# Modulation of air-sea fluxes by extra-tropical variability and its contribution to the warming hiatus

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# Global near-sfc. temperature variability (from NOAA)

**Trenberth et al 2014, Nature Climate Change**

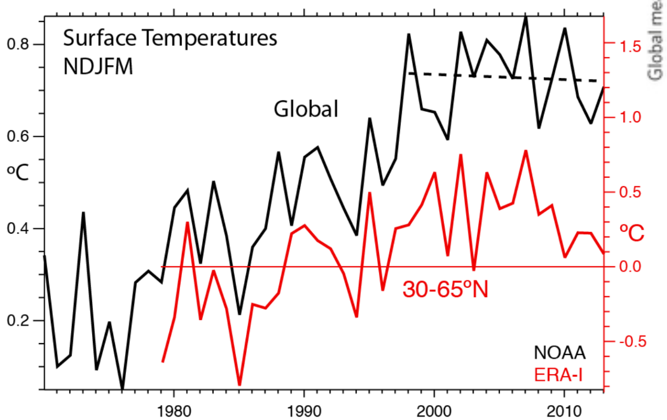
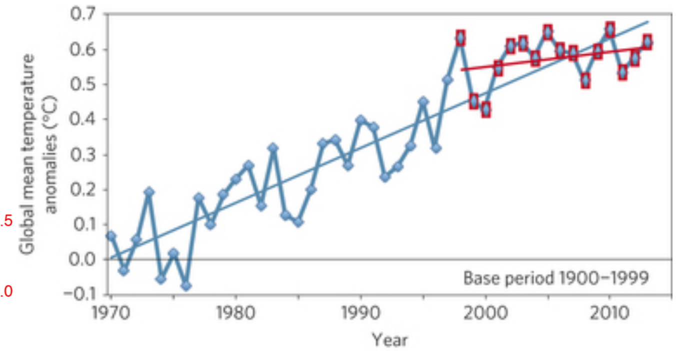



Fig. S1. For NDJFM, the global mean temperature for 1970 to 2013 and the linear trend for 1998-2013 (using NOAA data relative to the base period 1900-1999). Also shown in red are the temperature anomalies for 30-65°N relative to the mean for 1979-2013 from ERA-I data. In northern winter, when ENSO is strongest, the slight cooling trend in the 2000s exacerbates the hiatus and the coldest values are in La Niña years, however the coldest years for 30-65°N are years of negative NAO (see Figure S5).




Linear trends from HadCRUT:
1984-1998: 0.26 °C/decade
1998-2012: 0.04 °C/decade

# Pacific Decadal Oscillation (PDO)

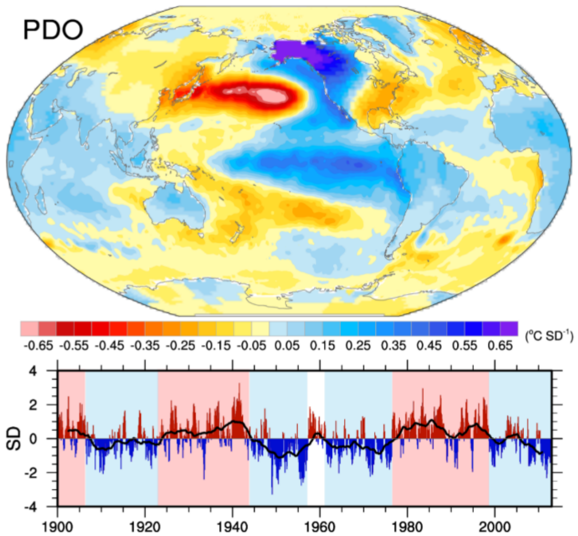



**Figure 2 | The PDO based on an EOF analysis of SST anomalies with the global mean removed from 1900 to 2012 in the 20°–70° N 110° E–100° W region of the North Pacific, which explains 25% of the variance.** The principal component time series, given below in normalized units, is regressed on global sea and land surface temperature anomalies to give the map above. The black curve is a 61-month running average. The light red and blue colours depict the positive and negative phases of the PDO. Note the reversal of the colour key in the top panel so that blue colours are positive, and hence the current negative phase has below-normal SSTs in the blue areas.

