The effect of solar TSI variations on the Earth's climate

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SUMMARY

(1) Introduction to simple climate models
(2) Upwelling-Diffusion Energy Balance Model (UD EBM)
(3) UD EBM test: response to volcanic forcing
(4) Paleo application to TSI forcing of the climate system
(5) Application to recent climate change – the role of the Sun

EQUILIBRIUM RESULTS AND DEFINITIONS

EQUILIBRIUM ENERGY BALANCE

Outgoing longwave | Incoming shortwave

Black body energy balance: $\sigma T^4 = (1-\alpha)\,Q_{solar}$
[T = global-mean surface temperature (ºK); α = albedo]

Equilibrium response to a solar forcing perturbation:

$$\Delta T_{equil} = \Delta Q_{solar}\,[(1-\alpha)/(4\,\sigma\,T^3)]$$

Generalization: $\Delta T_{equil} = \Delta Q\,[1/\lambda]$
[λ is called the feedback parameter]

Climate sensitivity is defined by: $S = 1/\lambda = \Delta T_{equil}/\Delta Q$
[i.e., equilibrium temperature change per unit of forcing]

An alternative sensitivity definition: $\Delta T_{2x} = \Delta Q_{2x}/\lambda = S\,(\Delta Q_{2x})$

[where ΔQ_{2x} = forcing for $2xCO_2 \approx 3.71 W/m^2$; $\Delta T2x \approx 1.5–6.0^oC$ ($\approx$ 90% C.I.)]

THE SIMPLEST TIME-DEPENDENT FORMULATION

$$C\, d\Delta T/dt \quad = \quad \Delta Q(t) \quad - \quad \Delta T/S$$

Change in heat content	Forcing = heat input	Heat lost to space

This is a one-box model. The heat capacity term (C) could be for the mixed layer of the ocean, or, to account for heat transport below the mixed layer, some larger quantity.

SIMPLE EXAMPLE: SINUSOIDAL FORCING

Forcing: $\Delta Q(t) = A \sin(\omega t)$

$\Rightarrow \quad C\, d\Delta T/dt + \Delta T/S = A \sin(\omega t)$

Solution:

It is useful to define a characteristic timescale, $\tau = SC$ [$\tau \sim 1$ to 5 years]

$\omega >> 1/\tau$: $\Delta T(t) = [A/(\omega C)] \sin(\omega t - \pi/2)$ [i.e., for high frequency forcing, monthly to annual timescale, the response is largely independent of sensitivity, S, lagging behind the forcing by one quarter of a cycle]

$\omega << 1/\tau$: $\Delta T(t) = S\, A \sin(\omega t)$ [i.e., for low-frequency forcing, timescale much greater than decadal, the response is linearly dependent on the sensitivity and roughly in phase with the forcing (no lag)]

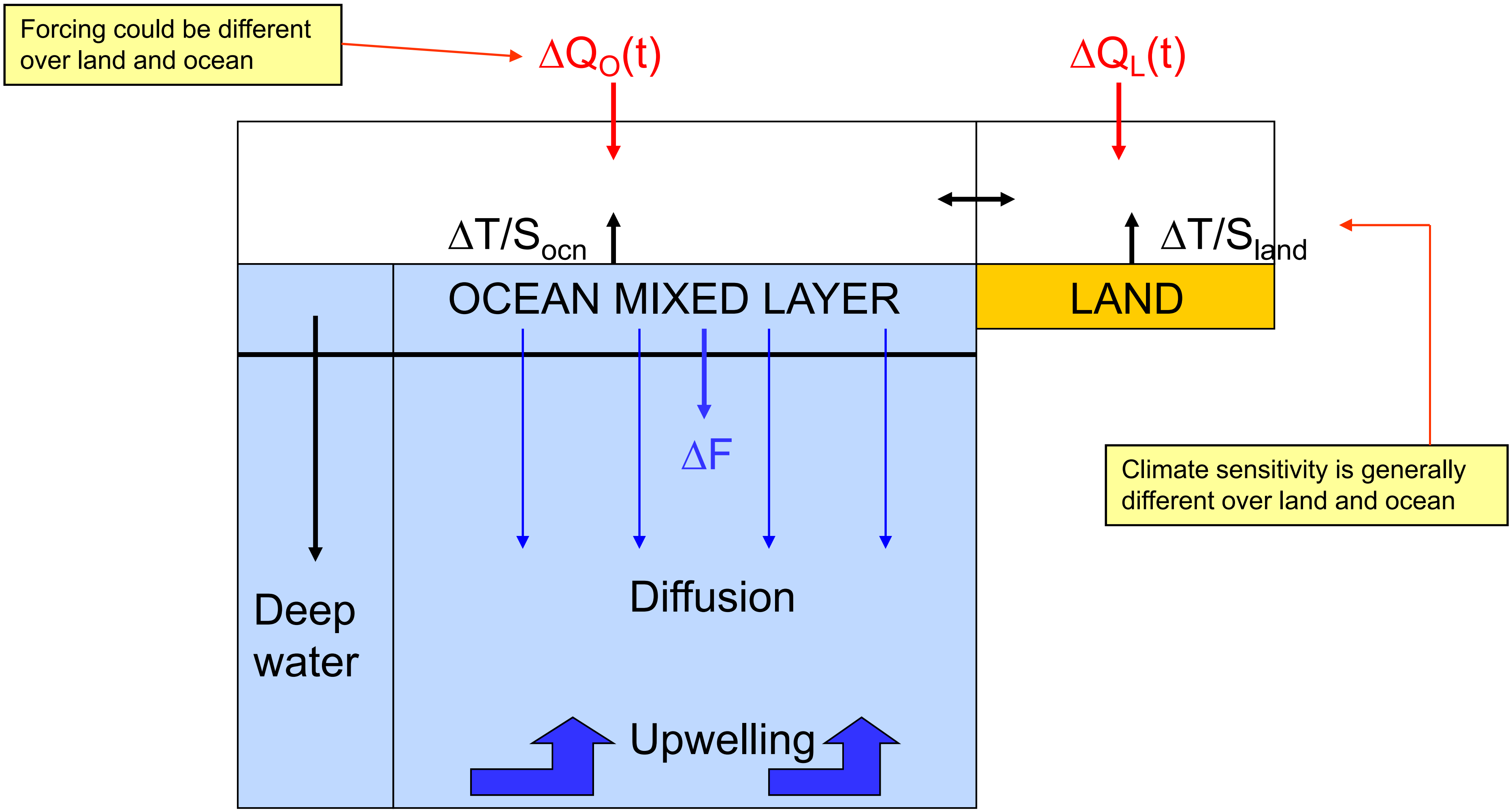
Hence, for solar cycle (11-year) forcing we might expect weak dependence on the climate sensitivity, and a lag of order one year.

A MORE COMPLEX MODEL
(MAGICC)

MAGICC = **M**odel for the **A**ssessment of **G**reenhouse-gas **I**nduced **C**limate **C**hange

MAGICC may be downloaded from http://www.cgd.ucar.edu/cas/wigley/magicc/index.html

MAGICC is an "Upwelling-Diffusion Energy Balance Model" (UD-EBM)



UD EBM: ocean equations

$$C\, d\Delta T_{ocn}/dt + \Delta T_{ocn}/S_{ocn} = \Delta Q(t) - \Delta F + k(\Delta T_{land} - \Delta T_{ocn})$$

[Energy balance for the ocean mixed layer]

where $\Delta F = K_z\, [\partial(\Delta\theta)/\partial z]_{z=0}$

[Heat transport out of the mixed layer into the deeper ocean]

… coupled to …

$$\partial(\Delta\theta)/\partial t - w\partial(\Delta\theta)/\partial z = K_z\, \partial^2(\Delta\theta)/\partial z^2$$

[Upwelling-diffusive heat transport below the mixed layer]

