A Decadal Prediction Case Study: Late 20th century N. Atlantic Ocean heat content

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

Yeager et al., 2012, *J. Clim.*, CCSM4 special issue.

OUTLINE

I. Late 20th century changes in N. Atlantic upper ocean heat content: a test case for decadal prediction systems
   - what caused the mid-1990's regime shift?

I. The CCSM4 suite of initialized CMIP5 decadal prediction (DP) experiments:
   - fully-coupled 10-yr 20C runs initialized at 5-yr intervals from historical ocean/ice states obtained from CORE-forced hindcast (HD) simulation
   - full-field initialization ➔ bias-correction relative to HD
   - 10-member ensembles for each start date (1961, 1966, ..., 2006)

II. Assessment of regional DP skill with a focus on mechanisms: do DP ensembles get it right for the right reasons?

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

	1981-85	1986-90	1991-95	1996-00
HD				
SPG				
STG				
Ishii				
Levitus				

Observed mid-1990's Regime Shift in the SPG

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

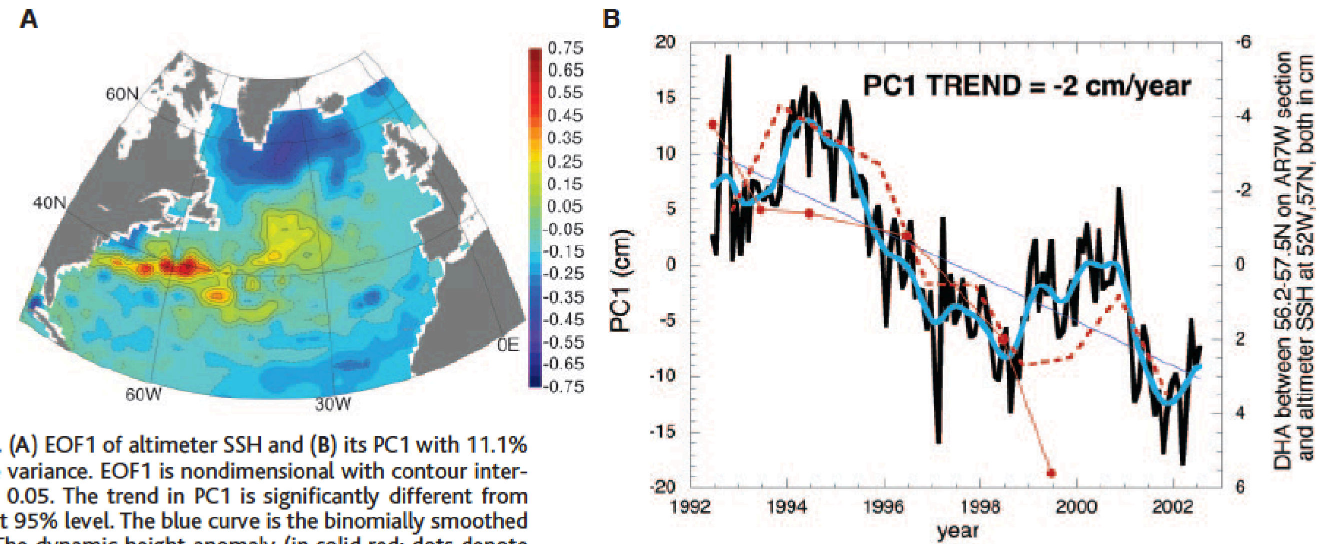


Fig. 1. (A) EOF1 of altimeter SSH and (B) its PC1 with 11.1% of the variance. EOF1 is nondimensional with contour interval of 0.05. The trend in PC1 is significantly different from zero at 95% level. The blue curve is the binomially smoothed PC1. The dynamic height anomaly (in solid red; dots denote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

Annual Mean Time Series

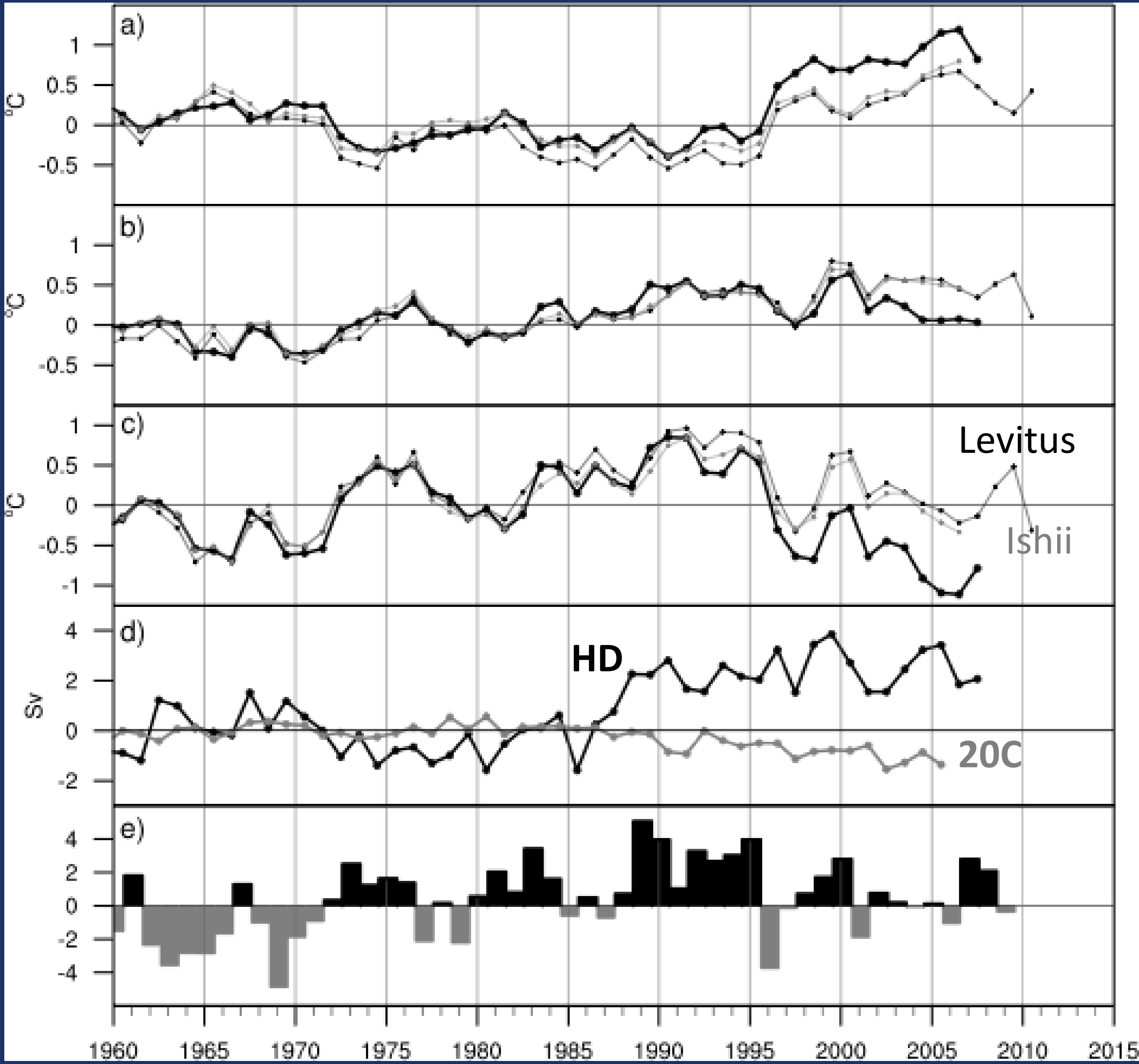
a. 275m SPG heat content

b. 275m STG heat content

c. Meridional heat content gradient (STG – SPG)

d. AMOC at 37.5^{o}N

e. Observed (djfm) NAO index



*relative to 1957-1990 clim.

Annual Mean Time Series

a. 275m SPG heat content

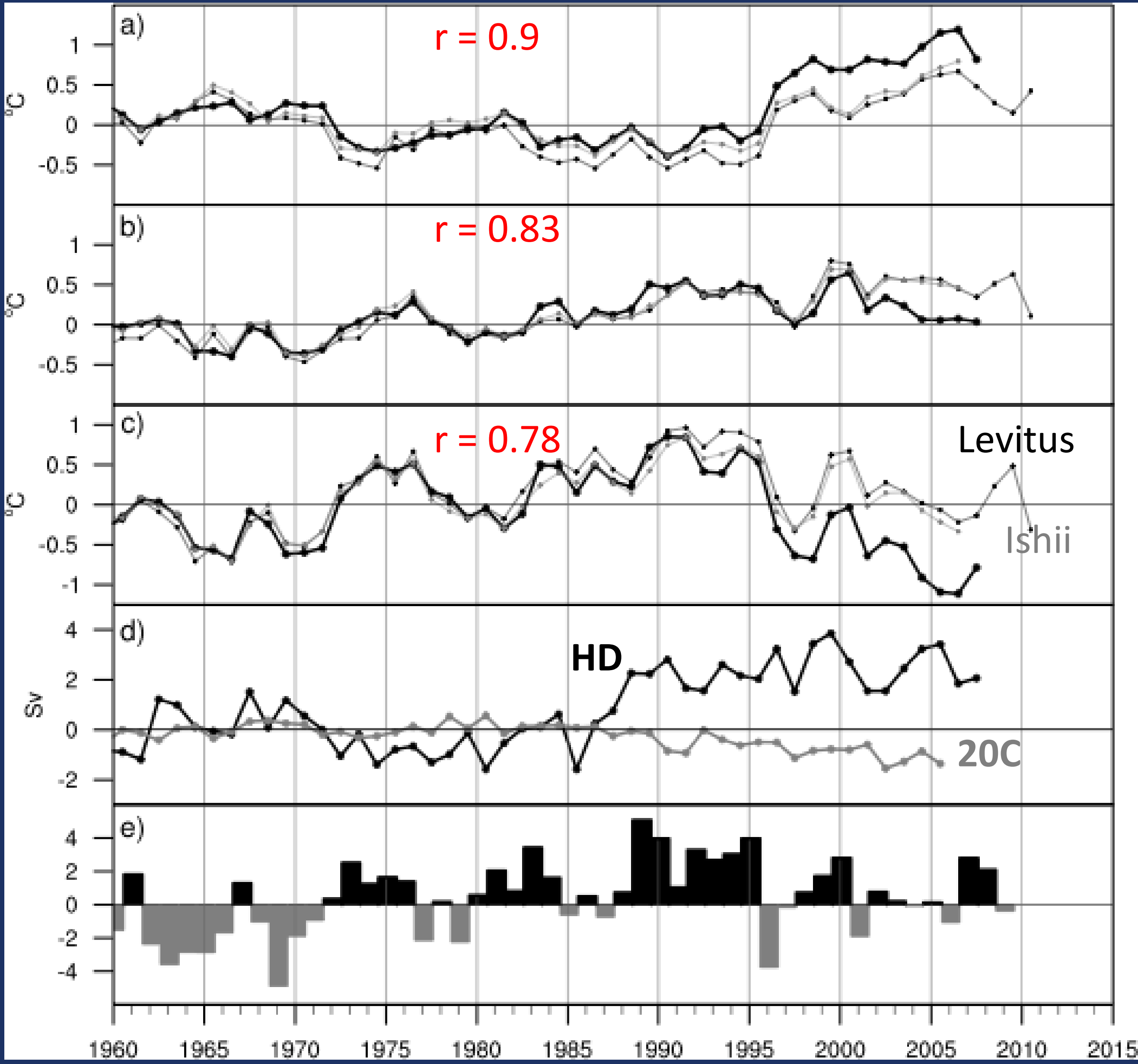
b. 275m STG heat content

c. Meridional heat content gradient (STG – SPG)

d. AMOC at 37.5°N

e. Observed (djfm) NAO index

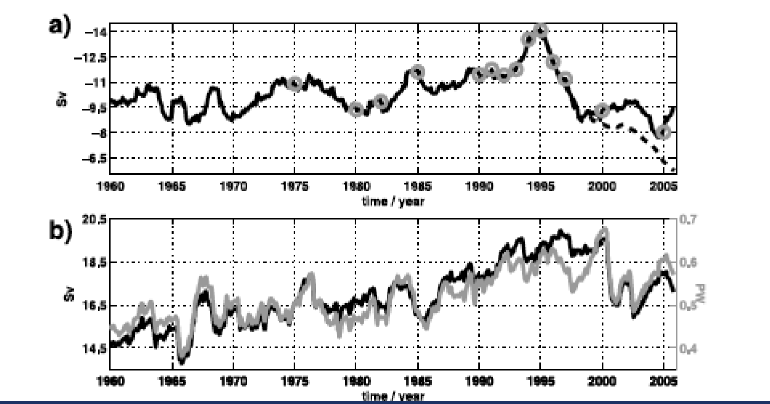
*relative to 1957-1990 clim.



