Climate Response to Solar Forcing

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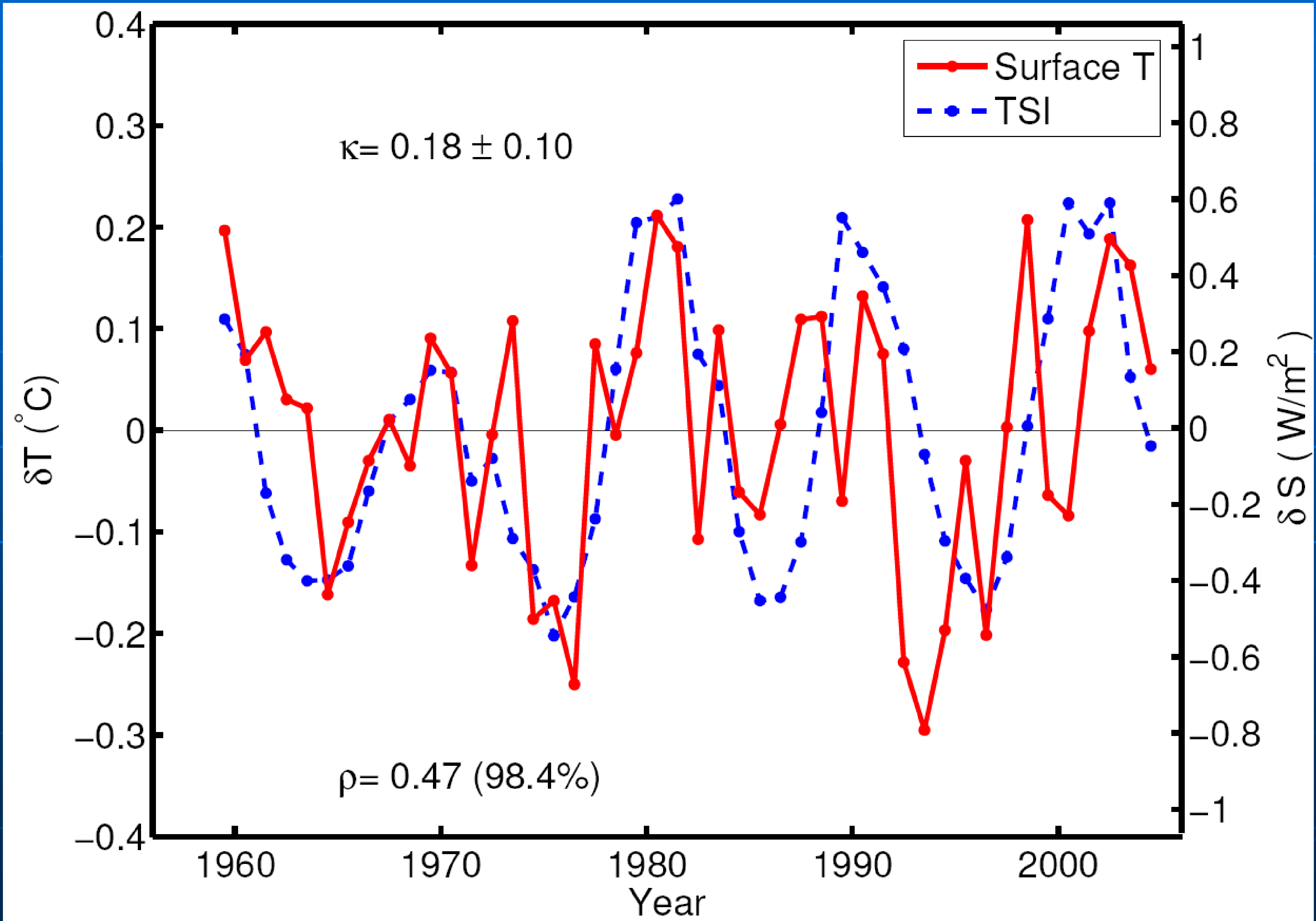
Introduction

- Camp and Tung (2007) and Tung and Camp (2007) established a statistically significant global pattern of warming related to the 11-year solar cycle, with a global mean warming at the surface of about 0.2 K. This is larger than previous results by about a factor of 2.
- Since even the previous low 0.1 K of solar-cycle response has not been explained by either EBM or by GCM, how do we explain this larger amplitude?
- The clue lies in the spatial pattern—similar to GHG warming--- also deduced from observation. Pattern inconsistent with stratospheric ozone heating being the main mechanism.

