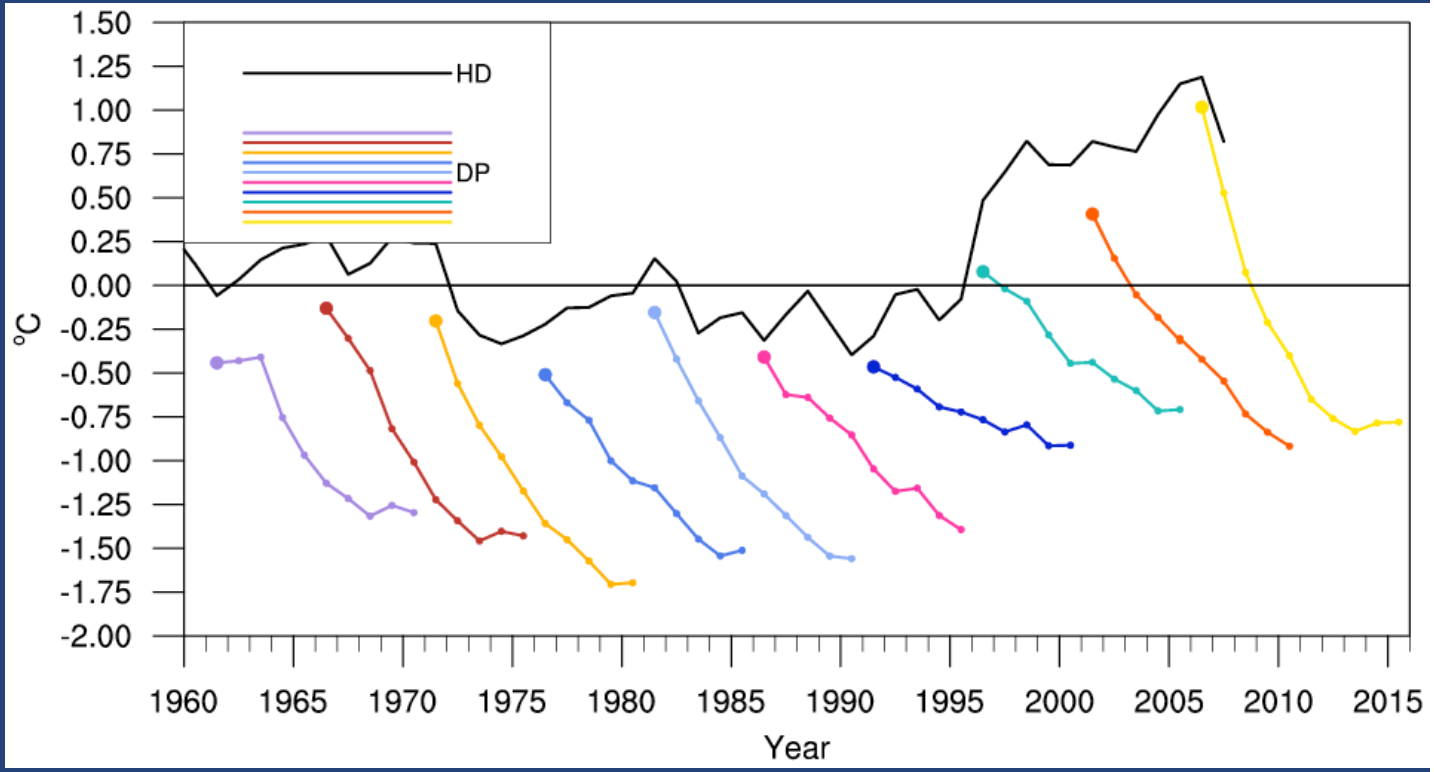


Persistent NAO+ ➔ strong HC dipole + AMOC spinup ➔ SPG HC rise + AMOC spindown

NAO$^+$ - NAO^n



275m Heat Content Anomaly in SPG box



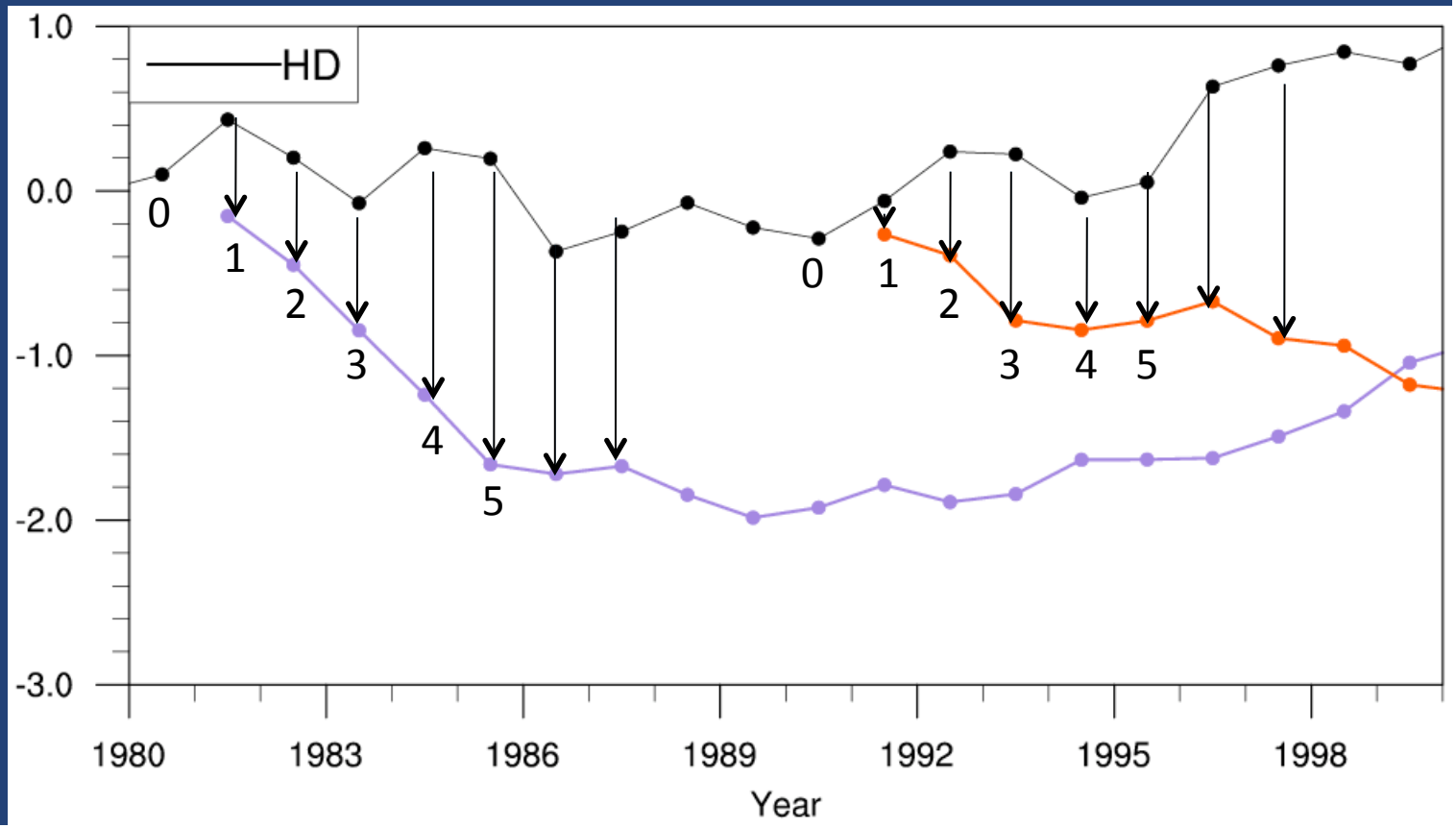
- 10-yr DP experiments initialized from HD on January 1 1961, 1966, ..., 2006
- Colored curves are 10-member ensemble means

Bias Correction: Method 1

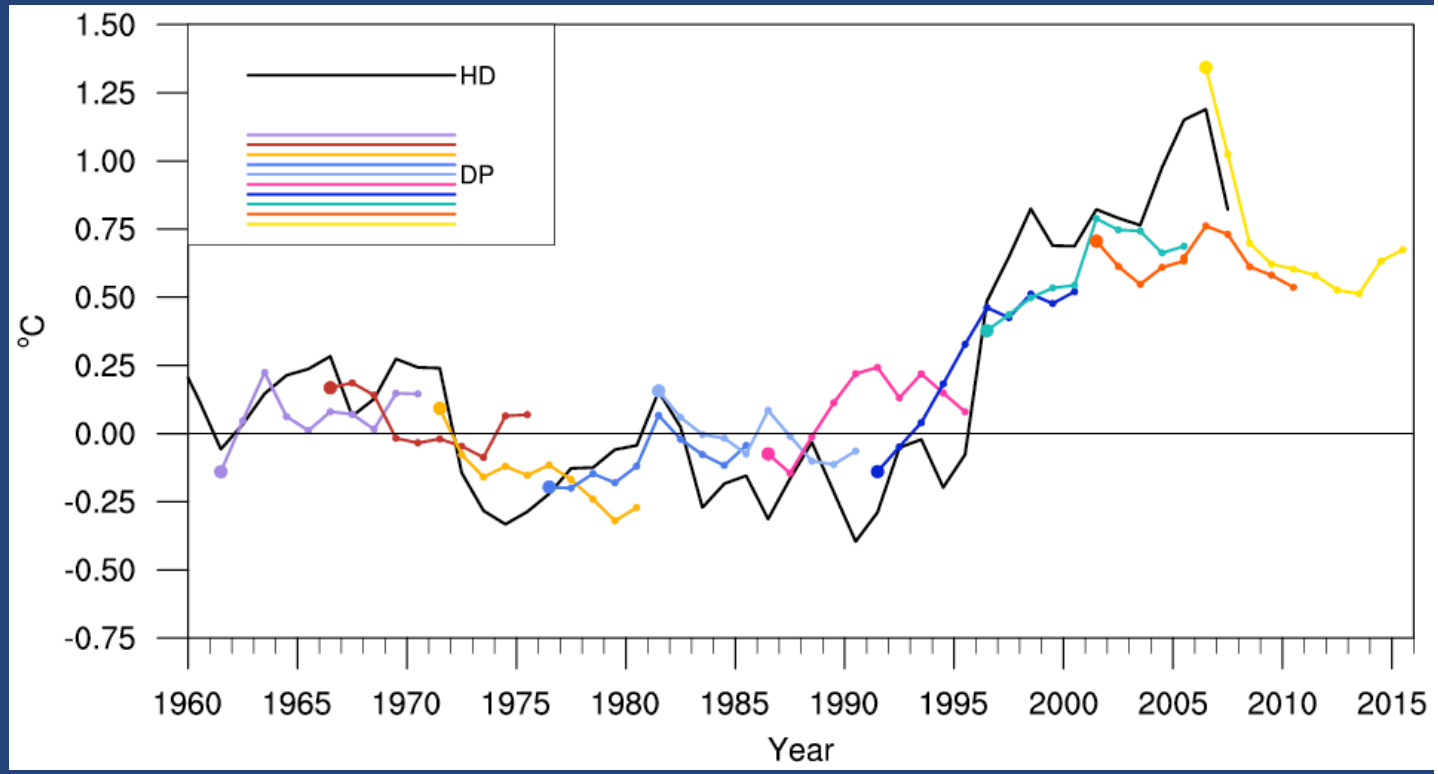
• For each field and spatial location (x,y,z), define the (10-member) ensemble-mean DP evolution away from the HD ocean state:

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

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



275m Heat Content Anomaly in SPG box



Bias-corrected DP experiments (Method 1)

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

(Both are >99% significant based on two-sided students t-test with dof = 7, 6)

275m Heat Content Anomaly in SPG box

Forecast Start Date	DP	20C	damped persistence
Jan 1, 1961	0.008	0.022 (55%)	0.000 (48%)
Jan 1, 1966	0.027	0.061 (60%)	0.131 (73%)
Jan 1, 1971	0.012	0.191 (85%)	0.104 (74%)
Jan 1, 1976	0.001	0.101 (76%)	0.059 (68%)
Jan 1, 1981	0.038	0.344 (91%)	0.200 (80%)
Jan 1, 1986	0.089	0.205 (70%)	0.092 (50%)
Jan 1, 1991	0.042	0.143 (71%)	0.264 (85%)
Jan 1, 1996	0.030	0.249 (86%)	0.478 (96%)
All dates	0.031(mse)	0.165 (98%)	0.166 (98%)

TABLE 1. For each forecast method, at each initialization date, the square error ($^\circ C^2$) between the ensemble mean 5yr average (yrs 6-10) forecast of upper ocean heat content in the region 50-10°W, 50-60°N and the ocean hindcast (our "truth"). Percentages in parentheses represent the probabilities that the squared error of the initialized forecast is *less* than the uninitialized forecast/damped persistence forecast method.

