



Solar Variability, Earth's Climate and the Space Environment

Where are we now? Where next?

Doug Rabin
NASA Goddard Space Flight Center



Thanks!

To the Local Organizing Committee for wonderful organization and support

Dibyendu Nandi (Chair), Ravindra Belur, Wendy Chou, Lewis Fox, Silvina Guidoni, Bill Hiscock, Maria Kazachenko, Toni Lee, Dana Longcope, Piet Martens, David McKenzie (EPO Lead), Andres Munoz, Jiong Qiu, Lucas Tarr, and Keiji Yoshimura

To the Scientific Organizing Committee

Judit Pap (Chair), Raimund Muscheler (Co-chair), Werner Schmutz (Co-chair), Susan Avery, Tom Bogdan, Joe Davila, Piet Martens, Kalevi Mursula, Dibyendi Nandi, Dean Pesnell, Doug Rabin, Jan Rybak, Kazunari Shibata, Drew Shindell and Gerard Thuillier

To MSU for friendly hospitality and a first-class venue

To the Workshop sponsors for making SVECSE possible

To all the participants for stimulating talks, posters, and debate

In a Nutshell

- The variability of the Sun affects Earth's climate on timescales 10^1 – 10^{10} y.
- The variability of the Sun affects Earth's space environment every hour of every day.
- Today, we can't (by consensus) predict the solar activity cycle to any useful degree
 - Near-term prospects for improvement using empirical precursors and semi-empirical models are real but “modest.”
 - Reconstructions of past solar activity over millennia appears to be converging and provide useful guidance for the “envelope” of what the Sun has done.
 - Studying other late-type dwarf stars is important for dynamo theory; finding strict “solar analogs” is tricky at best.
 - Basic work on dynamo theory is far from producing a self-consistent model, yet is encouraging (to me).
- Data assimilation models of the heliosphere and space are making rapid progress.

In a Nutshell (continued)

- It is clear from *Climate Change 2007* (IPCC) that consideration of solar total and spectral irradiance variations is now an accepted part of climate change modeling.
- Earth surface response can be understood as arising from the direct radiative heating of the Sun amplified by positive feedback processes well studied in GHG warming problems.
- Strong solar activity strongly warms the polar stratosphere, but the solar signal is only revealed by controlling for competing effects of comparable magnitude (QBO, ENSO).
- The 11-year solar signal in the upper stratosphere leads to circulation changes in the lower stratosphere and down to the troposphere at polar and equatorial latitudes.
- Mechanisms proposed to couple solar-induced perturbations of the stratosphere downward to the troposphere are not adequately established.

In a Nutshell (continued)

What should we do to promote scientifically productive interactions between the solar and climate communities?

- Improve reference spectral irradiance and quantify range of spectral variation for different levels of activity
- Use GCMs to investigate effects of solar infrared irradiance variations out of phase with the solar cycle.
- Improve identification and understanding of solar cycle effects in regional climate data, taking care to establish statistical significance in the presence of internal climate variations.
- Continue to investigate indirect stratosphere-troposphere coupling mechanisms.
- Refine reconstructions of past solar activity to bound what the Sun has done, guarding against false convergence due to inbreeding of models.*
- Continue to study solar structure to understand what the Sun might be capable of doing; obtain new types of observations (e.g., radius).

* Past performance is no guarantee of future results.

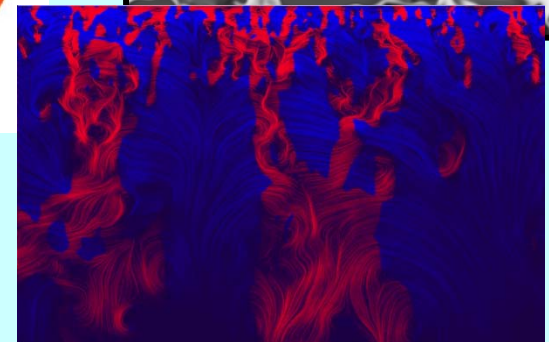
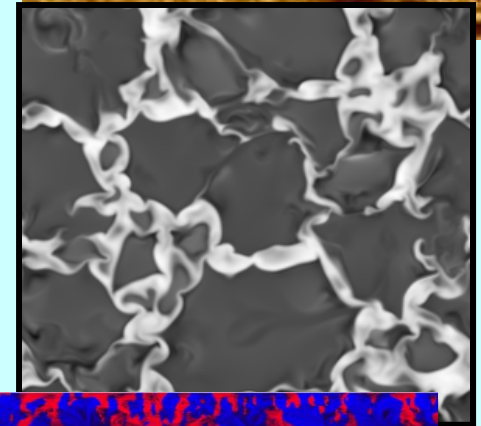
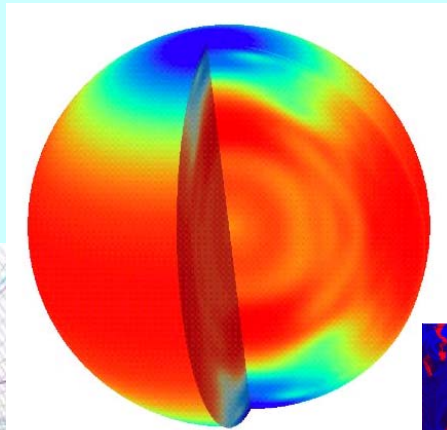
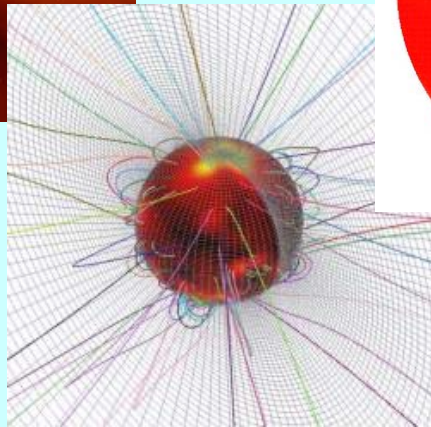
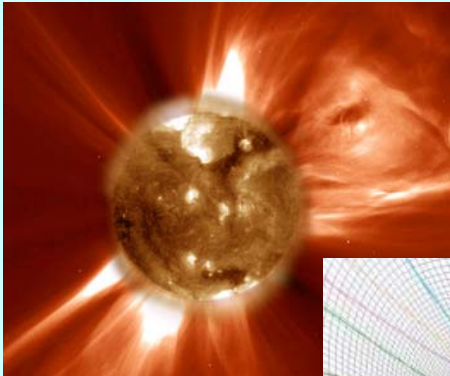
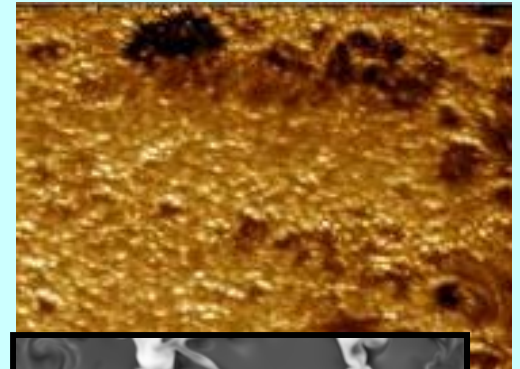
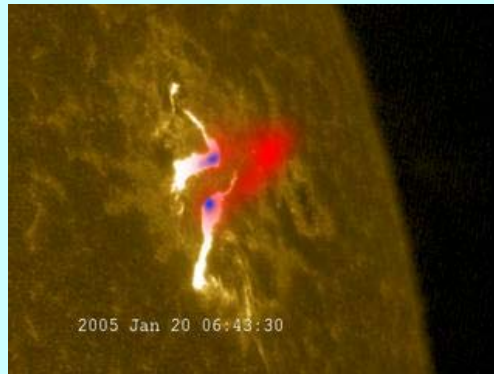
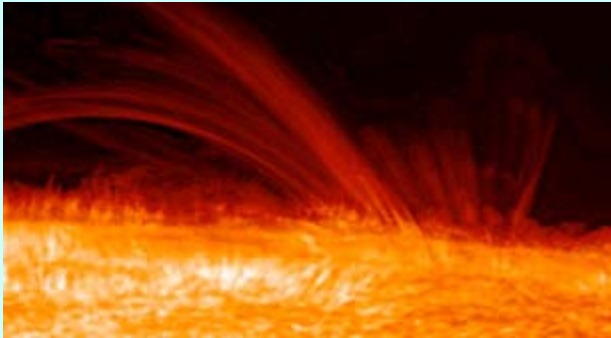
Apologia

- At the request of the SOC chair, I will not try to summarize the entire workshop ...
 - It would take too long.
 - Why hear at second hand everything you've heard directly?
- ... but will instead stress topics related to the Sun-Climate connection at the expense of solar surface processes, space weather, and upper atmospheric effects.
 - Not because these topics are less important ...
 - ... but because they are frequently discussed in other venues.
- *The material that follows was assembled from workshop participants, for which I thank them, and other sources. The proper attribution for a figure was not always evident, for which I apologize. None of the work is mine!*