# Trend simulations by Kosaka and Xie (Nature 2013)

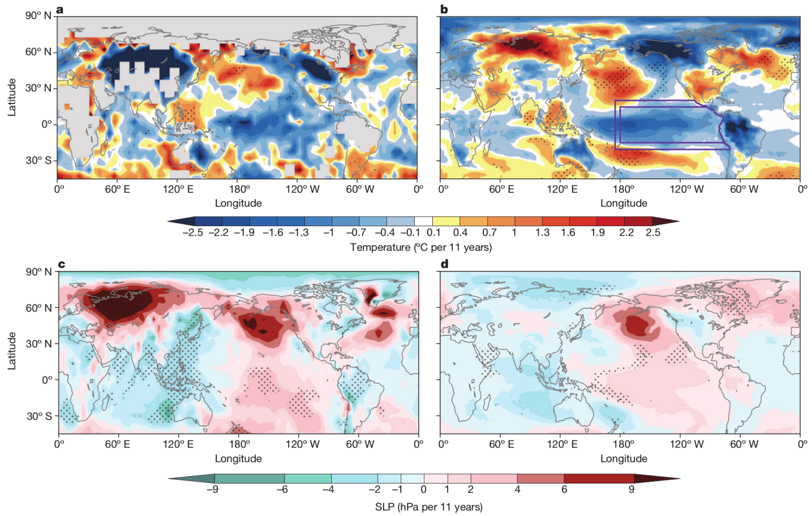
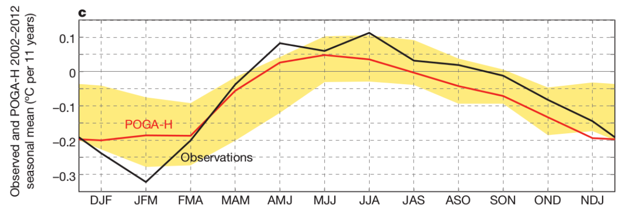
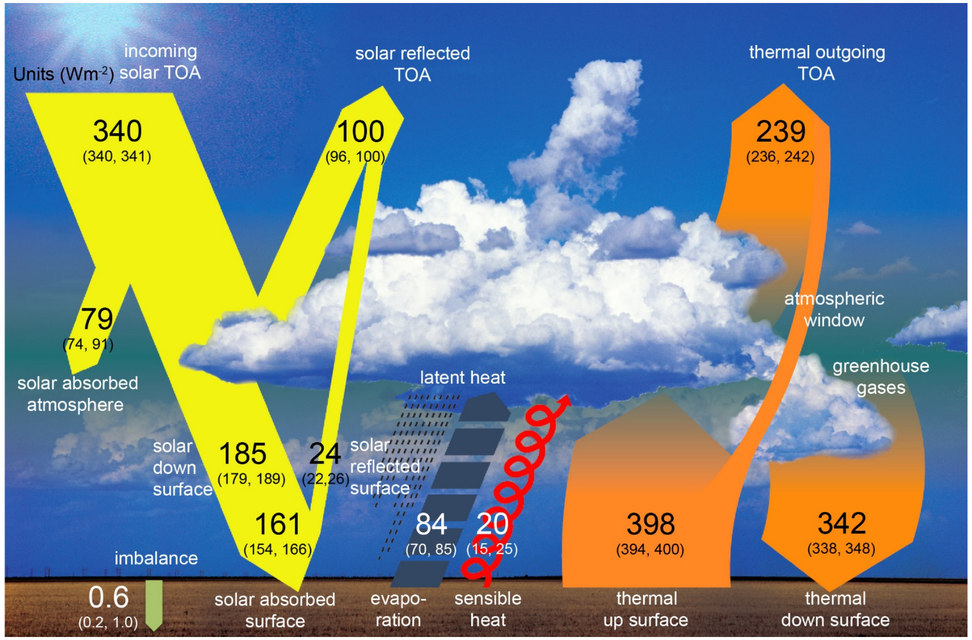



**Figure 2 | Observed and simulated trend patterns in boreal winter for 2002–2012.** **a** and **b** show near-surface temperature and **c** and **d** show SLP from observations (**a** and **c**) and POGA-H (**b** and **d**) in DJF. Grey shading represents missing values. Stippling indicates regions exceeding 95% statistical confidence. Purple boxes in **b** show the restoring region of POGA experiments.

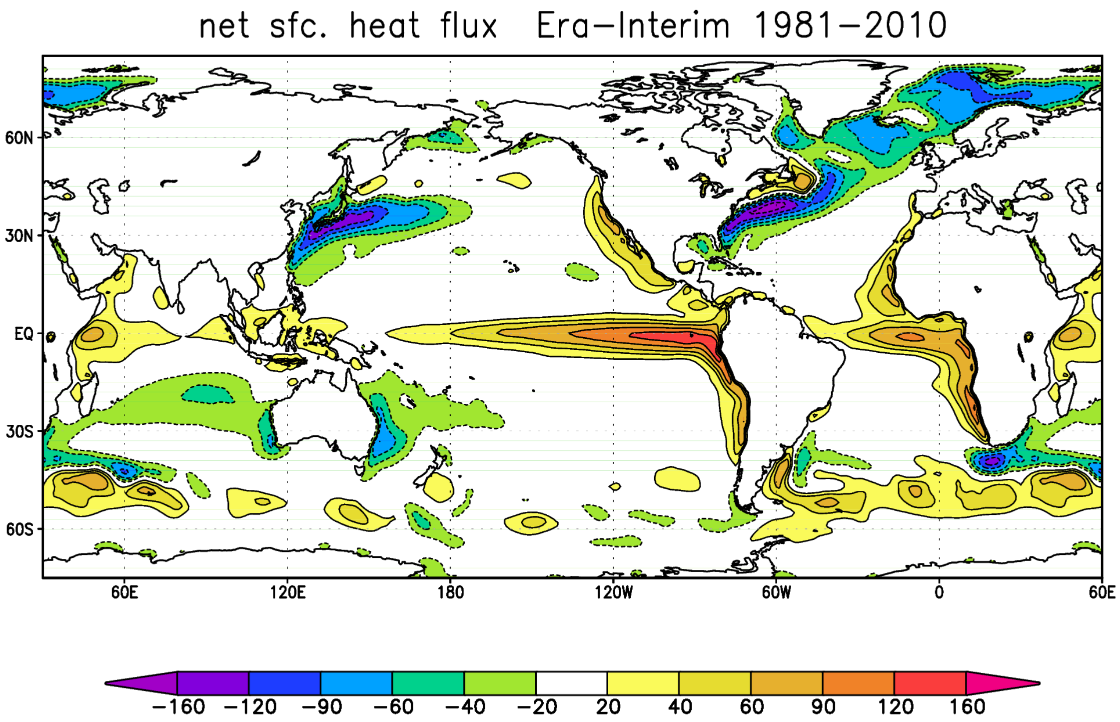


# Global energy balance

## from IPCC AR5-WG1 report



# Net heat flux at ocean surface from ERA-interim



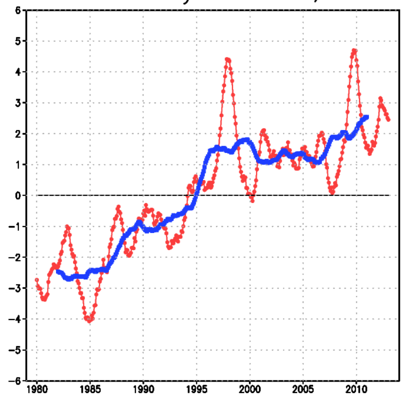
# Re-analysis data and numerical model

- Analysed data:
  - ERA-Interim re-analysis, 1979-2014
- Numerical model /simulations:
  - ECMWF System-4 re-forecasts + operational forecasts
  - 1981-2010 + 2011-2013
  - DJF season from 1 Nov. runs (fc. months 2-4)
  - 51-member ensembles
- Computation of trends:
  - From 5-year or 5-winter running means (to filter out ENSO)
  - Periods: tr1 = 1984 to 1998, tr2 = 1998 to 2011
  - Areas: 70S-70N, 20S-20N, 20N-70N, 40N-70N