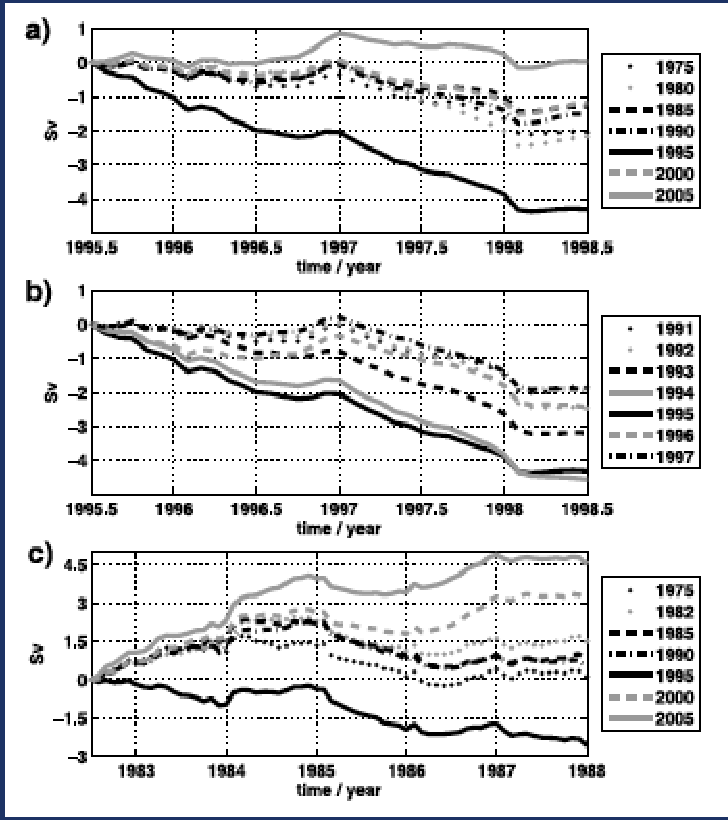
Ocean Preconditioning by persistent NAO$^+$

SPG BSF

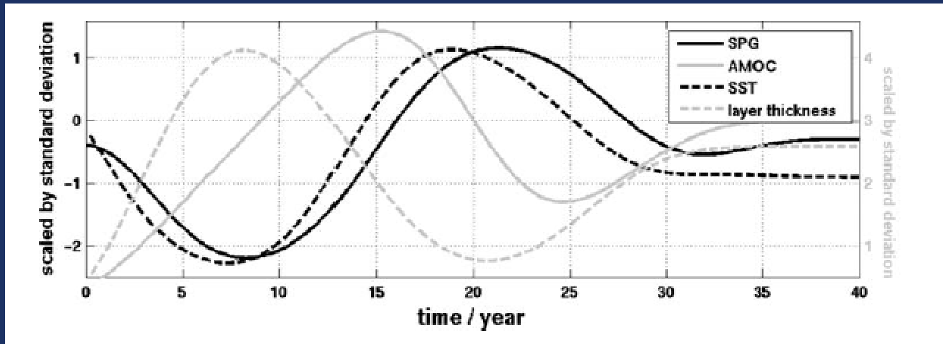
AMOC



SPG BSF dependence on i.c./forcing



NAO$^+$ - NAO^n

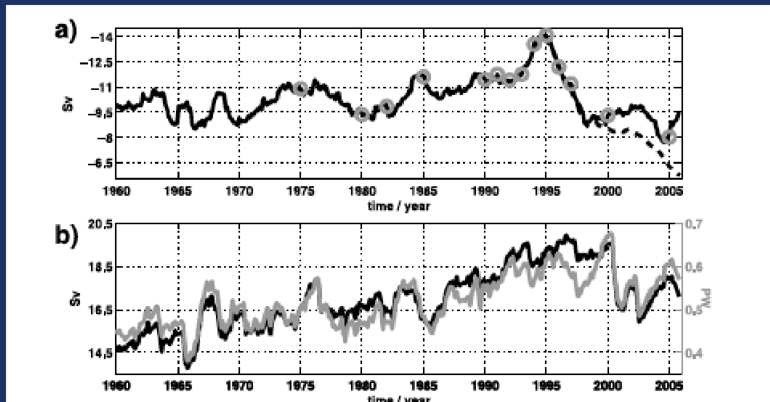


Lozier et al (*Science*, 2008)
Lohmann et al (*Clim Dyn*, 2009)
Lohmann et al (*GRL*, 2009)
Robson et al (*J Clim*, 2011)

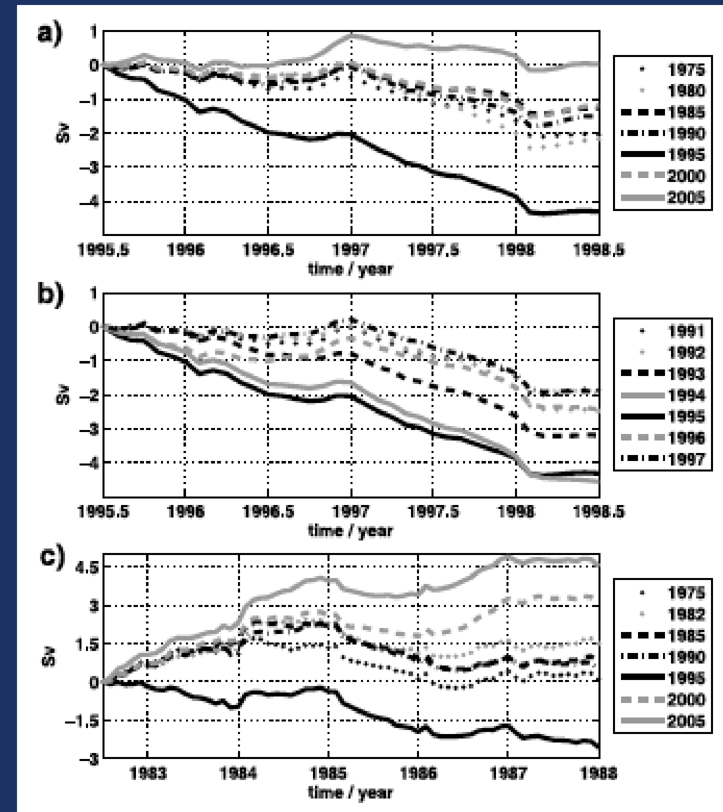
Ocean Preconditioning by persistent NAO$^+$

SPG BSF

AMOC

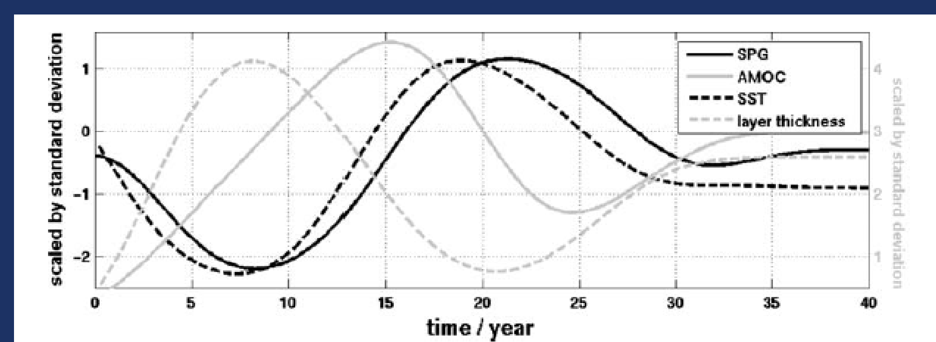


SPG BSF dependence on i.c./forcing



- ocean state in early 90's was primed for high latitude regime shift
- NAO+ ➔ AMOC/MHT spinup ➔ eventually...SPG HC rise + AMOC spindown
- HC dipole is ocean signature of persistent NAO+

NAO$^+$ - NAO^n



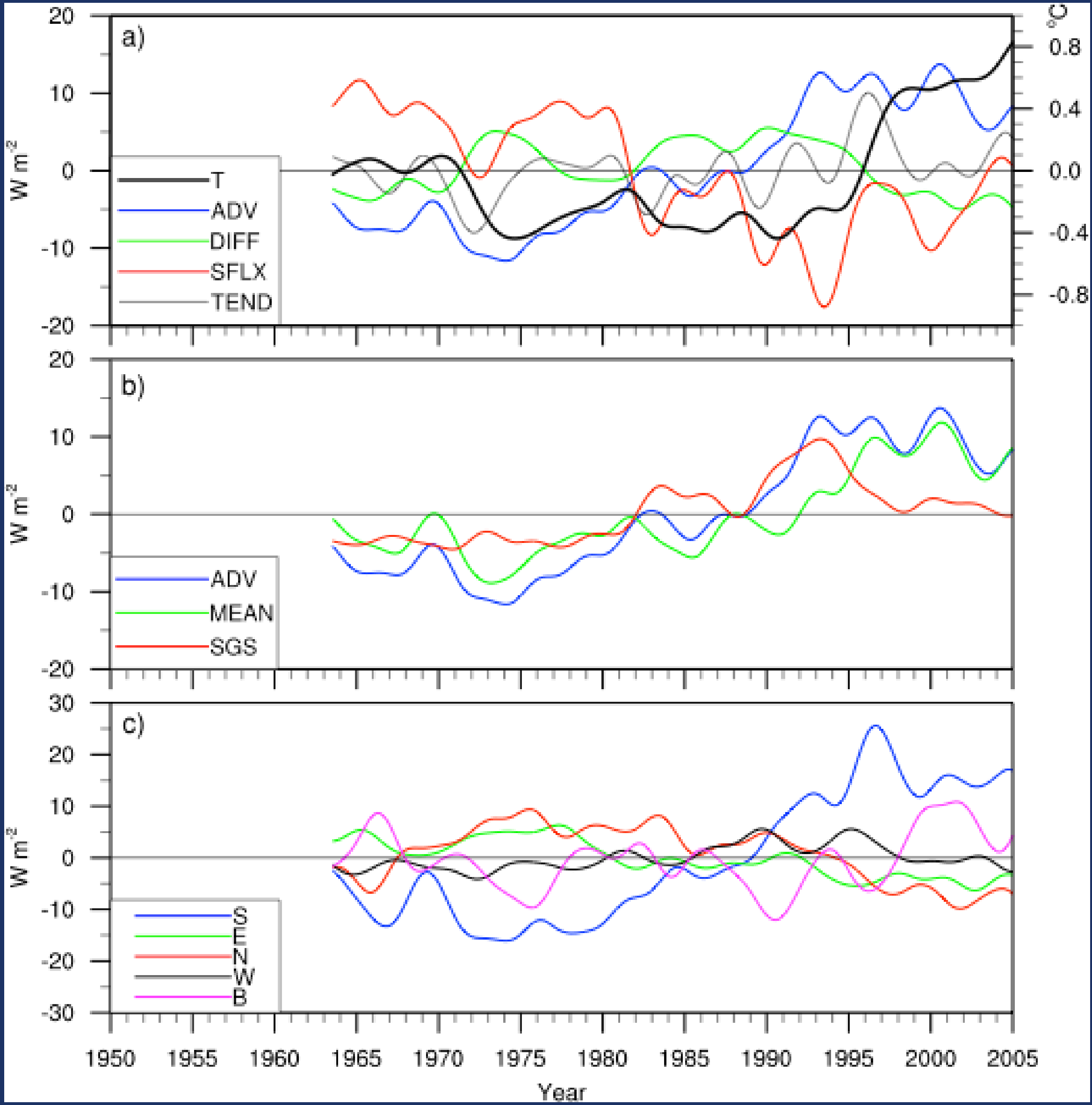
Lozier et al (*Science*, 2008)
Lohmann et al (*Clim Dyn*, 2009)
Lohmann et al (*GRL*, 2009)
Robson et al (*J Clim*, 2011)

Heat Budget of SPG box from HD

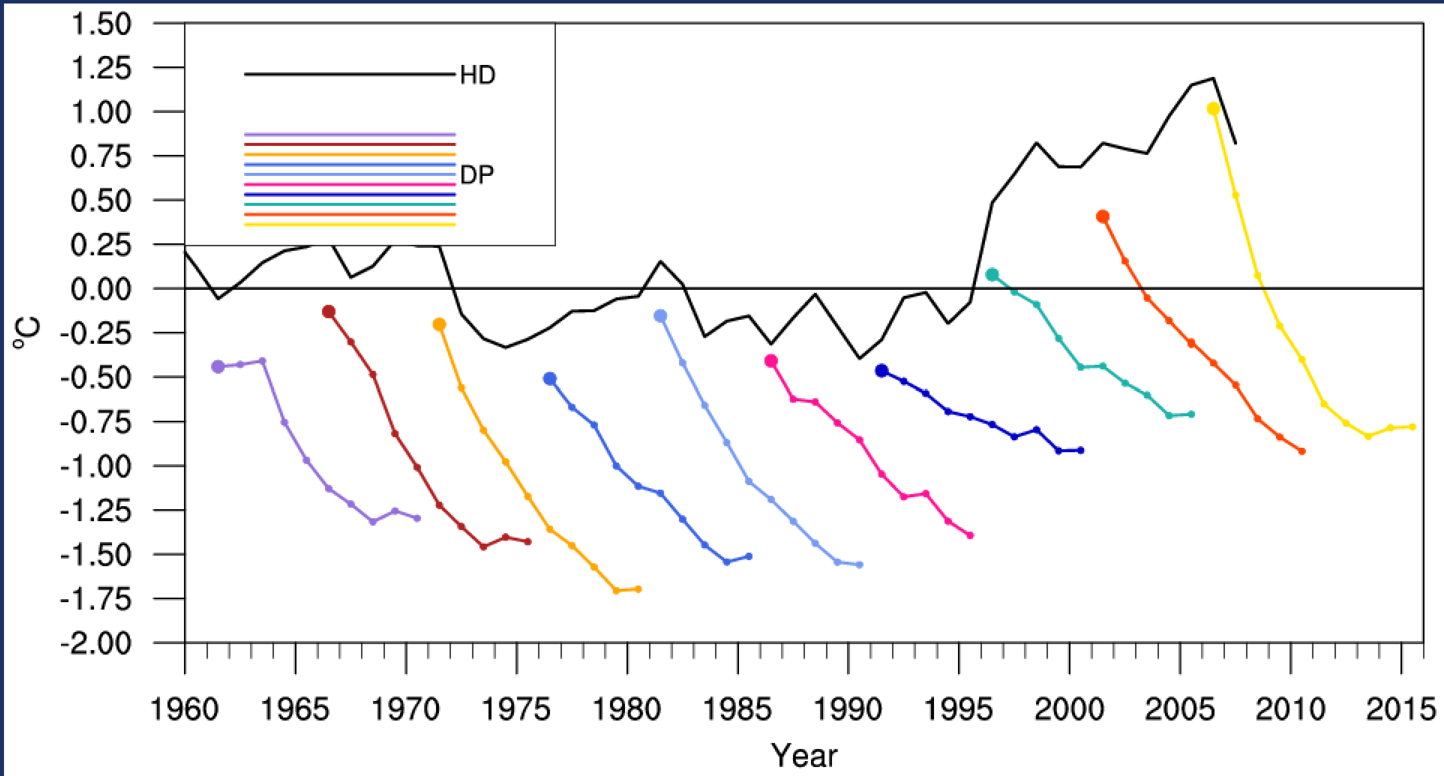
a. Net advective (ADV), diffusive (DIFF), and surface (SFLX) heat fluxes; tendency (TEND) and heat content (T).

b. Net advective (ADV) heat flux and its breakdown into resolved (MEAN) and sub-gridscale (SGS) components.

c. The directional components of the net advective (ADV) heat flux.