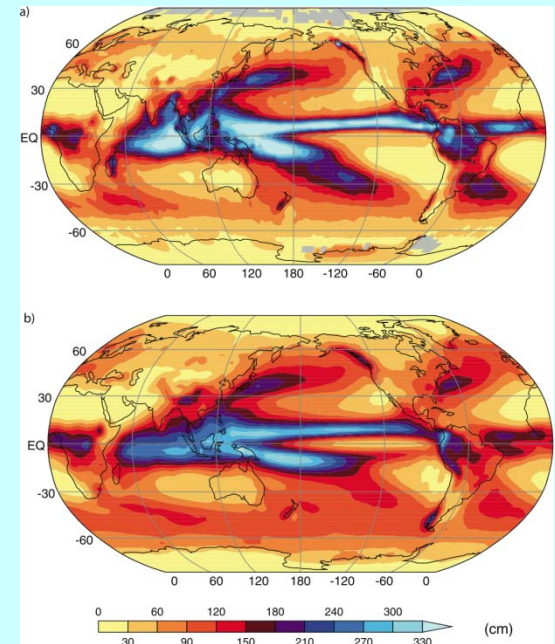
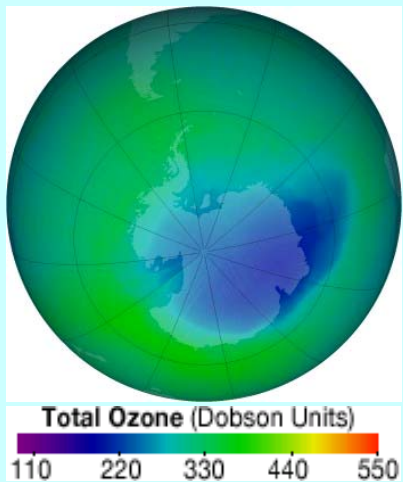
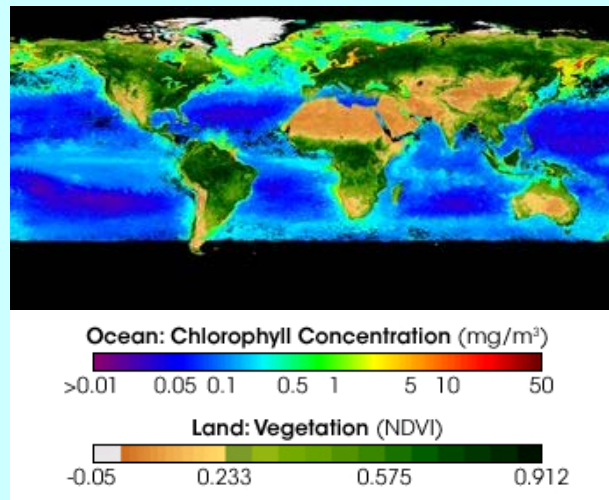
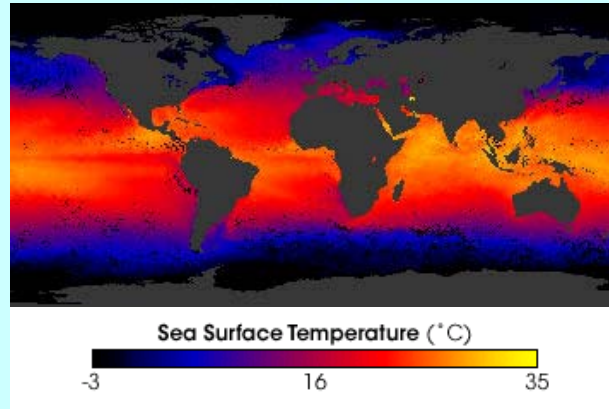
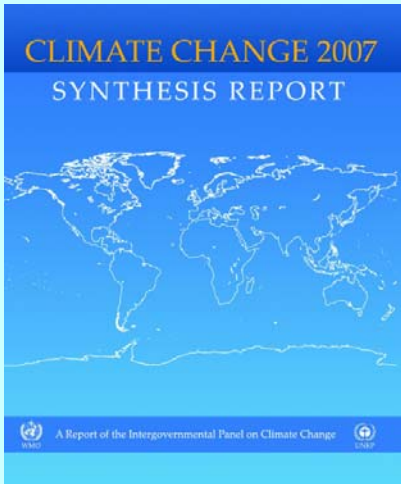
Outline

- Introduction
- Helioseismology
- Solar Dynamo
- Solar Cycle Prediction
- Reconstructions of Past Solar Activity
- Climate Response to Solar Forcing
- Where Next?

A Golden Era of Solar and Heliospheric Physics

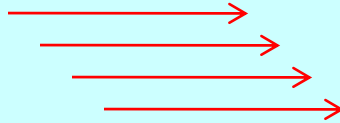


A Golden Era of Climate Science



Annual mean precipitation (cm), observed (a) and simulated (b), based on the multi-model mean. The Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) observation-based climatology for 1980 to 1999 is shown, and the model results are for the same period in the 20th-century simulations in the MMD at PCMDI.

They laughed when the Sun claimed a role.



What, Me
Worry?

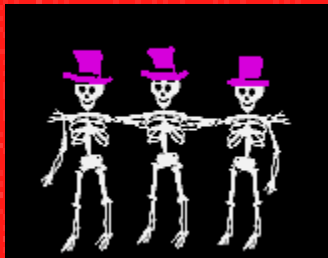
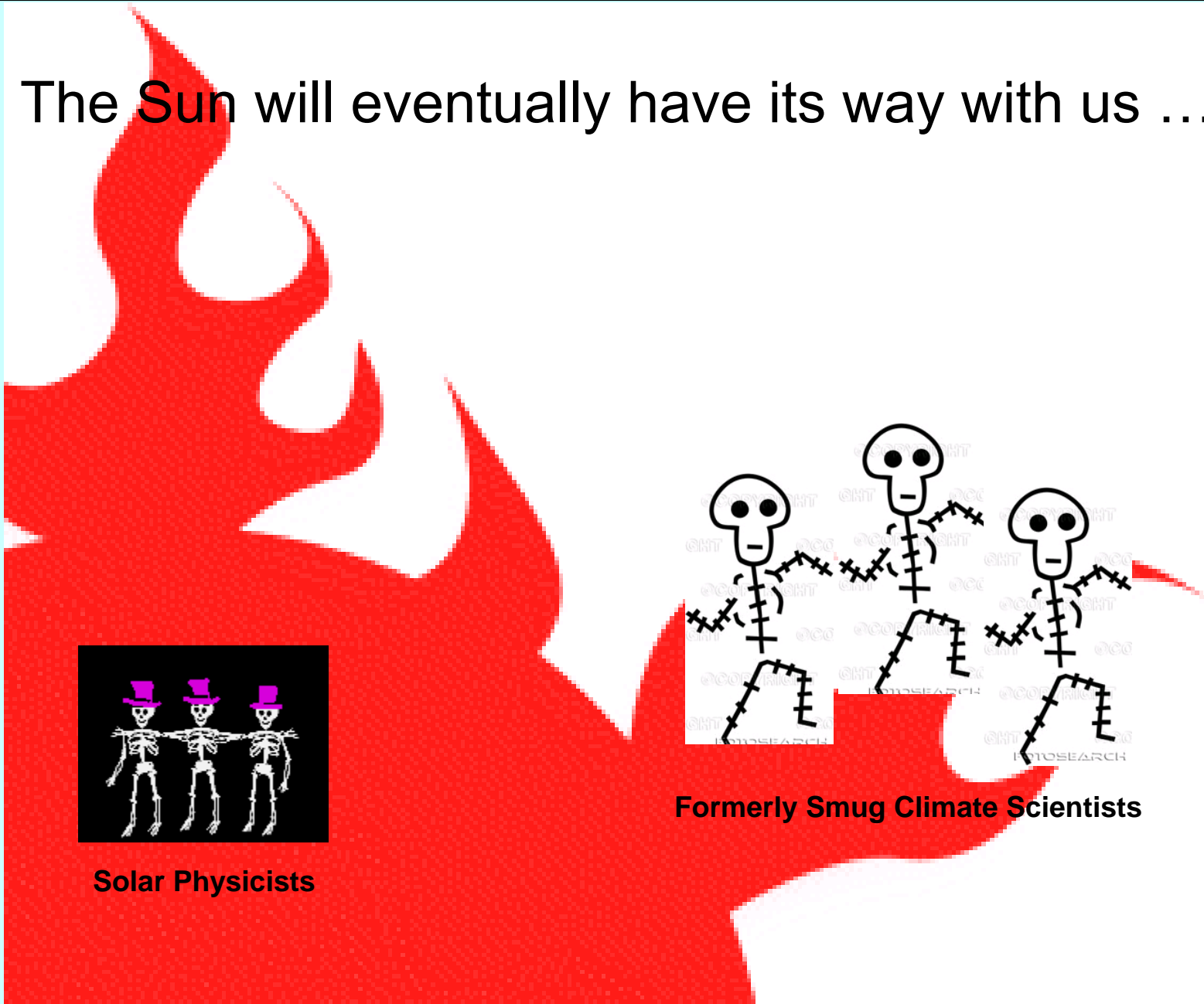


Solar Physicists

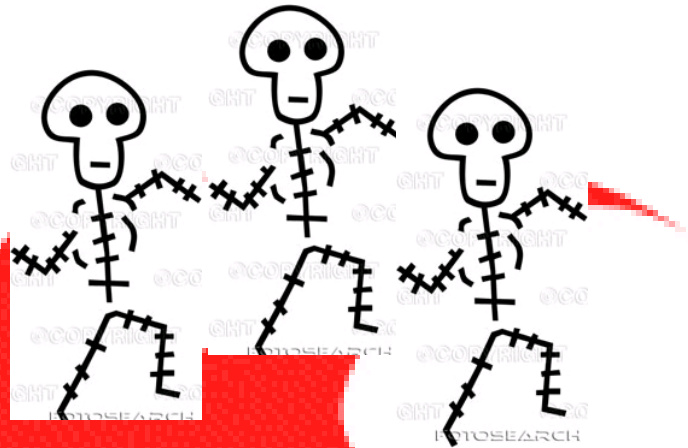


Climate Scientists

The Sun will eventually have its way with us ...