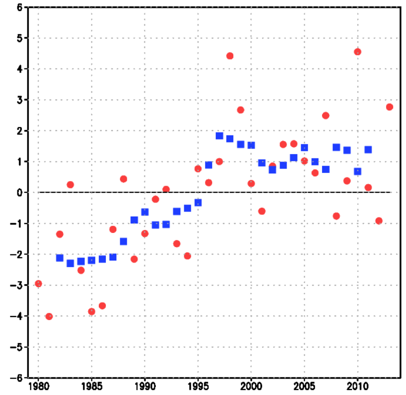
# Anomalies of net heat flux into the atmosphere

**NHF = LSH + SLRu + ASR**

From ERA-interim 1980-2013




**12-month means**
**5-year means**




**DJF means**
**5-winter means**

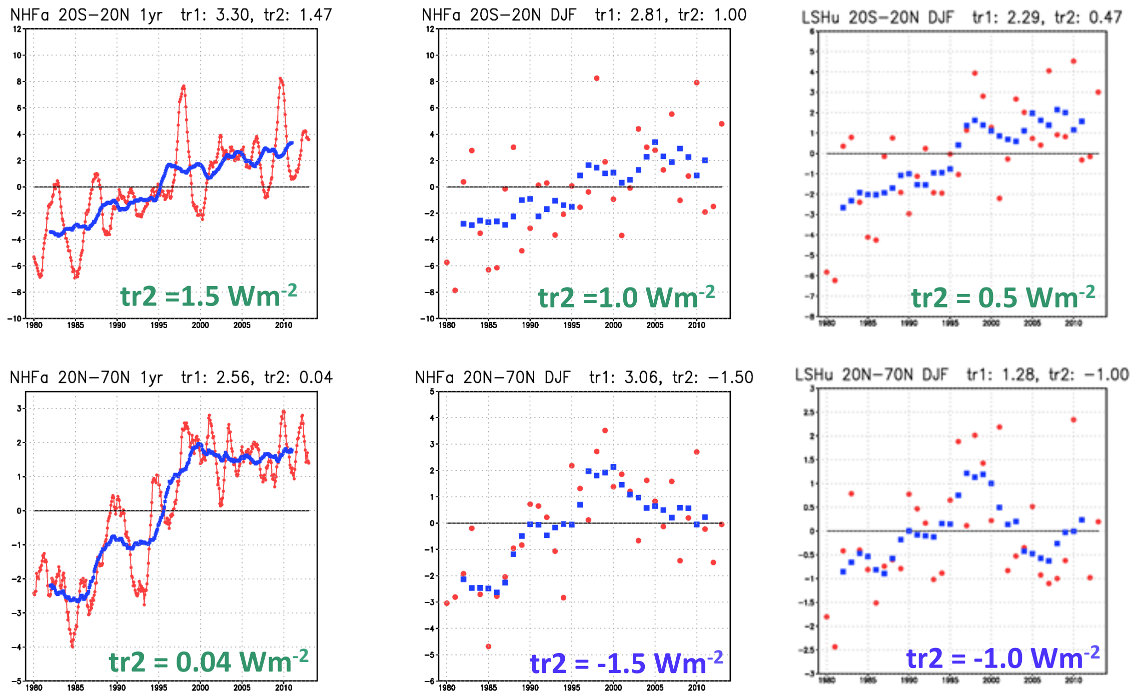
Equivalent global temperature trends in °C/decade:

**tr1 = 0.32, tr2 = 0.065** **tr1= 0.30, tr2 = - 0.027**

# Heat flux anomalies: tropics and NH extratropics

**Tropics 20S-20N**

**NH-ext 20N-70N**



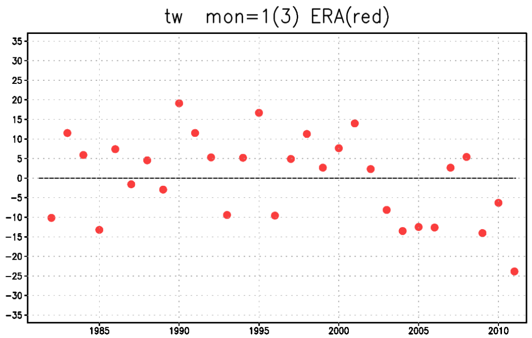

**1 year** **DJF**

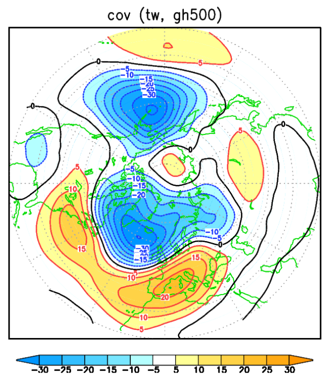
# Modulation of NH heat fluxes: the TW pattern in ERA-Interim