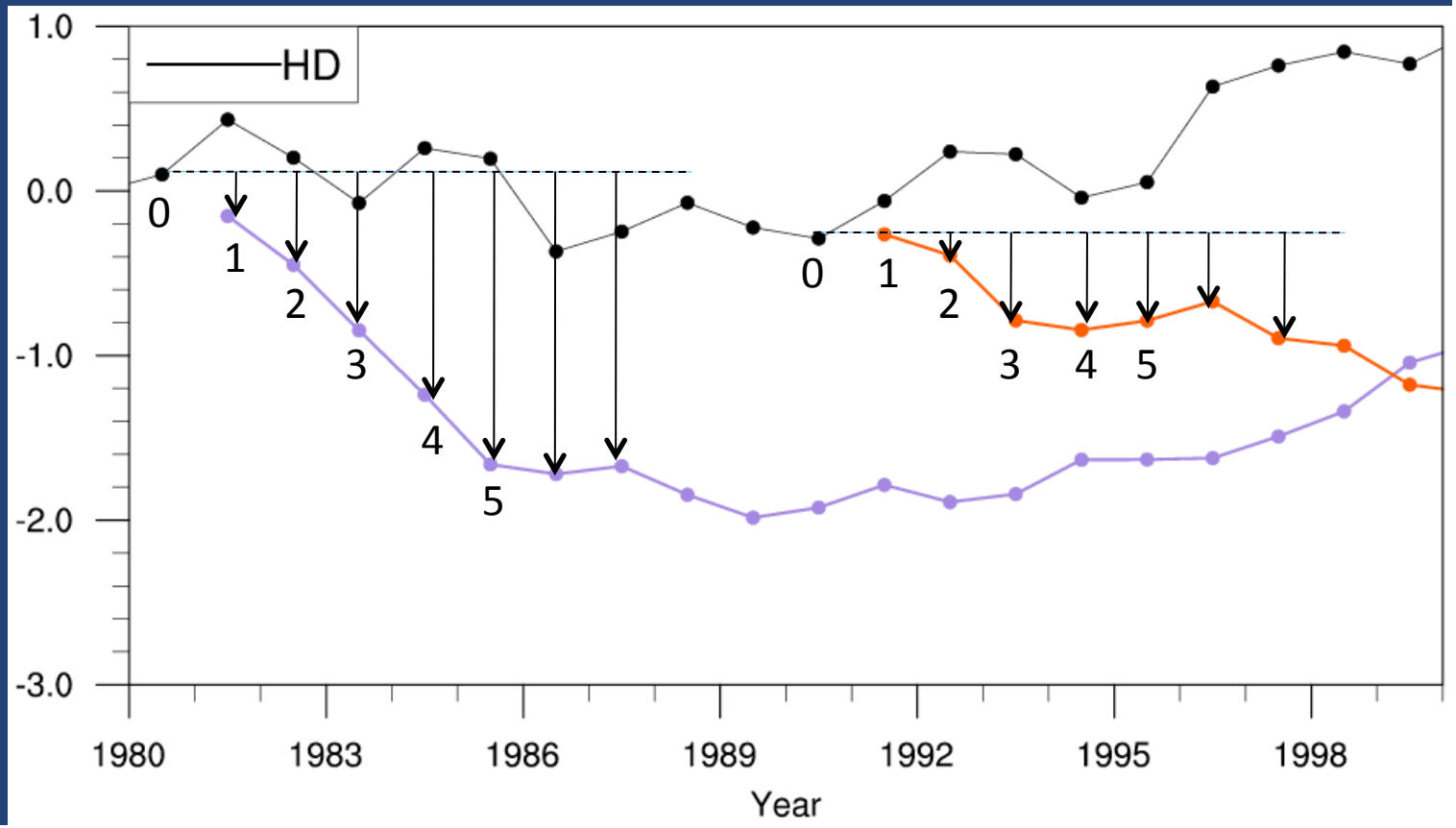
Bias-corrected DP experiments (Method 1)

Bias Correction: Method 2

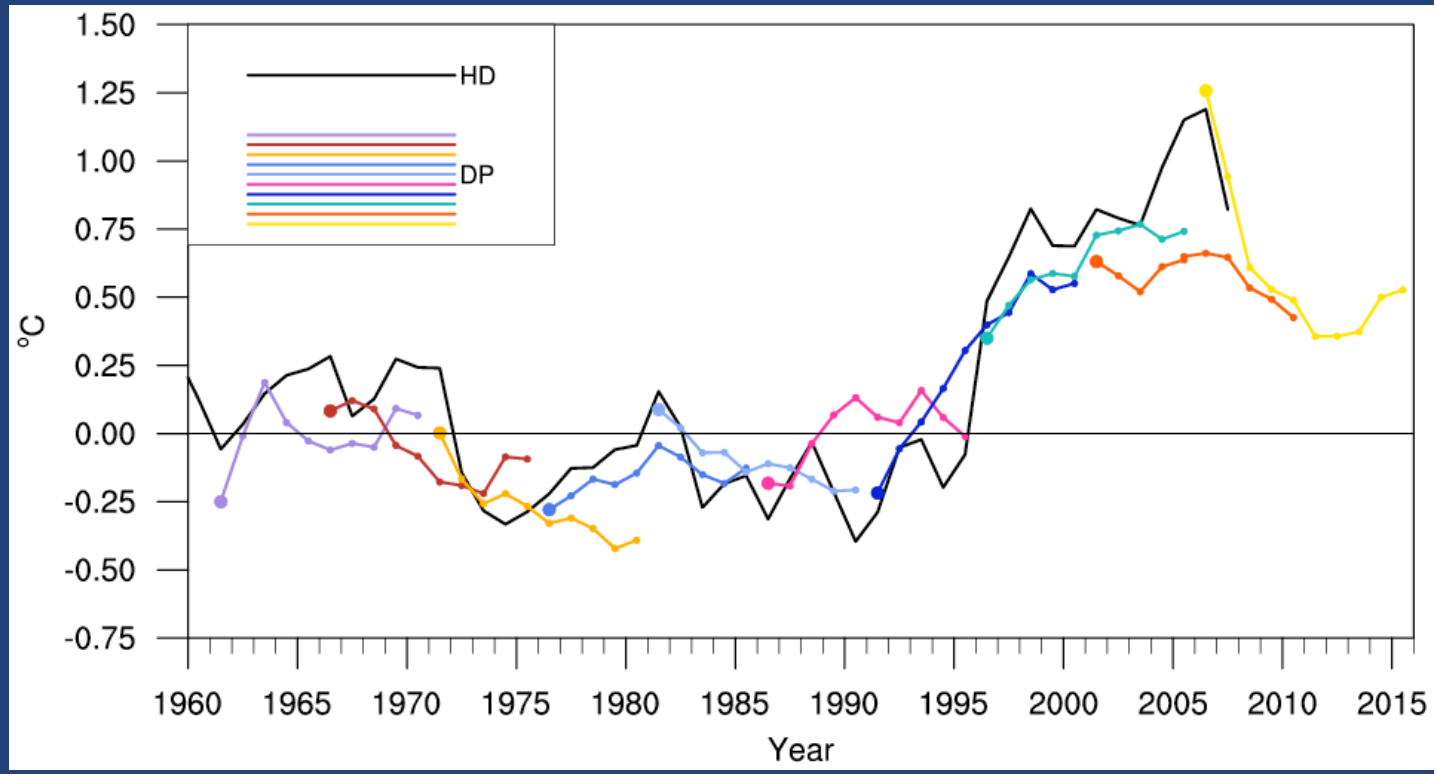
• For each field and spatial location (x,y,z), define the (10-member) ensemble-mean DP evolution away from the HD ocean state:

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

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



275m Heat Content Anomaly in SPG box

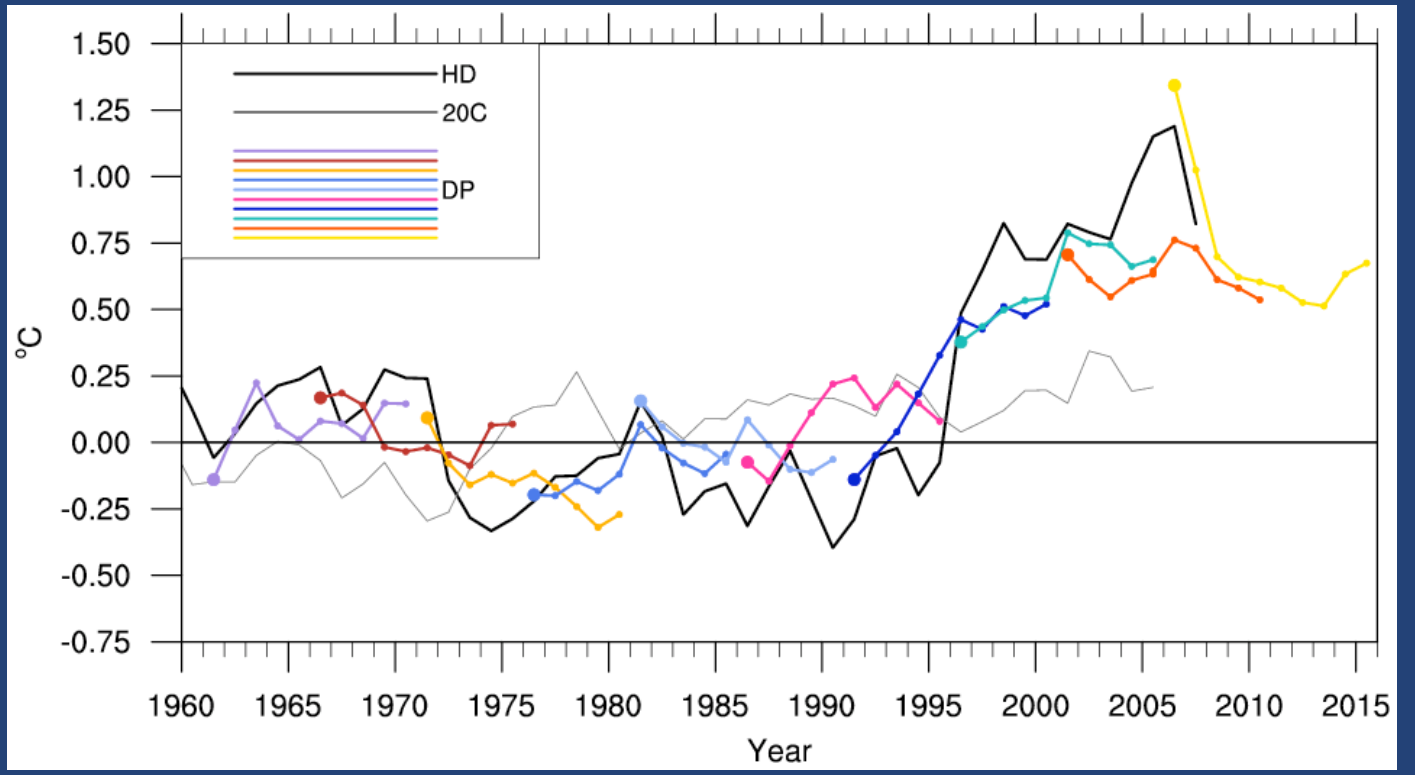


Bias-corrected DP experiments (Method 2)

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

(Both are >99% significant based on two-sided students t-test with dof = 7, 6)