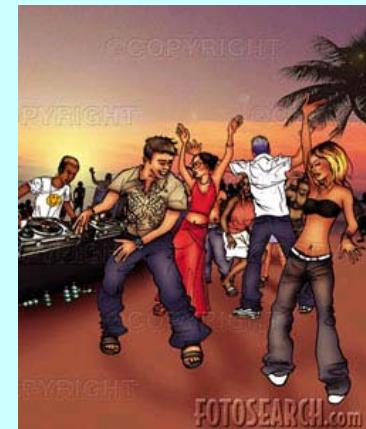


Solar Physicists



Formerly Smug Climate Scientists

... but in the meantime



Solar Physicists

Mutual Friends

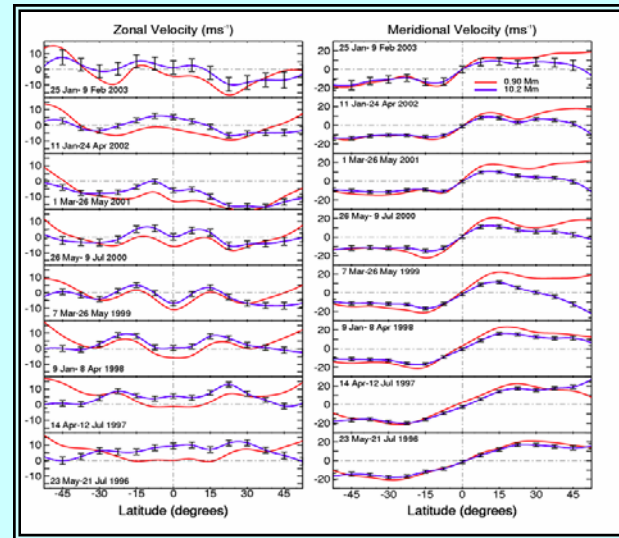
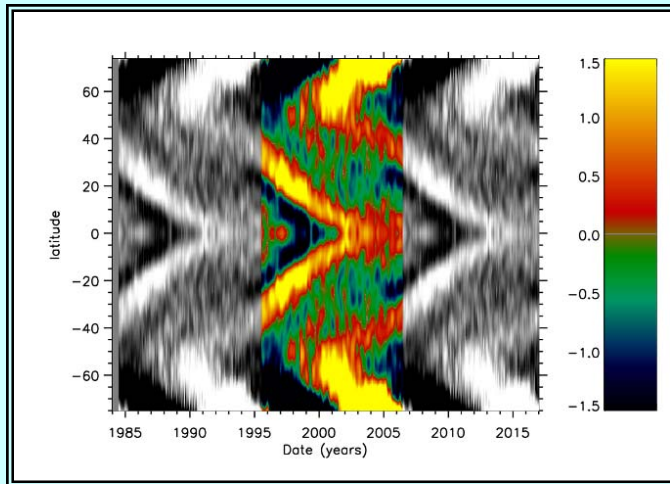
Climate Scientists

Outline

- Introduction
- Helioseismology
- Solar Dynamo
- Solar Cycle Prediction
- Reconstructions of Past Solar Activity
- Climate Response to Solar Forcing
- Where Next?

Helioseismology

Reveals solar interior structure to a degree Babcock could scarcely have imagined*



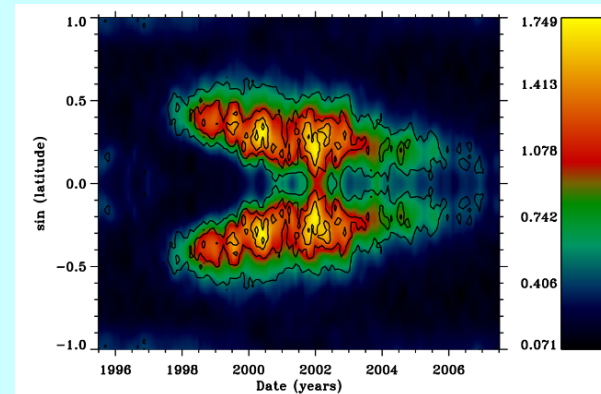
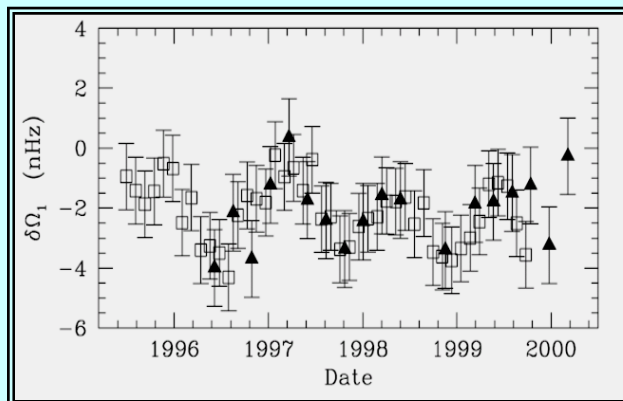
2003

2001

1999

1997

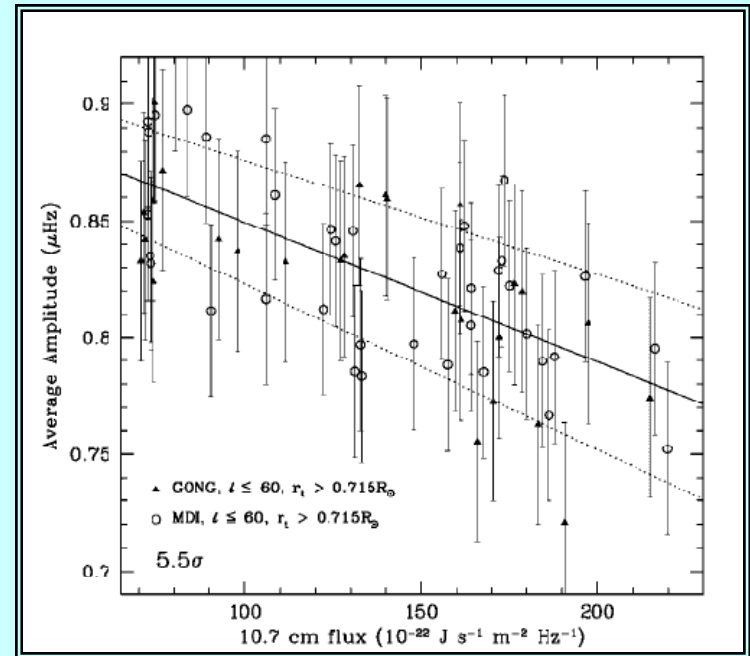
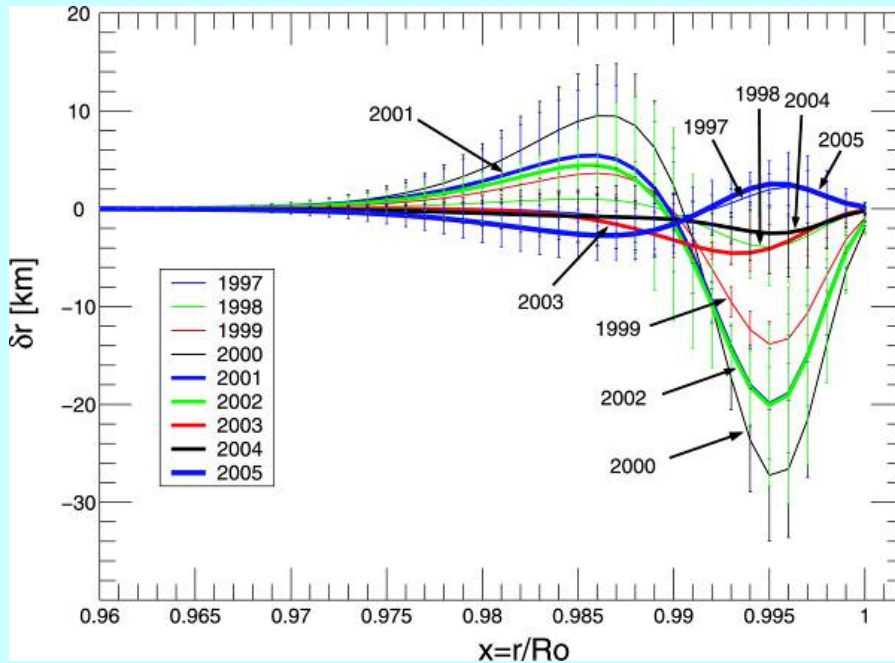
- “The observations uncover changing flow patterns deep inside the convection zone.”



* ... but lived to see

Helioseismology

- “Structural change is still hard to see.”



He ionization zone signature

Outline

- Introduction
- Helioseismology
- **Solar Dynamo**
- Solar Cycle Prediction
- Reconstructions of Past Solar Activity
- Climate Response to Solar Forcing
- Where Next?

Why is it so difficult to model the solar dynamo?

- Large separation in time and length scales (large Re , Rm , strong stratification)
 - Geodynamo: no stratification, $Rm < 1000!$
- Major dynamo ingredients are identified but location and relative contributions are not well known
 - Poloidal \rightarrow toroidal field (Ω -effect)
 - Differential rotation (observed)
 - Toroidal \rightarrow poloidal field (α -effect)
 - Babcock-Leighton (observed)
 - Convective (uncertain)
 - Tachocline (uncertain)
 - Transport
 - Meridional flow (top layers of CZ)
 - Turbulent diffusivity (photosphere)
 - Turbulent pumping (uncertain)
- Surface magnetic fields: players or tracers?