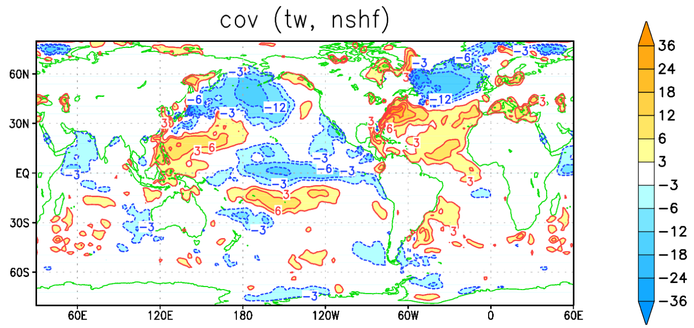
**Thermally-balanced Wave index (positive in COWL phase) :**

**Zonal wanenumber-2 component of net surface heat flux (NSHF, positive downward) in the 40-70N latitude band**

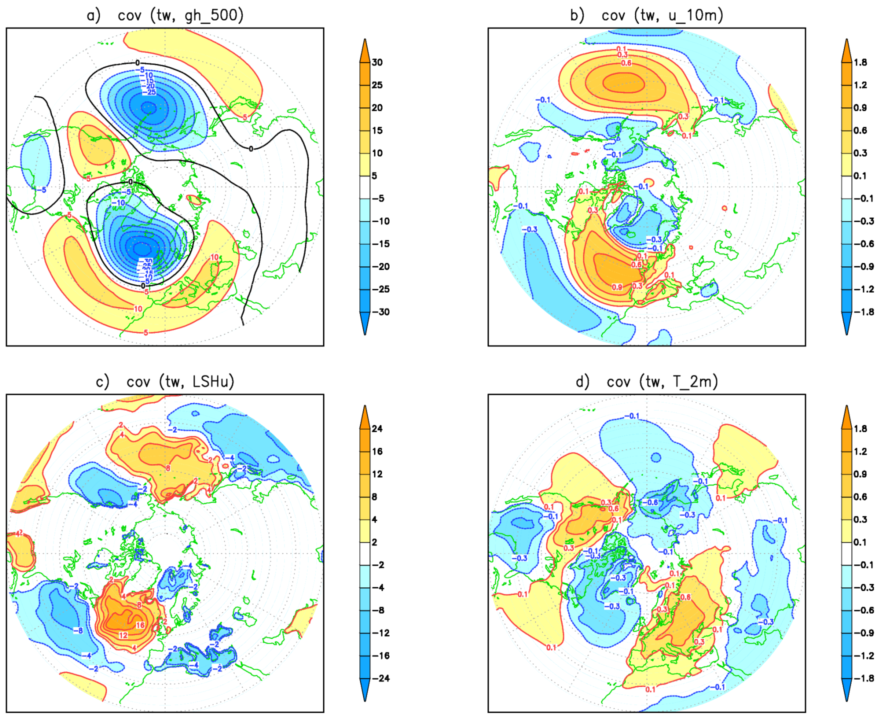
**TW = - NSHF [60W-30E]**
**+ NSHF [30E-120E]**
**- NSHF [120W-150W]**
**+ NSHF [150W-60W]**



# Covariances with TW index in S4



Consider a variability index V, computed from analyses and ensemble fc. for N seasons.

$V_j$ = variability index in season j (j = 1, … N) from analysis

$V_{i,j}^e$ = variability index in season j (j = 1, … N) from the i-th member of an ensemble forecast (i = 1, … M)

$$V_j^{em} = M^{-1} \sum \{V_{i,j}^e\}_{i=1,M}$$ : ensemble mean

We can define a weighted mean of ensemble members in such a way to reproduce (within a give error margin) a prescribed time series $V_j^*$ for index V:

$$V_j^{e*} = \sum \{ w_j^* V_{i,j}^e \}_{i=1,M} / \sum \{ w_j^* \}_{i=1,M}$$

A simple way to achieve this is to define member weights as

$$w_j^* = \exp [ - ( V_{i,j}^e - \alpha V_j^*)^2 / 2 \beta^2 ]$$

where β is the width of the weight distribution, and α an "inflation factor" .

To investigate the impact of COWL-like variability, we define V = TW index, and compute two weighted ens. means:

**Ens_A (V* = TW index from ERA)** **Ens_0 (V* = 0 TW anomaly)**

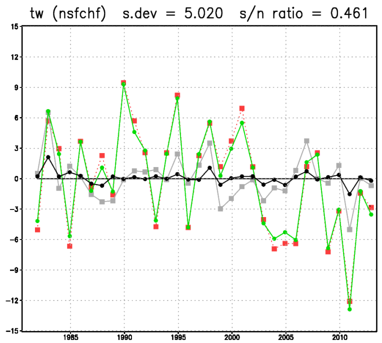
# Weighted ensemble means of S4 re-forecasts

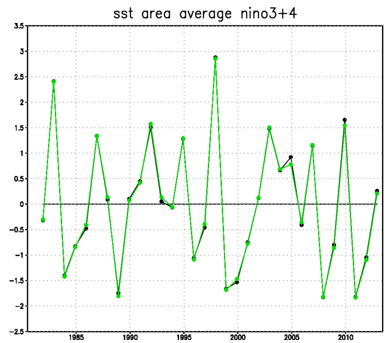
- Reference variability index V: TW /COWL
- Ens_A : V* = TW index from ERA Interim
- Ens_0 : V* = 0
- β = 0.5 * TW standard deviation in ERA
- inflation factor: **α** = 1.2