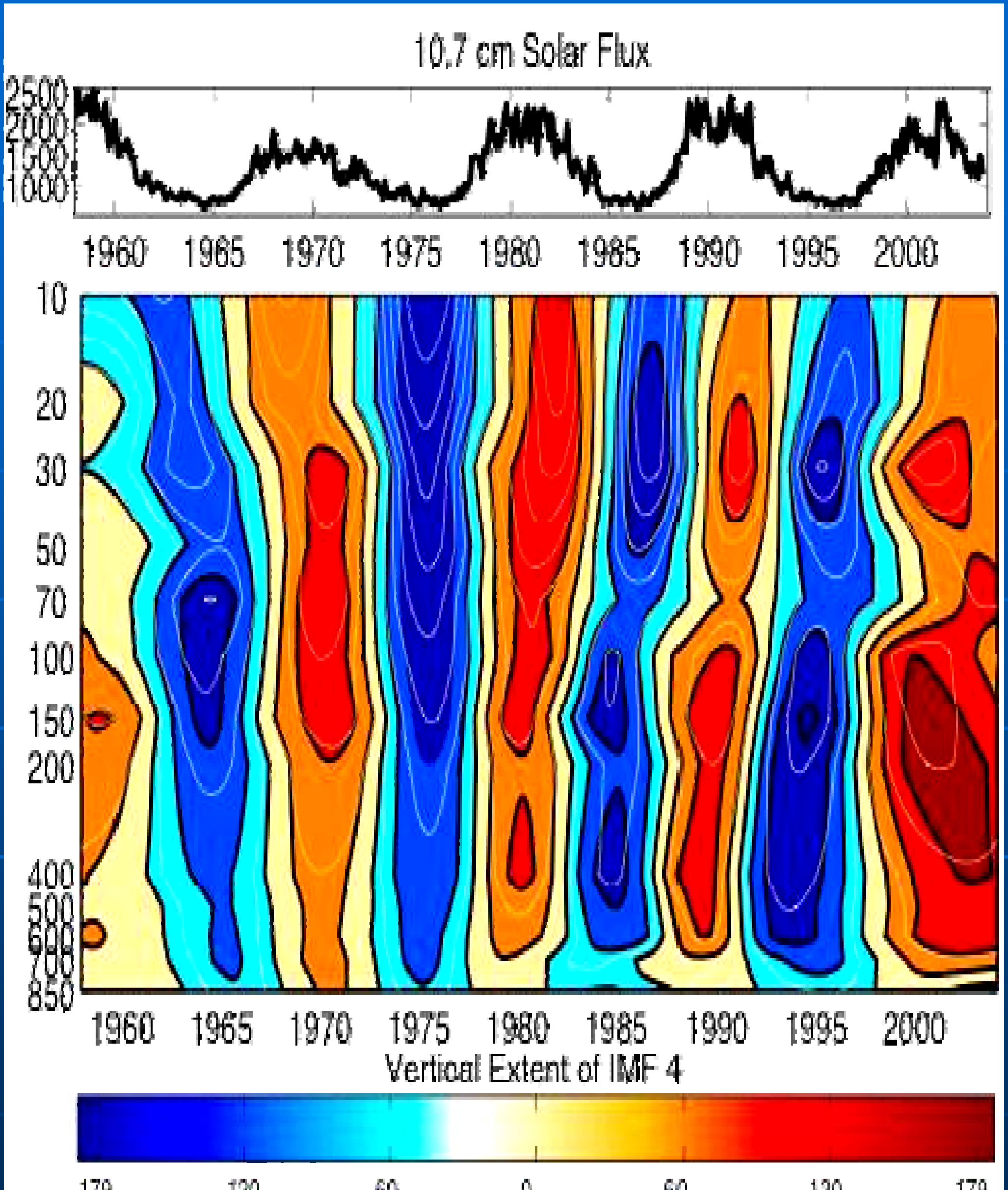
---:global mean, annual mean surface temp



Coughlin and Tung, 2004

Empirical Mode De-composition:Amplitudes of IMF 4 (geopotential height averaged 20N-90N) normalized by the square root of the density.