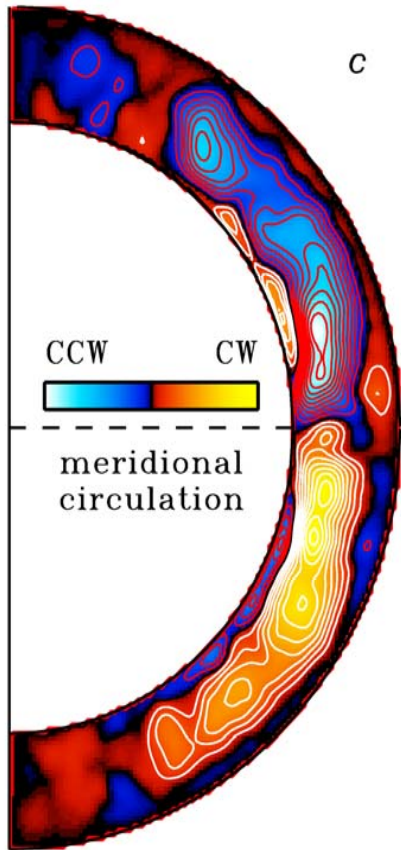
Solar dynamo – key questions

- Role of tachocline
 - Overshoot/tachocline dynamo
 - Ω and α effect in tachocline
 - Distributed dynamo
 - Interface dynamo
 - Ω effect in tachocline
 - α effect in convection zone
 - Convection zone dynamo
 - Ω effect, α effect in convection zone
 - Base of CZ/Overshoot: Flux storage
- Role of meridional flow
 - Surface: essential ingredient
 - Bulk of CZ: flow structure, magnetic diffusivity
- Origin of the alpha-effect
 - Convective α effect (classic mean field theory)
 - Tachocline instabilities (hydro + magnetic)
 - Babcock-Leighton mechanism
 - Rising flux tubes (magnetic buoyancy) + Coriolis force
 - Tilt angle of active regions (only observed α effect)
- What determines flux and field strength of dynamo?

Flux transport dynamo

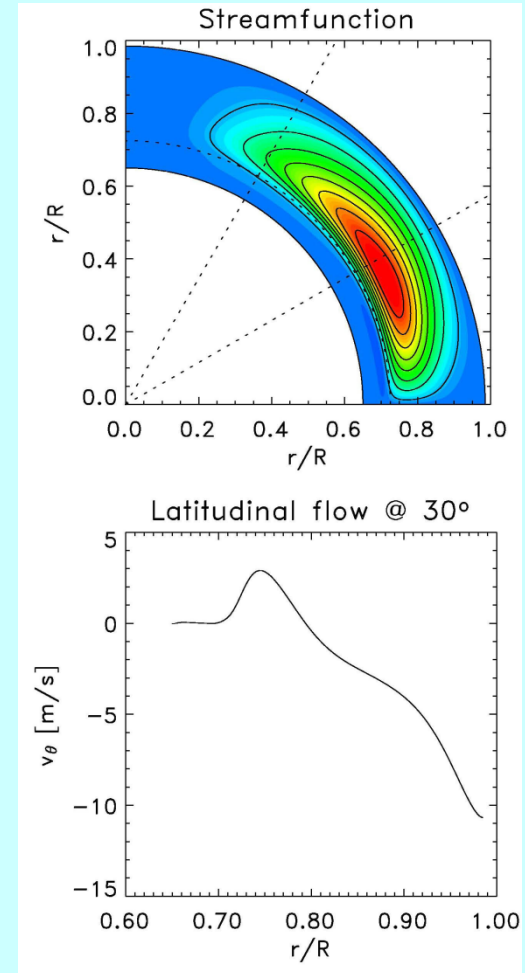
- Babcock-Leighton flux transport dynamo
 - most robust and promising mean field scenario for solar cycle
- Meridional flow structure seems to be a very reasonable assumption (limited observations + theoretical investigations)
- Can tolerate Lorentz force feedback
 - $B_{\max} < 15 \text{ kG}$ (100 kG impossible to transport by meridional flow)
- **Unknown amplitude of turbulent transport processes biggest weakness**
 - Parametrized in mean field models through scalar magnetic diffusivity:
 - $\eta < 10^{11} \text{ cm}^2/\text{s}$ (advection dominated regime)
 - $\eta \sim 1/3 v \text{ Hp}$ ($10^{12} - 10^{13} \text{ cm}^2/\text{s}$)
 - Flux transport dynamo requires at least factor of 10 less magnetic diffusivity to operate
 - Not impossible, but also not evident from any theoretical or numerical investigation
 - Theory of DR: $v \sim 1/3 v \text{ Hp}$ quite reasonable
 - Additional turbulent transport
 - Turbulent pumping (downward and equatorward)
 - Can partially compensate for effects of high diffusivity
 - Substantial effect on flux transport dynamos (Guerrero, Dal Pino 2008)

Meridional flow structure



3D simulation
Miesch et al. (2008)

- Poleward at surface (observed)
- Return flow not observable through helioseismology
 - 50 Mm depth still poleward (Gizon & Rempel 2008)
- Mass conservation
 - Equatorward at base
- Theory:
 - Meanfield models
 - Typically equatorward
 - 3D simulations
 - Most recent (high res.): Equatorward
 - Low resolution runs: Multiple flow cells
- Overall: Equatorward flow at base of CZ very reasonable



Meanfield model
Rempel (2005)

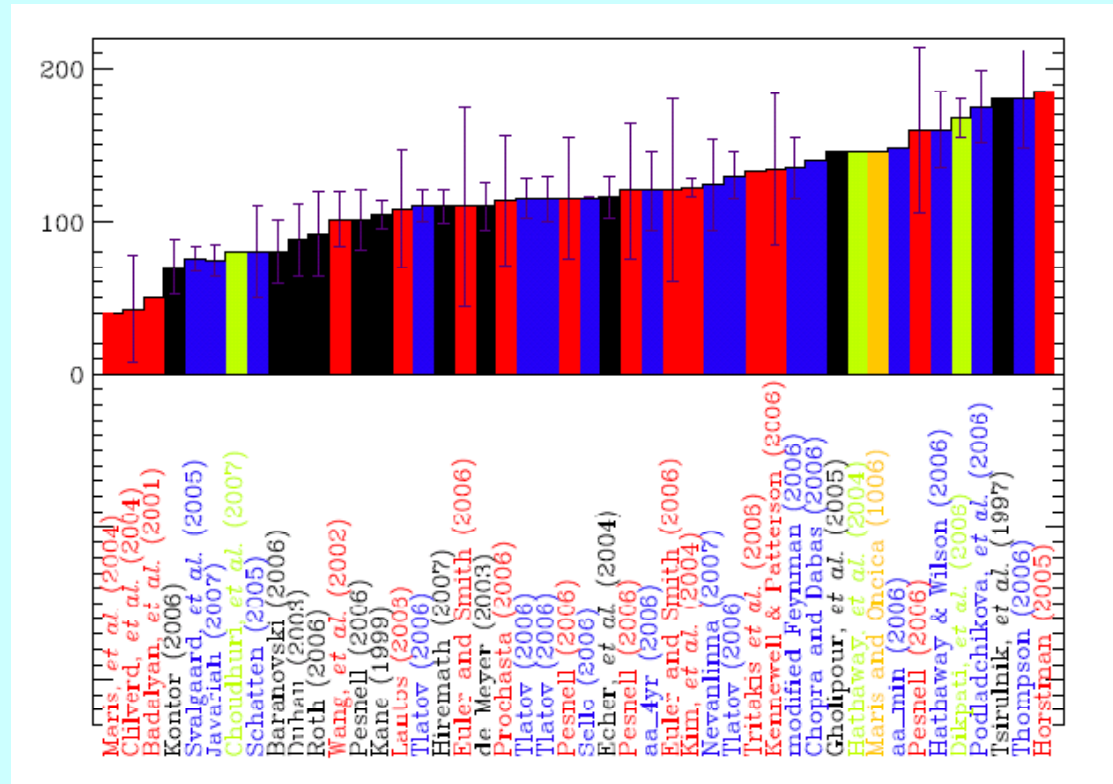
Outline

- Introduction
- Helioseismology
- Solar Dynamo
- **Solar Cycle Prediction**
- Reconstructions of Past Solar Activity
- Climate Response to Solar Forcing
- Where Next?