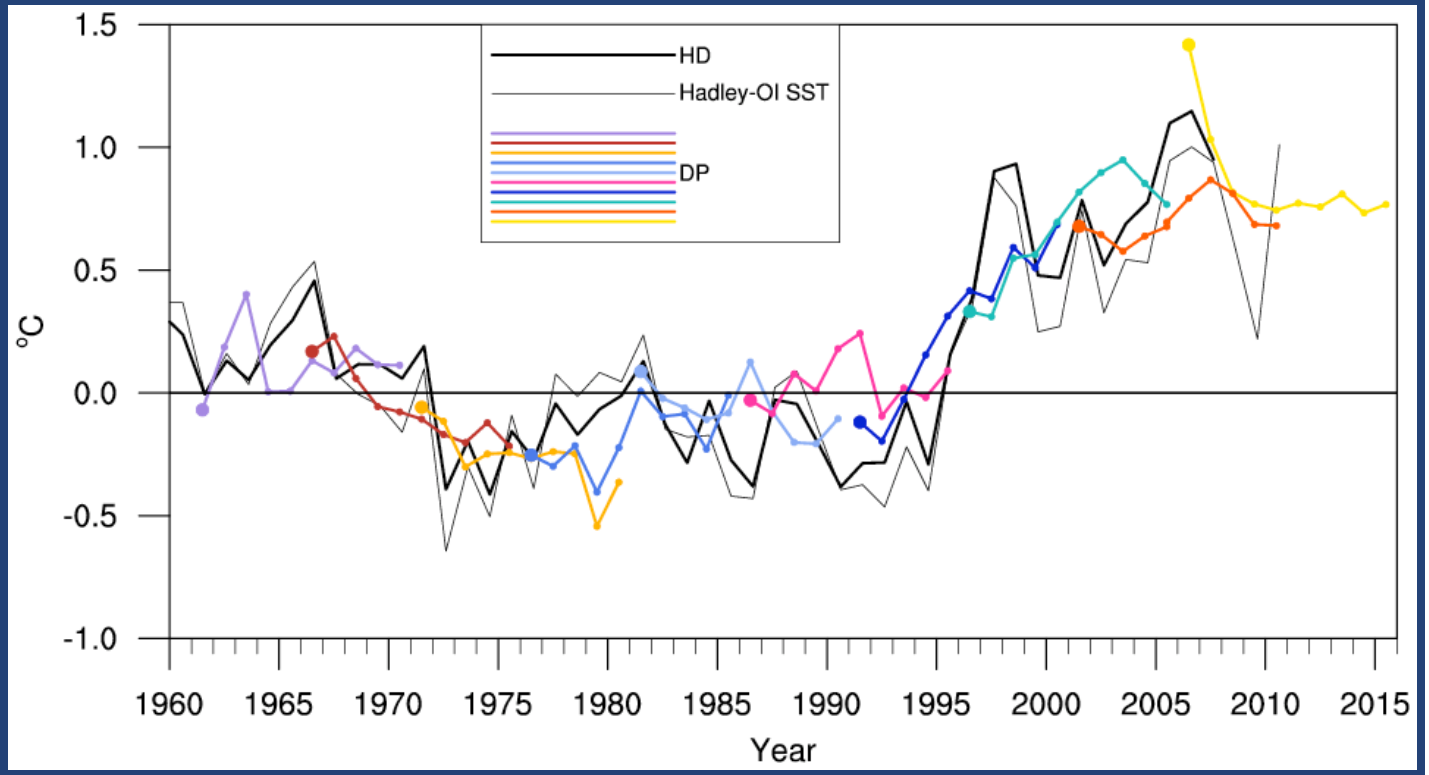
275m Heat Content Anomaly in SPG box



Bias-corrected DP experiments (Method 1) & uninitialized 20C ensemble (grey)

HD/20C correlation of lag1-5 pentads (N=9): 0.31
HD/20C correlation of lag6-10 pentads (N=8): 0.33

SST Anomaly in SPG box



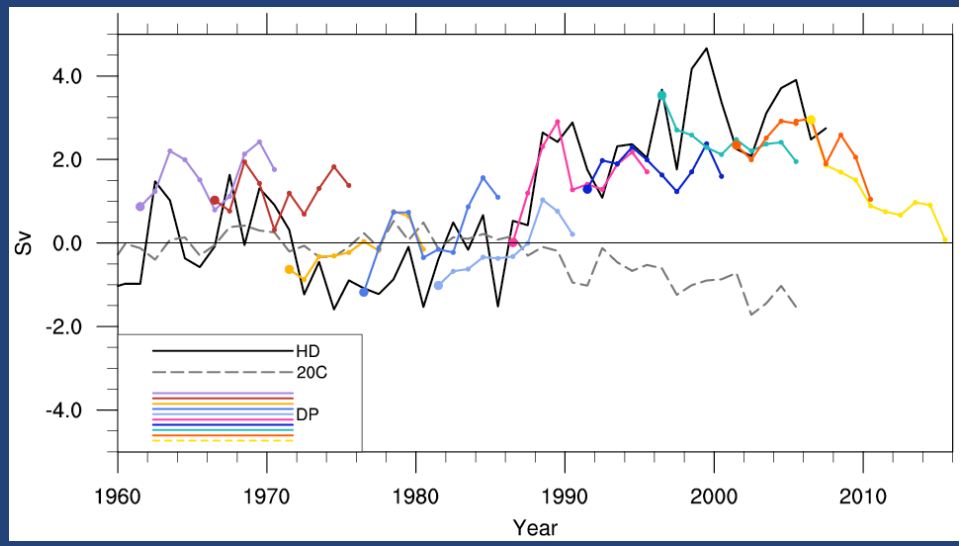
HD/DP correlation of lag1-5 pentads (N=9): 0.93
HD/DP correlation of lag6-10 pentads (N=8): 0.94

(Both are >99% significant based on two-sided students t-test with dof = 7, 6)

AMOC Predictions

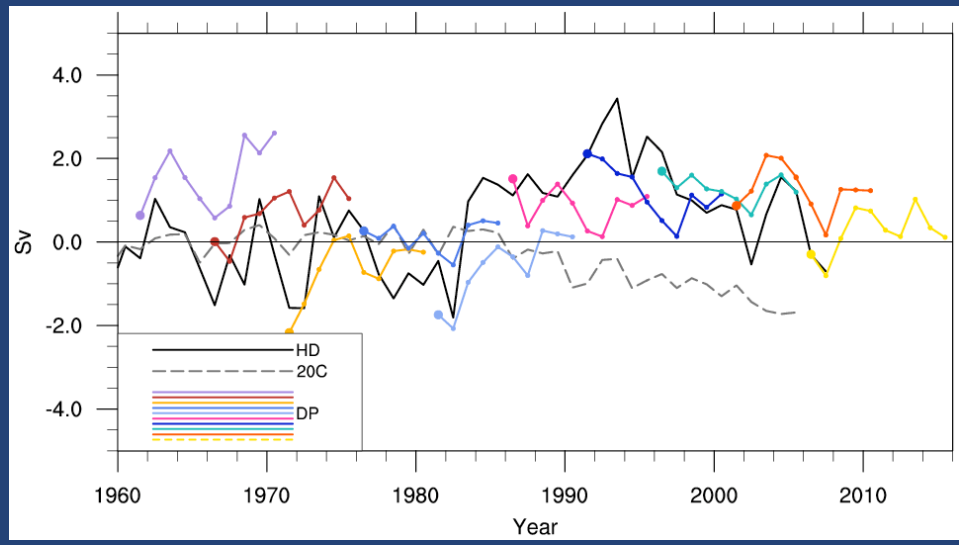
37°N

lag1-5 pentads (N=9): r = 0.90 (>99%)
lag6-10 pentads (N=8): r = 0.62 (>90%)