275m Heat Content Anomaly in SPG box



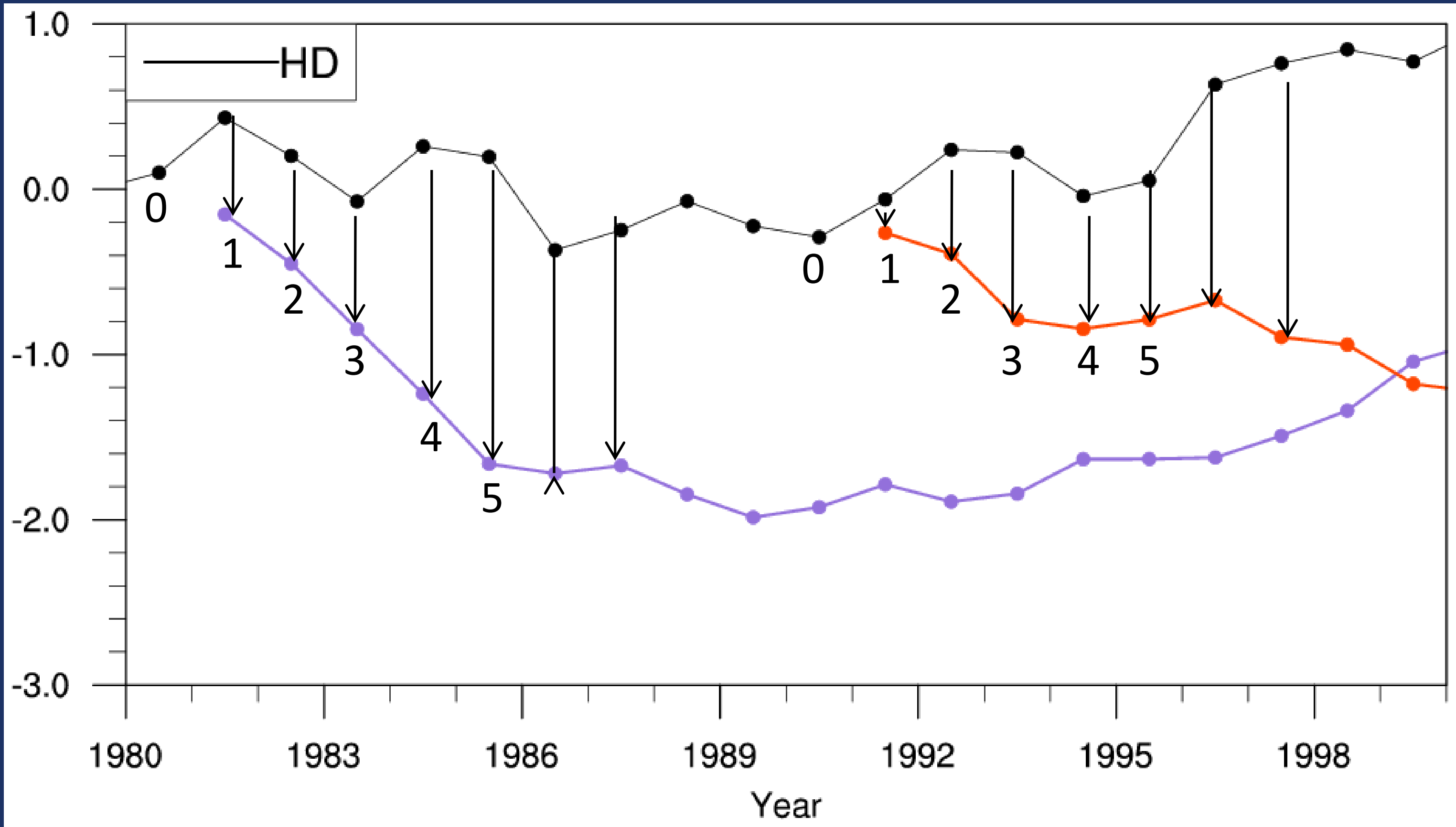
- 10-yr DP ensembles initialized from HD on January 1 1961, 1966, ..., 2006

Bias Correction

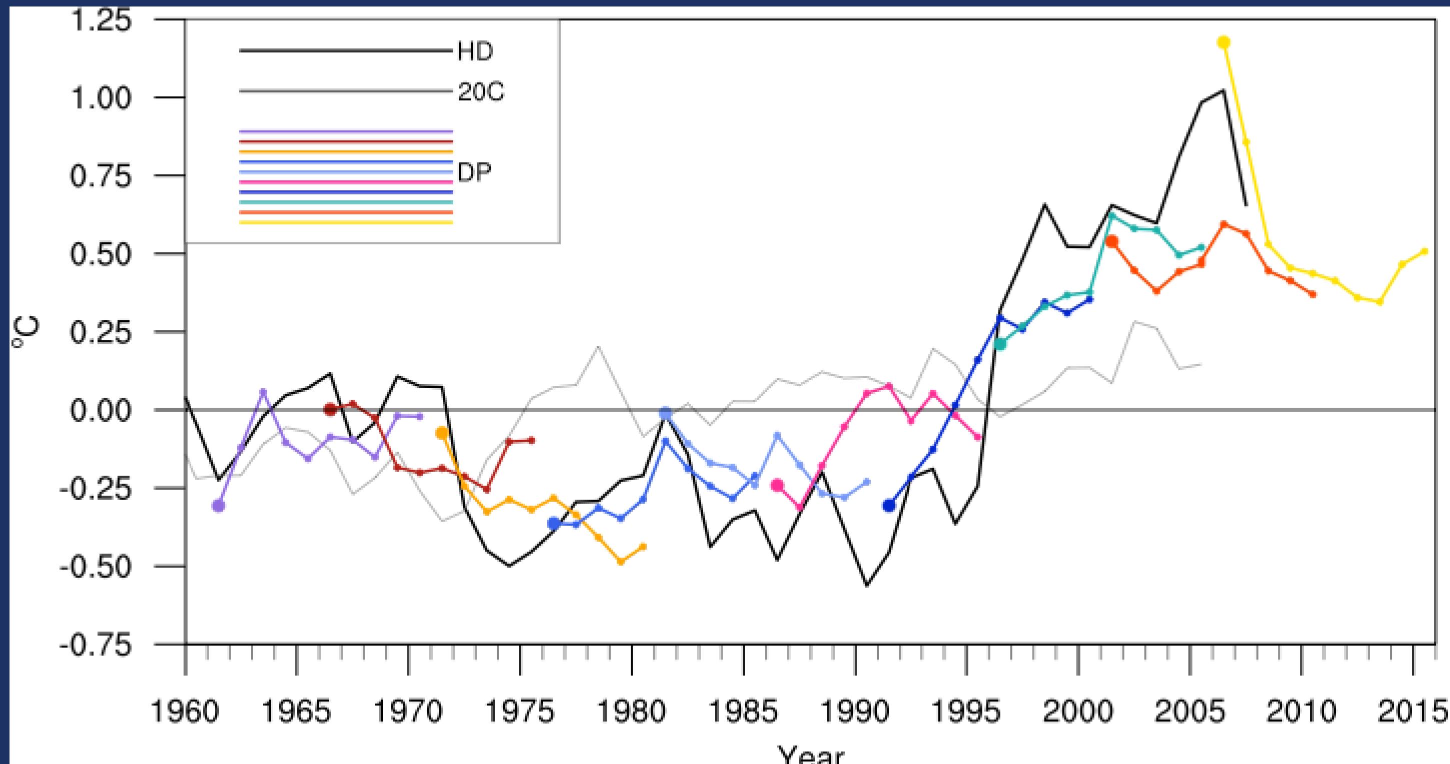
- Adopt methods used in seasonal-interannual forecasting (e.g, Stockdale, *MWR*, 1997)
- Define mean drift (relative to HD) as a function of lead time:

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

where “<>” is average over all start dates, except the one being corrected.



275m Heat Content Anomaly in SPG box



Bias-corrected DP experiments (color)

HD/DP correlation of lag1-5 pentads (N=9): 0.95

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

Correlations are >95% significant based on HD-initialized AR(1) parametric bootstrap

Assessing Statistical Significance

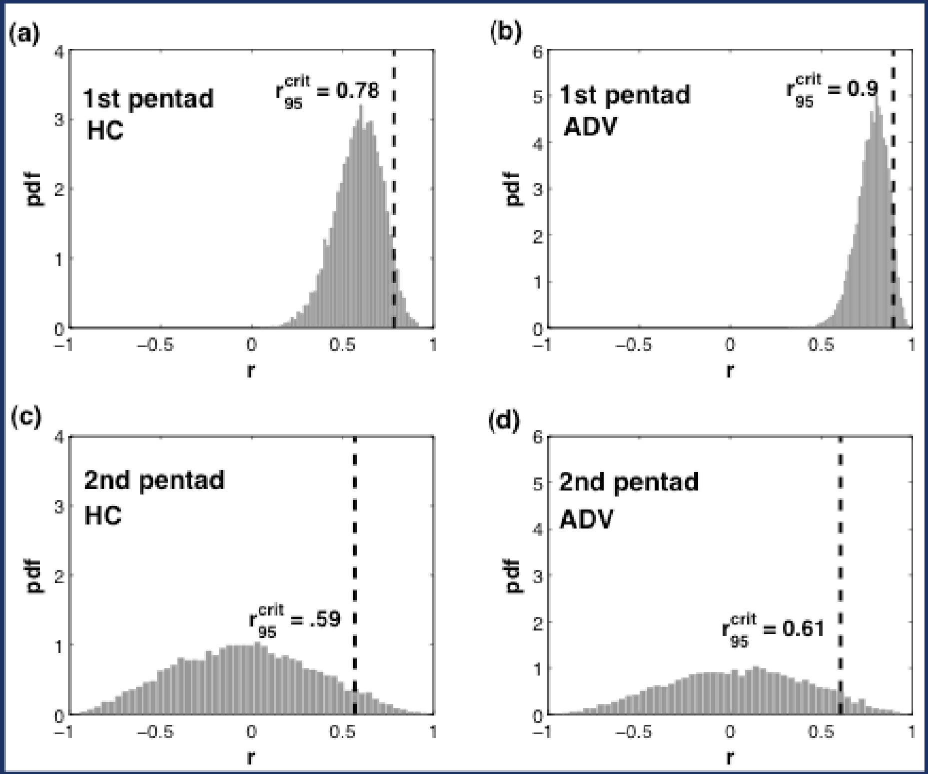
- Choose null hypothesis that pentadal correlation test-statistic can be explained by AR(1) + linear trend:

$$z_t = f_t + \alpha z_{t-1} + \varepsilon, \qquad \varepsilon \sim N(0, \sigma^2).$$