UD EBM Test: Response to volcanic forcing

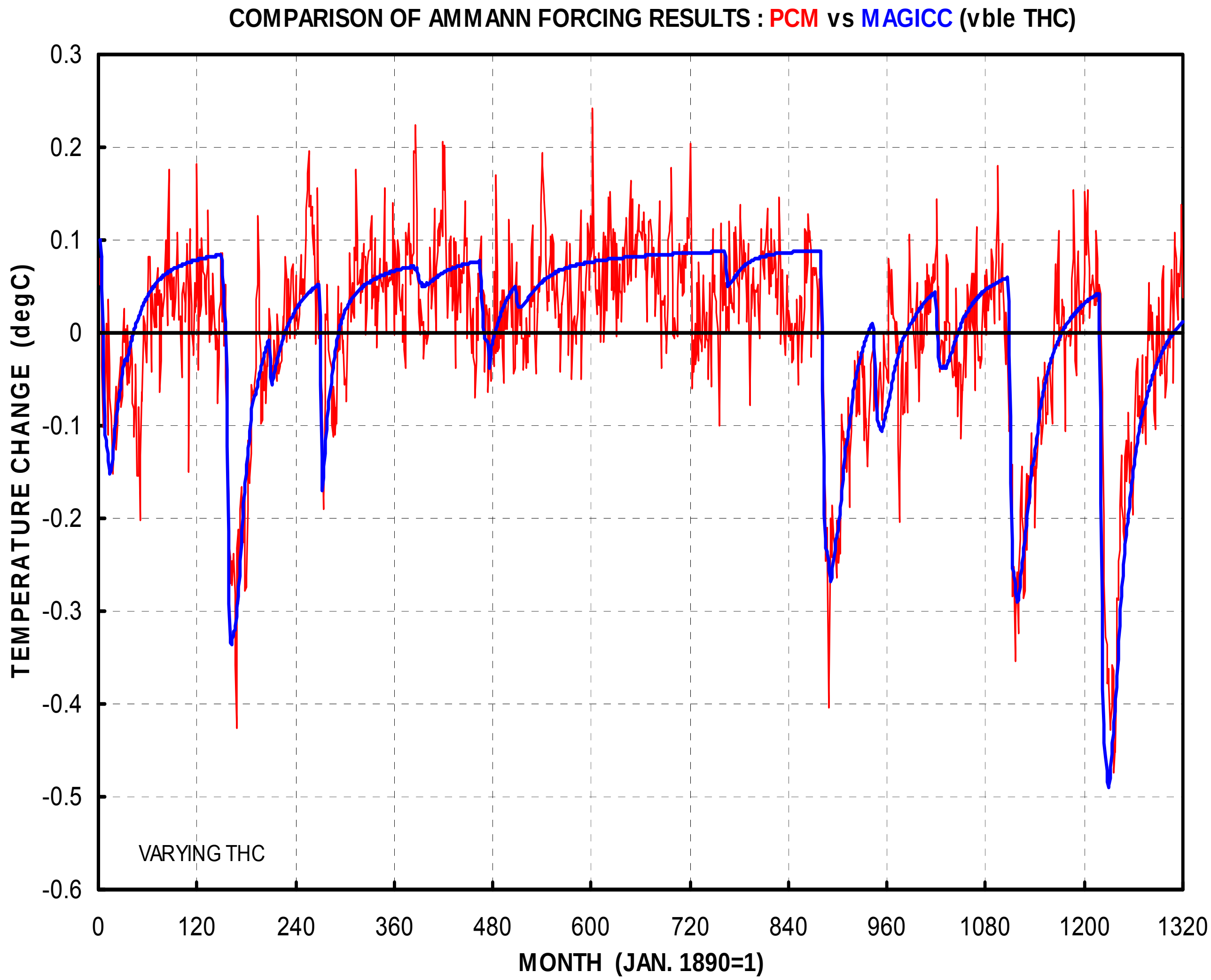
- In this comparison, the UD EBM is first calibrated against an AOGCM (the NCAR Parallel Climate Model – 'PCM') forced with a 1%/yr compound CO2 increase (linear forcing).
- Then the UD EBM is driven with the volcanic forcing history over the past 100+ years, and the results compared with those for PCM with the same forcing.

- Note that the UD EBM gives only the 'pure' signal as output, while the AOGCM gives both the signal plus internally-generated noise.
- To compare the UD-EBM and the AOGCM we need to enhance the signal-to-noise ratio for the AOGCM results. We do this by running an ensemble of realizations and averaging the multiple realizations.

From: Wigley, T.M.L., Ammann, C.M., Santer, B.D. and Raper, S.C.B., 2005: The effect of climate sensitivity on the response to volcanic forcing. *Journal of Geophysical Research* **110**, D09107, doi:10.1020/2004JD005557.

EFFECT OF VOLCANIC ERUPTIONS

16-member ensemble-mean from PCM [signal plus noise] compared with simulation using the simple UD EBM 'MAGICC' [pure signal].



PALEOCLIMATE APPLICATION

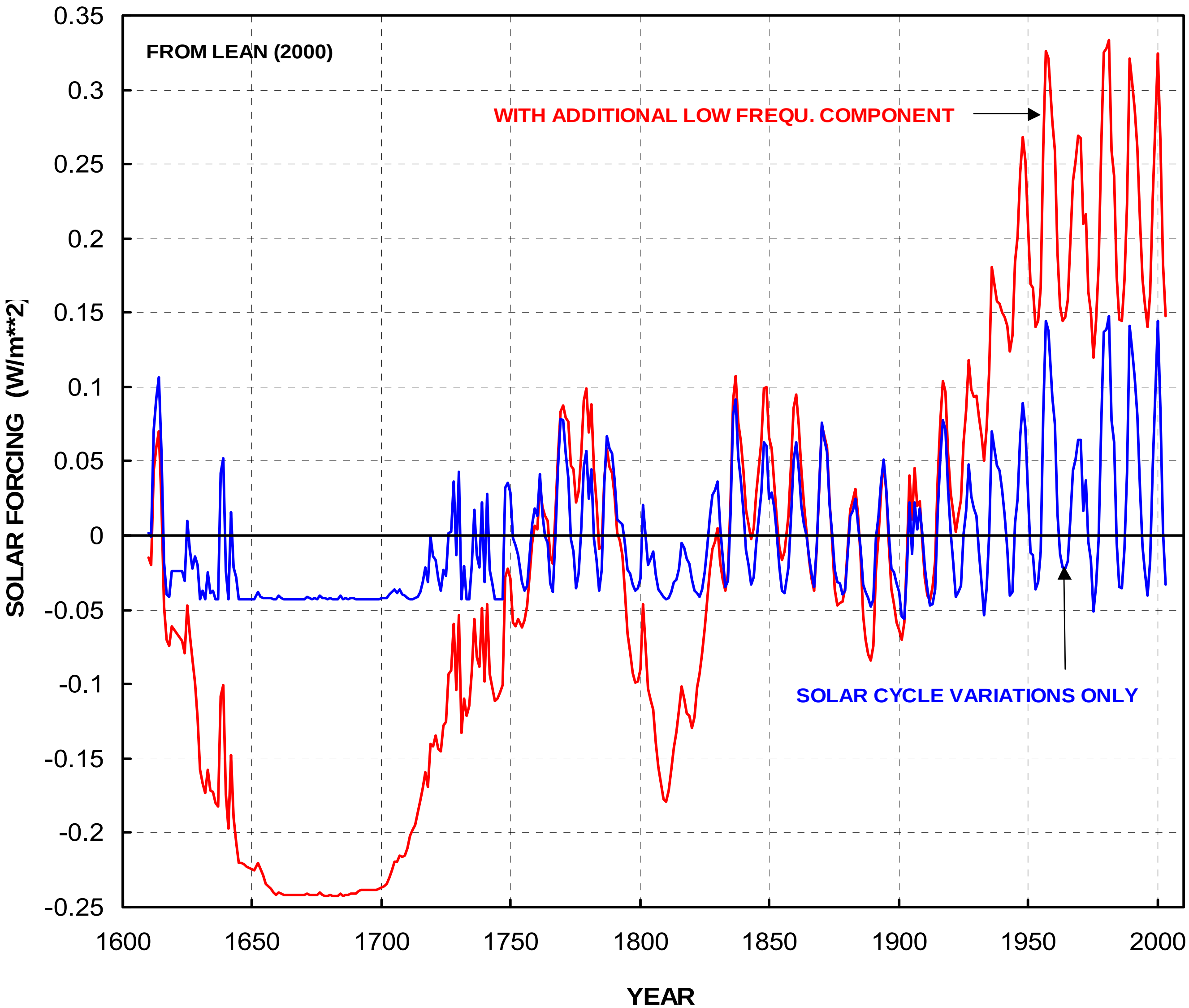
The goal here is to compare model simulations with reconstructed paleotemperatures for the NH over the past 1000 years.

For the model, the forcings are from solar irradiance changes, volcanoes and anthropogenic sources (GHGs, aerosols).

The primary source of uncertainty is the climate sensitivity.

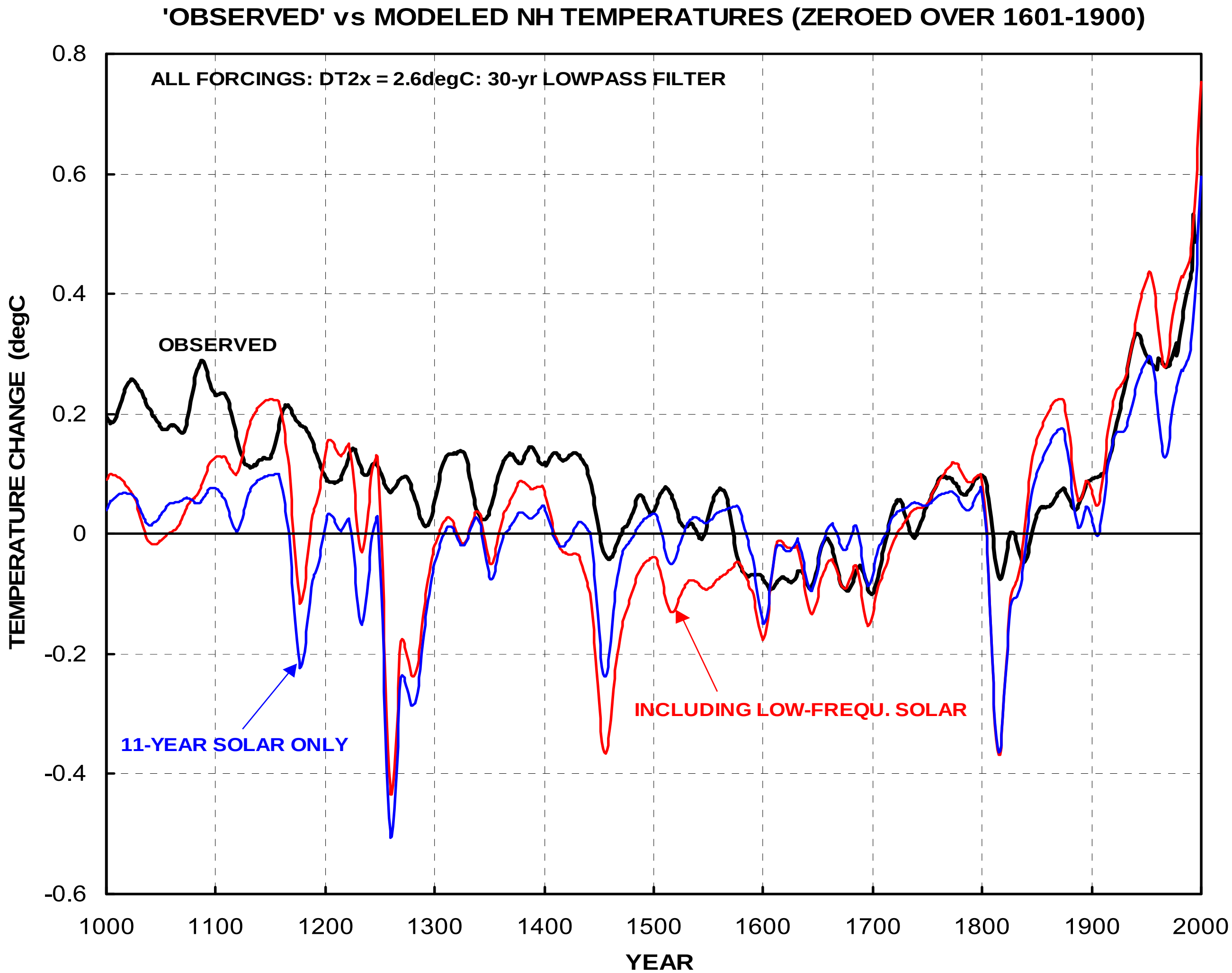
Another source of uncertainty is the magnitude of solar forcing, specifically the low-frequency (“secular”) component. This is the uncertainty that we will examine here.