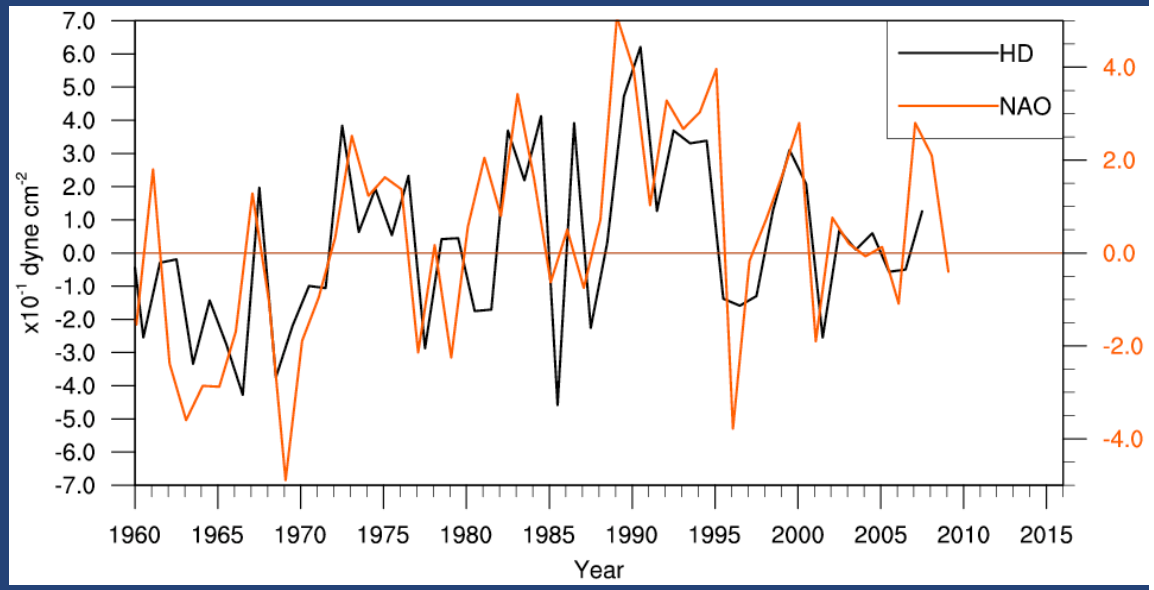
45°N

lag1-5 pentads (N=9): r = 0.6 (>90%)
lag6-10 pentads (N=8): r = -0.1

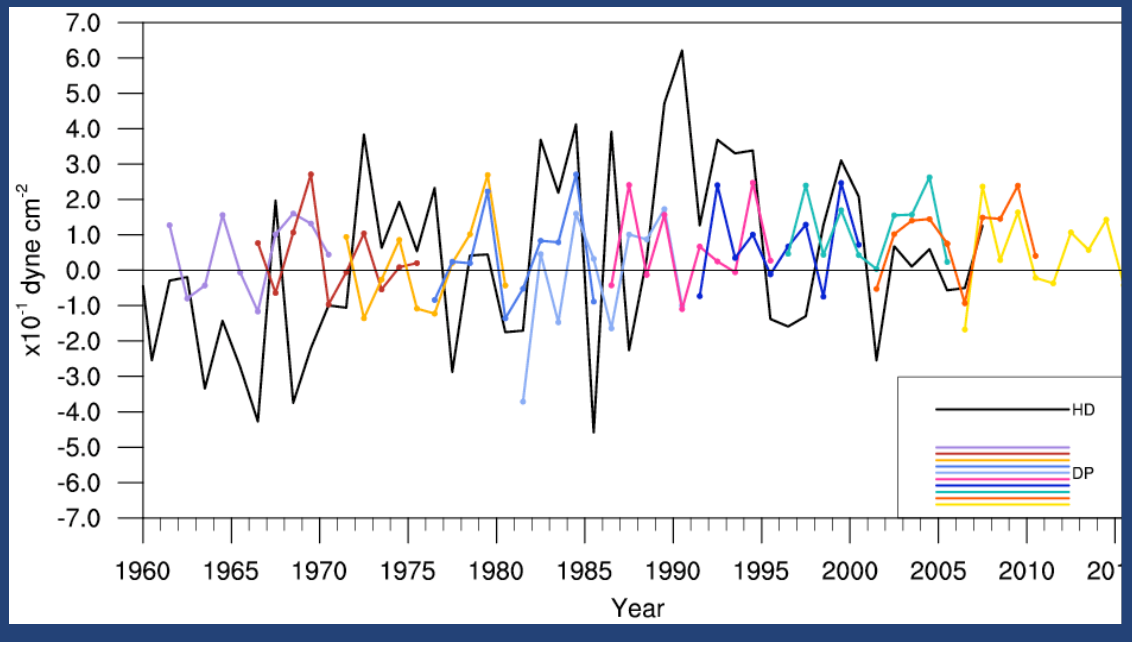


Zonal Wind Stress Anomaly in SPG box

Correlation = 0.7 ➔ SPG TAUX is a reasonable proxy for NAO



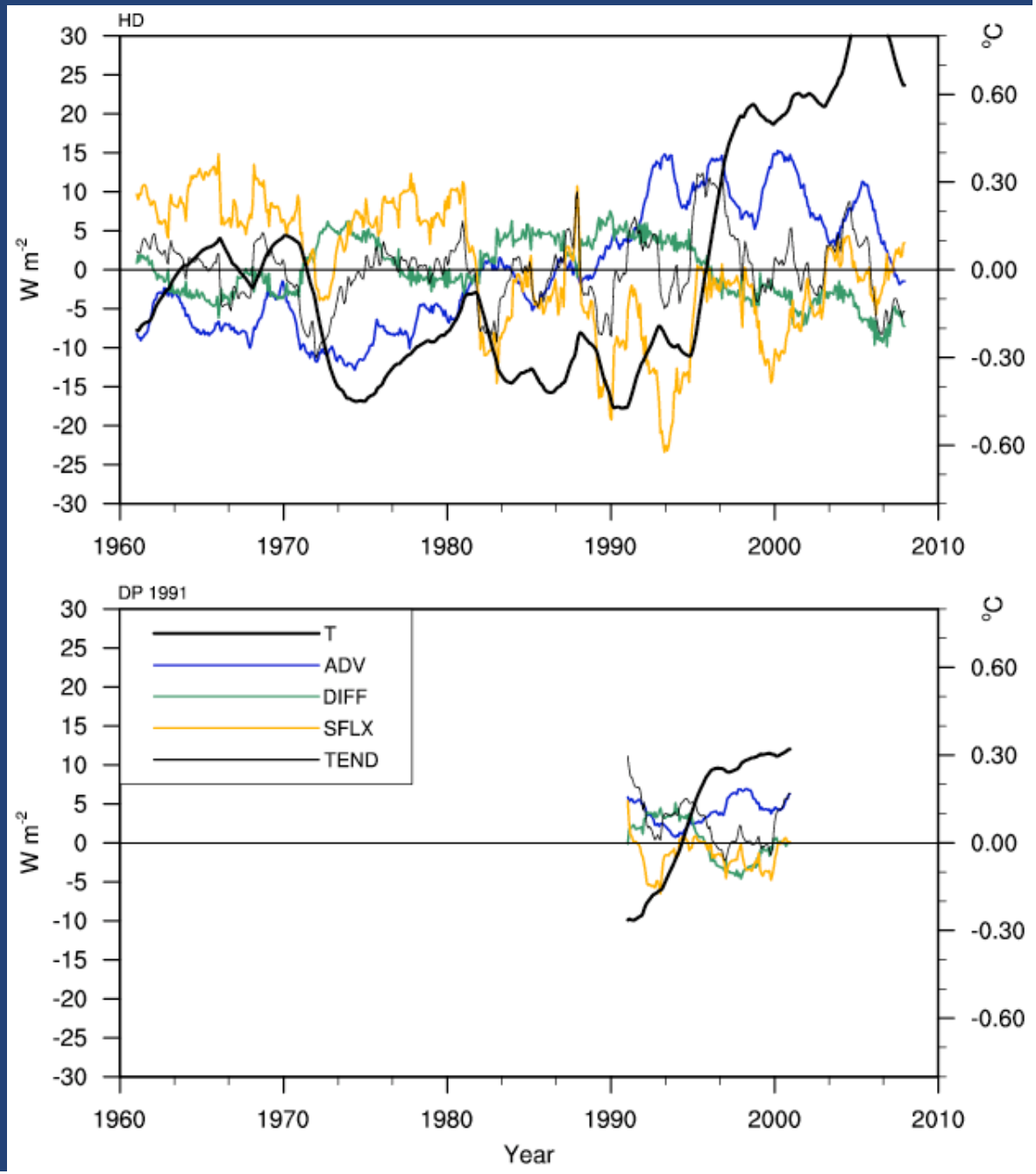
➔ DP ensembles show low skill at predicting NAO variations



Heat Budget of SPG box

HD

1991 DP

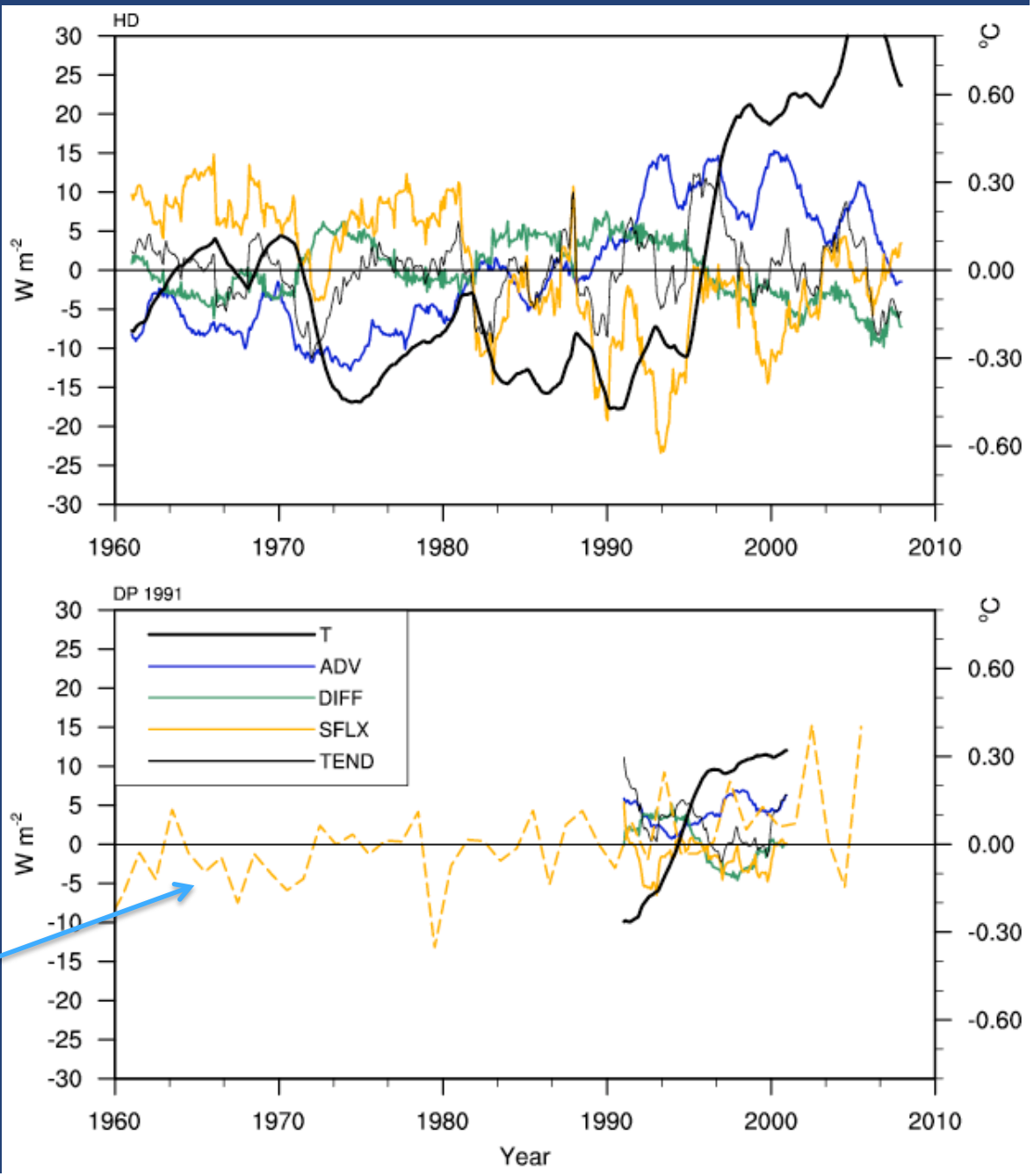


Heat Budget of SPG box

HD

1991 DP

uninitialized
20C

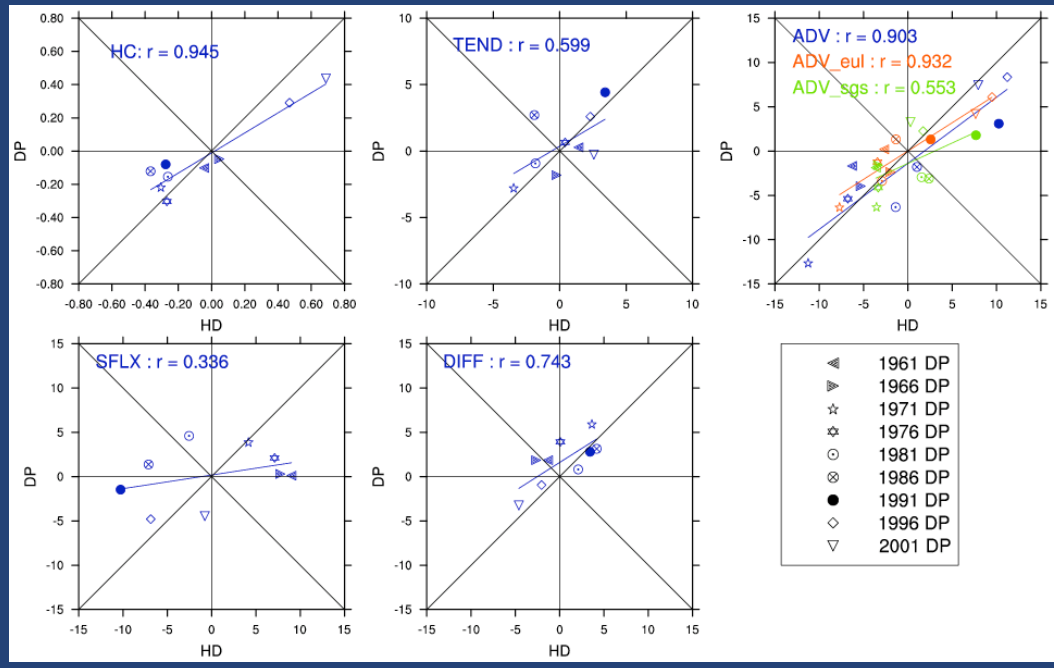


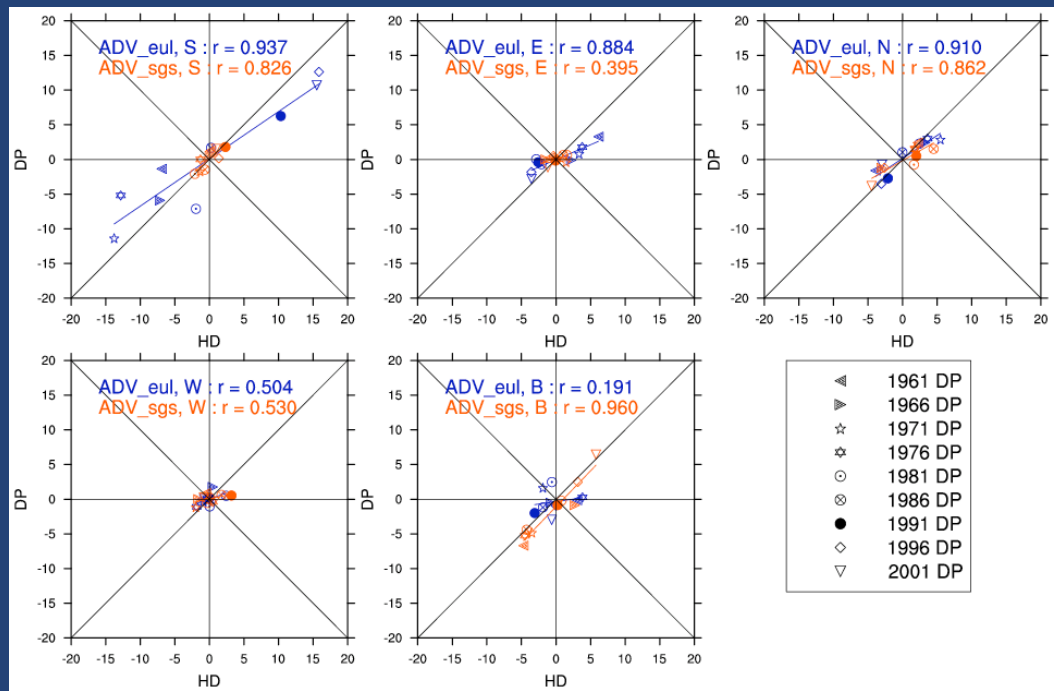
Comparison of pentadal mean Heat Budget terms: lags 1-5