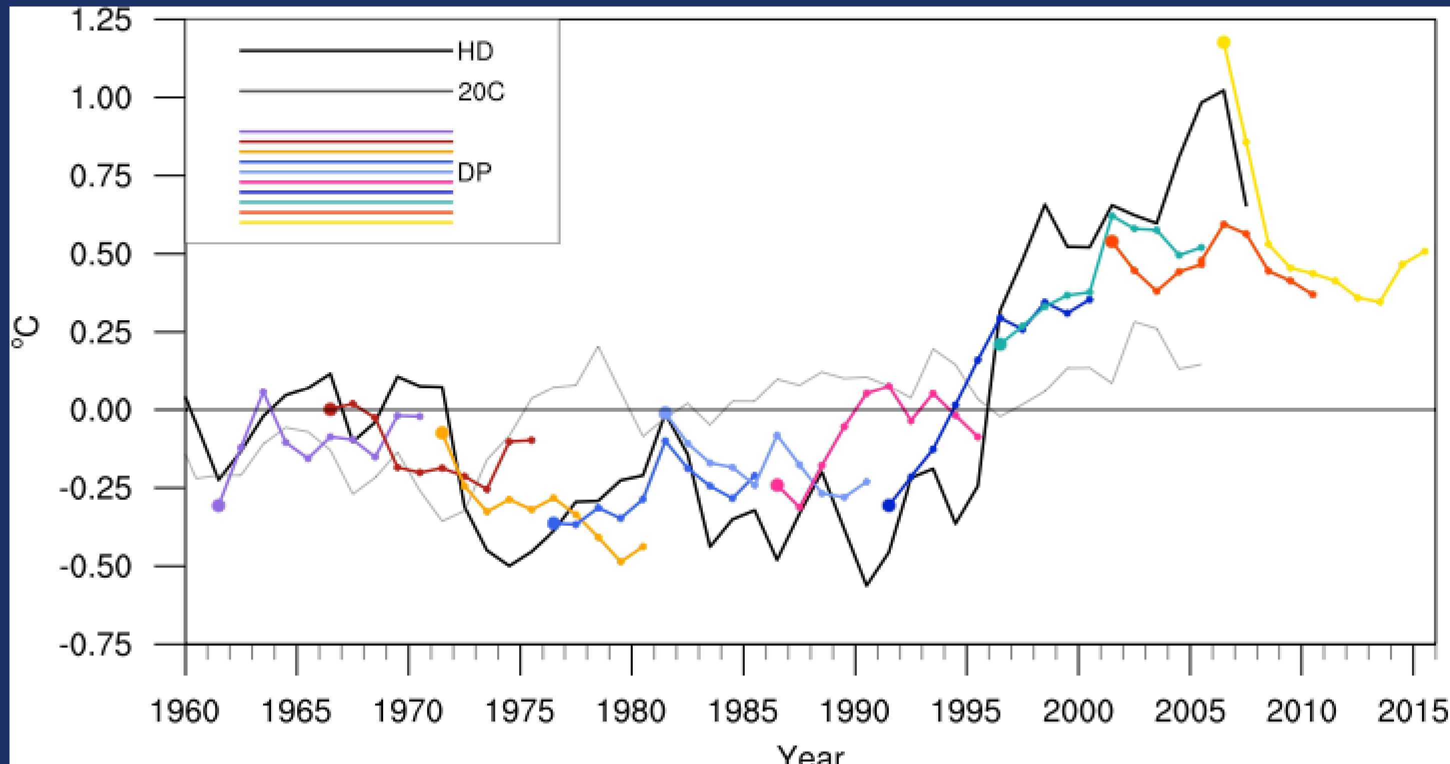
- Estimate parameters of this model (α, σ, f) using one 155-yr 20C integration.

- Build distribution of possible correlation scores that could be realized by 10-member ensembles of this model, after initialization from HD, as in DP experiments.

- Variable-specific PDF's obtained using this approach are shown, along with 95% confidence levels.



275m Heat Content Anomaly in SPG box



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 ➔ but, mechanism is incorrect (SFLX ↑, ADV ↓)

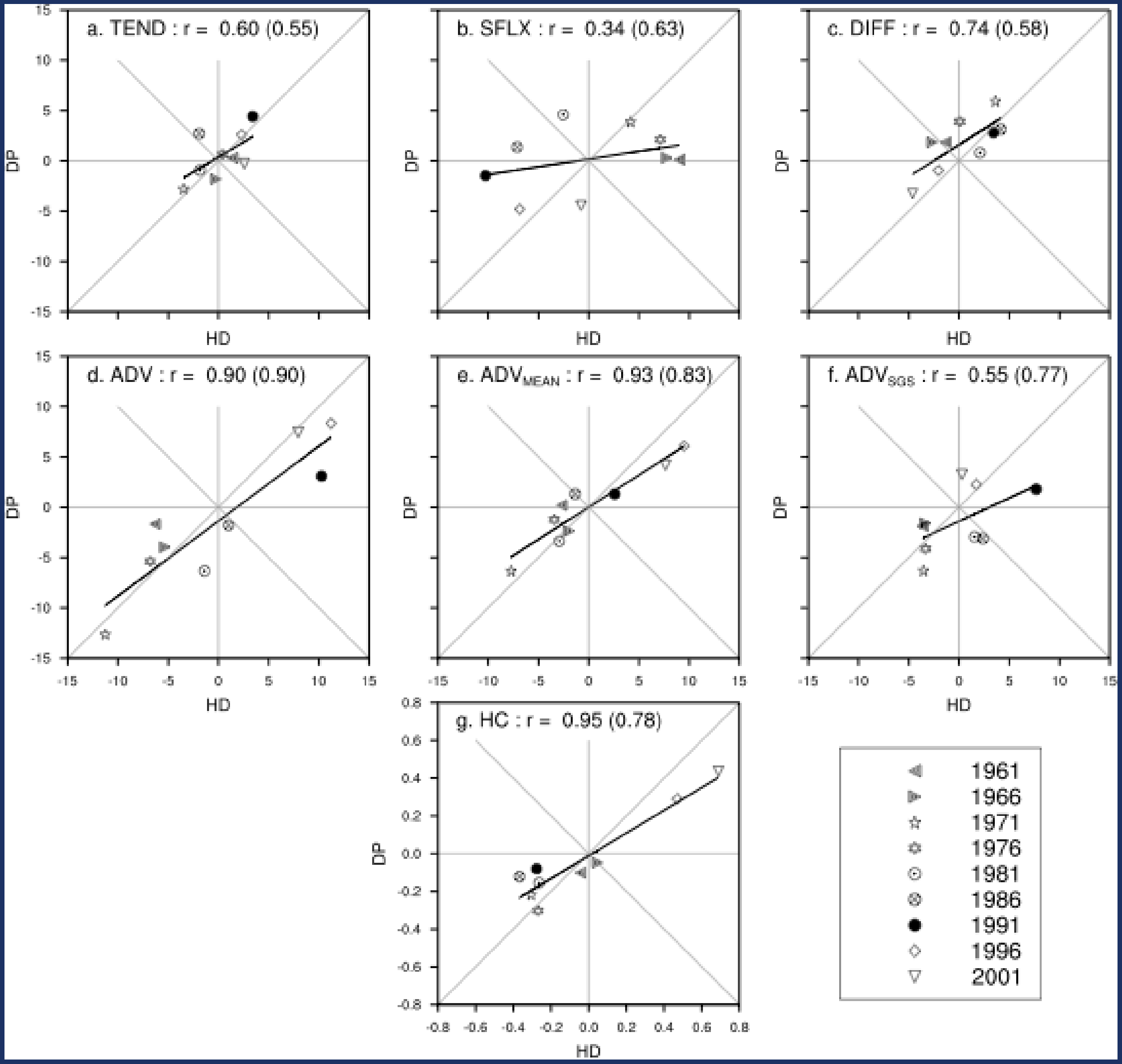
Comparison of budget terms:
first pentad

- high HC skill derives in part from large range in i.c.'s, but DP's significantly outperform damped persistence because of TEND skill.

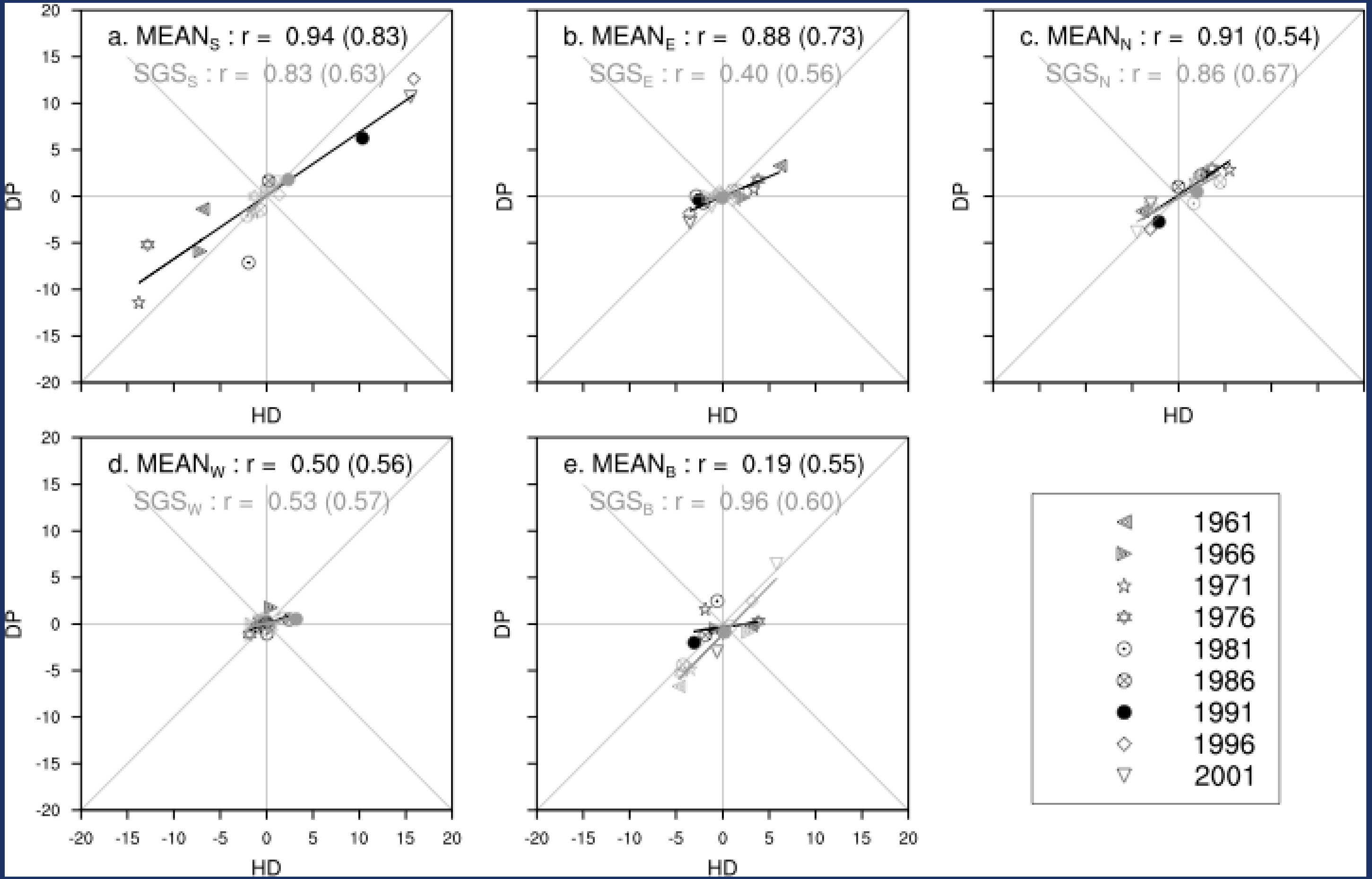
- TEND skill derives from ADV & DIFF terms

- poor prediction of SFLX (NAO), with much lower pentadal range in DP (?)

- better prediction of MEAN than SGS advection



Comparison of budget terms: first pentad



- ADV skill derives primarily from MEAN heat advection from south
➔AMOC initialization

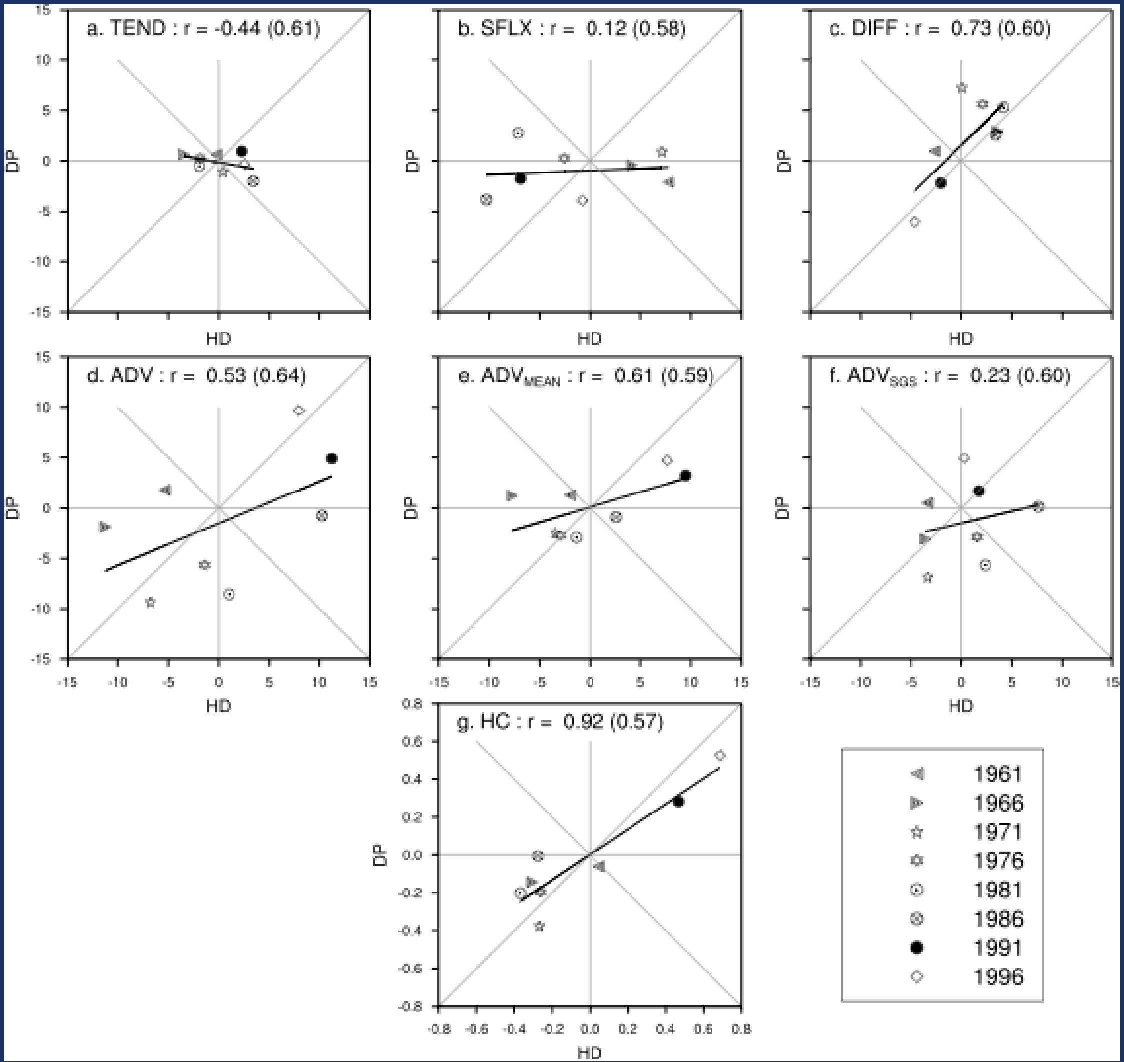
- large SGS fluxes through bottom contribute to ADV skill