TWO SOLAR FORCING CASES



NH TEMPERATURE RESPONSE

(comparison of two solar forcing possibilities)

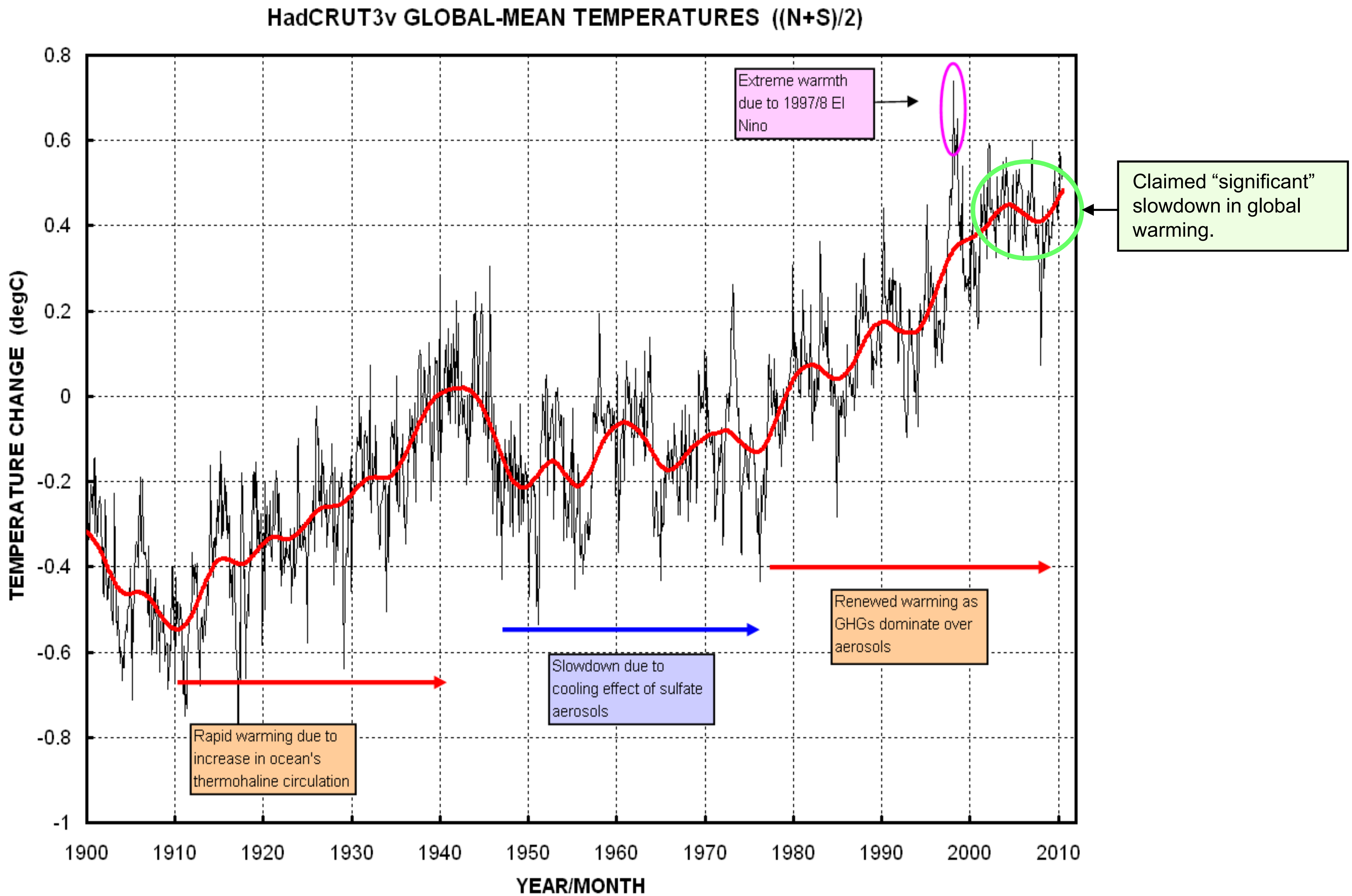


Does the inclusion of the low-frequency ("secular") solar component improve the fit?

From: Foukal, P., Fröhlich, C., Spruit, H. and. Wigley, T.M.L., 2006: Physical mechanisms of solar luminosity variation, and its effect on climate. *Nature* **443**, 161–166.

APPLICATION TO 20th CENTURY CLIMATE CHANGE

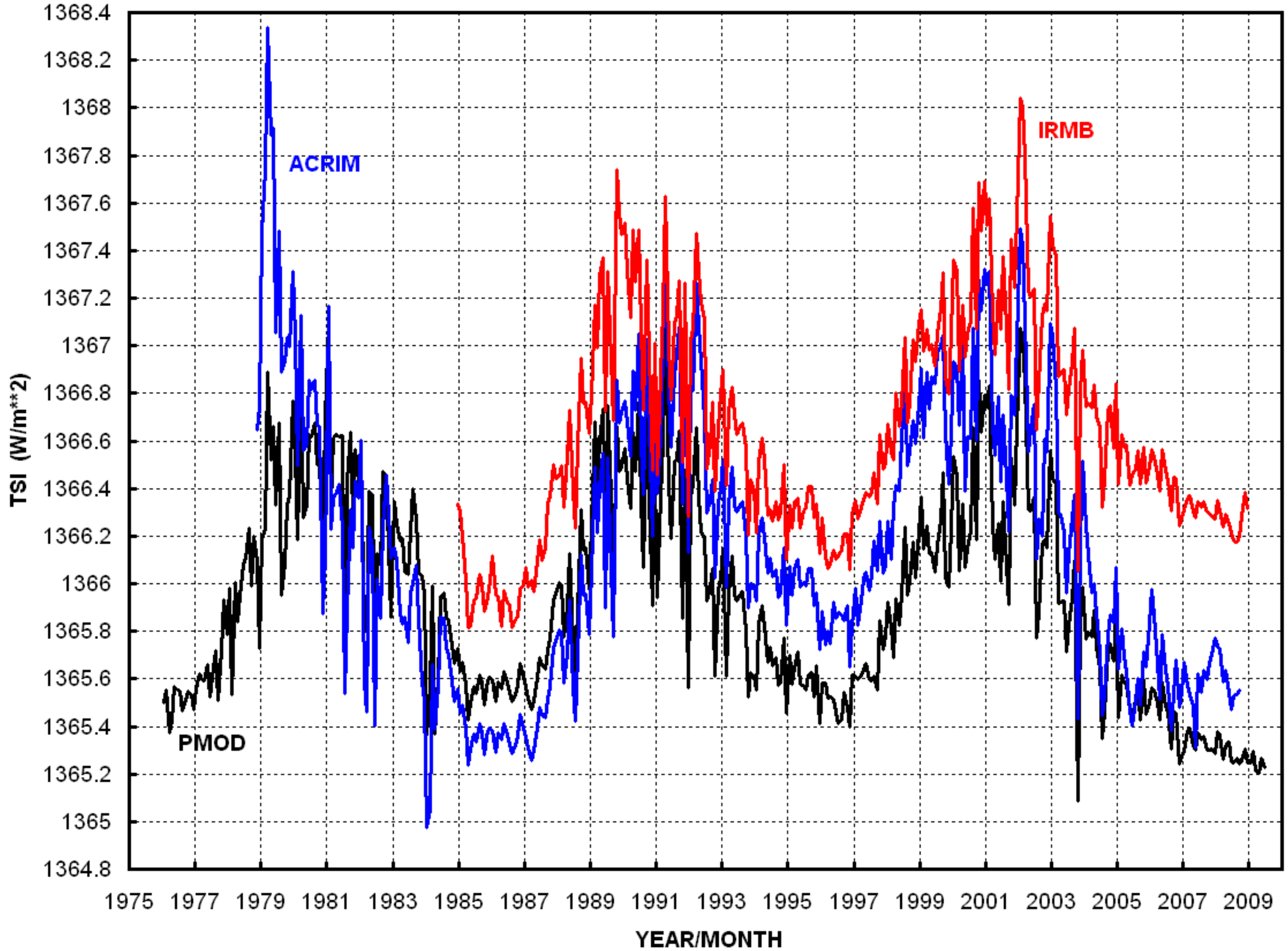
RECENT CHANGES IN GLOBAL-MEAN TEMPERATURE