Temperature differences (peak to peak amplitudes) at 700 hPa are ~0.3 C (equator) to ~0.6 C (N. pole). Couldn't get surface value at the time, too noisy. No spatial information was used. Use spatial information next.

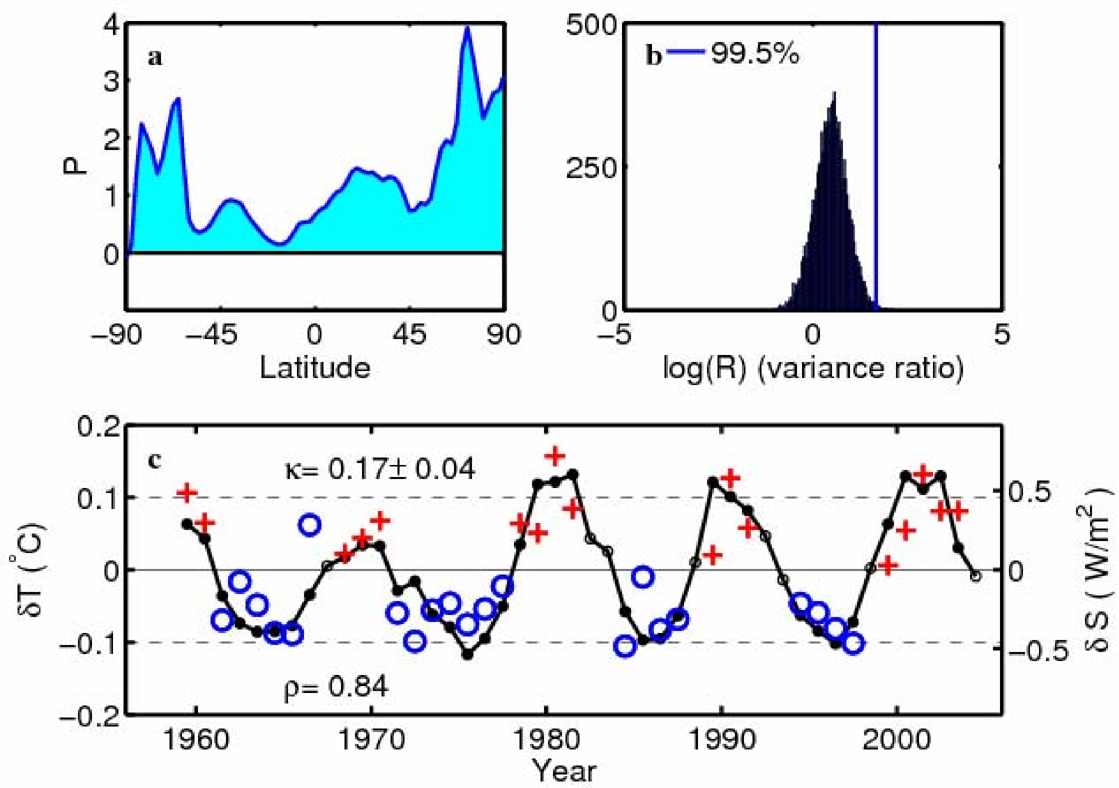


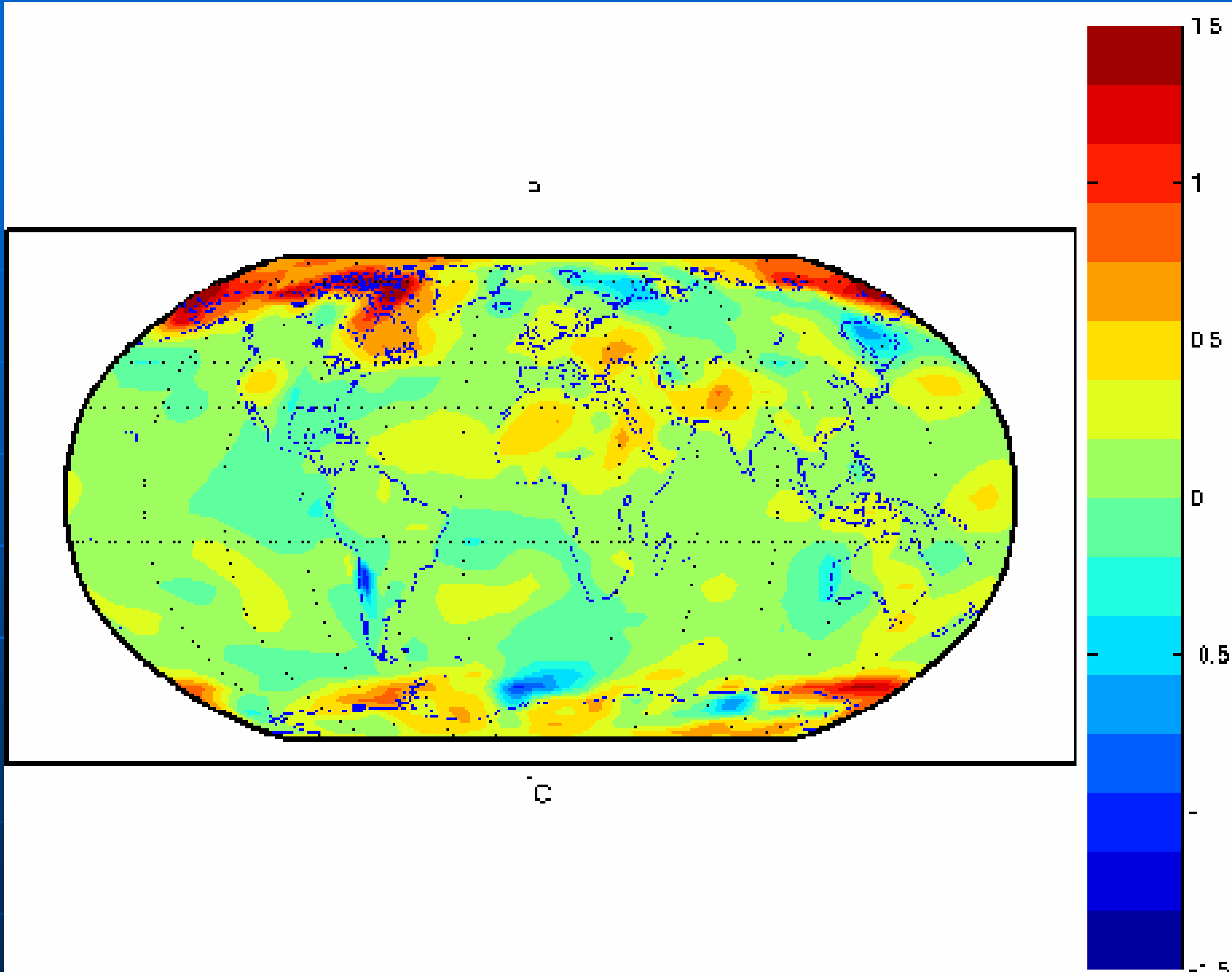
Amplitudes at 700 hPa (meters*20)

LDA method finds the best spatial pattern that separates solar max years from solar min years