Comparison of budget terms: second pentad

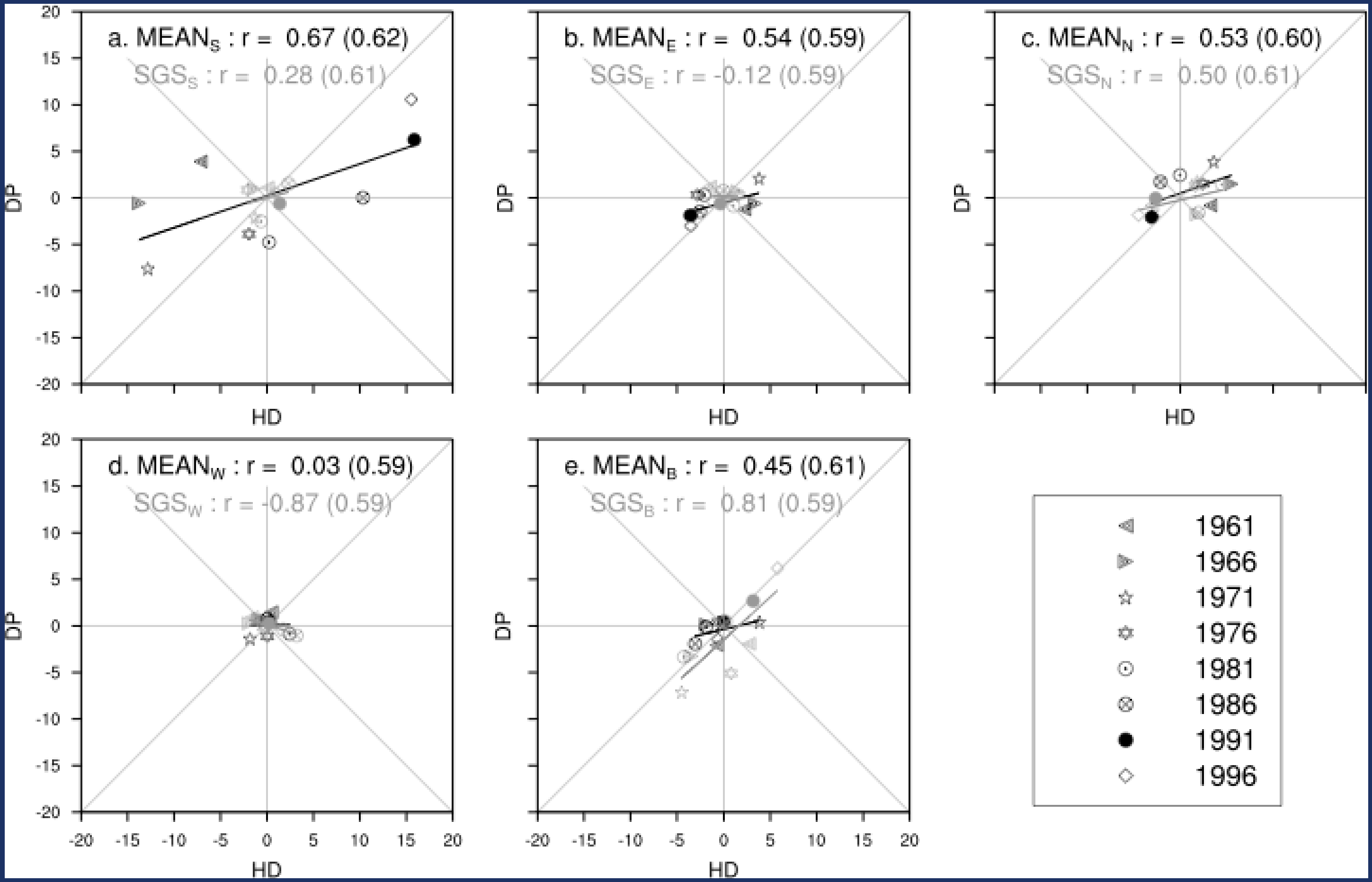
- very significant HC correlation is now less associated with i.c.'s, more with skillful TEND in first pentad

- low TEND skill suggests little benefit of extending DP's

- BUT, DIFF remains highly correlated...



Comparison of budget terms:
second pentad



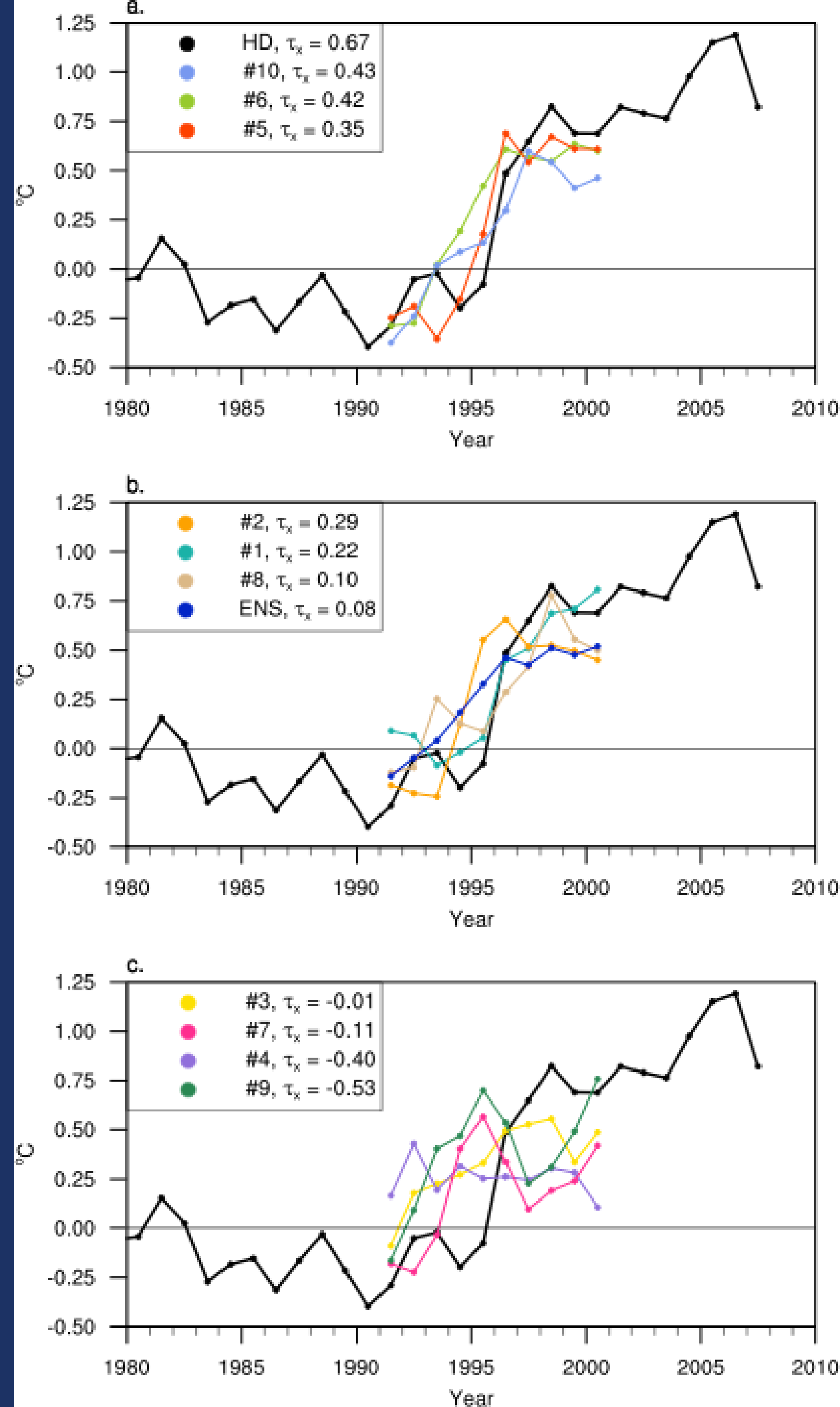
• Skillful SPG heat content prediction beyond a decade might be possible if $MEAN_S$ skill could be maintained longer (better AMOC prediction)

1991 DP ensemble

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

b. Most ensemble members get regime shift too early.