Solar Cycle "Prediction"

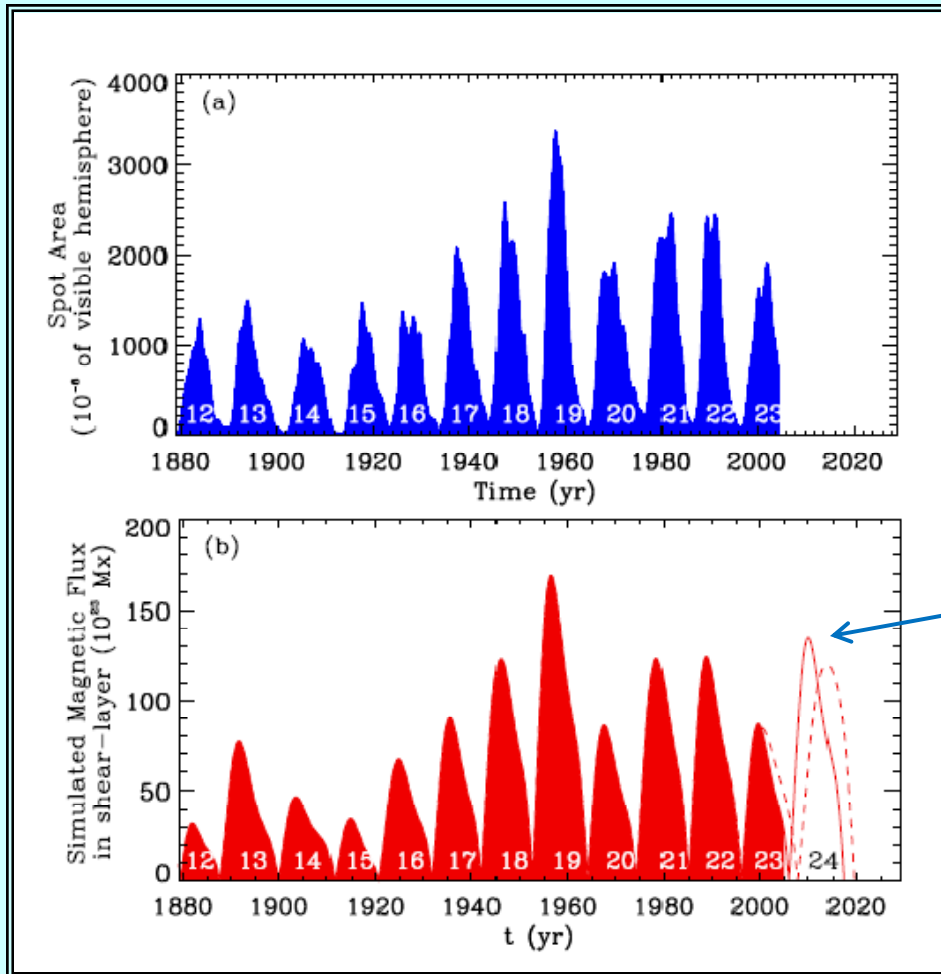
WASHINGTON (AP) -- The peak of the next sunspot cycle is expected in late 2011 or mid-2012 -- potentially affecting airline flights, communications satellites and electrical transmissions. But forecasters can't agree on how intense it will be.

A 12-member panel charged with forecasting the solar cycle said Wednesday it is evenly split over whether the peak will be 90 sunspots or 140 sunspots.



Pesnell 2007

Are dynamo models ready to help?

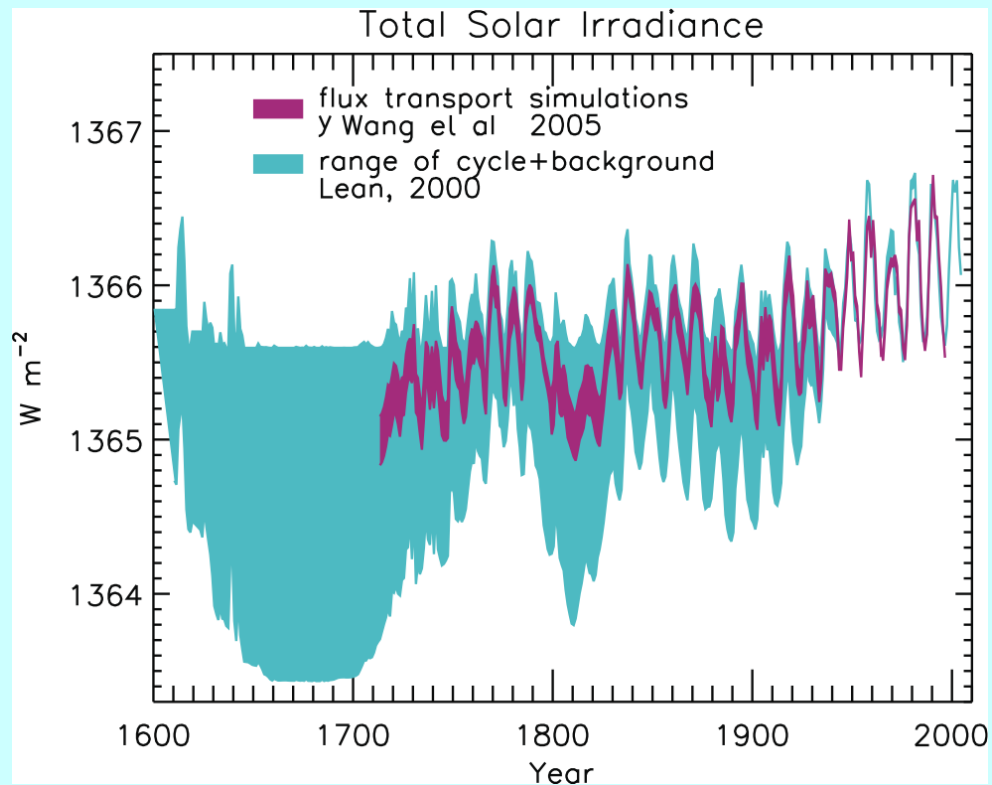


- Dikpati et al. 2006
- Predicts strength of next cycle using flux-transport dynamo model, calibrated with helioseismic data and driven by sunspot area data.
- Using time-varying measured meridional flow gives different prediction from using mean value alone.

Outline

- Introduction
- Helioseismology
- Solar Dynamo
- Solar Cycle Prediction
- Reconstructions of Past Solar Activity
- Climate Response to Solar Forcing
- Where Next?

Reconstruction of Past Solar Activity



Climate Change 2007
(IPCC)

Figure 2.17. Reconstructions of the total solar irradiance time series starting as early as 1600. The upper envelope of the shaded regions shows irradiance variations arising from the 11-year activity cycle. The lower envelope is the total irradiance reconstructed by Lean (2000), in which the long-term trend was inferred from brightness changes in Sun-like stars. In comparison, the recent reconstruction of Y. Wang et al. (2005) is based on solar considerations alone, using a flux transport model to simulate the long-term evolution of the closed flux that generates bright faculae.

Reconstruction of Past Solar Activity

Table 2.10. Comparison of the estimates of the increase in RF from the 17th-century Maunder Minimum (MM) to contemporary solar minima, documenting new understanding since the TAR.

| Reference | Assumptions and Technique | RF Increase from the Maunder Minimum to Contemporary Minima ($W\ m^{-2}$) ^a | Comment on Current Understanding |
|--|--|--|--|
| Schatten and Croosz (1990) | Extrapolation of the 11-year irradiance cycle to the MM, using the sunspot record. | ~0 ~ 0 $W\ m^{-2}$ | Irradiance levels at cycle minima remain approximately constant. |
| Lean et al. (1992) | No spots, plage or network in Ca images assumed during MM. | 0.26 0.26 | Maximum irradiance increase from a non-magnetic sun, due to changes in known bright features on contemporary solar disk. |
| Lean et al. (1992) | No spots, plage or network and reduced basal emission in cell centres in Ca images to match reduced brightness in non-cycling stars, assumed to be MM analogues. | 0.45 0.45 | New assessment of stellar data (Hall and Lockwood, 2004) does not support original stellar brightness distribution, or the use of the brightness reduction in the Baliunas and Jastrow (1990) 'non-cycling' stars as MM analogues. |
| Hoyt and Schatten (1993) ^b | Convective restructuring implied by changes in sunspot umbra/penumbra ratios from MM to present: amplitude of increase from MM to present based on brightness of non-cycling stars, from Lean et al. (1992). | 0.65 0.65 | As above |
| Lean et al. (1995) | Reduced brightness of non-cycling stars, relative to those with active cycles, assumed typical of MM. | 0.45 0.45 | As above |
| Solanki and Fligge (1999) ^b | Combinations of above. | 0.68 0.68 | As above |
| Lean (2000) | Reduced brightness of non-cycling stars (revised solar-stellar calibration) assumed typical of MM. | 0.38 0.38 | As above |
| Foster (2004) Model | Non-magnetic sun estimates by removing bright features from MDI images assumed for MM. | 0.28 0.28 | Similar approach to removal of spots, plage and network by Lean et al. (1992). |
| Y. Wang et al. (2005) ^b | Flux transport simulations of total magnetic flux evolution from MM to present. | 0.1 0.1 | Solar model suggests that modest accumulation of magnetic flux from one solar cycle to the next produces a modest increase in irradiance levels at solar cycle minima. |
| Dziembowski et al. (2001) | Helioseismic observations of solar interior oscillations suggest that the historical Sun could not have been any dimmer than current activity minima. | ~0 ~ 0 | |

Notes:

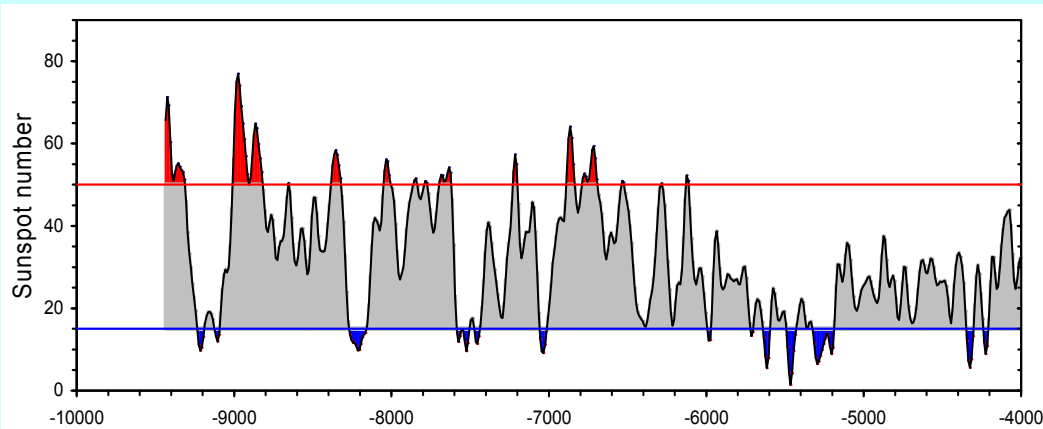
^a The RF is the irradiance change divided by 4 (geometry) and multiplied by 0.7 (albedo). The solar activity cycle, which was negligible during the Maunder Minimum and is of order $1\ W\ m^{-2}$ (minimum to maximum) during recent cycles, is superimposed on the irradiance changes at cycle minima. When smoothed over 20 years, this cycle increases the net RF in the table by an additional $0.09\ W\ m^{-2}$.