EFFECT OF TSI CHANGES

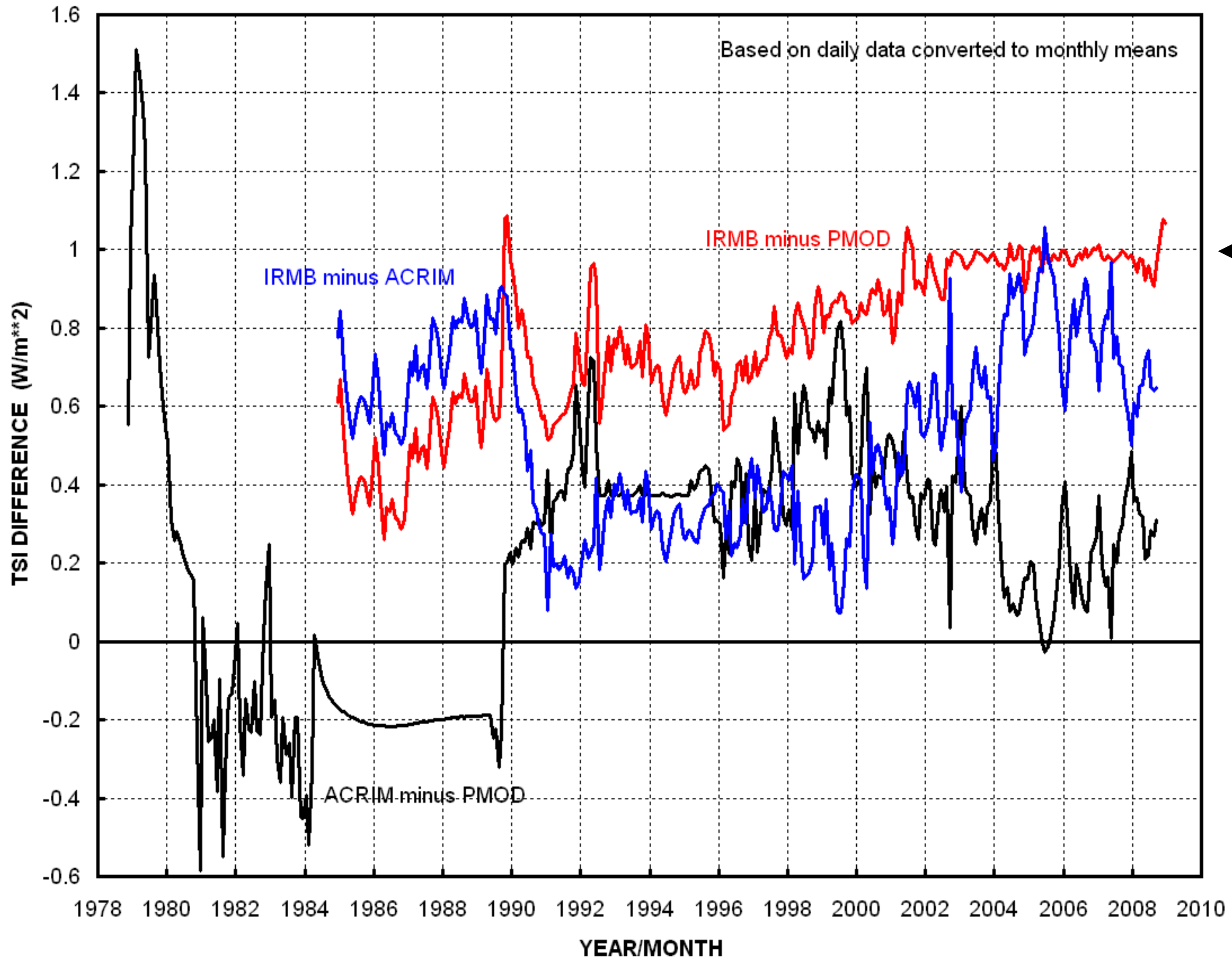
The satellite TSI record is a composite of data from different satellites. Three composites have been produced, which differ noticeably from each other.

COMPARISON OF DIFFERENT TSI COMPOSITES (monthly means)

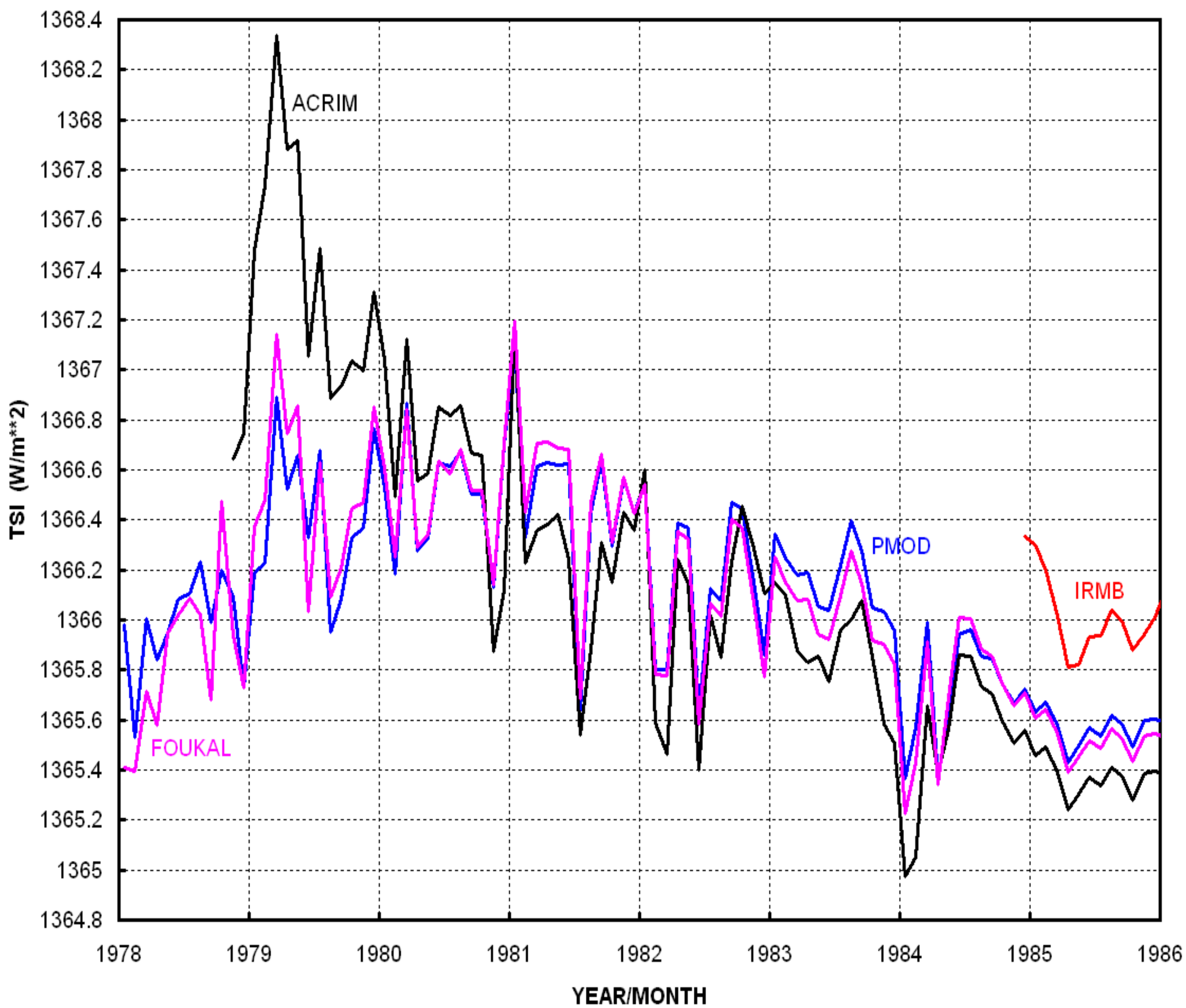


Active **C**avity **R**adiometer **I**rradiance **M**onitor/ **P**hysicalisch-**M**eteorologische **O**bservatorium **D**avos/
Institut **R**oyal **M**eteorologisches **B**elgique