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

- Surface heat flux anomalies (NAO) are poorly predicted

- Tendency of some states sensitive to atm i.c.'s? Perhaps room for improvement

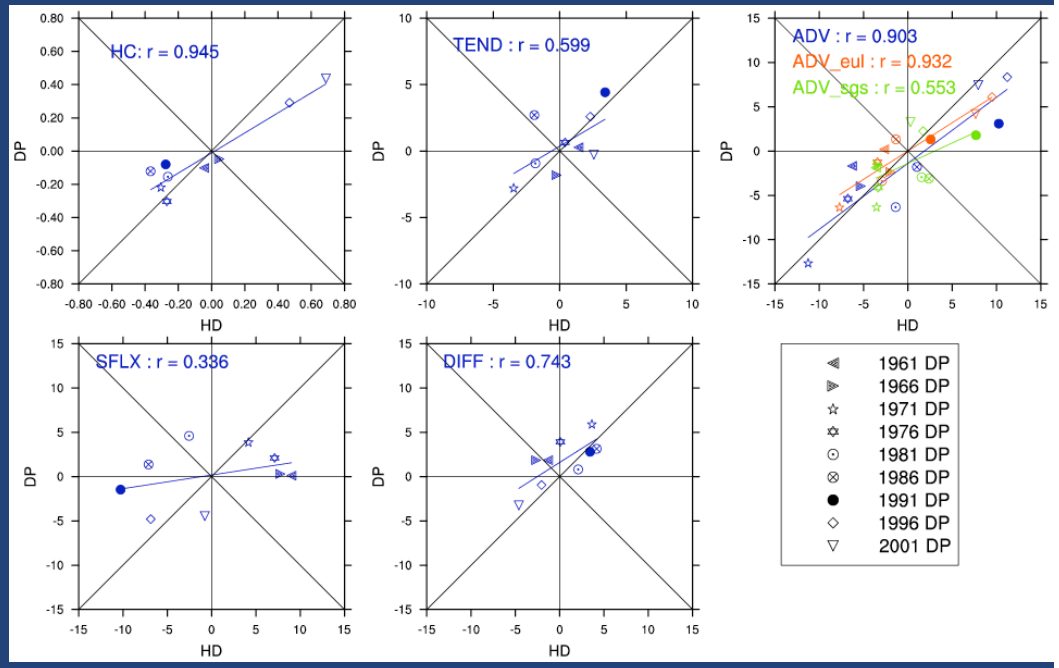


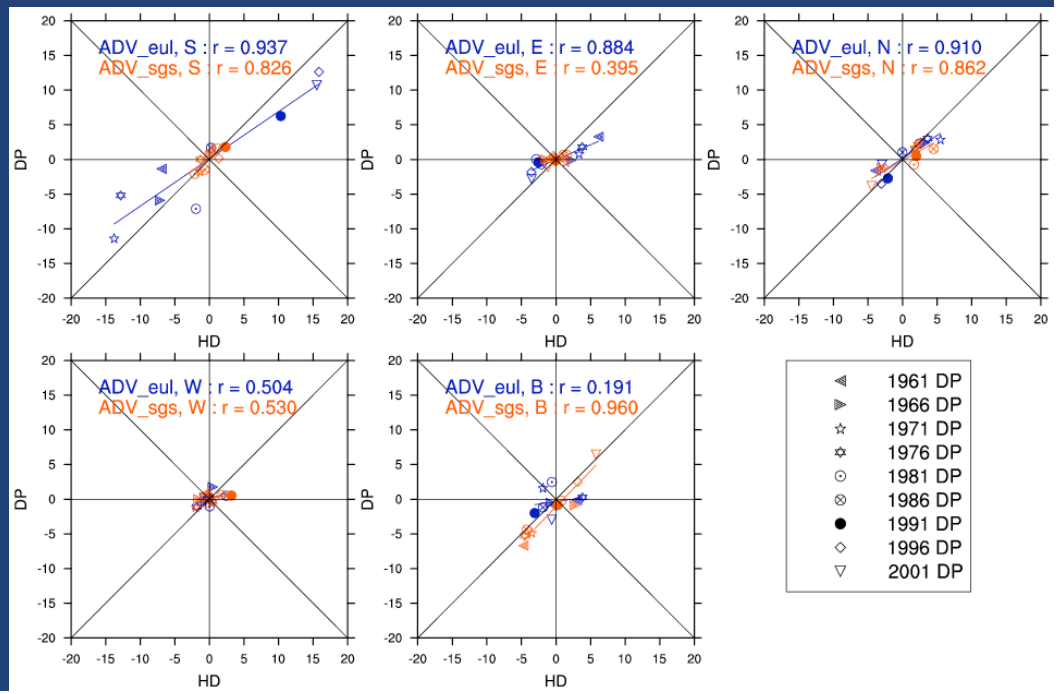


Comparison of pentadal mean Heat Budget terms: lags 1-5

- 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

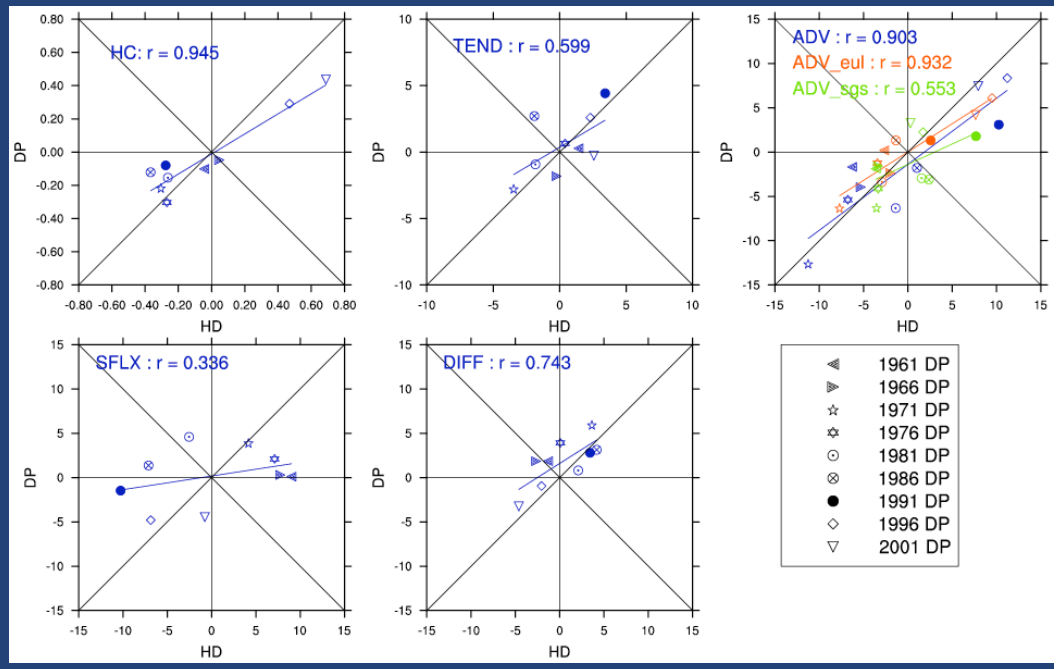


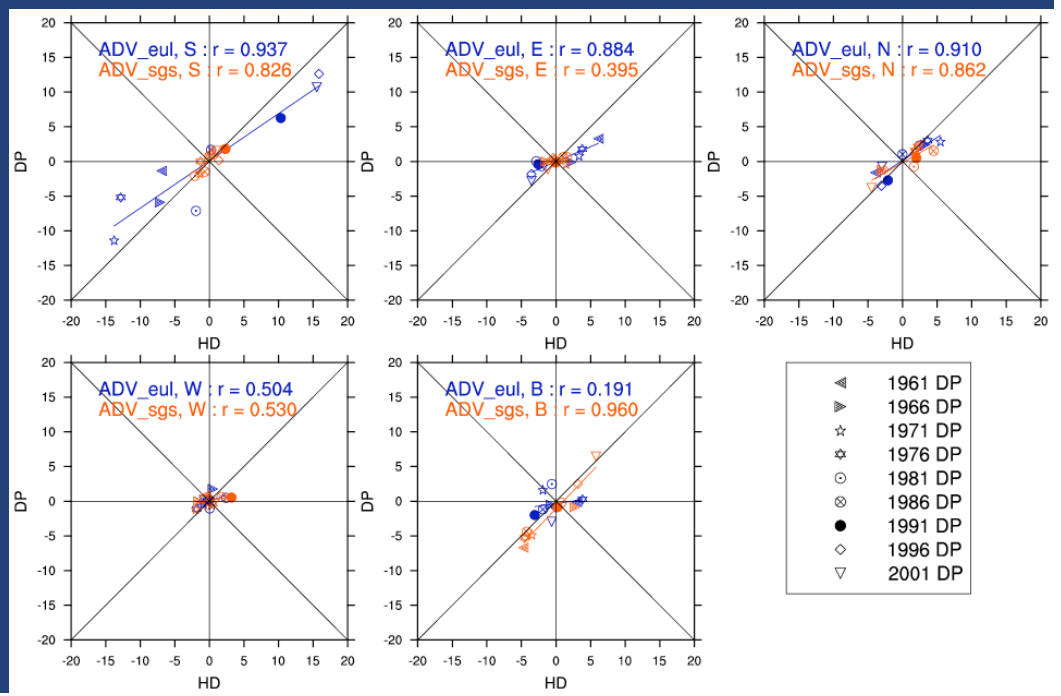


Comparison of pentadal mean Heat Budget terms: lags 1-5

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

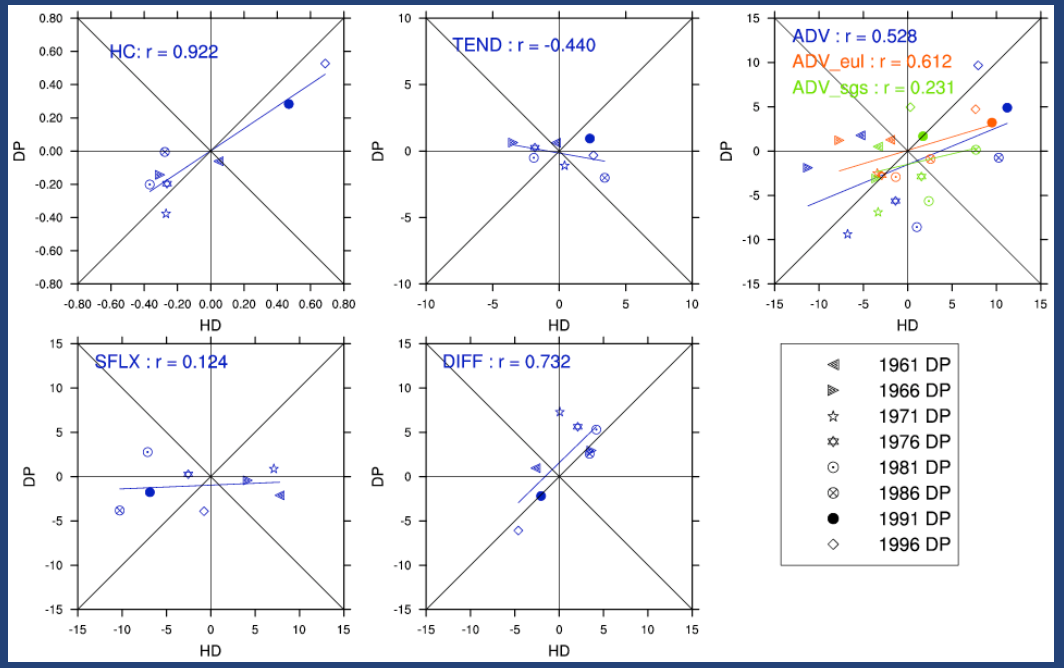
- 1991 DP ensemble gets tendency correct despite too weak cooling and too little ADV heating. These (nearly compensating) flux biases are associated with poor ensemble prediction of the observed NAO+ between 1991-1995. This explains the early timing of predicted regime shift.

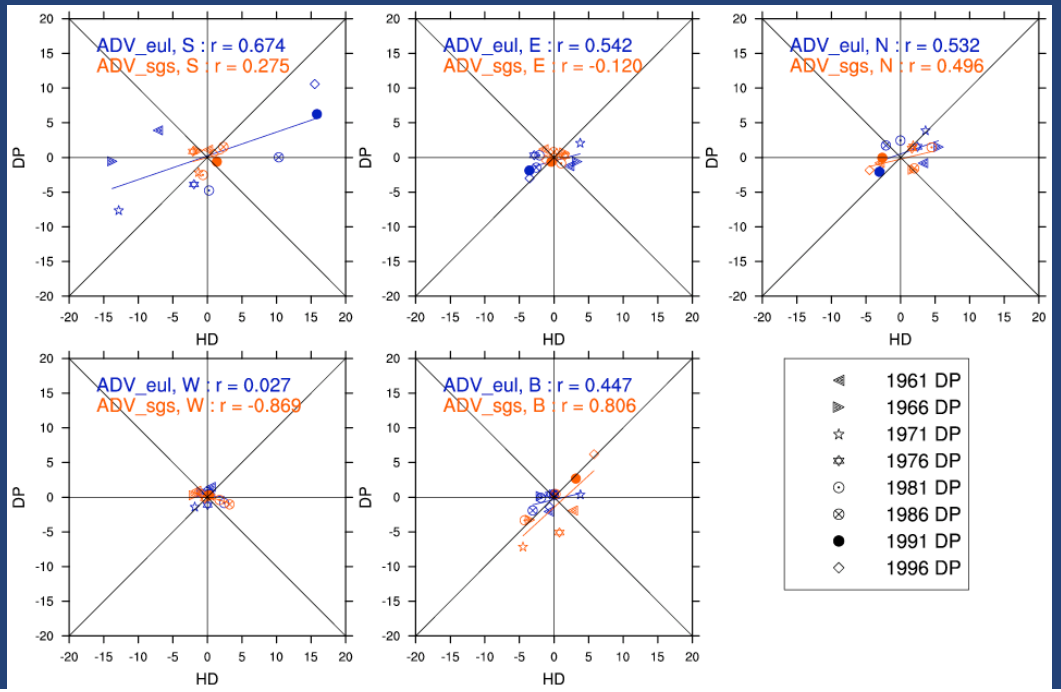




Comparison of pentadal mean Heat Budget terms: lags 6-10

- Poor prediction of lag6-10 tendency
- Potential for skillful prediction beyond lag 10 with better high latitude AMOC prediction?
- Diffusive flux anomalies remain highly correlated