# DJF variability in weighted S4 ensembles

**TW index**:

ERA-int
Ens_mean
Ens_A
Ens_0



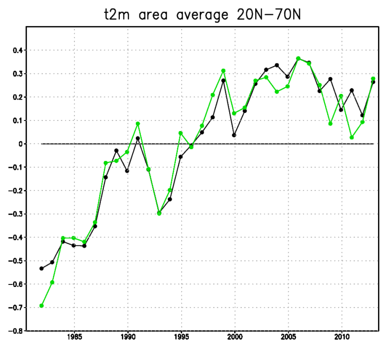



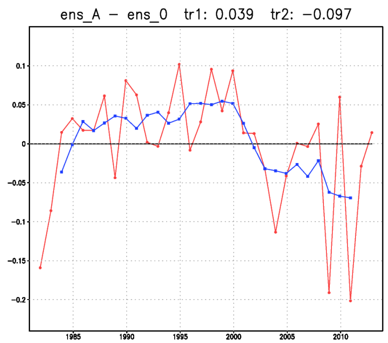

**SST Nino3+4**

Ens_A
Ens_0

**T.2m NHe**:

Ens_A
Ens_0



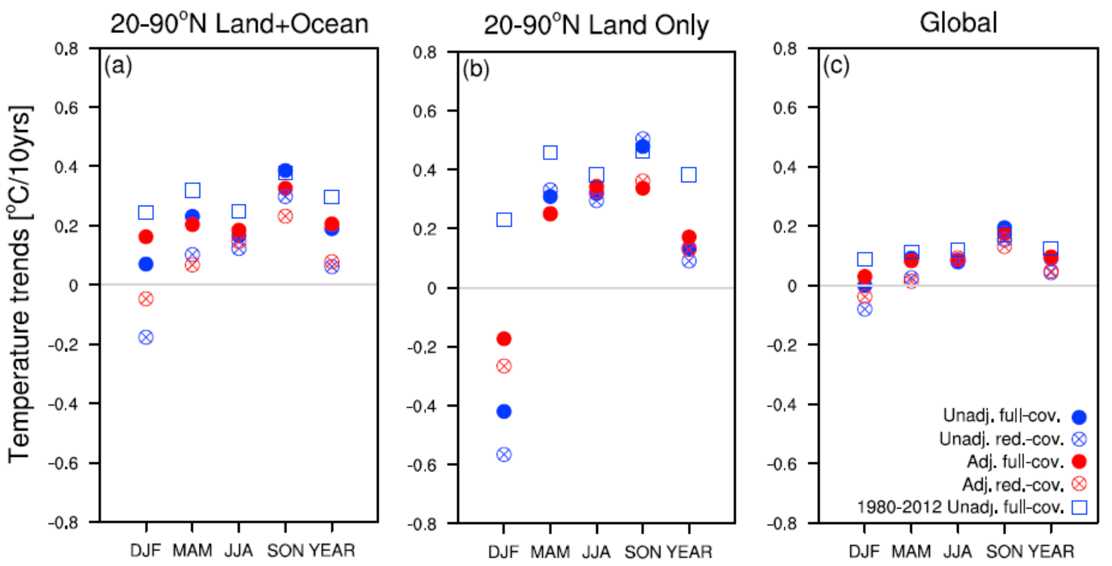

**T.2m NHe**:

Ens_A-Ens_0
5-win mean

tr2 = -0.1°C/10yr

# Statistical correction of ERA-interim trends

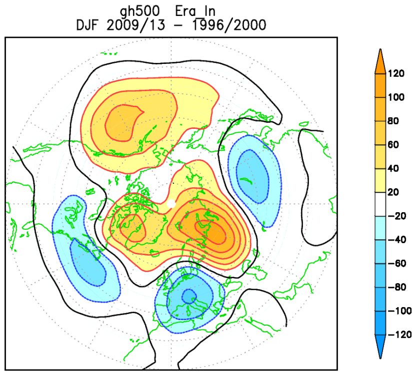
Saffioti et al 2015

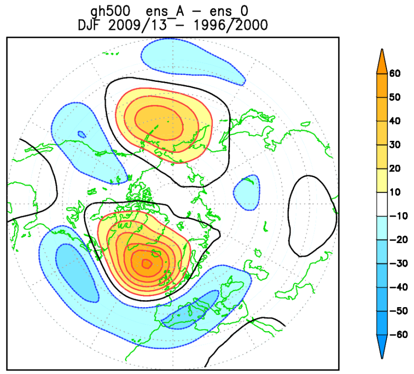


# Anomaly change: DJF 2009/13 – 1996/2000

**ERA**

**GH 500**



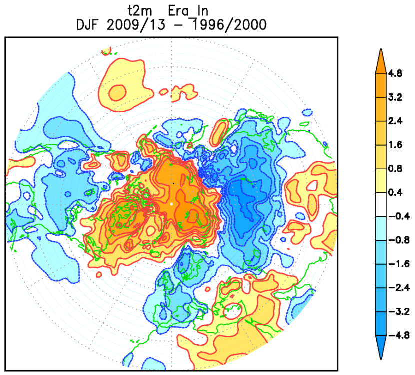

**Ens_A - Ens_0**

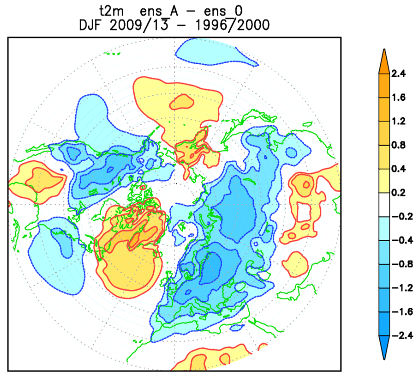
**GH 500**

**T 2m**

**Europe**
(20W-40E, 30N-70N):

**-0.34°C**

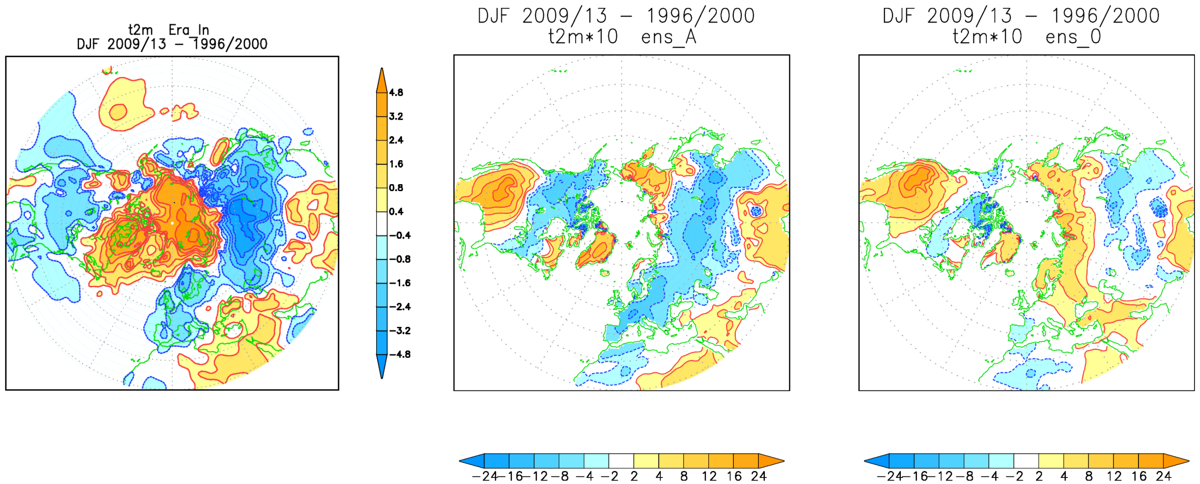



**T 2m**

**Europe**
Ens_A:
**-0.49°C**
Ens_0:
**0.21°C**

# Anomaly change: DJF 2009/13 – 1996/2000

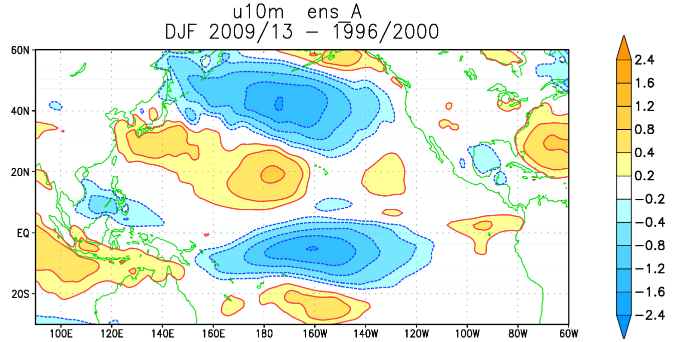



**ERA** **Ens_A** **ENS_0**

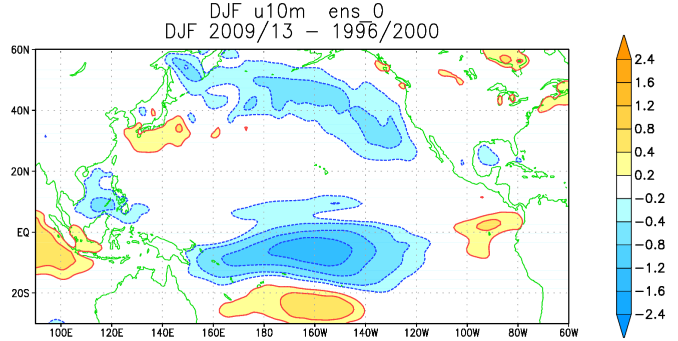
**T 2m**

# Decadal changes in U_10m in the Pacific

**Ens_A**




**Ens_0**

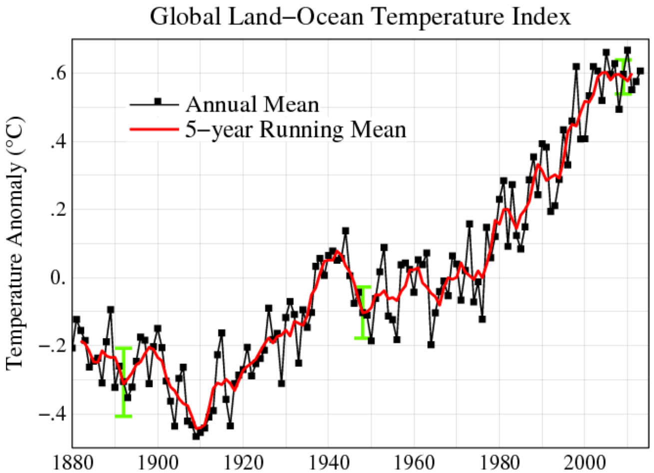