Polar amplification of warming →

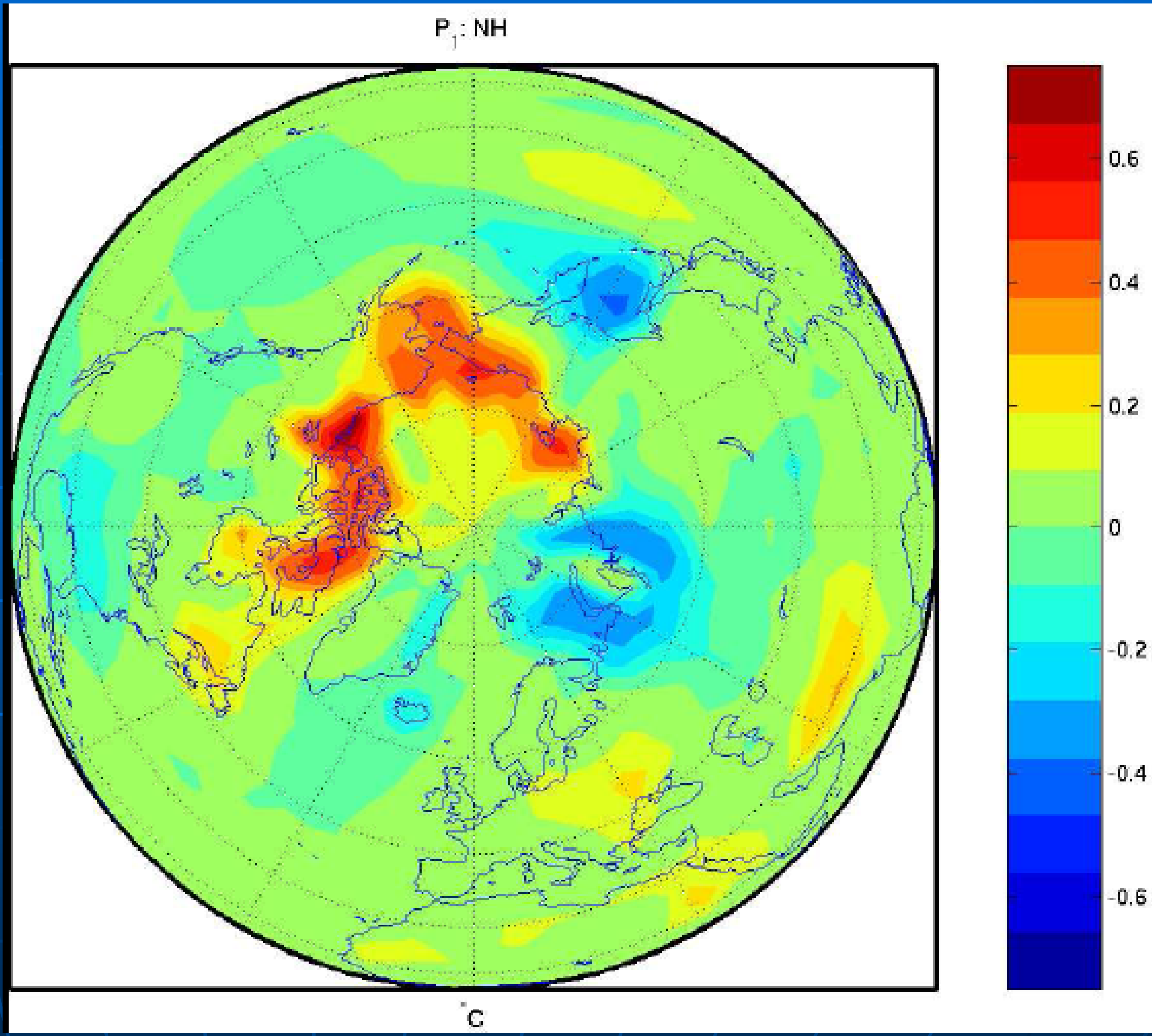
Global mean warming
δT~0.2 K →
Correlation coef: 0.84