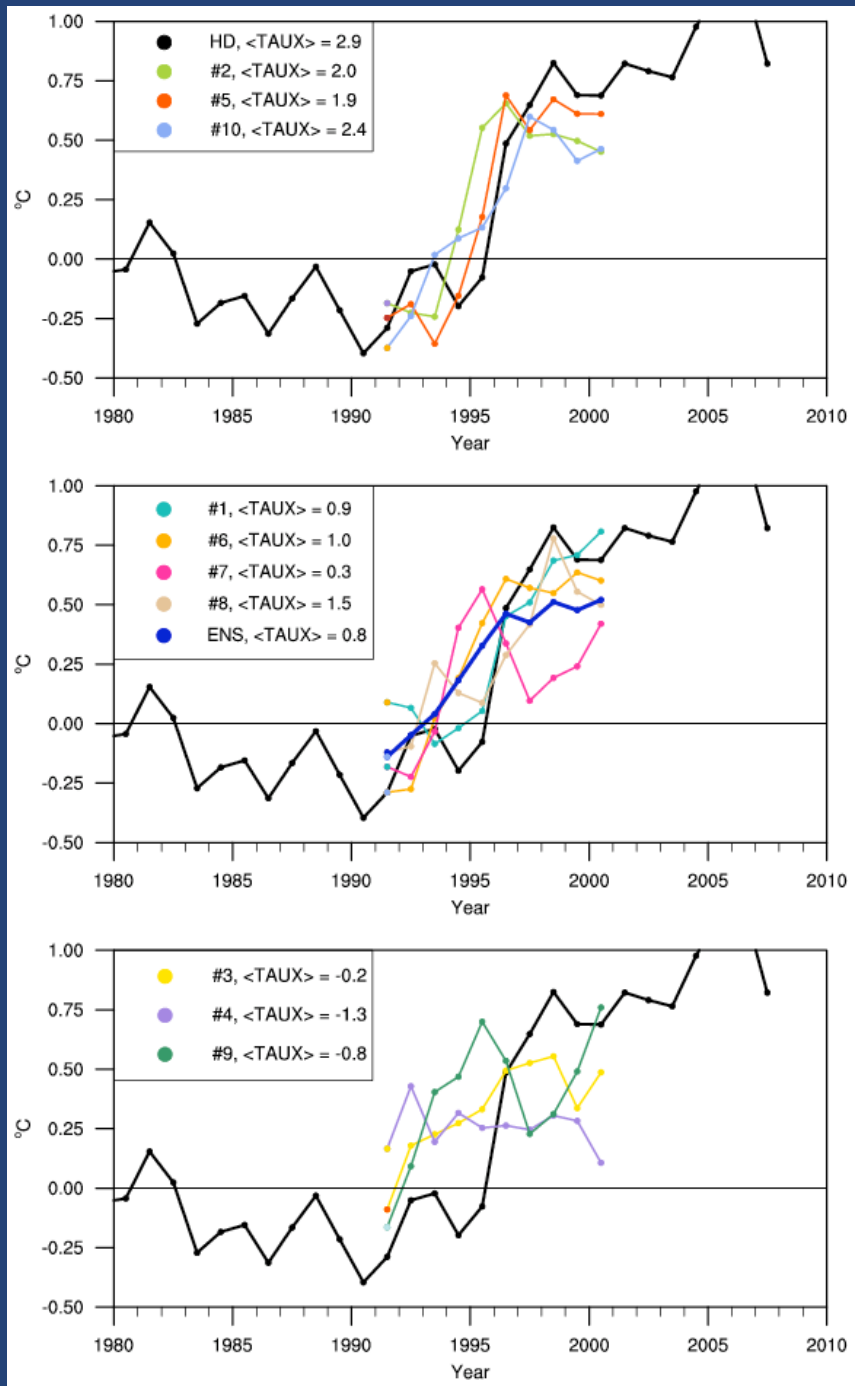


1991 DP ensemble

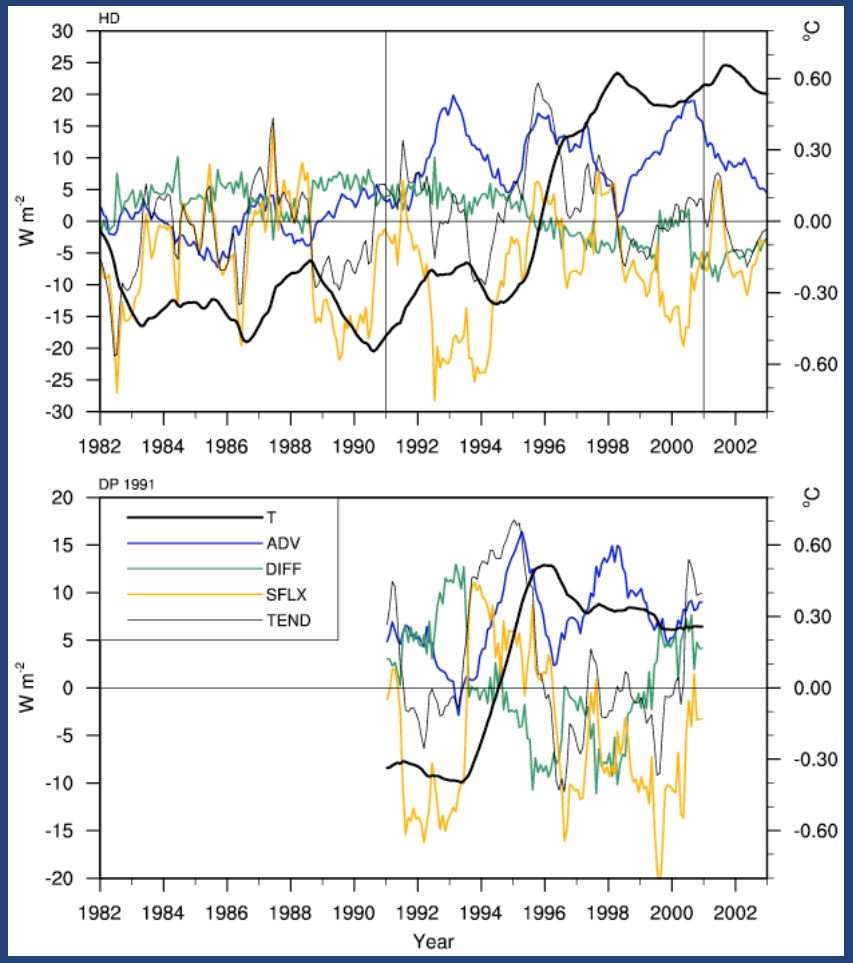
• Ensemble members which simulate strong NAO+ between 1991-1995 generate closest match to HD

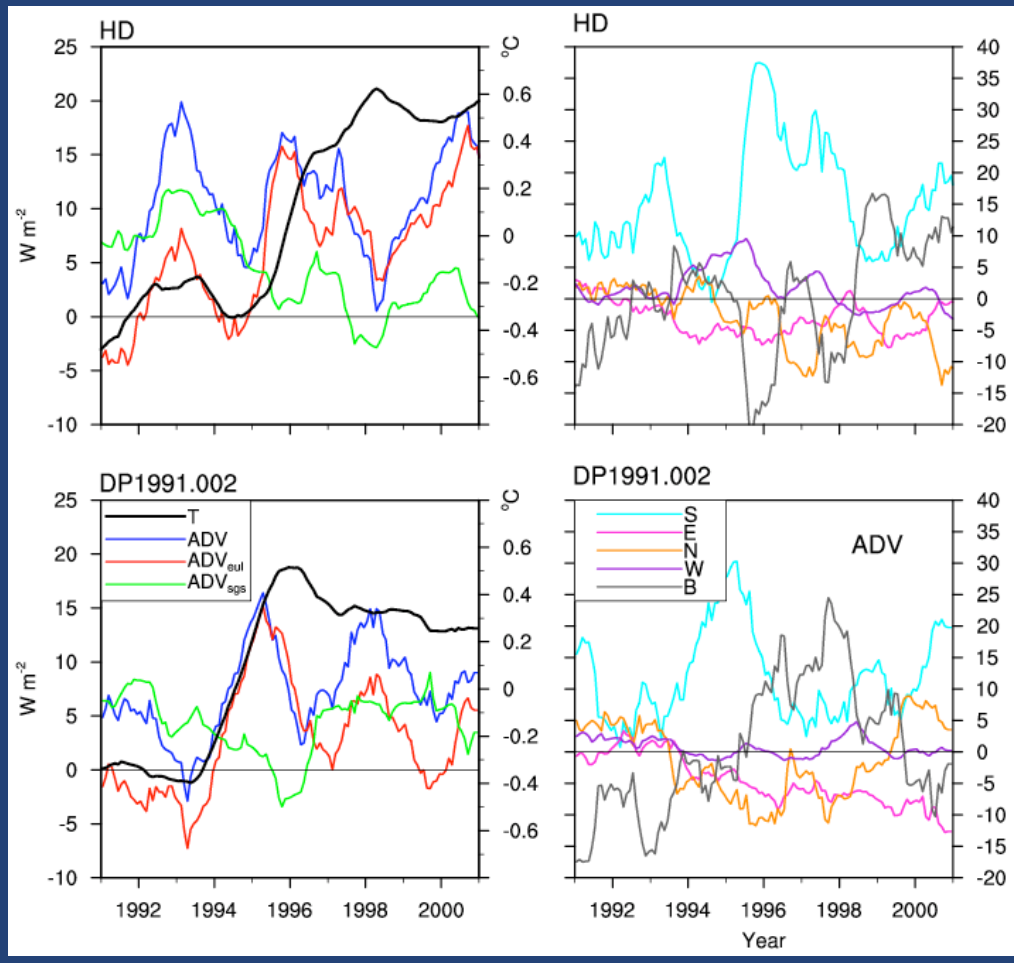
•Most ensemble members get regime shift too early.

• Ensemble members which simulate weak NAO between 1991-1995 show too rapid/weak HC rise



Heat Budget of SPG box





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

➔ confidence that bias-corrected fields from full field initialization are physically consistent and meaningful

Conclusions

- The CCSM4 CMIP5 DP runs show skill at predicting North Atlantic SPG heat content & SST changes up to a decade in advance. External forcing does not appear to be contributing to skill in this region in a manner consistent with actual mechanisms.

- 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 in this region is degraded by poor prediction of surface heat flux tendency (NAO) and (eventually) poor AMOC prediction.

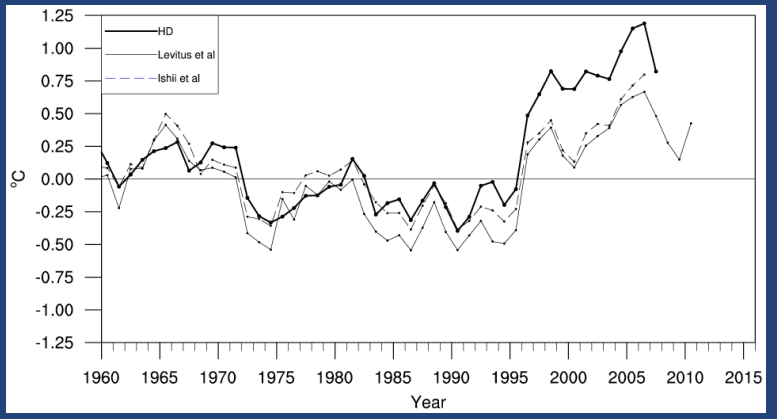
- The mid-90's regime shift is captured despite poor NAO prediction because of strong preconditioning of the 1991-initialized DP run for large advective & diffusive fluxes into the SPG.

- 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 and poor NAO prediction.