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

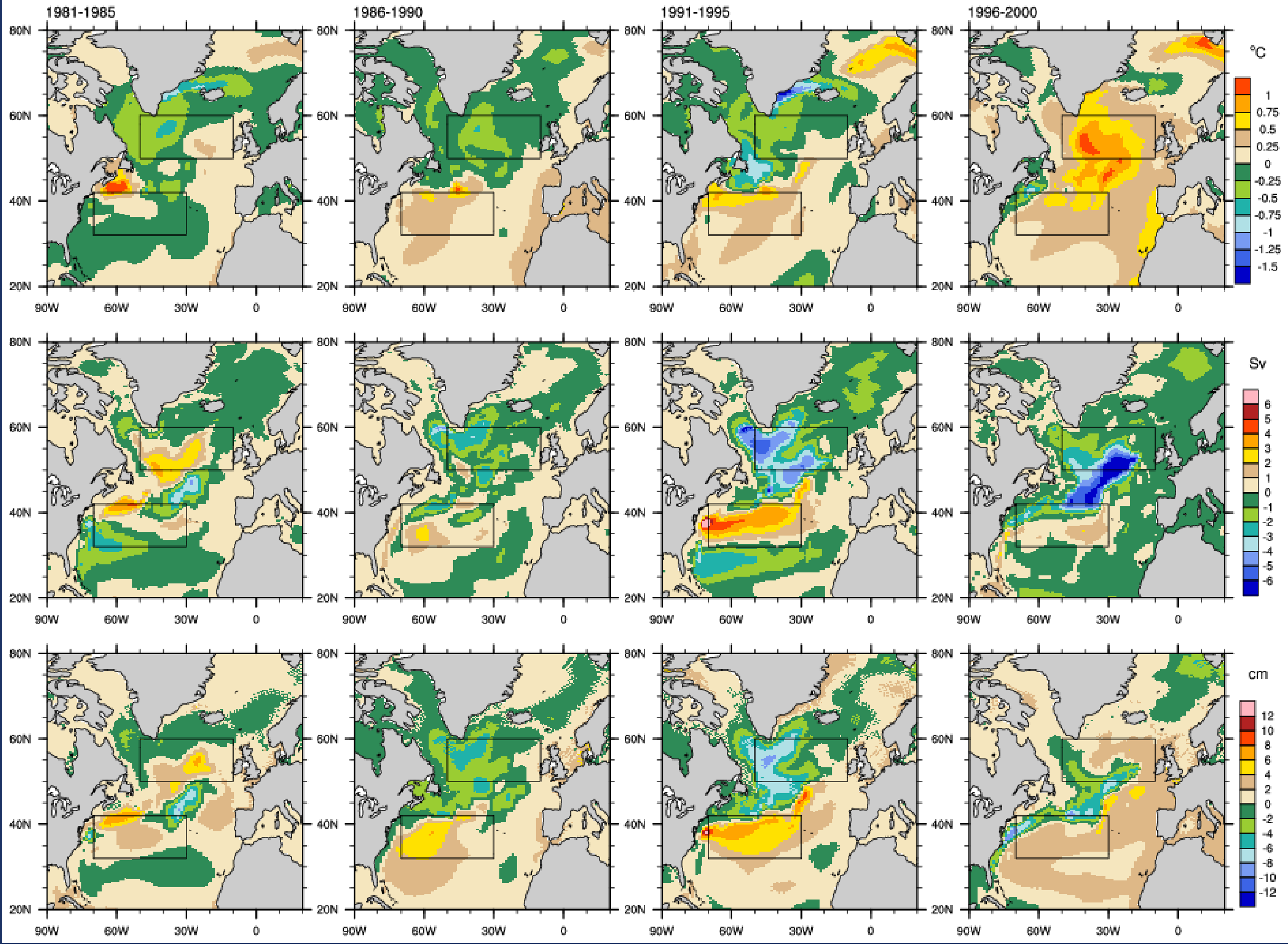


Conclusions

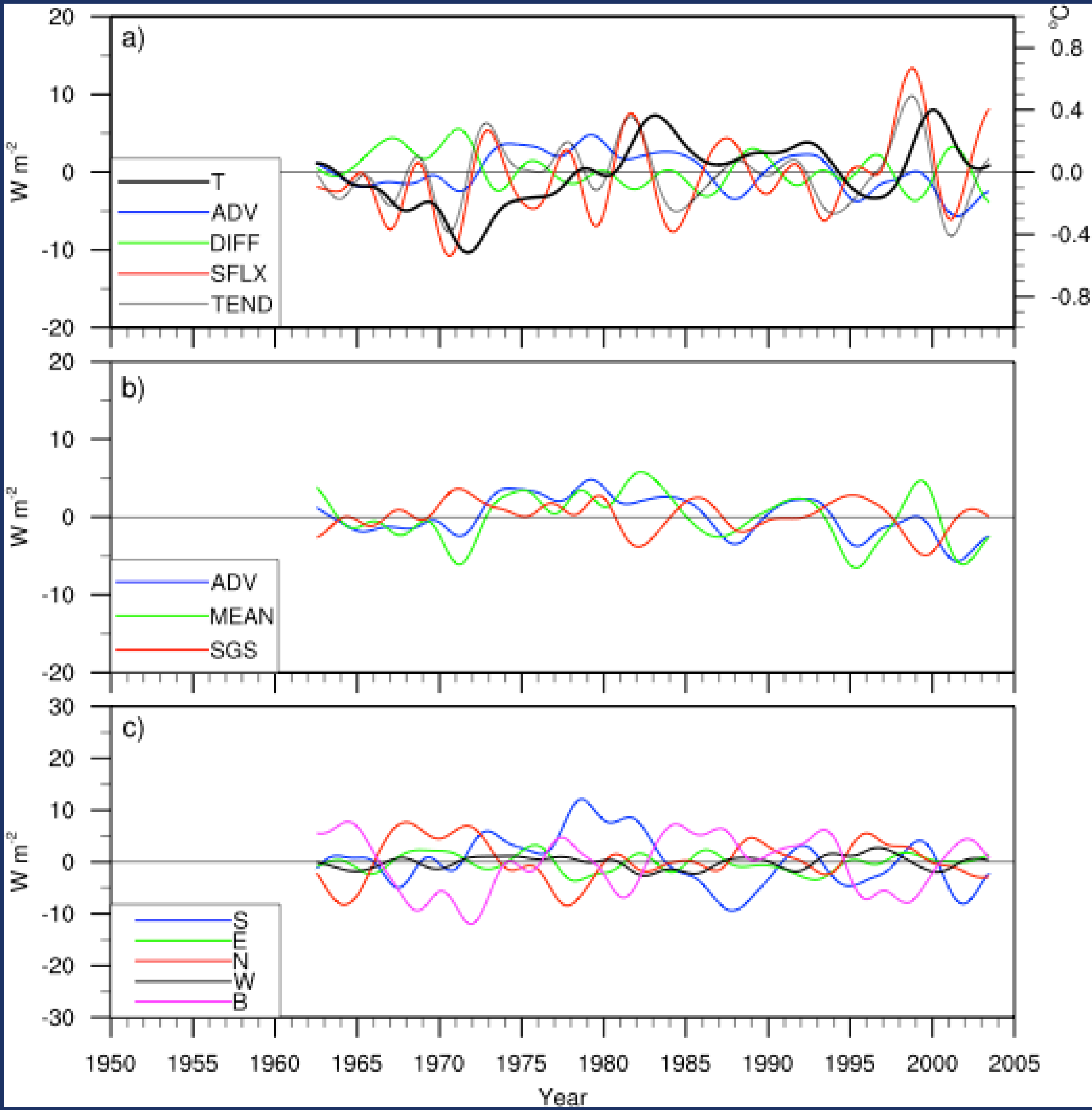
- The CCSM4 CMIP5 DP runs show significant skill at predicting North Atlantic SPG heat content & SST changes up to a decade in advance. External forcing does not appear to be contributing to skill in this region in a manner consistent with actual mechanisms.
- Most of the skill derives from MEAN heat advection from the south, which we attribute to correct AMOC initialization. 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 (NAO). There are hints that SPG air-sea flux may be too weak in CCSM4.
- 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.