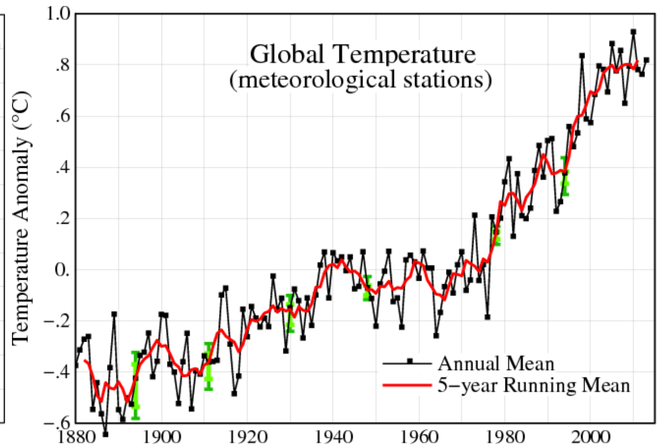
# Conclusions

- Although the recent reduction in global warming trend can be detected in both the tropics and the extratropics, the seasonality in the trend hiatus (strongest in DJF) is mostly originated in the northern extratropics (according to Era-Interim fluxes).
- Changes in the phase of the COWL pattern, and the associated heat flux anomalies, gave a significant contribution to the slow-down in NH warming trends during the winters of the last 15 years.
- Weighted ensemble means derived from the ECMWF System-4 re-forecasts, which reproduce nearly identical tropical SST anomalies but differ in terms of strong vs weak COWL variability, indicate that the change in the prevailing COWL phase in DJF accounts for a decrease in the NH warming trend by ~ 0.1 degree per decade (with strong cooling tendencies over land), contributing to the negative sign of the DJF global trend after 1998. It is also responsible for near-surface wind anomalies which decrease the forcing of the wind-driven circulation in the North Pacific.