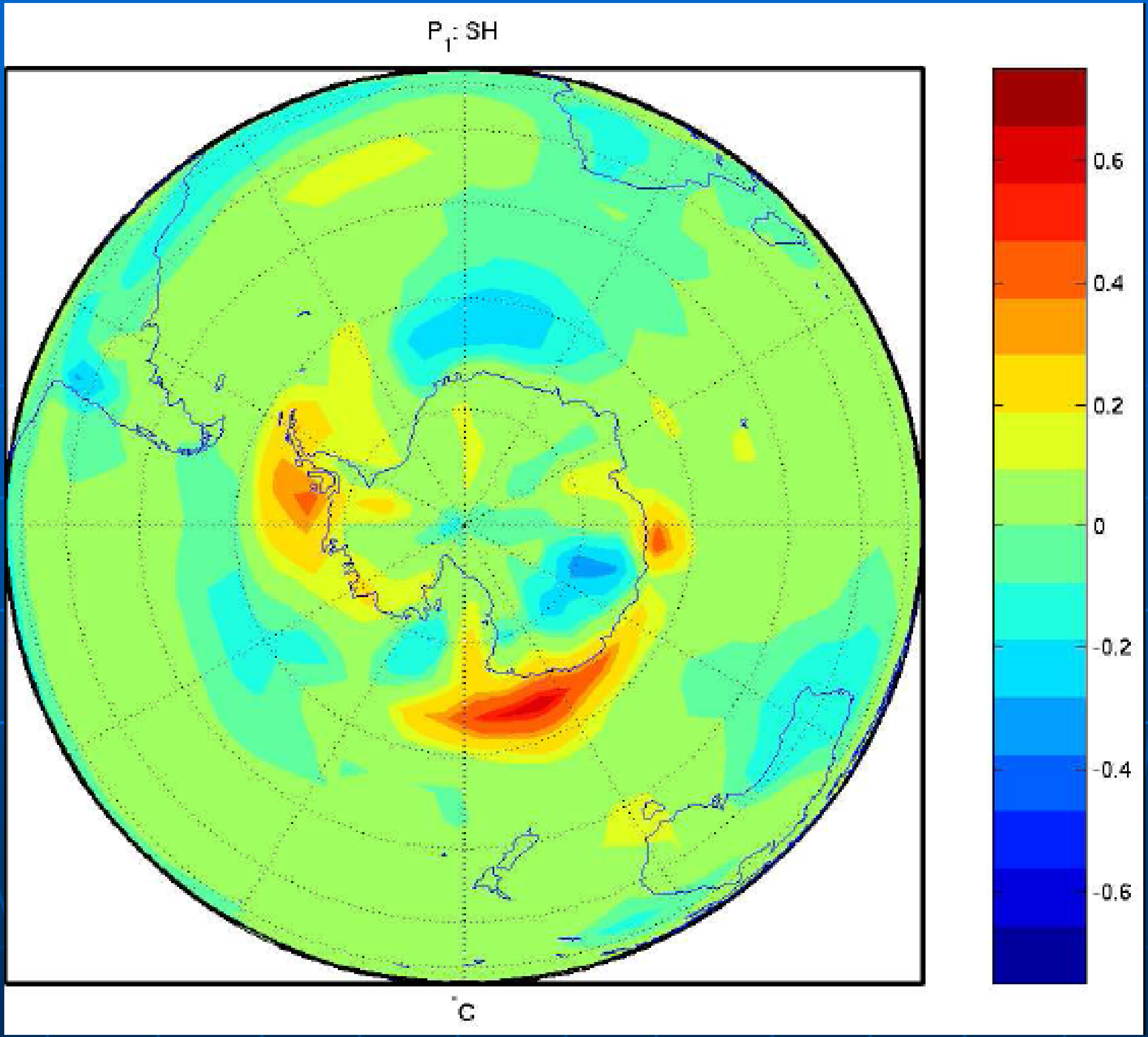




1 5
1
D 5
D
0.5

Warming near seasonal sea-ice edge, suggestive of ice-albedo feedback being responsible for polar amplification





P1: SH
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
°C

Solar cycle and Global Warming

- Radiative forcing from solar-min to solar-max:

  ~0.18 watts m^{-2}.
- periodic warming ~0.2K
- Transient (periodic) climate sensitivity:

  $\lambda=\delta T/\delta RF \sim 1$ K/(Wm^{-2})

- Radiative forcing for double CO_{2}:

  ~3.7 watts m^{-2}
- Equilibrium warming:

  Should *most probably* be at least 3.7 K,

  since equilibrium λ> transient λ.

Contrast with Schwartz (2007): ~1.1 K.

“Back of envelope calculation” for solar cycle forcing of RF=0.18 Wm^{-2} balancing RF by radiative cooling~$B\delta T$

$$\delta T \sim [\delta Q \cdot (1-\overline{\alpha})/B] = RF/B \sim 0.18/1.9 \sim 0.1K$$