N Atlantic Pentadal Anomalies

	1981-85	1986-90	1991-95	1996-00
HD SST				
HD BSF				
HD SSH				



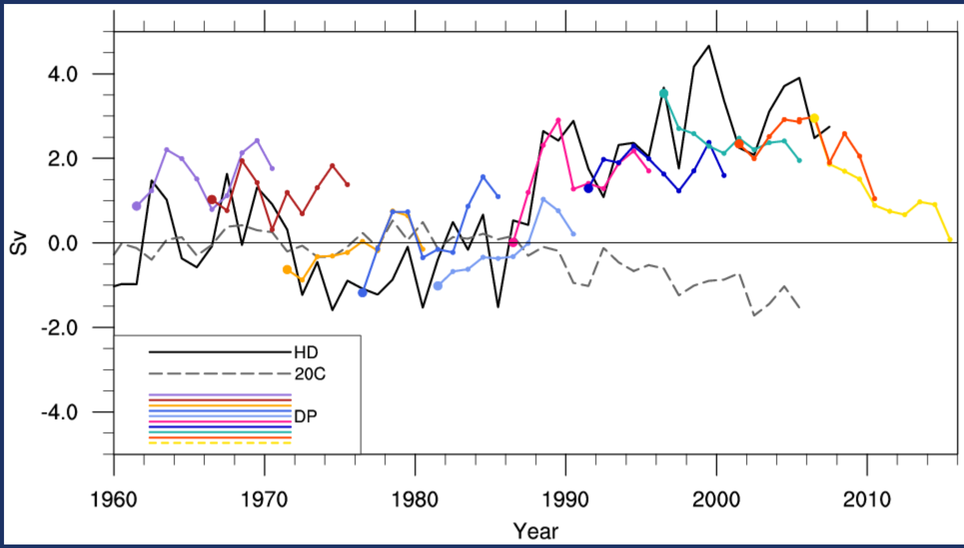
Heat Budget of SPG box from one 20C



AMOC Predictions

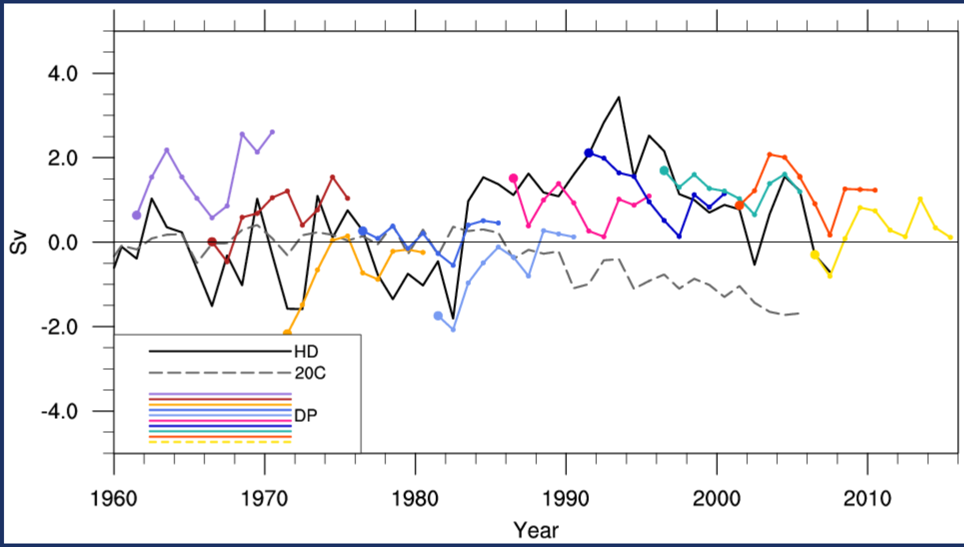
37°N

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



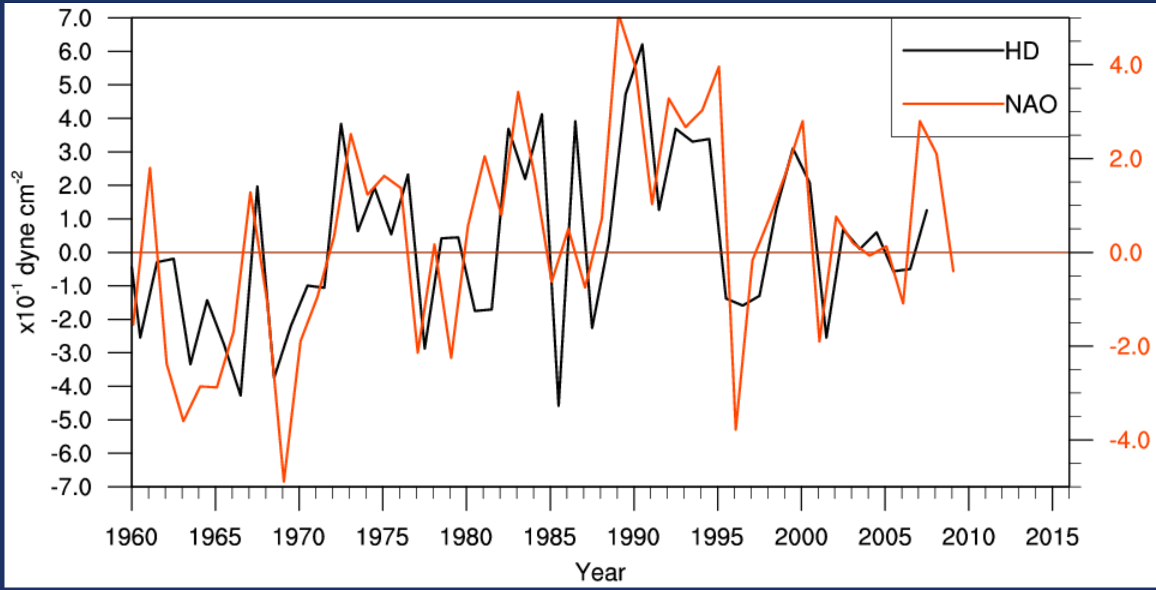
45°N

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



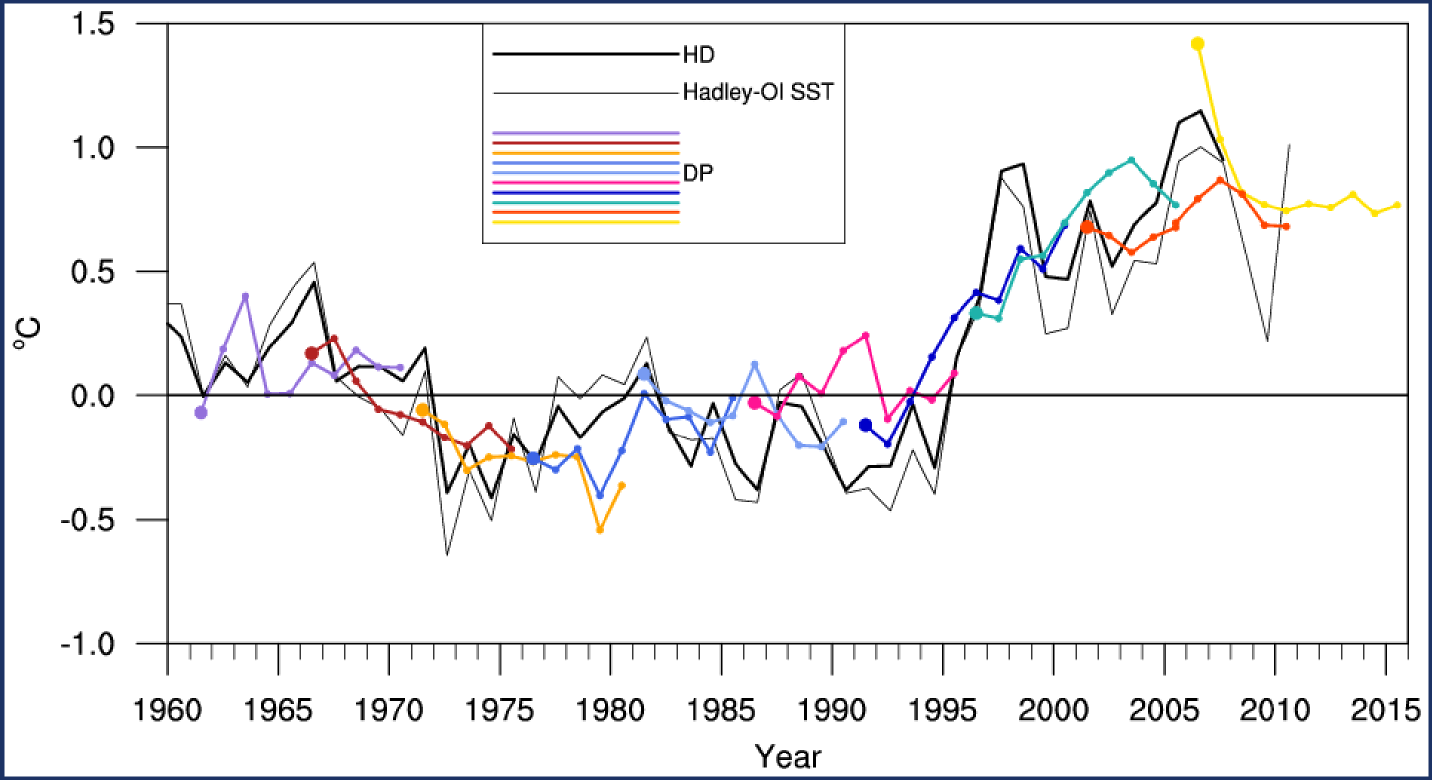
Zonal Wind Stress Anomaly in SPG box

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



➔ DP ensembles show low skill at predicting NAO variations

SST Anomaly in SPG box



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

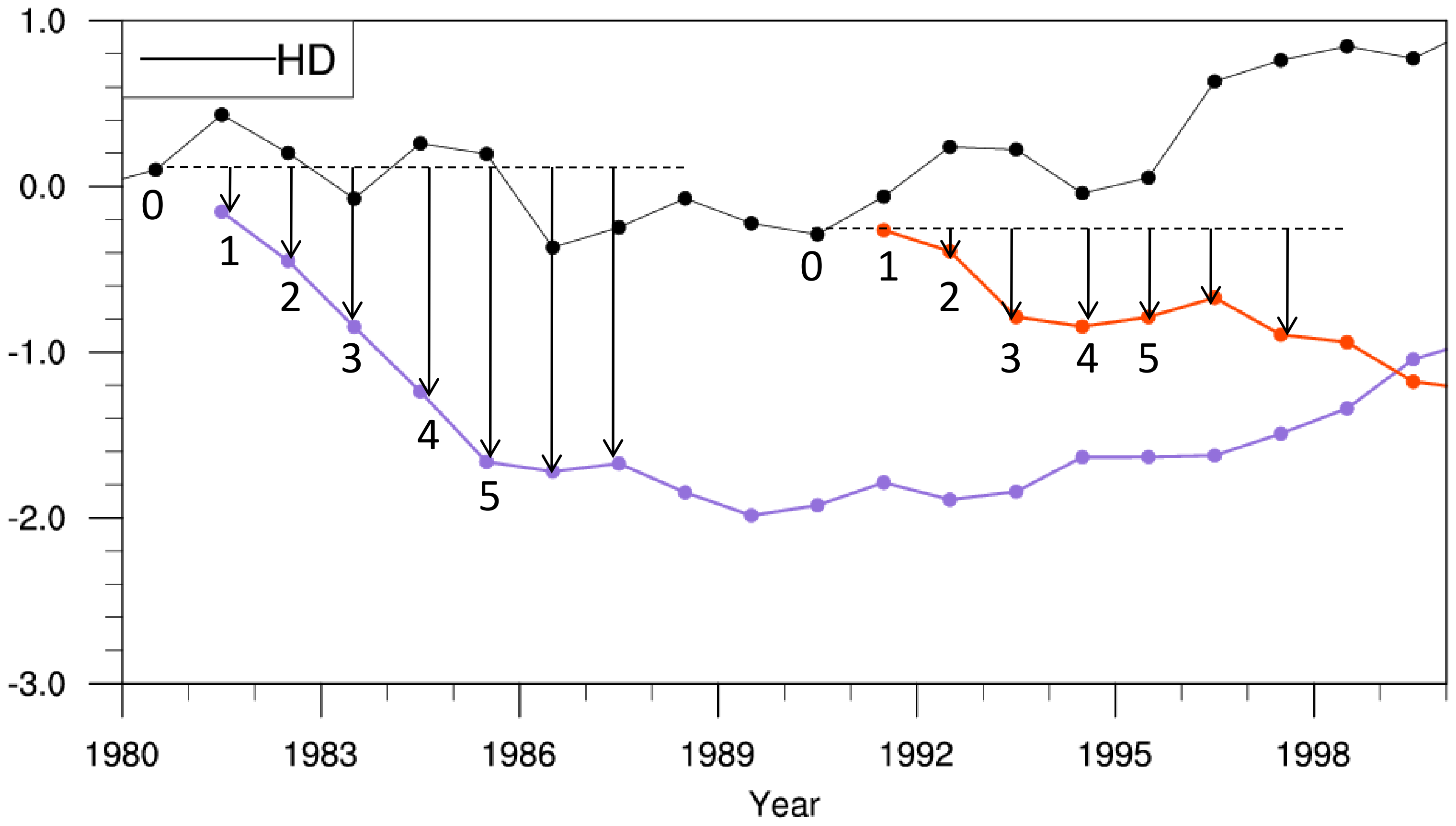
HD/DP correlation of lag6-10 pentads (N=8): 0.94

Bias Correction: Method 2

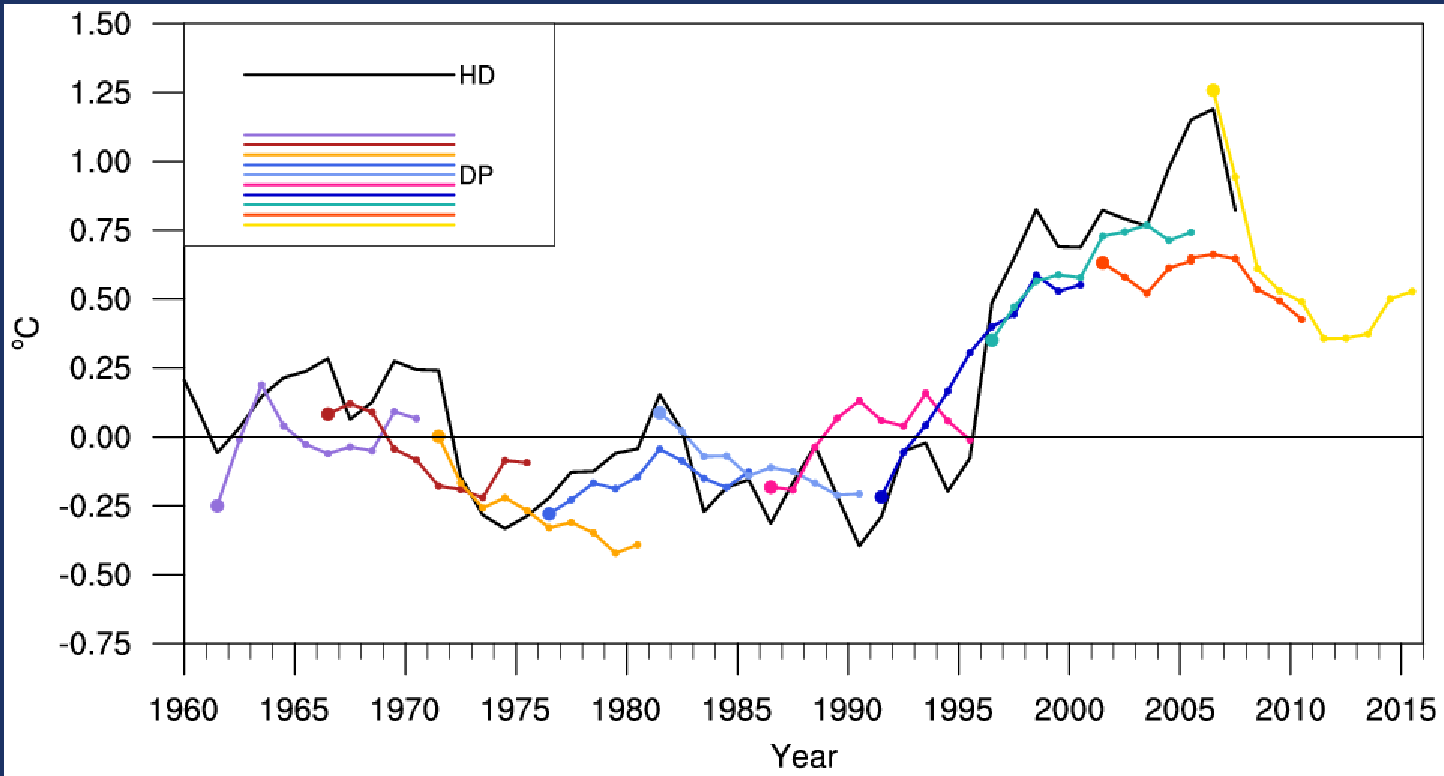
- For each field and spatial location (x,y,z), define the (10-member) ensemble-mean DP evolution away from the HD ocean state:

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

- 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)

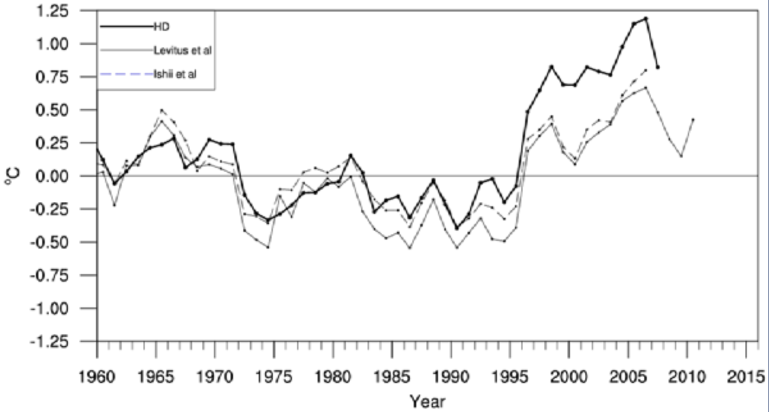
HD/DP correlation of lag1-5 pentads (N=9): 0.94