DIFFERENCES BETWEEN DIFFERENT TSI COMPOSITES



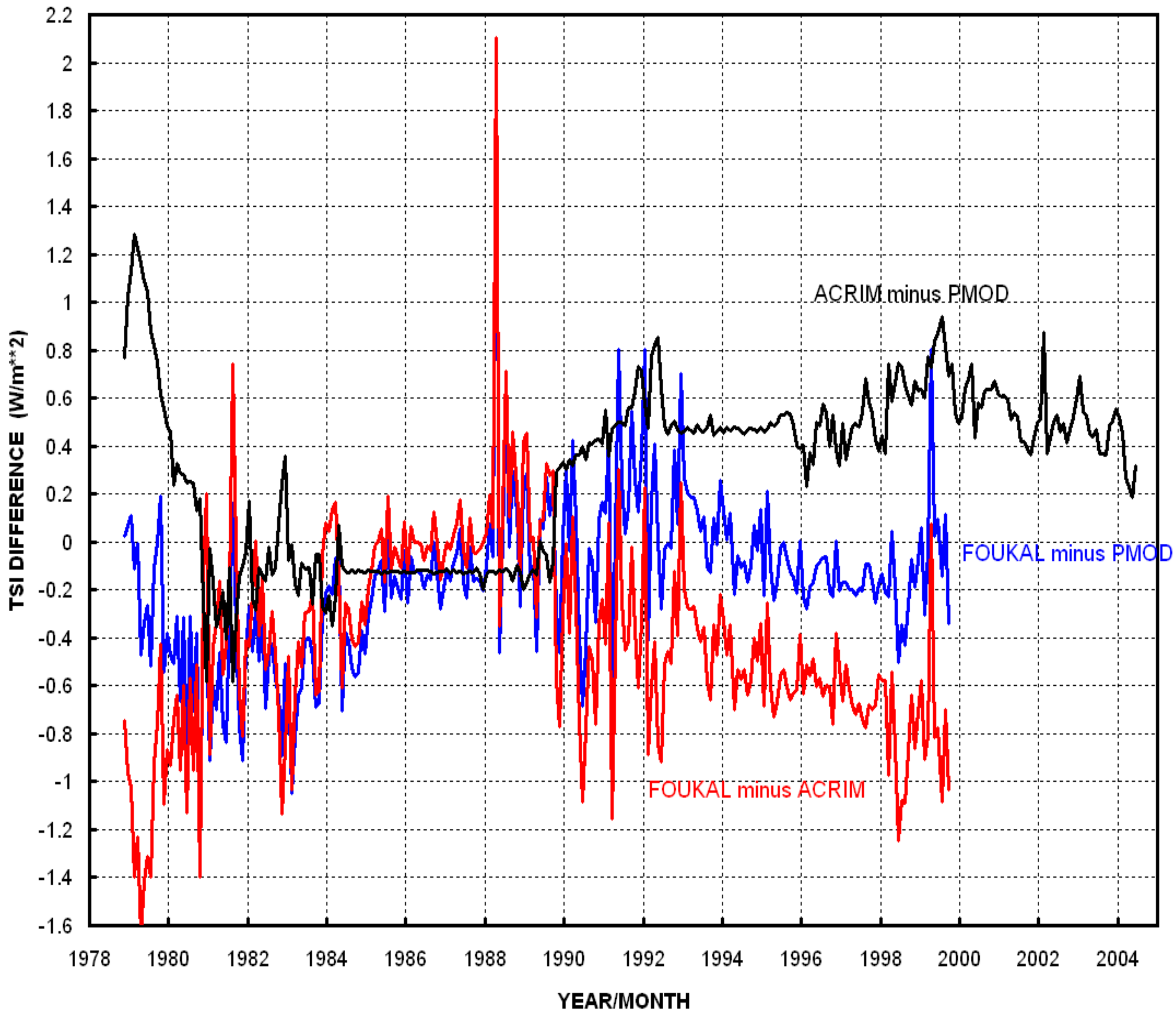
NOTE: 1 W/m2 TSI = 0.175 W/m2 forcing. The temperature effect of this difference would be small. The issue, however, is the difference in the changes or trends, where the effects would be even smaller.



In my climate model runs I use a composite of Foukal's reconstruction and PMOD. For the overlap period, Foukal and PMOD are very similar (as can be seen here). I use Foukal to Nov. 1978, then PMOD.

Foukal, P., 2002: A comparison of variable solar total and ultraviolet outputs in the 20th century. *Geophys. Res. Letts* **29**, 4377–4380, doi:10.1029/2002GL015474.