“Phenomenological Model”:

$$\delta T \sim f[\delta Q \cdot (1-\overline{\alpha})/B] \sim f\,0.1K$$

Time-dependent Held & Suares climate model with dynamical transport (annually averaged)

$$C\frac{\partial}{\partial t}T = Qs(y)(1-\alpha(y)) - (A+BT) + \nabla \bullet (Heat\ Fluxes)$$

where

$C = h$eat capacity of the lower atmosphere and upper few meters of ocean

$\equiv B\tau.$

Global Average (overbar denotes global average except for α):

$$C\frac{\partial}{\partial t}\overline{T} = Q(1-\overline{\alpha}) - (A+B\overline{T}) - \frac{\partial}{\partial z}\overline{F_z},$$

$$where: \overline{\alpha} = \int_0^1 \alpha(y)s(y)dy.$$

Perturbation Equation
small perturbation, linear response

$$Q = Q_0 + \delta Q.$$

First variation

(Taylor expansion, B and α depend on T):

$$C\frac{\partial}{\partial t}\delta T = \delta Q(1-\overline{\alpha}) - B\delta T(1-g) - \frac{\partial}{\partial z}\delta F_z$$

$$g = ((-\frac{\partial A}{\partial T} - T\frac{\partial B}{\partial T} - Q\frac{\partial \overline{\alpha}}{\partial T})/B)_0 = g_1 + g_2.$$

Climate gain factor: $f = 1/(1-g)$.

Feedback processes

- g_1: water-vapor feedback: more water vapor in the upper troposphere more greenhouse effect.
- $g_{2:}$ ice-snow albedo feedback: less ice/snow cover, lower albedo, earth absorbs more heat.
- cloud feedback: more convection more clouds, traps more heat or reflects more to space. Has effect in both g's.

For the 11-year solar cycle, the heat flux into the ocean is diffusive and does not reach the main thermocline (White et al, 1997);the mixed layer thus appears to be semi-infinite. Ocean response to solar cycle :

$\delta T(z) = \delta T(0)\exp\{-\mu z\},$ z increasing with ocean depth.

$$\delta F_z = CD\frac{\partial}{\partial z}\delta T,$$

where D~1.0 cm^2/s, typical ocean diffusivity.

So the energy balance is (dropping overbars):

$$B\tau\frac{\partial}{\partial t}\delta T = \delta Q\cdot(1-\alpha) - B\delta T(1/f + D\mu^2).$$

Peridic solution for oscillatory forcing

$\delta Q(t) = a\cos(\omega t)$:

$$\delta T = \left(\frac{a(1-\overline{\alpha})}{B}\right)\frac{\cos\omega(t-\Delta)}{\sqrt{1+\varepsilon^2}}\widetilde{f},\quad \widetilde{f} = \frac{f}{1+D\mu^2 f\tau}$$

$$= [\delta Q(t-\Delta)\cdot(1-\overline{\alpha})/B]\frac{\widetilde{f}}{\sqrt{1+\varepsilon^2}} \approx [0.1K]\frac{\widetilde{f}}{\sqrt{1+\varepsilon^2}},$$

where: $\varepsilon = \widetilde{f}\omega\tau$; $\omega\Delta = \tan^{-1}(\varepsilon)$; $\omega = 2\pi/11yr$.

Δ is the delay in the response to solar cycle, which is measured and can be used to obtain ε. White et al (1997) found largest correlation in ocean temperature with solar index at zero lag, with $\pm$ 2year error bar. Coughlin and Tung (2004) found atmospheric lag to be also small.

For $\Delta \sim 1$ year, then $f\tau \sim 1.7$ years, the thermal inertia for the radiating layer is short ($\tau \sim 6$ months).

Also, since $f > \widetilde{f}$, the climate is more sensitive than that deduced from "phenomenological models".

$f \approx 3.2$.

Summary

- Direct radiative heating (TSI) due to solar cycle variability can explain the observed global mean warming of ~0.2 K provided that the initial warming is amplified by a factor of 3 by the positive water-vapor, cloud and albedo feedback processes.
- About the same factor of climate gain as in greenhouse warming, in contrast to Schwartz (2007) JGR, who found $f<1$, but who treated C as ocean inertia and heat flux to the ocean ignored. This interpretation is inconsistent with the derivation of EBM where C is the thermal inertia of the layer receiving the radiation and radiating at temperature T. Deep ocean is not involved in radiation.
- EBM in Tung and Camp (2007): direct heating of the surface is energetically consistent with the observed response.
- GCM simulation: When the SST is not imposed, and the feedback processes are allowed, as in the coupled atmosphere-ocean models used for greenhouse gas warming problem, the solar cycle response can be simulated. See our poster: "Solar-cycle response in global climate models assessed by IPCC AR4", GC43A-0935, this afternoon at 1340h.
- No need for fudge factors….