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

275m Heat Content Anomaly

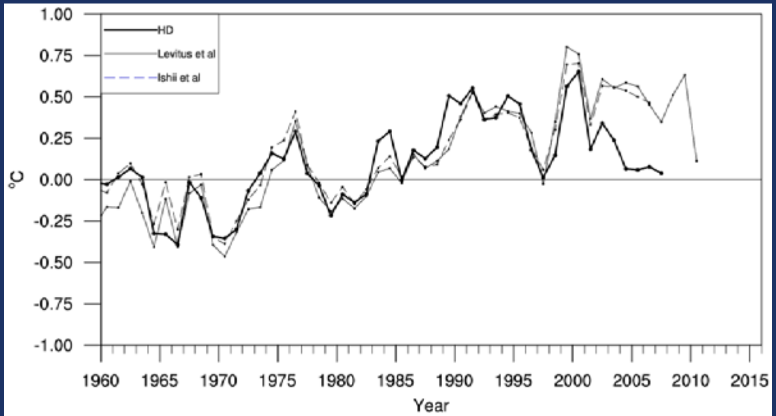
SPG

1960-2007 correlation with Levitus is 0.9



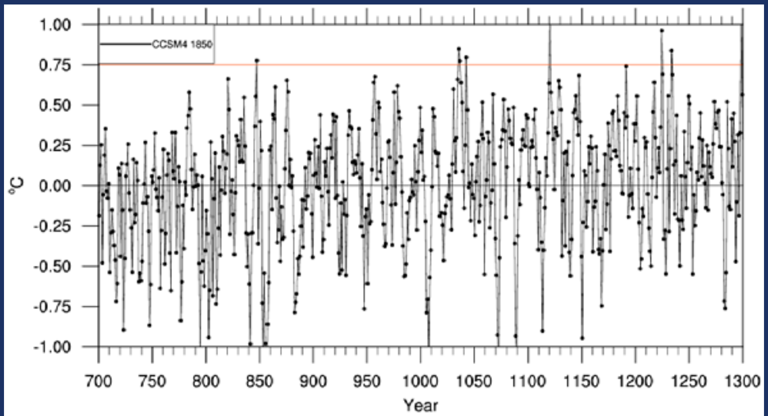
STG

1960-2007 correlation with Levitus is 0.83



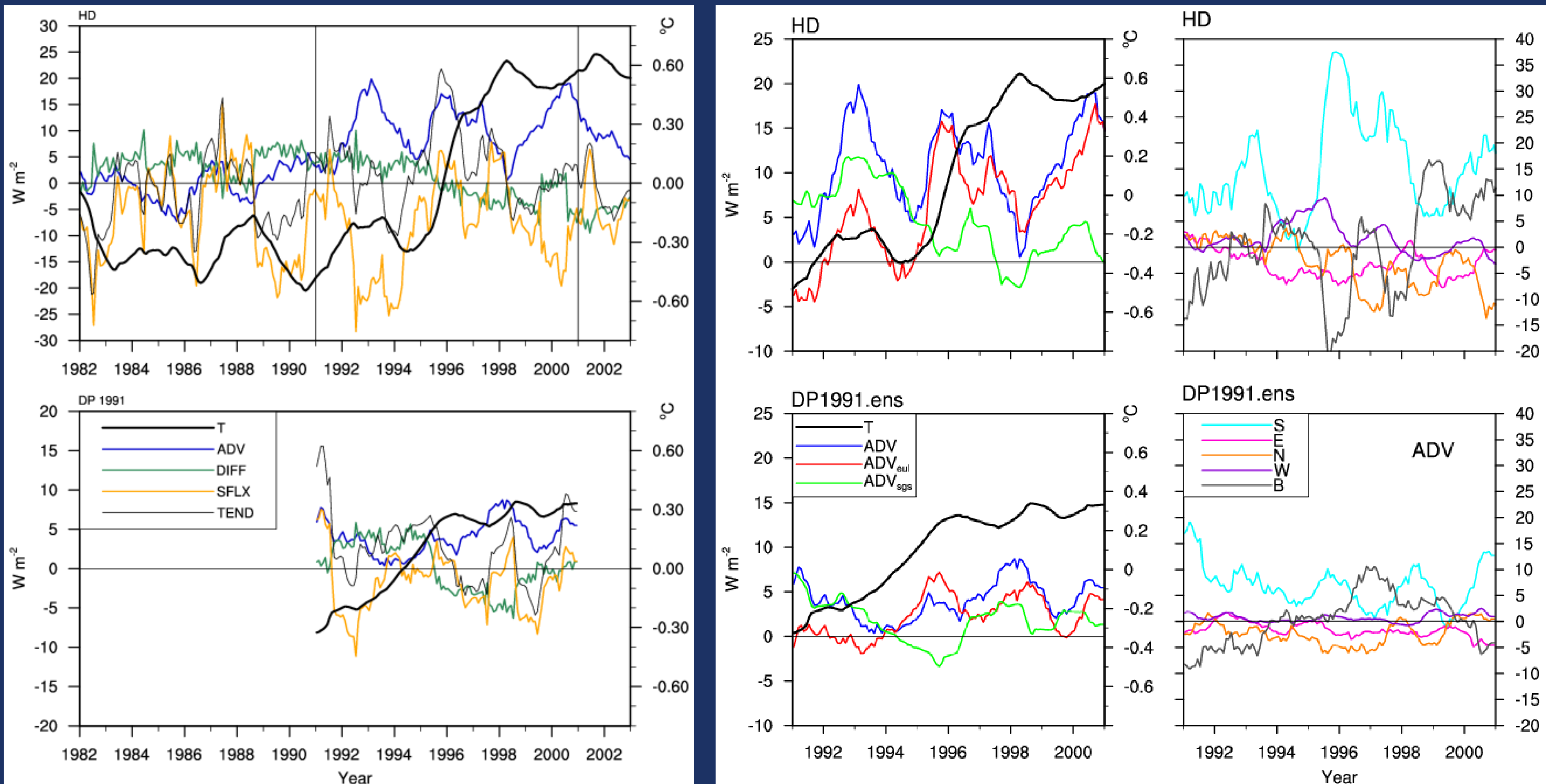
STG-SPG

CCSM4 1850 control



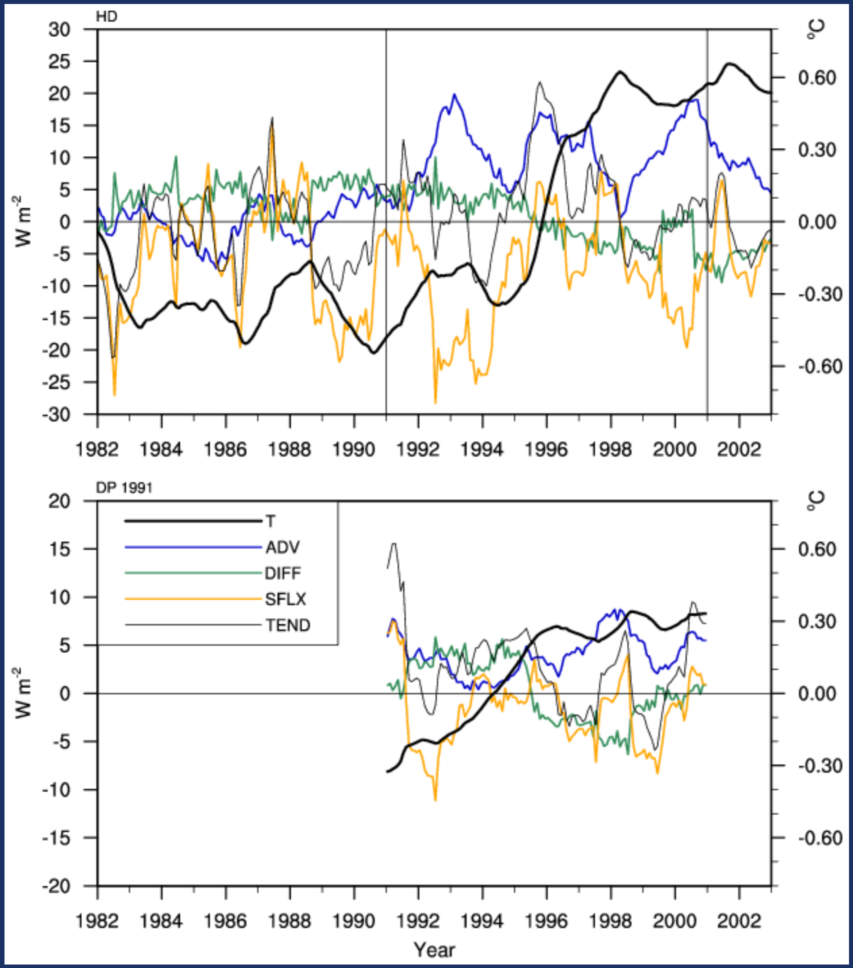
*1957-90 climatology

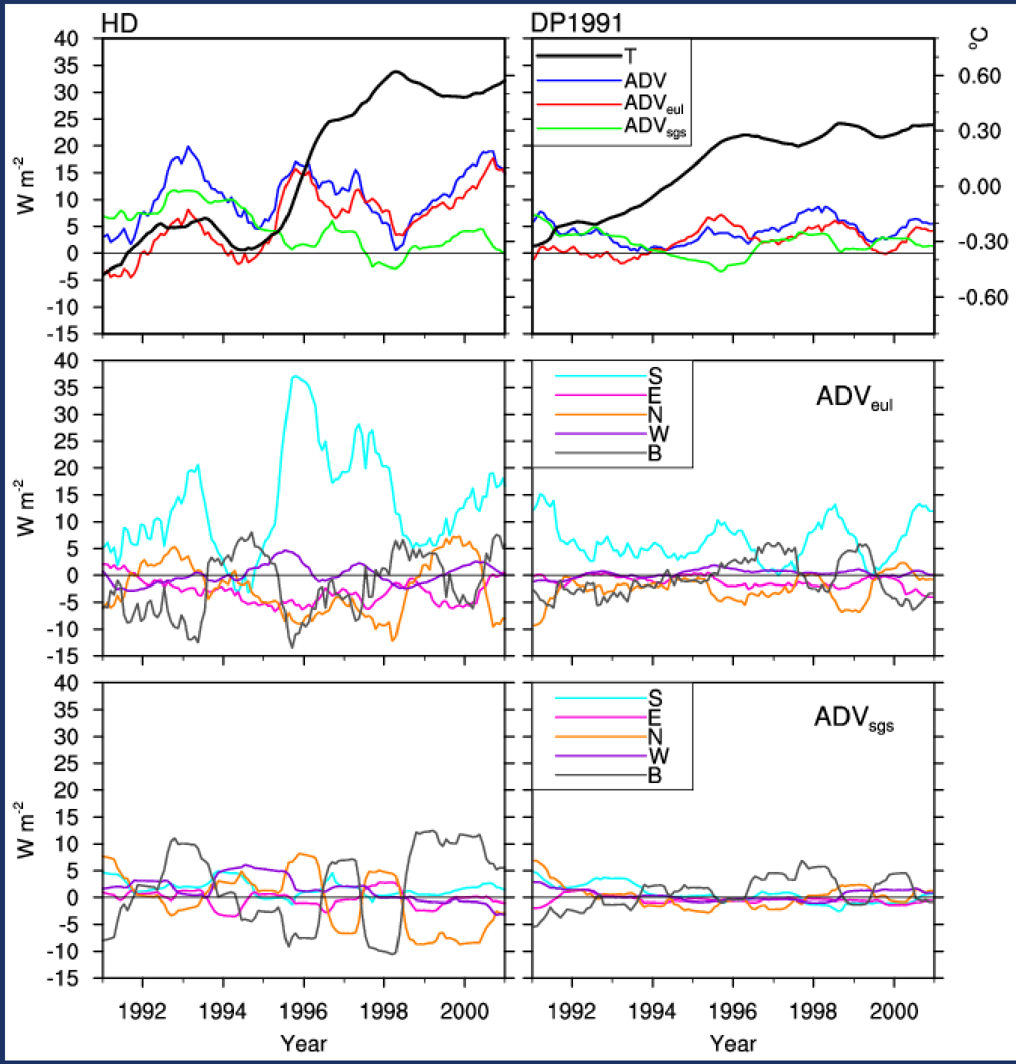
Heat Budget of SPG box



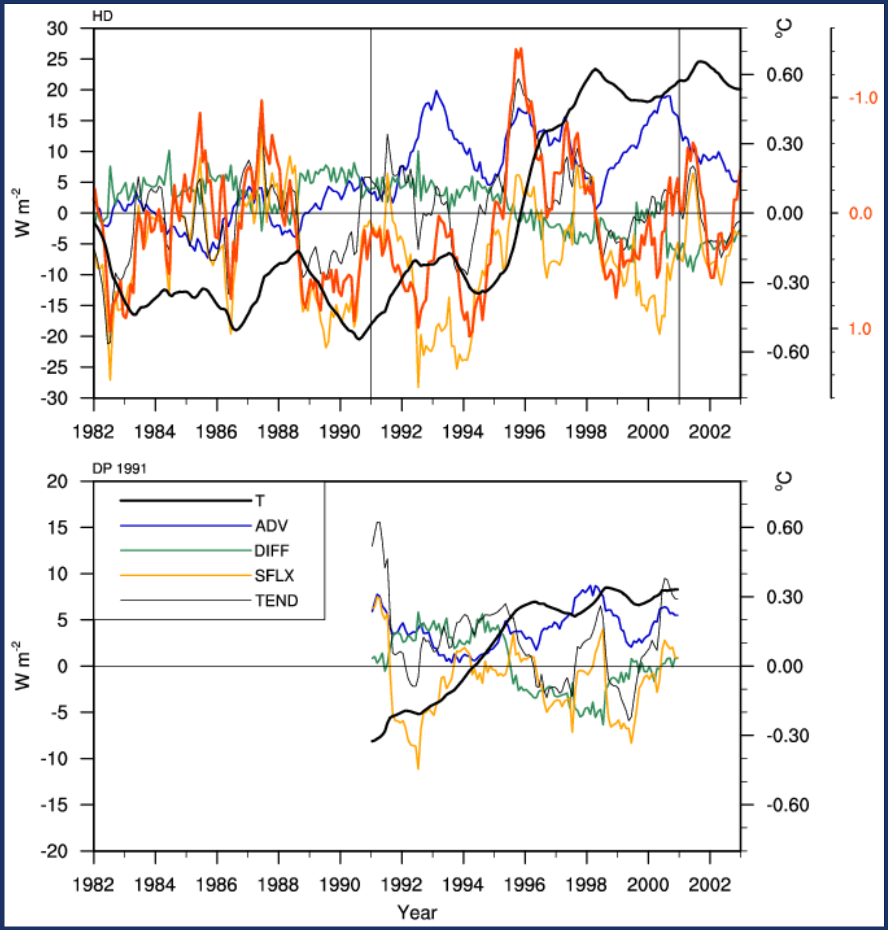
Monthly budget terms from HD (top panels) and DP1991 ensemble mean (bottom panels).

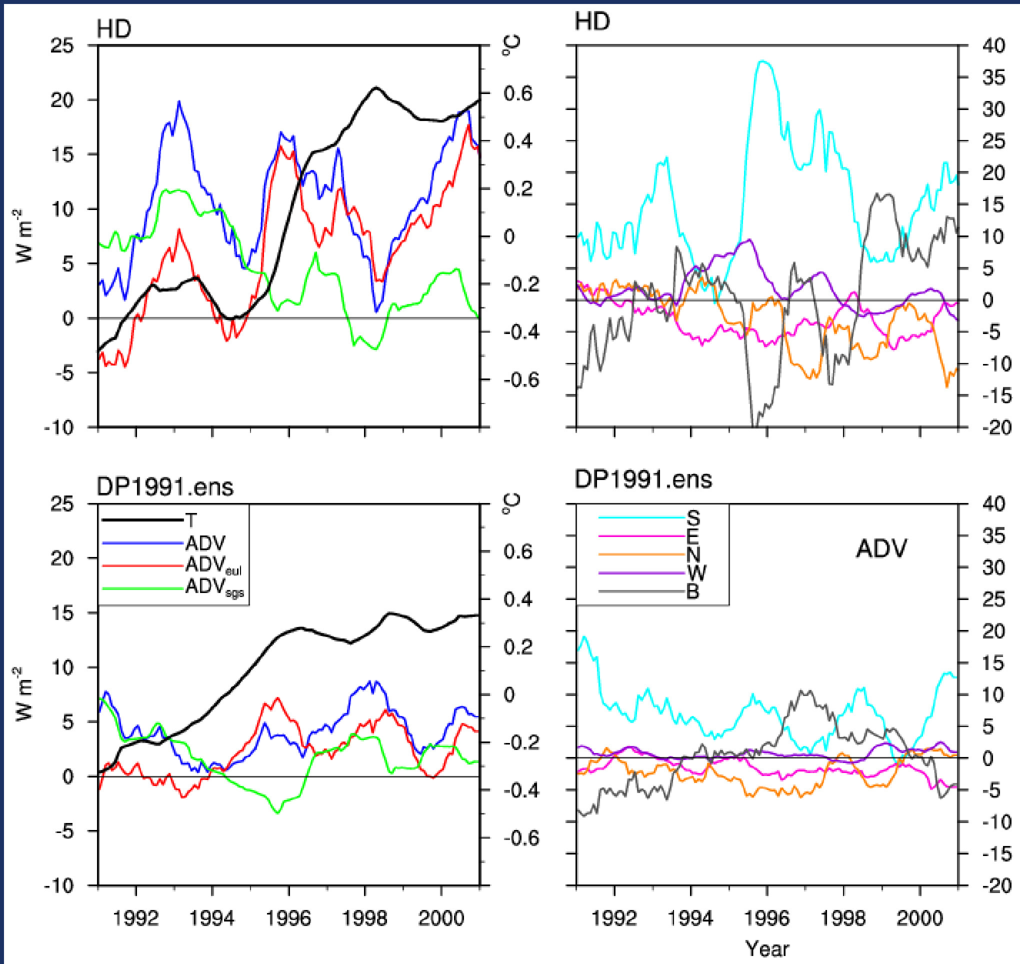
Heat Budget of SPG box





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