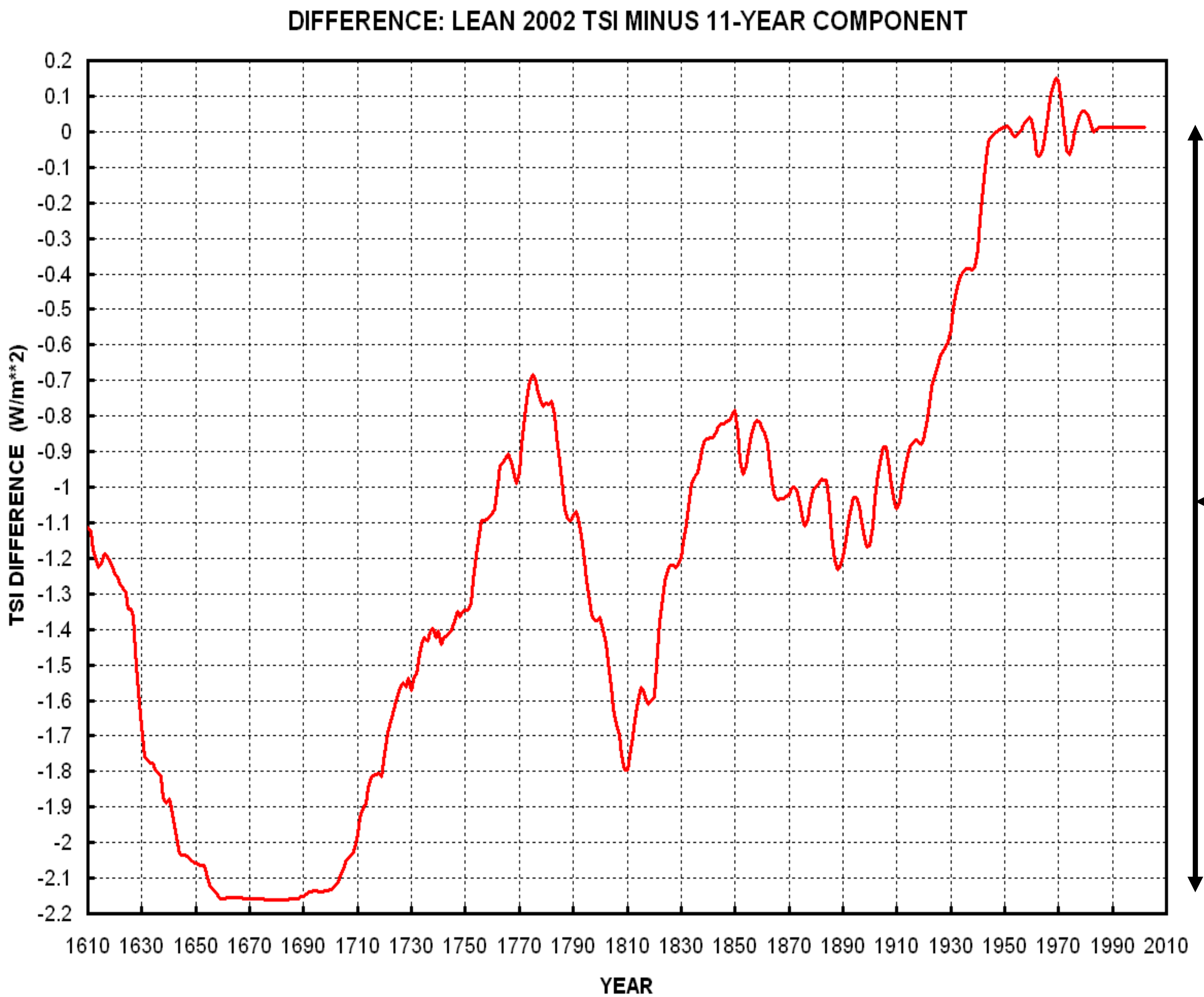
TSI DIFFERENCES COMPARED TO FOUKAL



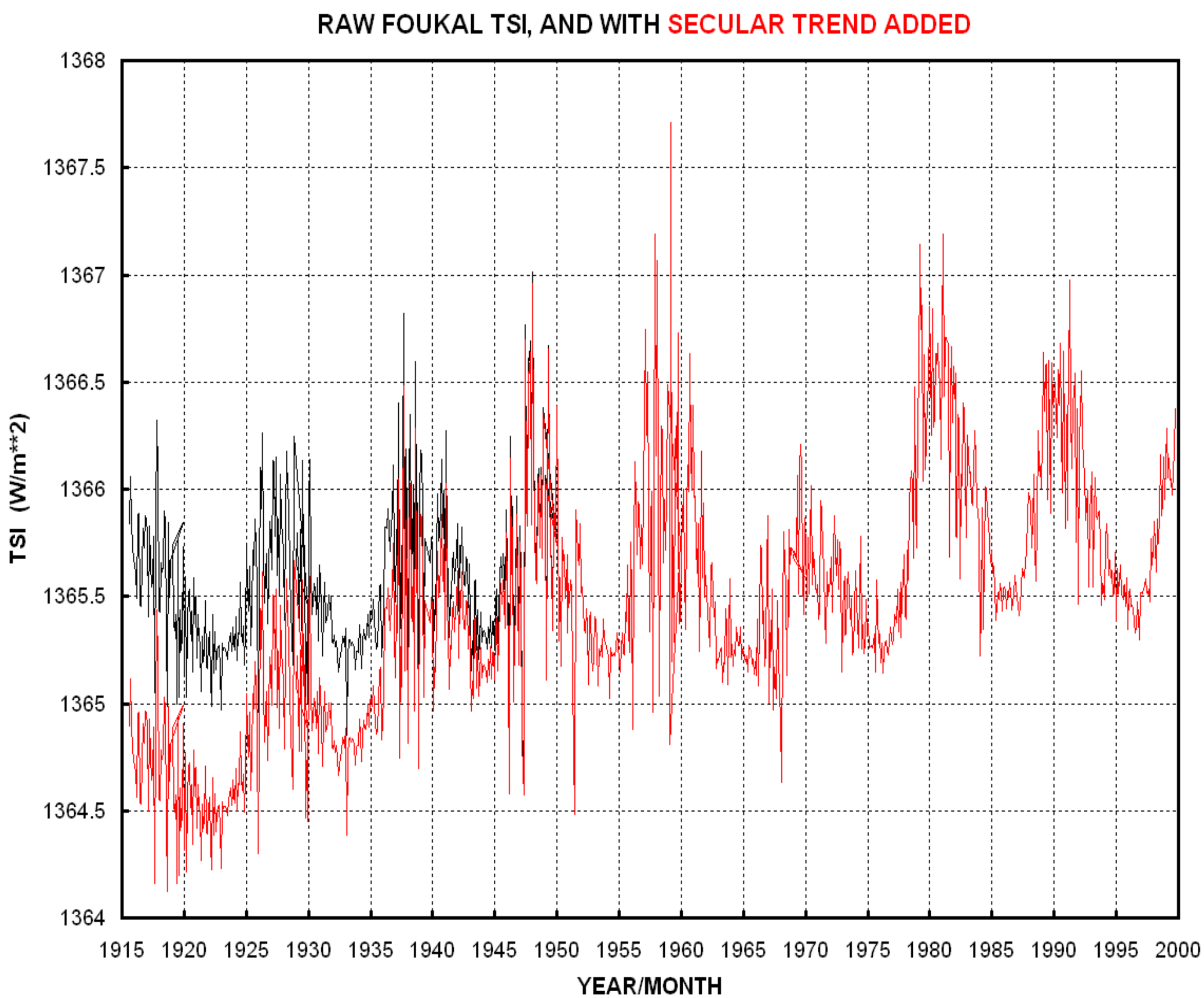
The climate effect of the Foukal-PMOD differences is negligible.

THE SECULAR TREND ISSUE

The Foukal record has no secular trend. There is uncertainty about the magnitude of the secular component. At one extreme, the secular component is thought to be negligible. The other extreme is epitomized by Lean (2000, 2002) – see next slide. More recent work (Wang et al., 2005) has a secular component about half way between these extremes.



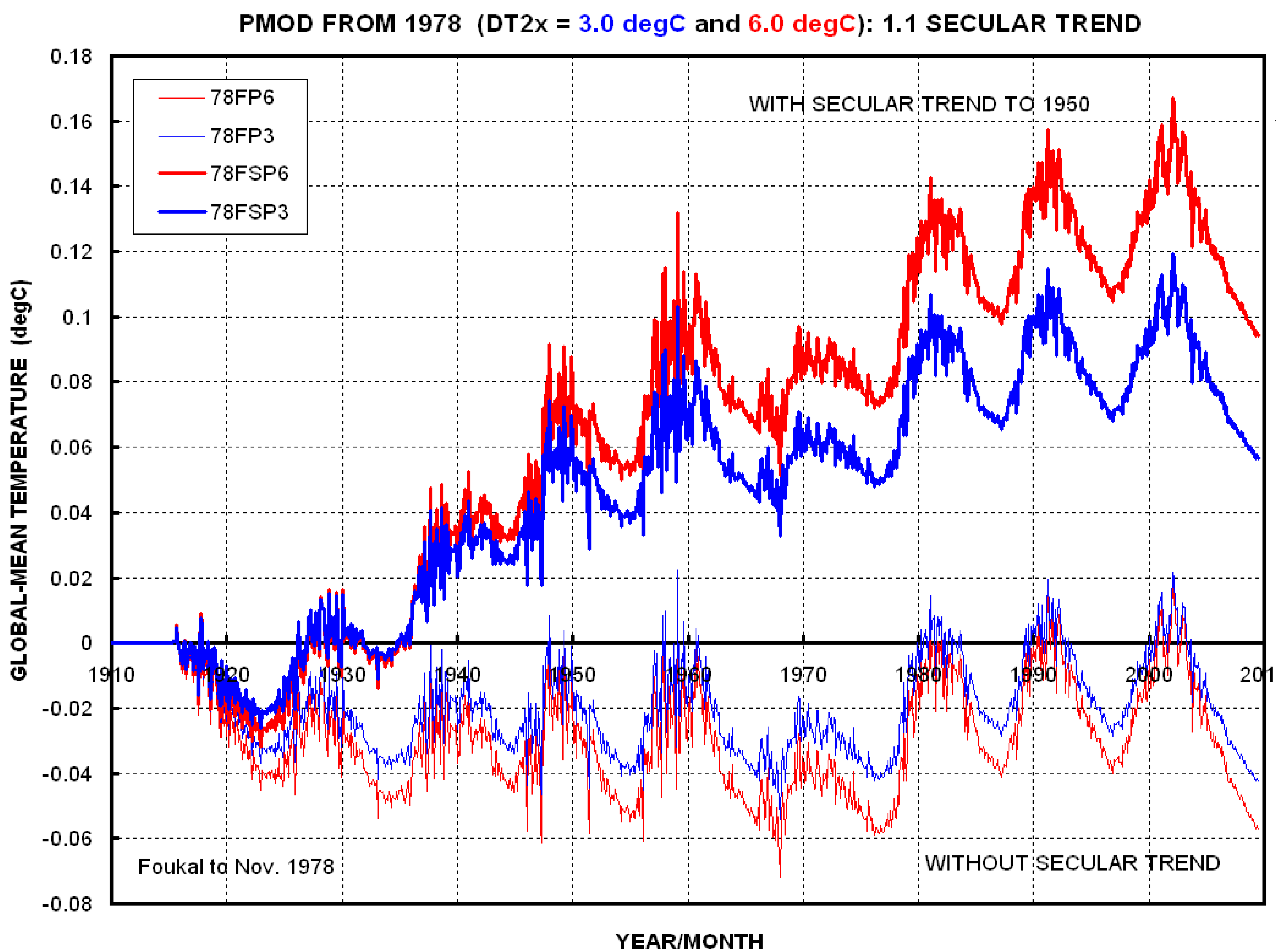
Lean (2002) secular component. In terms of radiative forcing, this difference is 0.38 W/m2. In Wang et al., the secular term is considerably smaller



To assess the sensitivity of results to the secular component I consider three cases, one where there is no secular component, and two where there is a secular component, either from Lean et al. (2002) or from Wang et al. (2005).

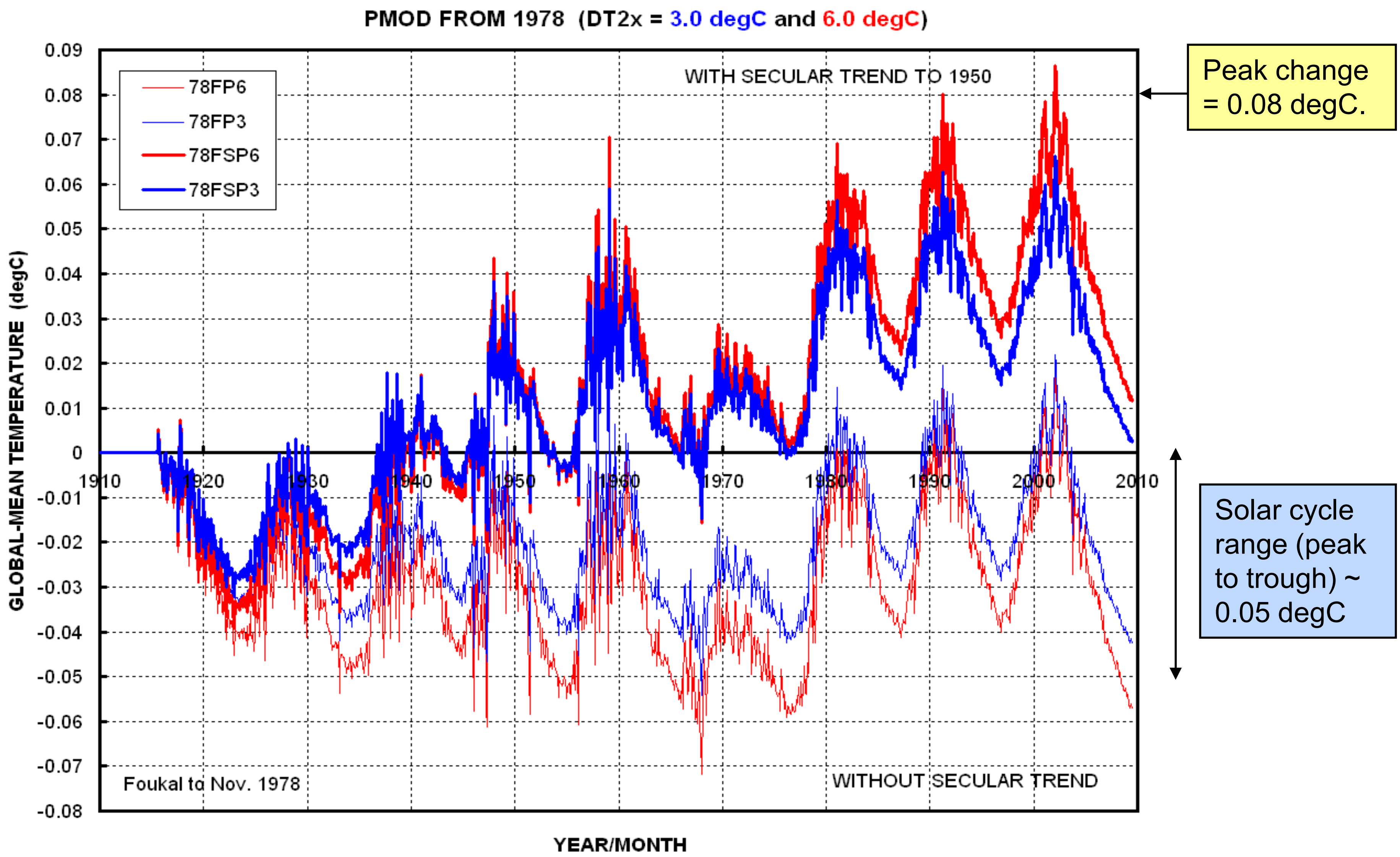
The Wang et al. case is shown here. The Lean et al. case has about twice the secular trend.