^b These reconstructions extend only to 1713, the end of the Maunder Minimum.

Climate Change 2007
(IPCC)

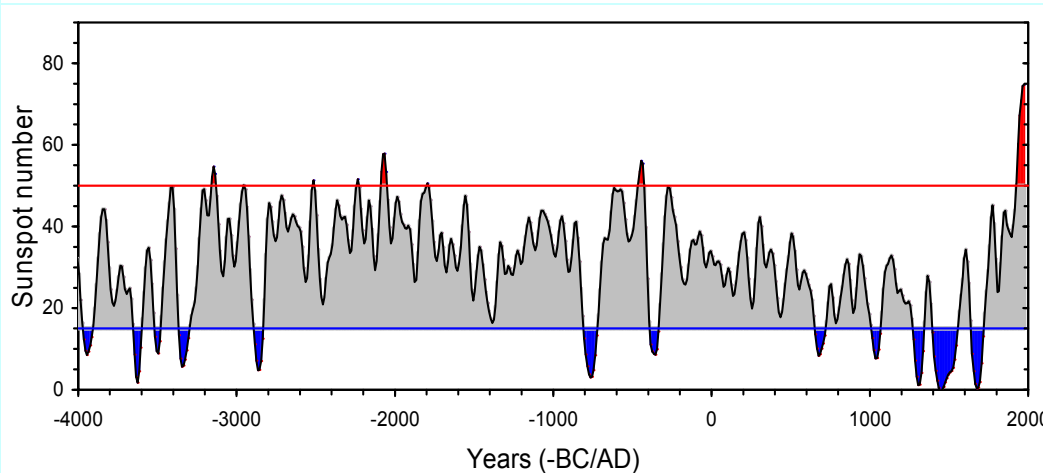
$$RF = (\Delta TSI / 4) * 0.7$$

Sunspot number reconstructed from ^{14}C



Smoothed Sunspot
number over 11400 y

27 Grand minima
19 Grand maxima



Minima cover
1880 yr \approx 17% of time
Maxima cover
1030 yr \approx 9% of time

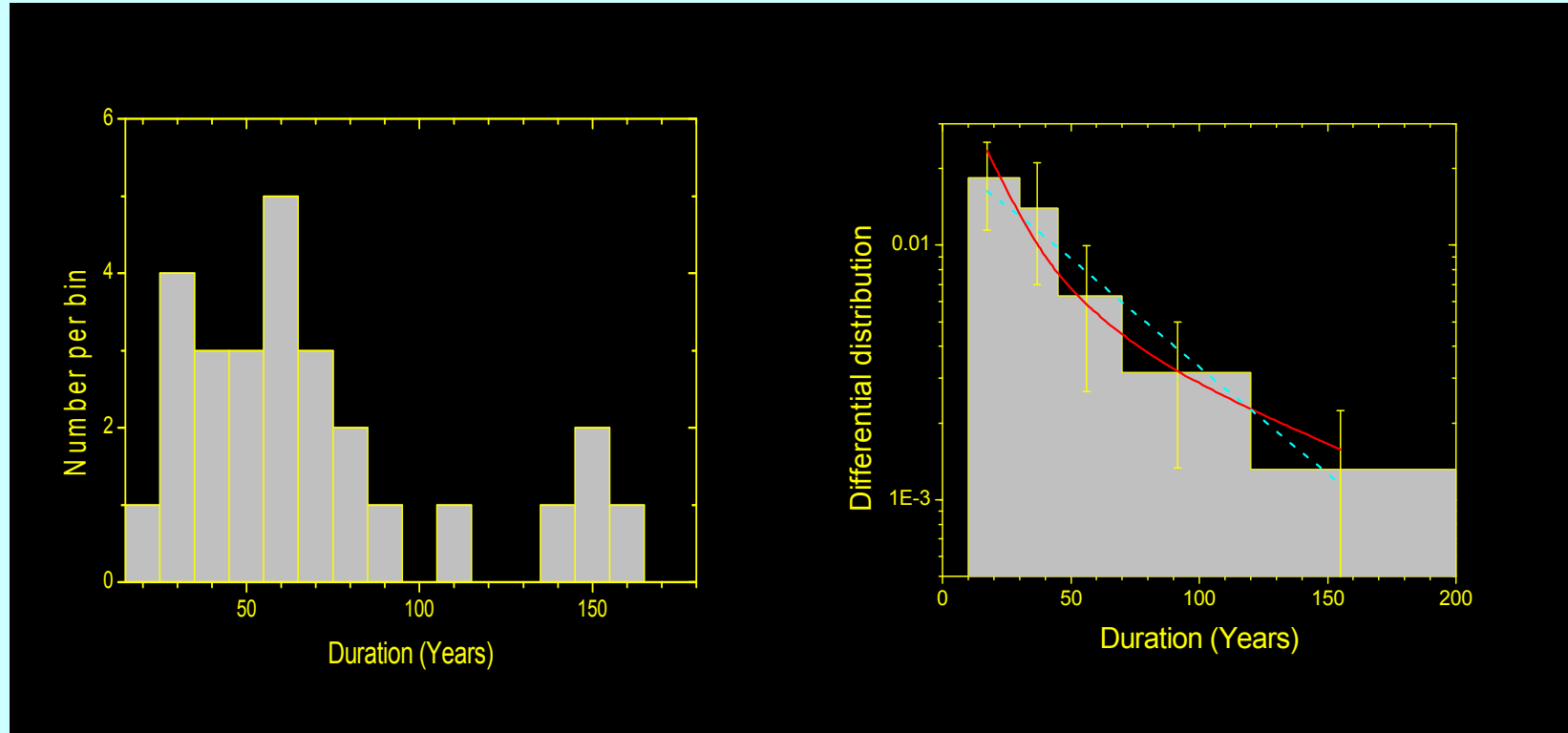
Solanki, Usoskin, Kromer, Schüssler, Beer, *Nature*, 2004