275m Heat Content Anomaly

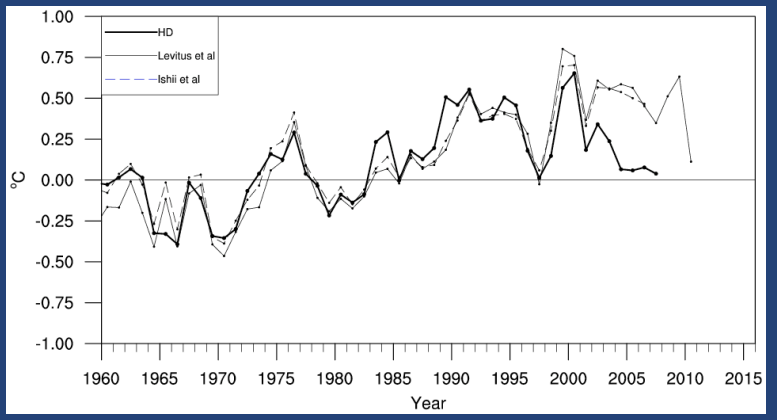
SPG

1960-2007 correlation
with Levitus is 0.9



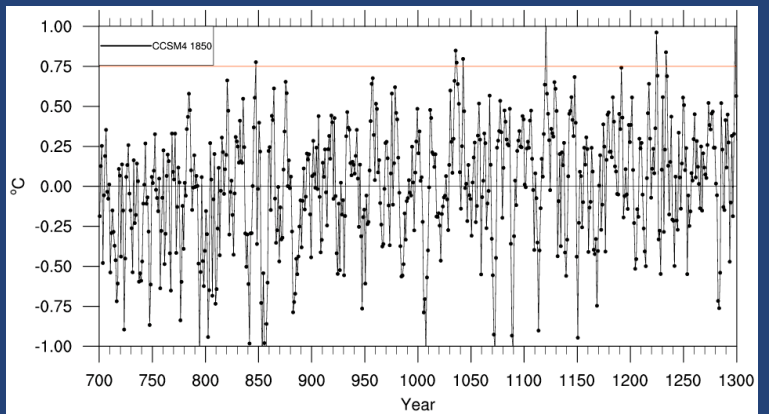
STG

1960-2007 correlation
with Levitus is 0.83



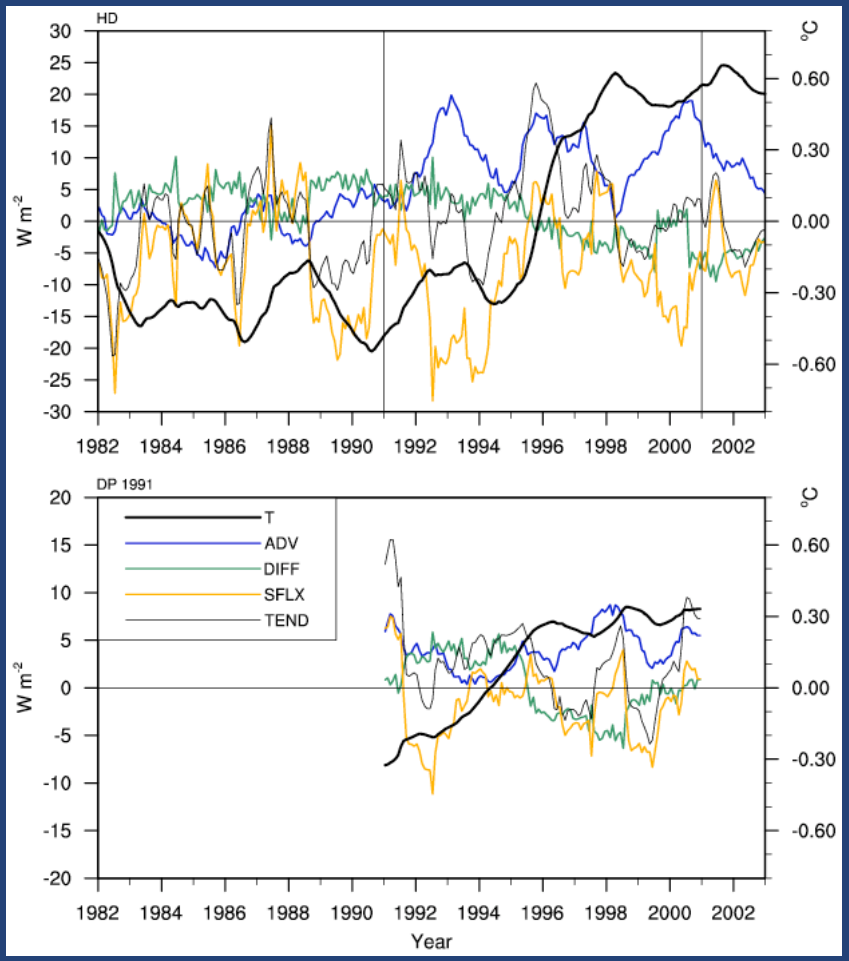
STG-SPG

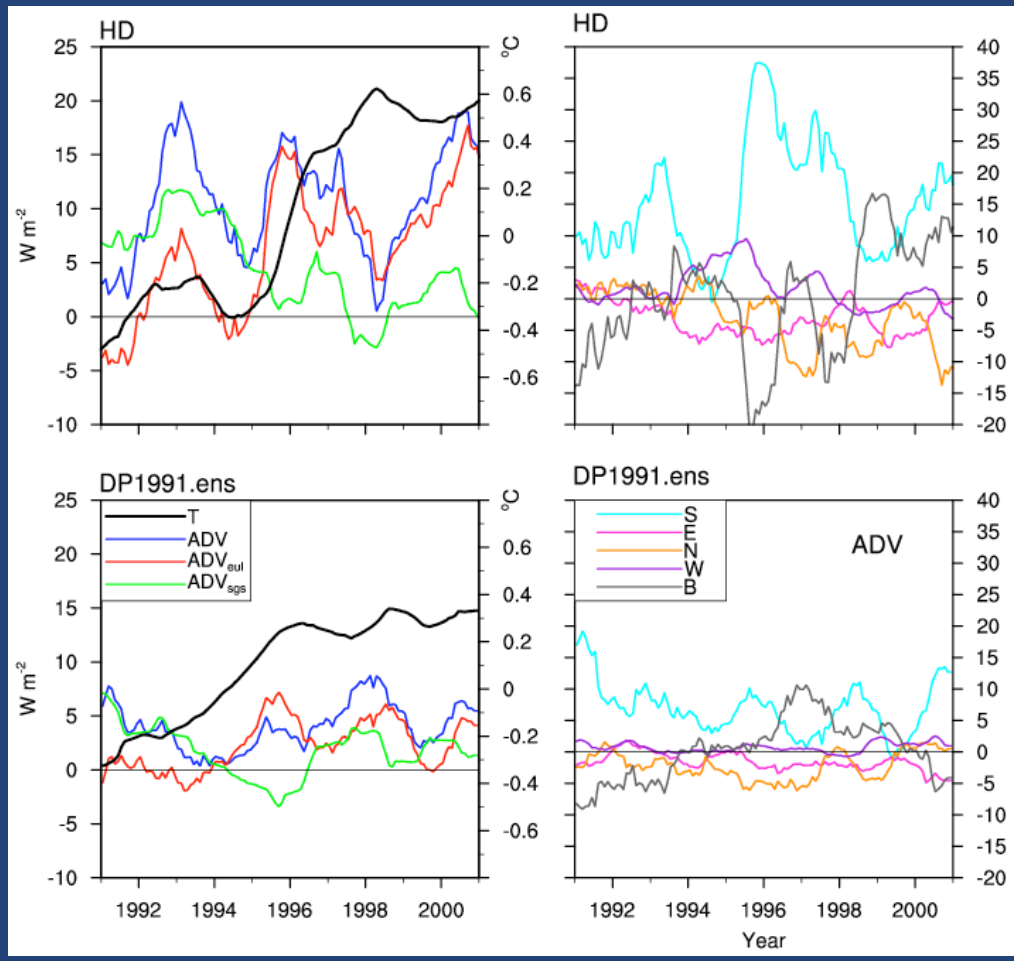
CCSM4 1850 control



*1957-90 climatology

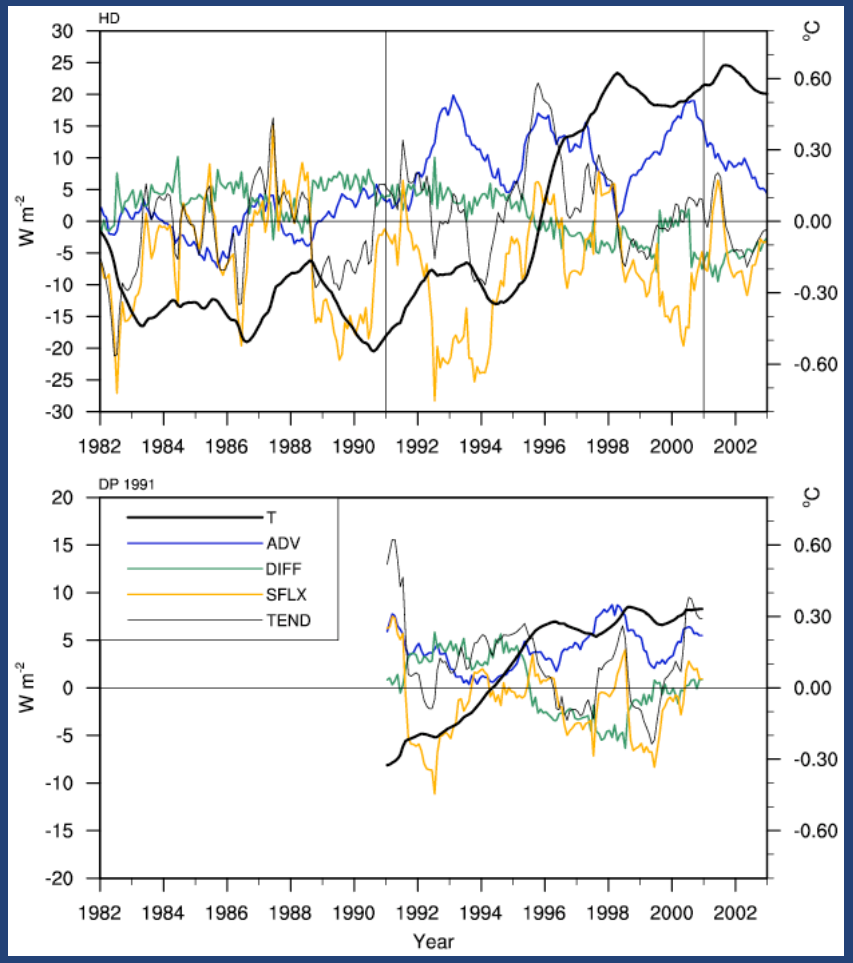
Heat Budget of SPG box

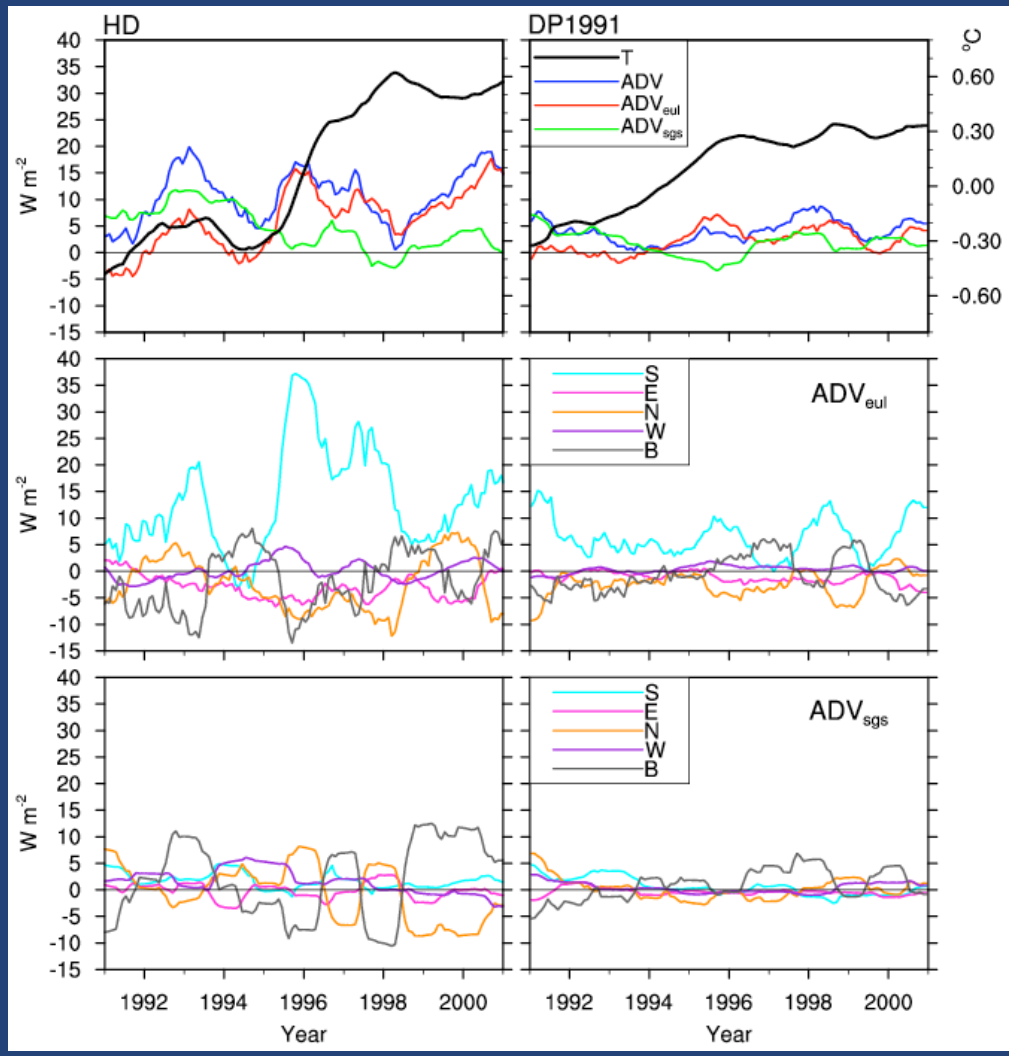




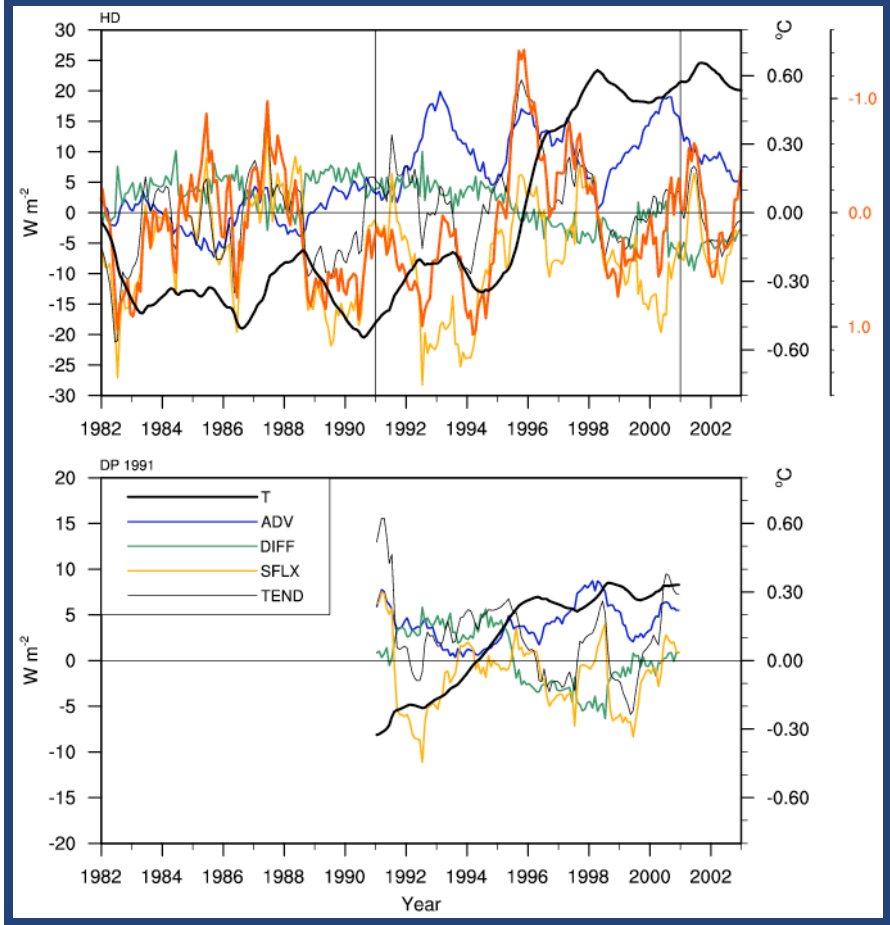
Monthly budget terms from HD (top panels) and DP1991 ensemble mean (bottom panels).

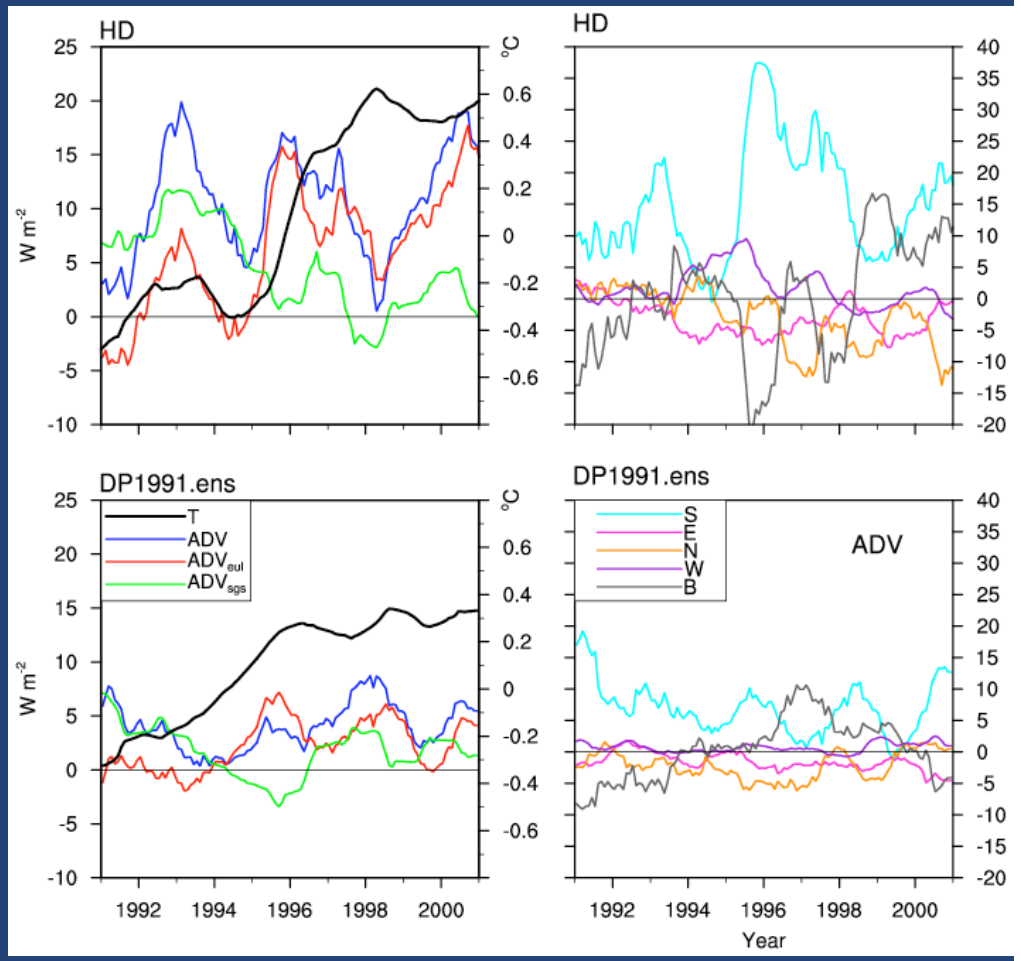