RESPONSE TO TSI FORCING: Lean et al. secular trend

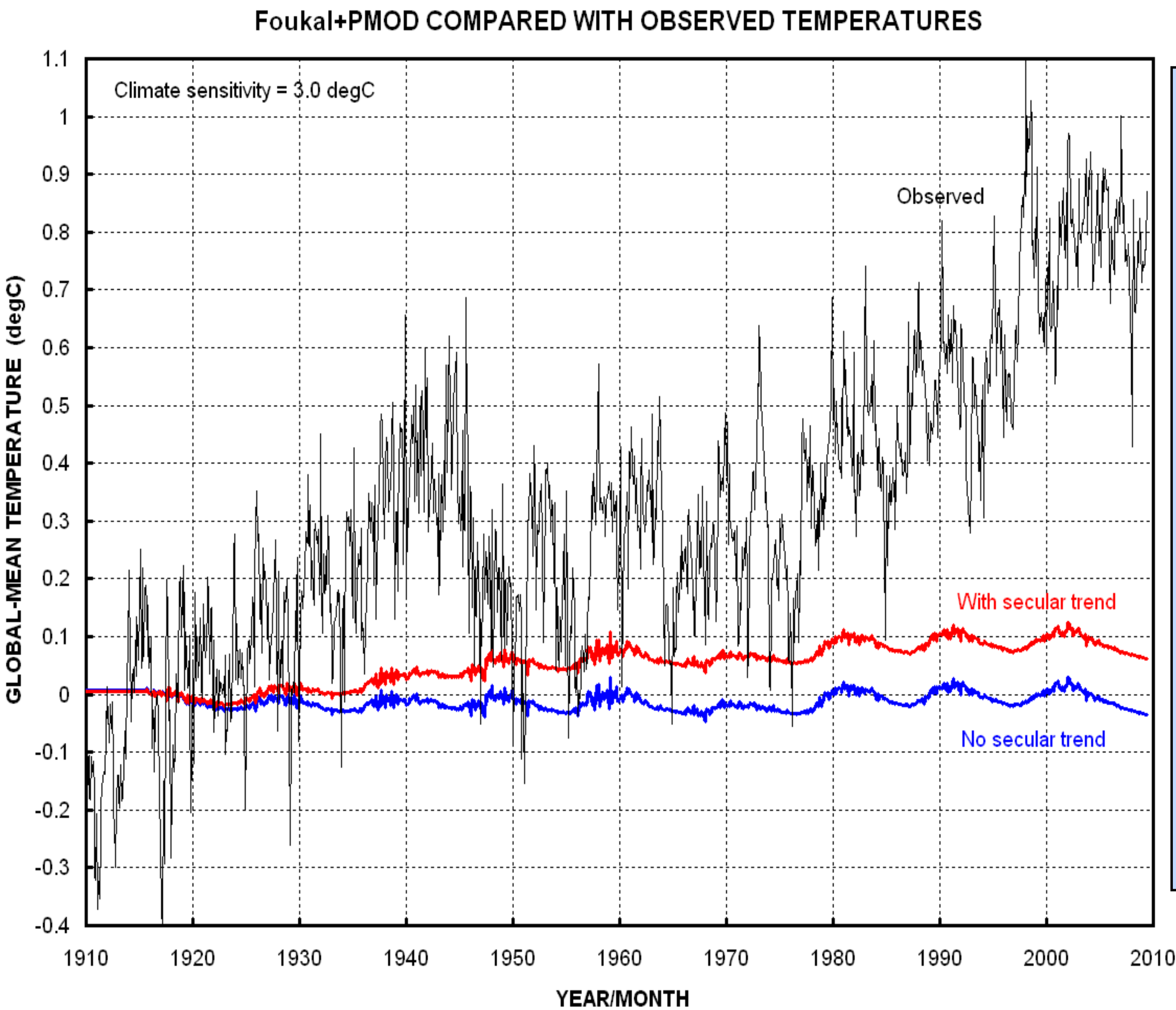


Peak change = 0.16 degC.

RESPONSE TO TSI FORCING: Wang et al. secular trend



RESPONSE TO SOLAR FORCING COMPARED TO OBSERVATIONS



POINTS TO NOTE:

(1) The contribution from direct TSI forcing to 20th century warming is close to zero.

(2) This result does not depend on the climate sensitivity, nor on the assumed secular trend

(3) The direct TSI contribution to early 20th century warming is also very small.

(4) TSI-induced cooling since 2000 (0.06 degC) partly explains the observed warming slowdown.

Wang et al. secular trend.

SO … HOW DOES ONE EXPLAIN THE EARLY 20th CENTURY WARMING?

The conventional explanation is that it was due to solar forcing. This appears to be wrong.

In 1987, Wigley and Raper suggested it could be due to an increase in the ocean's thermohaline circulation, specifically, a change in the rate of formation of North Atlantic deep water.

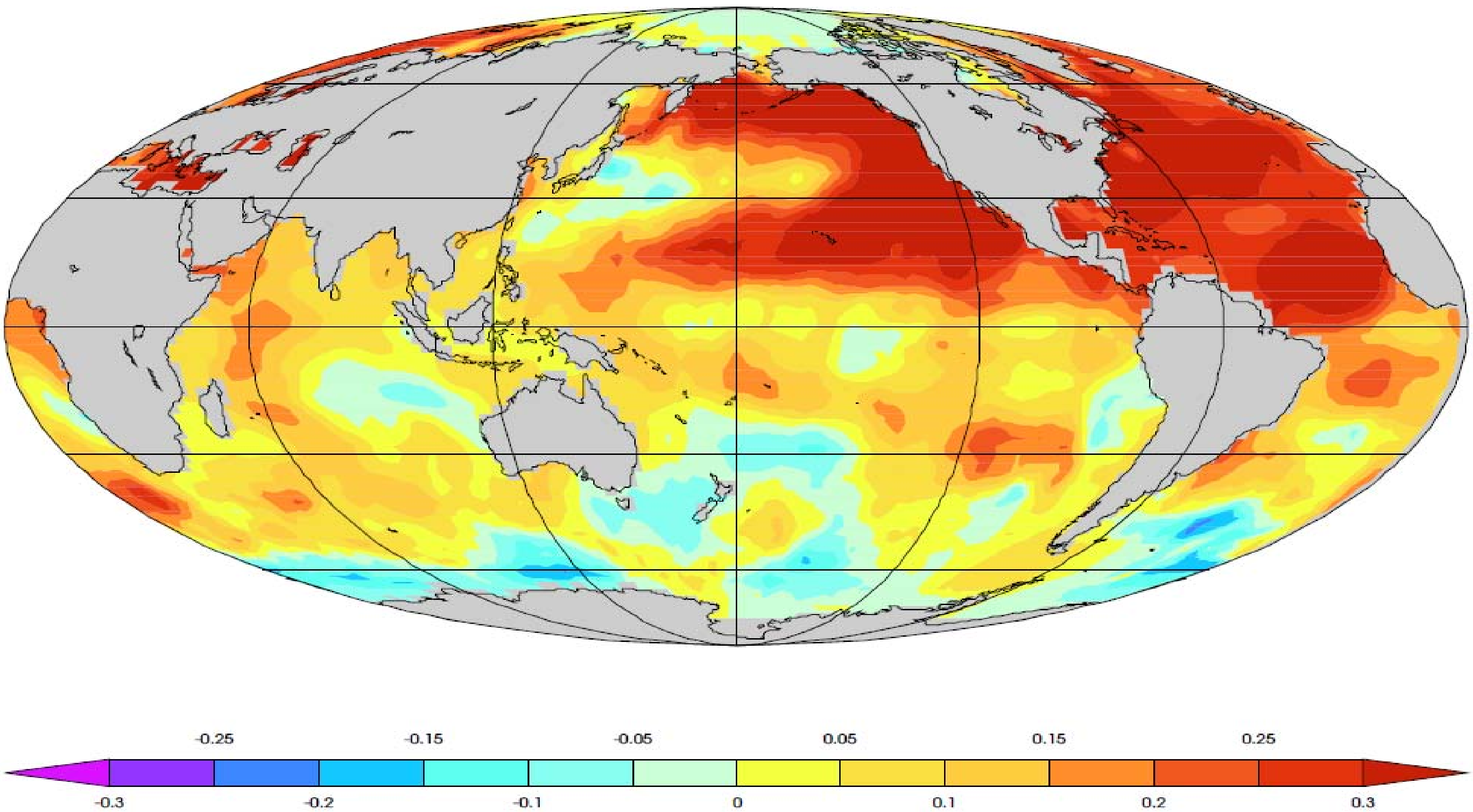
This idea was supported by the work of Schlesinger and Ramankutty (1995).