Usoskin, Solanki & Kovaltsov, *A&A*, 2007

Durations of Grand Minima and Maxima

Minima

Maxima



Maunder

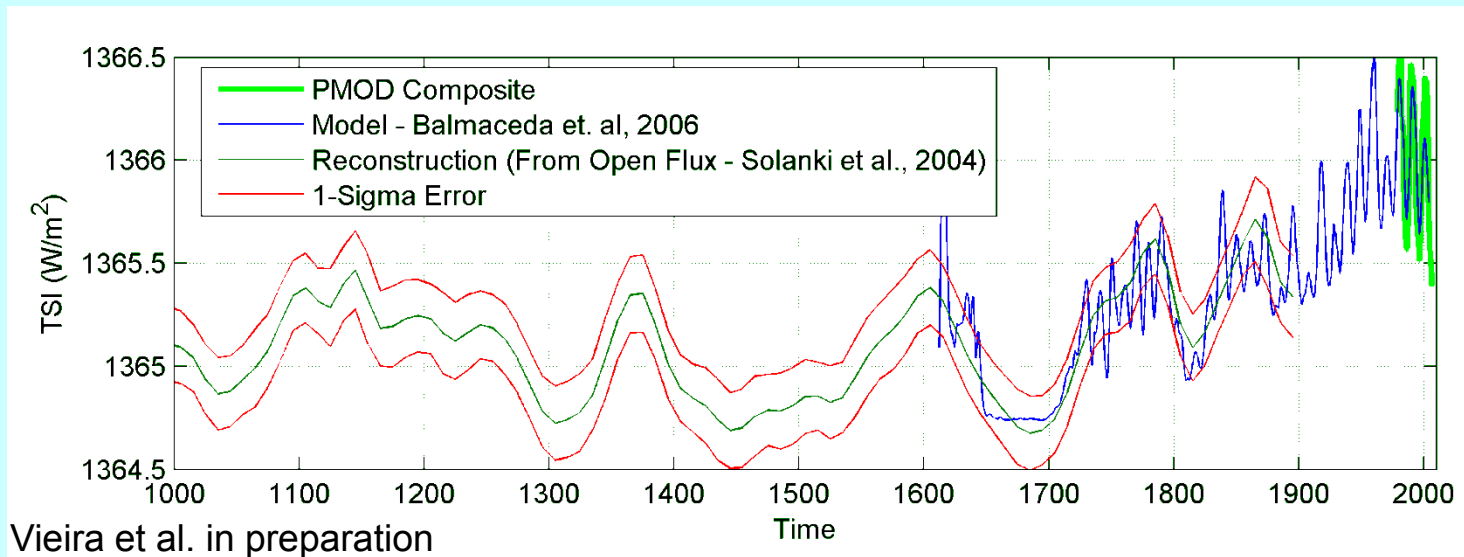


Spörer

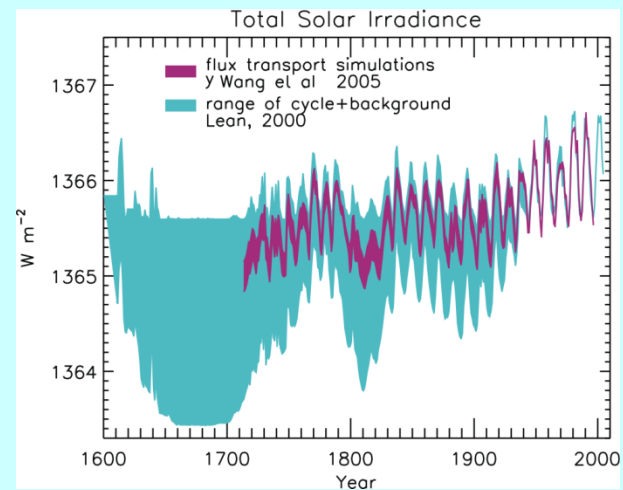
Quasi-Bimodal

Exponential

Irradiance over the last 1000 y



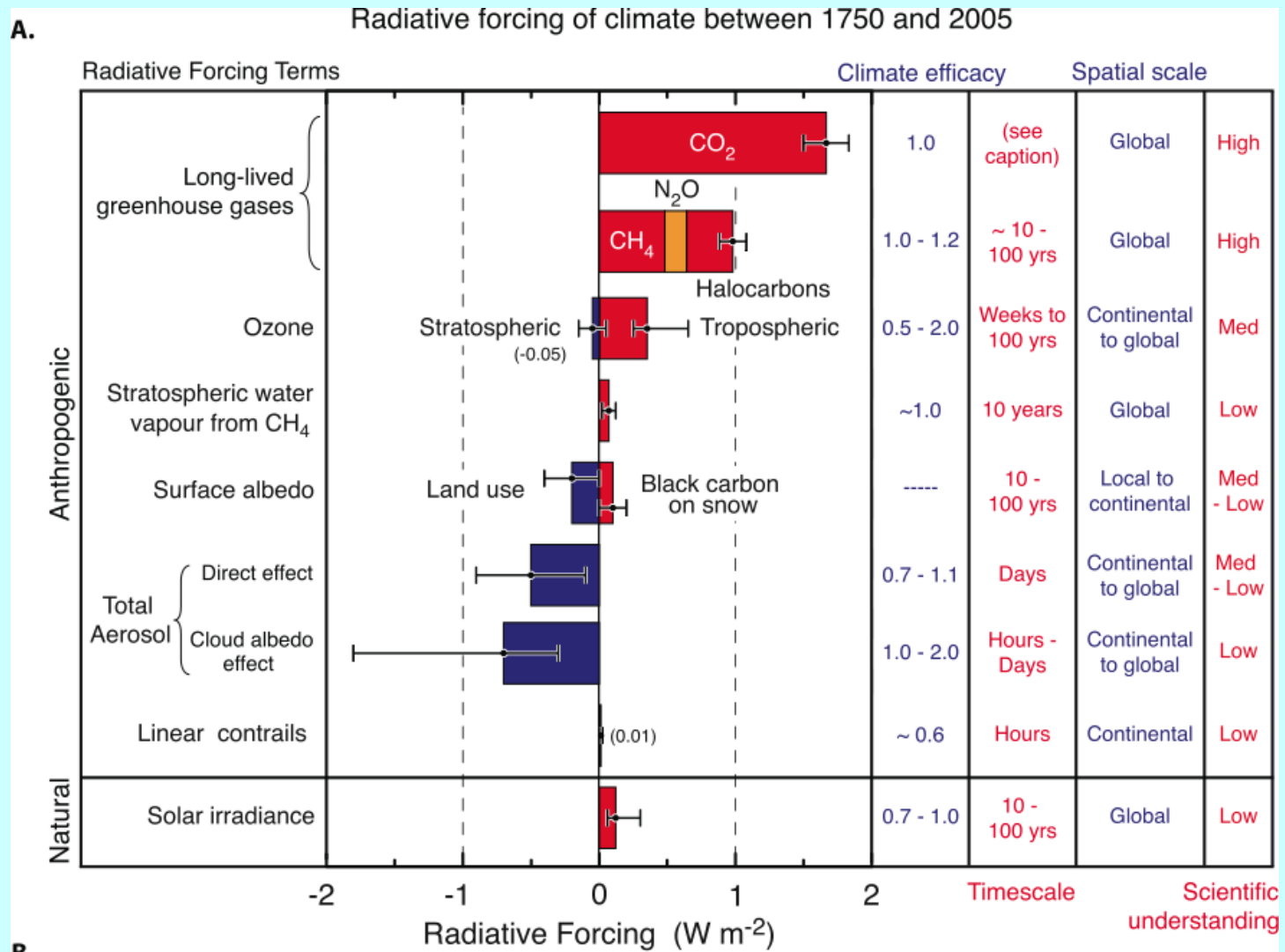
- Use SN obtained from ^{14}C data to reconstruct TSI over 11400 years
- Only cycle averages can be reconstructed with ^{14}C data
- Make use of near-linear relationship between 10-year averages of SN and of reconstructed TSI since Maunder minimum



Outline

- Introduction
- Helioseismology
- Solar Dynamo
- Solar Cycle Prediction
- Reconstructions of Past Solar Activity
- **Climate Response to Solar Forcing**
- Where Next?

Radiative Forcing of the Climate since 1750

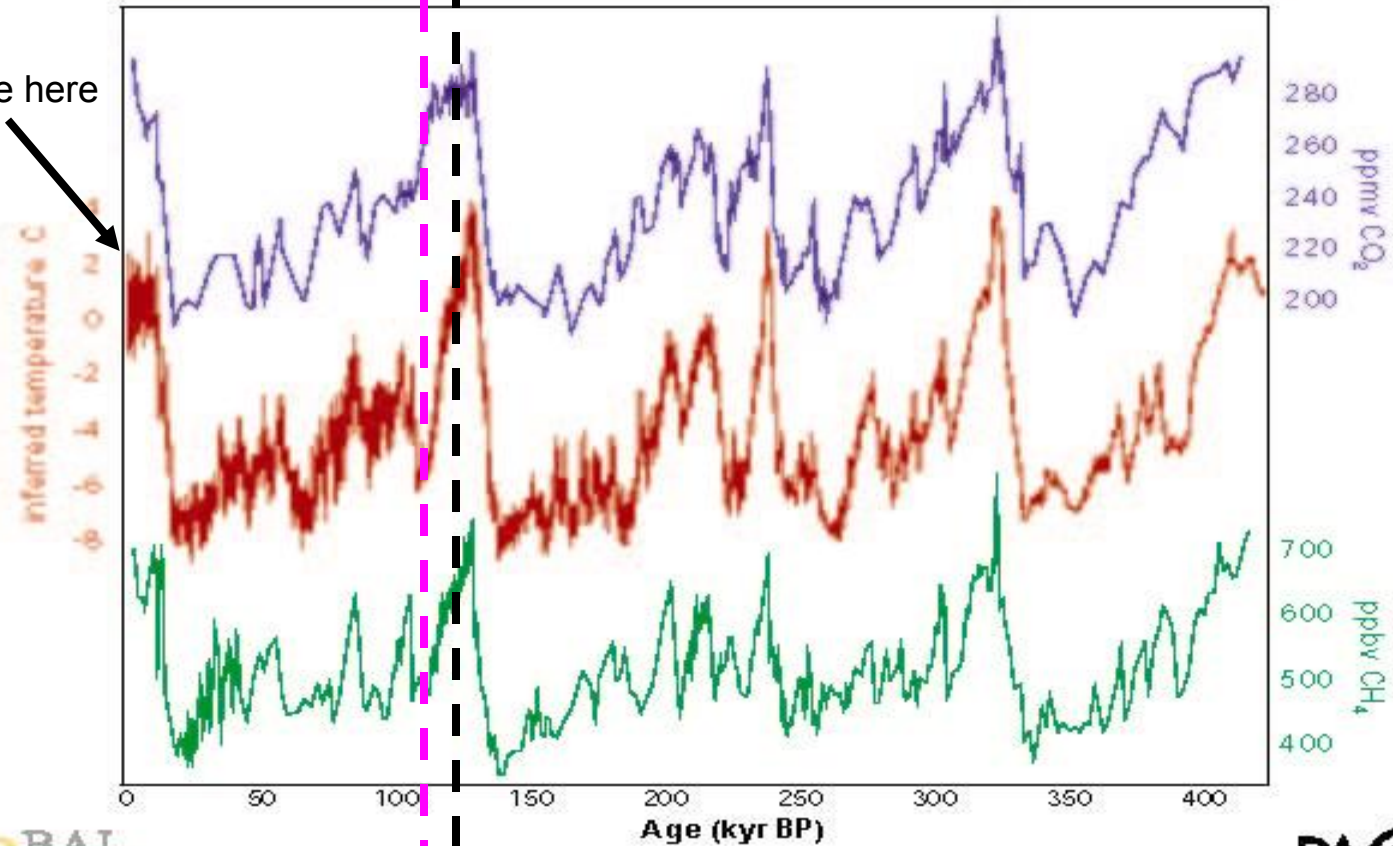


Climate Change 2007 (IPCC)

Orbital Forcing and Glaciation

4 glacial cycles recorded in the Vostok ice core

You are here



GLOBAL
I G B P
CHANGE

J.R. Petit et al., *Nature*, **399**, 429-436, 1999.