# Global near-sfc. temperature variability (from NASA-GISS)

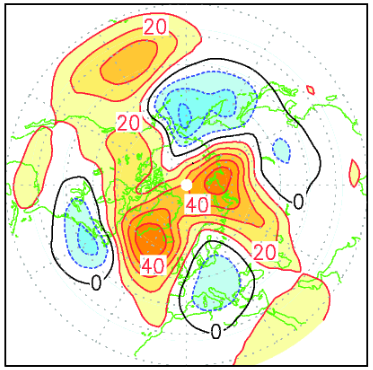
## anomalies from 1951-1980 global mean

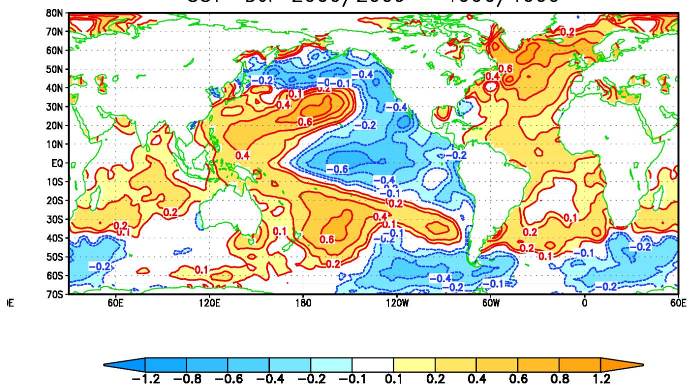


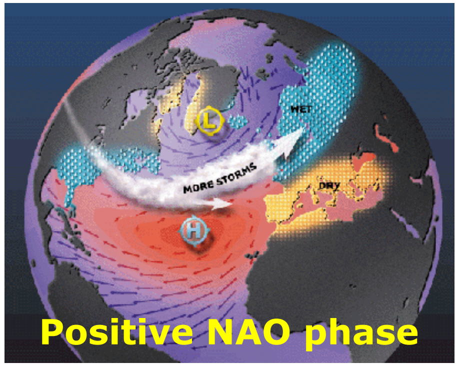
# Observed variability in the last two decades

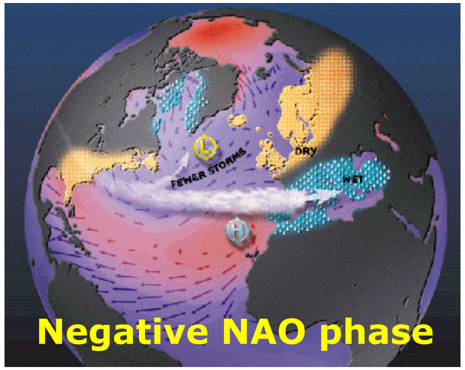
a) OBS Z500 00/09–90/99





# The North Atlantic Oscillation (NAO)



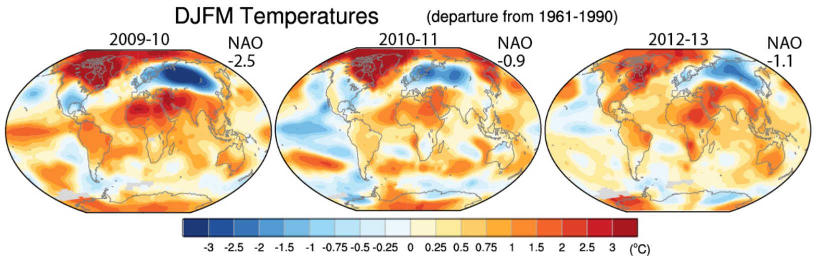
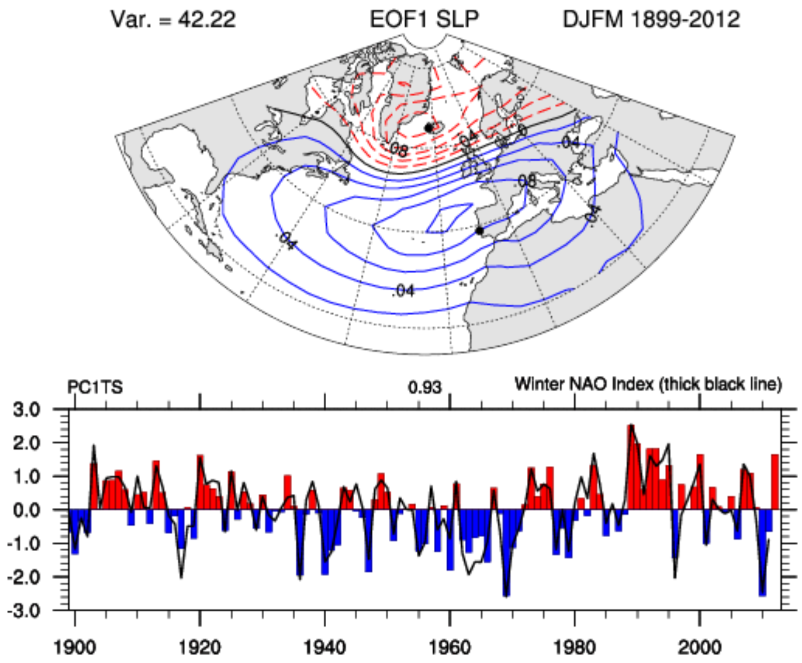




Fig. S5. Surface temperature anomalies relative to 1961-90 from GISS for the months of DJFM for northern winters of 2009-10, 2010-11, and 2012-13, which were negative NAO winters (in 2011-12 the NAO value was 1.7). The corresponding normalized NAO index value for each winter is in upper right.