The pattern of warming supports this idea, and the effect is quantitatively realistic – see next slides.

Wigley, T.M.L. and Raper, S.C.B., 1987: Thermal expansion of sea water associated with global warming. Nature **330**, 127–131.

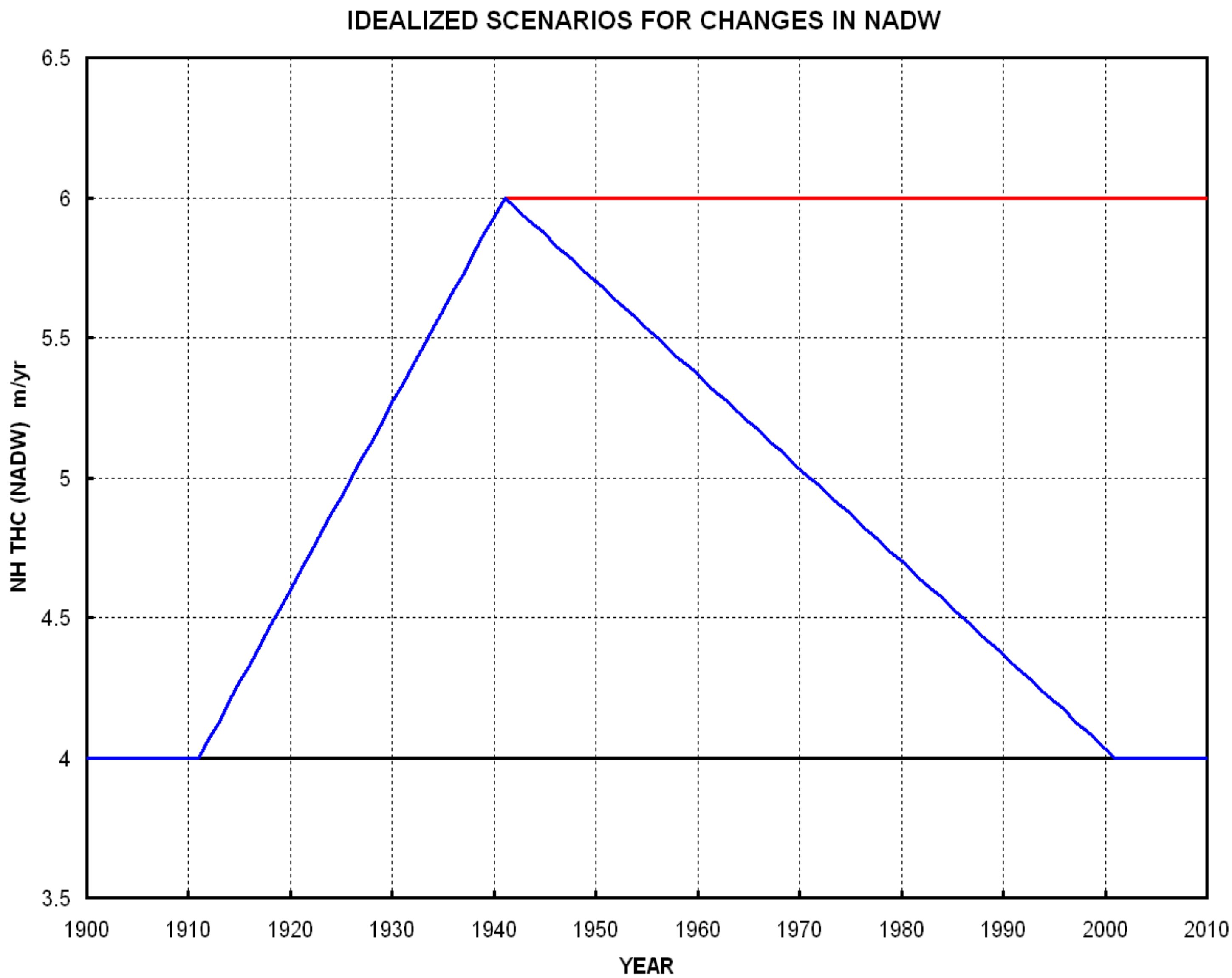
Schlesinger, M.E. and Ramankutty, N. 1994: An oscillation in the global climate system of period 65–70 years. *Nature* **367**, 723–726.

Linear temperature trends: Jan. 1910 – Dec. 1940

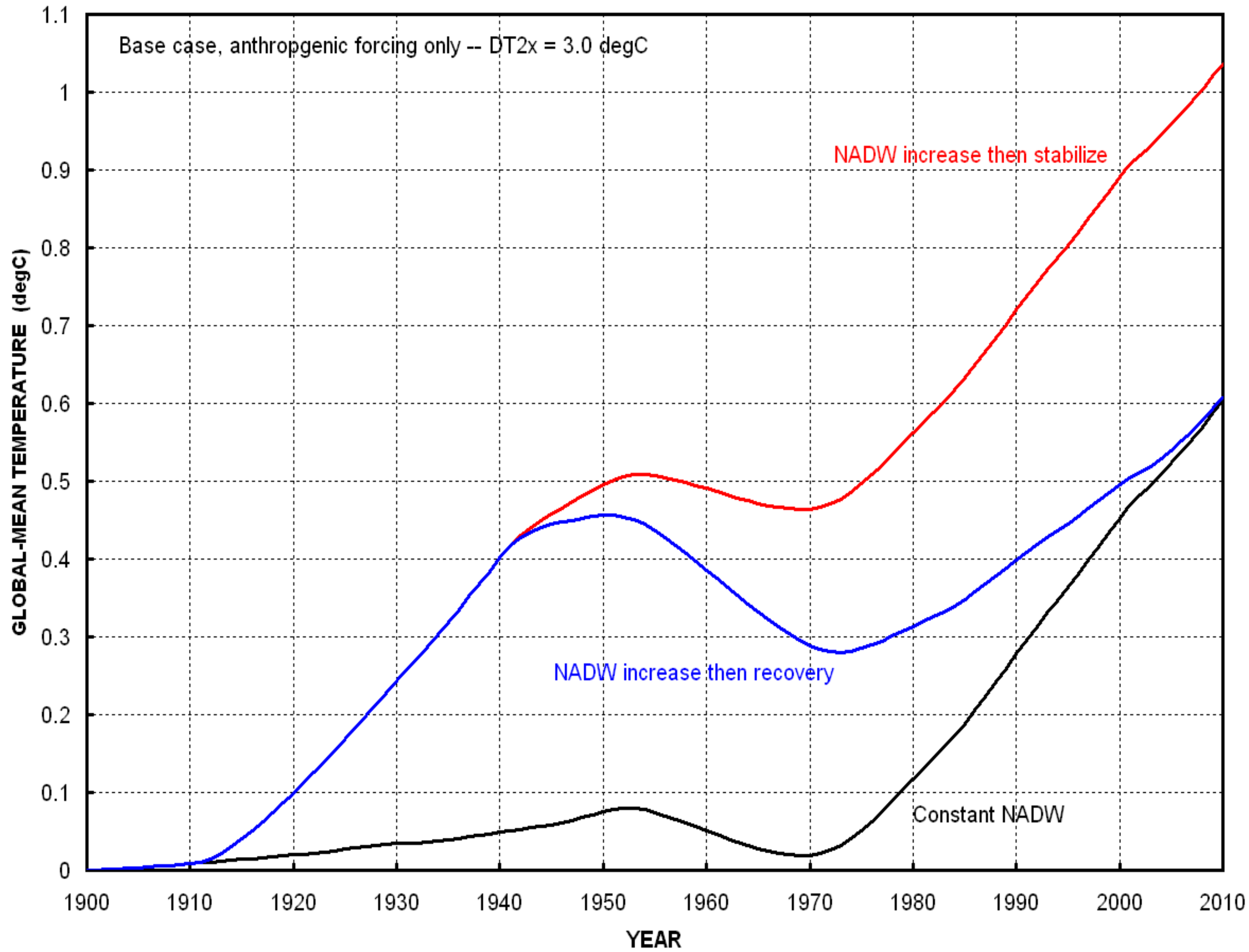


Trend in degC/decade

EFFECT OF A CHANGE IN NADW FORMATION RATE (1)



EFFECT OF A CHANGE IN NADW FORMATION RATE (2)



ISSUE: If this effect is real, are the NADW changes purely internal – or are they triggered by small external forcing changes?

CONCLUSIONS

The climate response to TSI forcing is only weakly dependent on the climate sensitivity.

Model simulations suggest that the effect of the Maunder Minimum on global-mean temperatures must be very small – perhaps negligible.

Results of model simulations depend on assumptions regarding the "secular" TSI trend (i.e., low-frequency changes that are not directly associated with the solar cycle). They are, however, only weakly dependent on these assumptions.

Over the 20th century, the total TSI-induced temperature trend is either near zero (no secular term), 0.06 degC (Wang et al. trend), or 0.12 degC (Lean et al. trend). In all cases the contribution to the observed warming trend is small.

For the early 20th century (1910 to 1940) warming trend, the TSI influence is also very small. The most likely cause of this warming is a change in NADW formation rate.