Heat Budget of SPG box





Heat Budget of SPG box



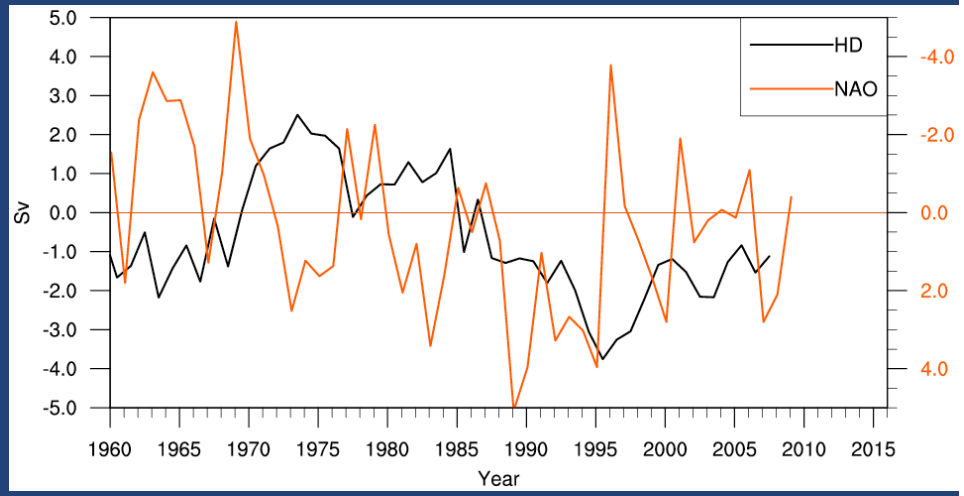


SPG Box Heat Budget

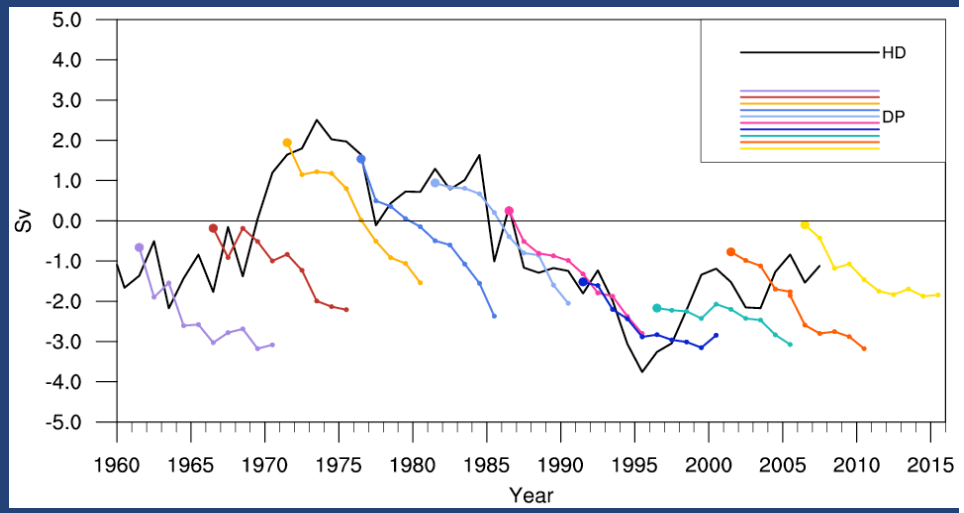
	HD (W/m²)	DP (W/m²)
ADV	47	46
ADV: eul,sgs	18,29	18,28
ADV: S,E,N,W,B	149,-65,-98,9,50	149,-65,-97,10,49
ADV_{eul}: S,E,N,W,B	138,-53,-58,11,-20	138,-53,-58,11,-20
ADV_{sgs}: S,E,N,W,B	11,-12,-40,-1,70	11,-12,-40,-1,69
SFLX	-60	-60
DIFF	14	17
TEND	1	2

- 1961-2007 climatology

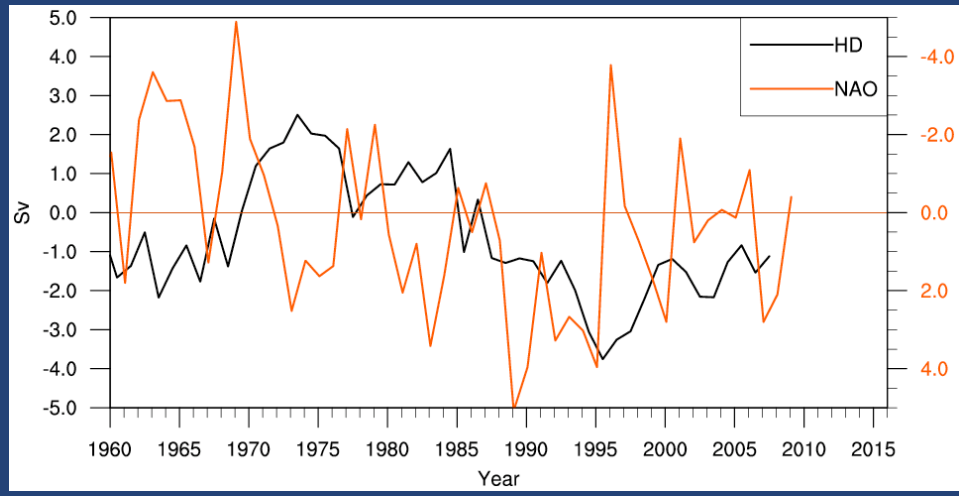
Barotropic Streamfunction (BSF) predictions



raw



Barotropic Streamfunction (BSF) predictions



bias-corrected