# NAO variability from months to decades



# Global warming trends induced by surface heat fluxes

Globally averaged heat balance for an atmospheric column:

$$d\text{MSEC} / dt = \text{LSH\_u} + \text{NSR\_a} + \text{SLR\_u} - \text{DLR\_d} - \text{OLR\_u}$$

- MSEC = vertical integral of moist static energy in an atm. column
- LSH_u = sum of latent and sensible heat flux (+ upward)
- NSR_a = net solar radiation absorbed by the atmosphere
- SLR_u = longwave radiation emitted by the surface (+ upwards)
- DLR_d = downward-emitted longwave radiation at the surface (+ downward)
- OLR_u = outgoing longwave radiation (positive upward)

For a uniform tropospheric change of 1 $^o$C/decade: $d\text{MSEC} / dt \approx 0.04\ \text{W/m}^2$

$$\text{OLR\_u} + \text{DLR\_d} \approx \text{LSH\_u} + \text{NSR\_a} + \text{SLR\_u}$$

# Relating flux and and temperature anomalies

Let us write the total longwave radiation emitted by the atmosphere towards the open space (OLR) and the surface (DLR) as the energy emitted by a blackbody at temperatures $T^*_1$ and $T^*_2$ respectively:

$$OLR = \sigma \, T^{*\,4}_1$$

$$DLR = \sigma \, T^{*\,4}_2$$

where is the Stefan-Boltzmann constant. Linearizing the S-B equations, the change in emitted longwave radiation corresponding to a small, uniform temperature anomaly $\delta T^*$ is given by:

$$\delta OLR + \delta DLR = 4 \, \sigma \, ( T^{*\,3}_1 + T^{*\,3}_2 ) \, \delta T^* = R \, \delta T^*$$

Recent estimates (ref) for OLR (239 $Wm^{-2}$) and DLR (342 $Wm^{-2}$) give $R = 8.66 \, Wm^{-2} \, {}^oC^{-1}$.

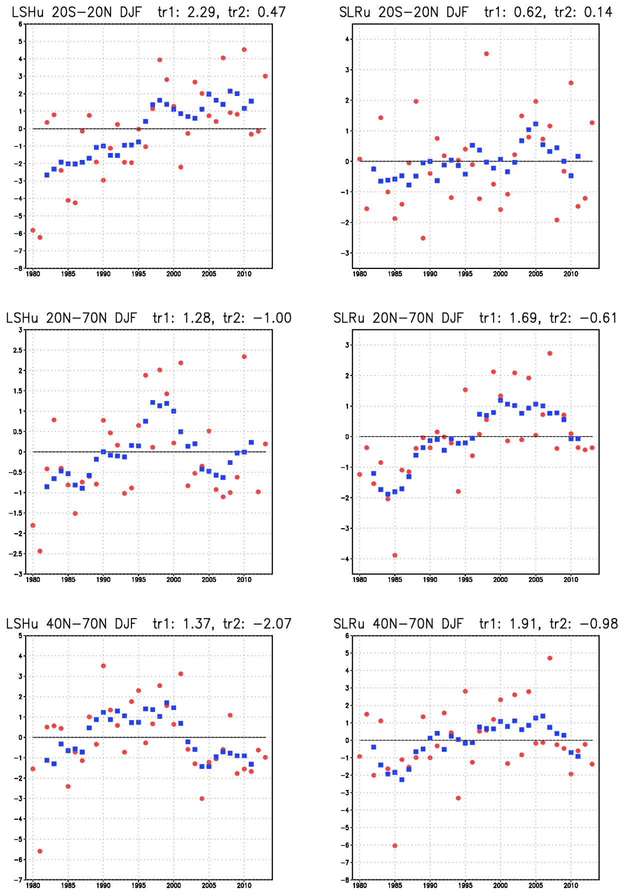
$$R \, \delta T^* = \delta \, LSH\_u + \delta \, SLR\_u + \delta \, NSR\_a = \delta \, NHF\_a$$

# LSH & SLR anomalies

**20S-20N**
**tr2 = 0.47, 0.14 Wm$^{-2}$/dec.**

**20N-70N**
**tr2 = -1.00, -0.61 Wm$^{-2}$/dec.**

**40N-70N**
**tr2 = -2.07, -0.98 Wm$^{-2}$/dec.**



# Dynamical modes of variability

- **Annular mode variability**:

  zonally symmetric variability induced by baroclinic or planetary waves – zonal mean flow interactions

  - Feldstein and Lee 1996
  - Limpasuvan and Hartmann 2000
  - Kimoto, Jin, Watanabe and Yasutomi 2001
  - Eichelberger and Holton 2002

- **Thermal equilibration of planetary waves**:

  Variability in the phase of planetary waves with respect to the surface temperature distribution

  - Mitchell and Derome (1983)
  - Shutts (1987)
  - Marshall and So (1990)
  - Molteni, King, Kucharski and Straus (2010)

## **Dynamical modes of variability: indices** (from Molteni et al. 2010)

- **Annular Mode index**:

  AM = Difference in zonally-averaged MSLP anomaly,
  [30-45 N] – [55-90 N]

- **Thermally-balanced Wave index (positive in COWL phase)** :

  Zonal wanenumber-2 component of net surface heat flux (NSHF, positive downward) in the [40-70 N] latitudinal band:

  TW = - NSHF [60W-30E] + NSHF [30E-120E]
  - NSHF [120W-150W] + NSHF [150W-60W]