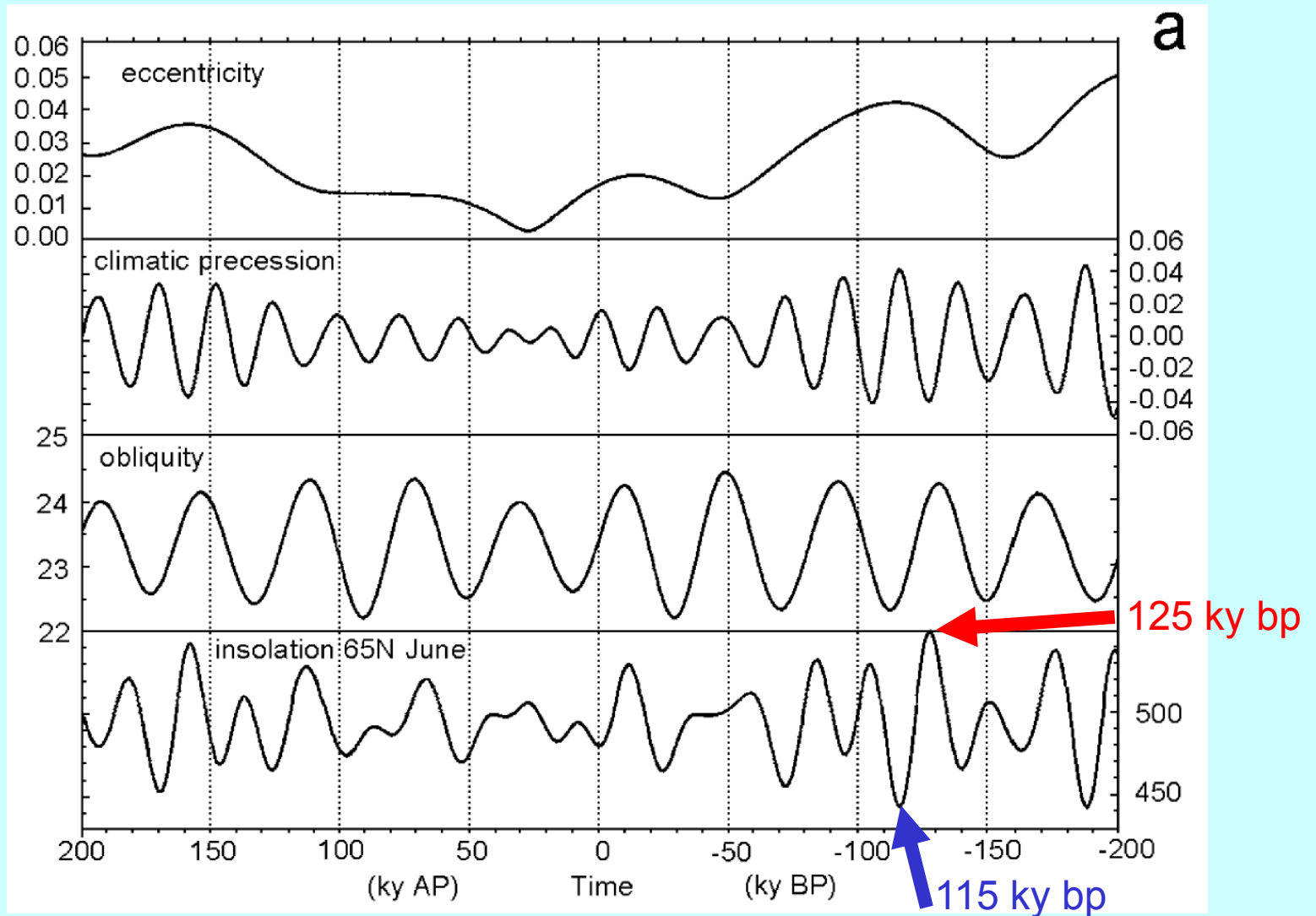
PAGES
PAST GLOBAL CHANGES

6.1

115 ka bp

125 ka bp

Orbital Forcing and Glaciation



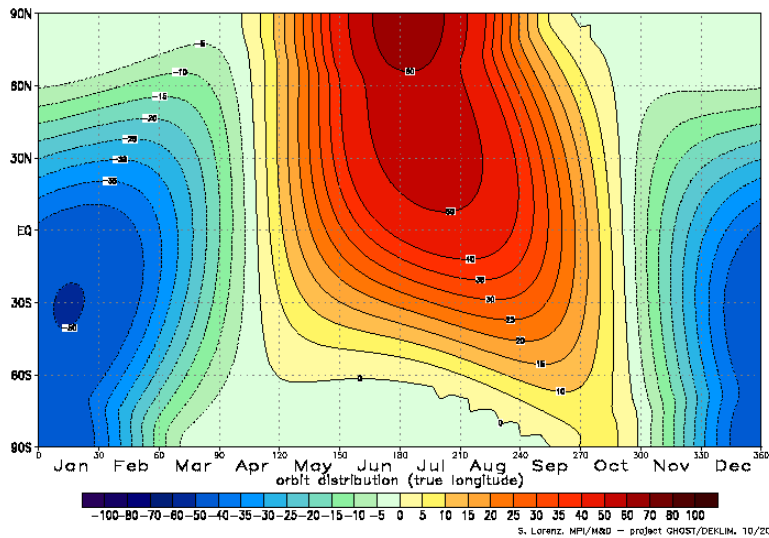
Orbital Forcing and Glaciation

Radiation anomaly compared to present day

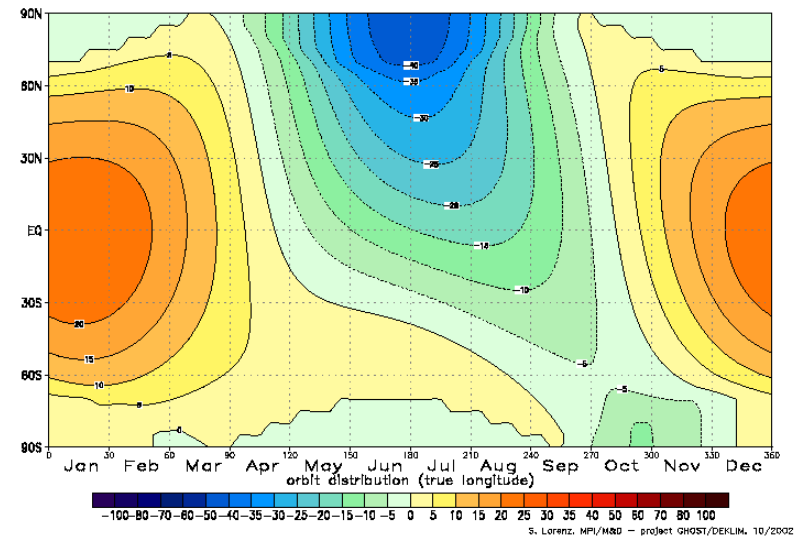
125 ky BP

115 ky BP

Insolation (Berger 1978): latitude/orbit distribution [Wm^{-2}]
time = 125 ky BP (anomaly from today)



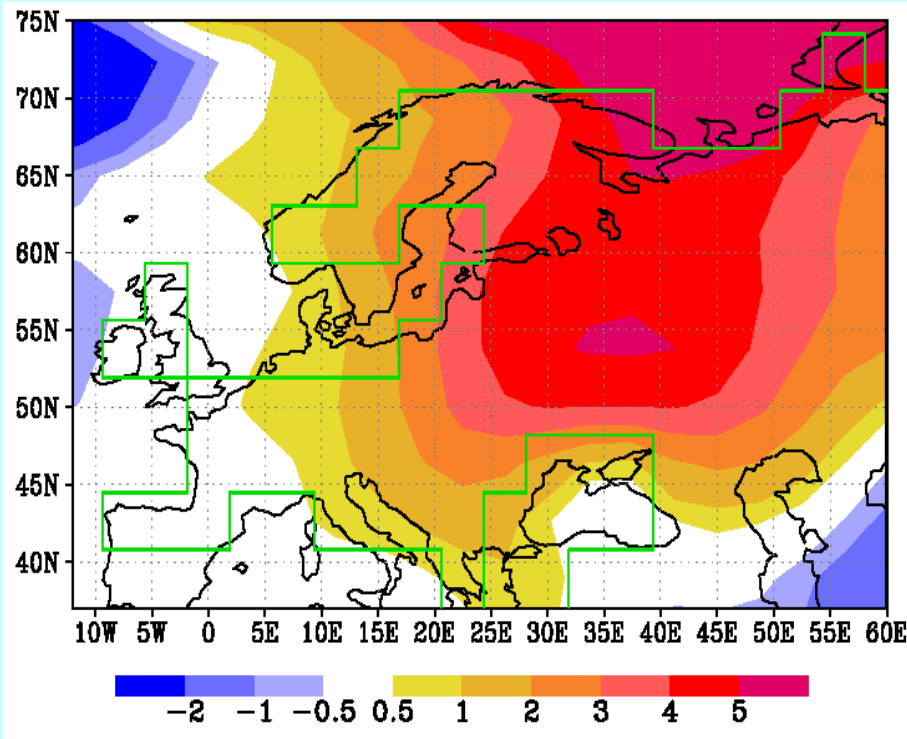
Insolation (Berger 1978): latitude/orbit distribution [Wm^{-2}]
time = 115 ky BP (anomaly from today)



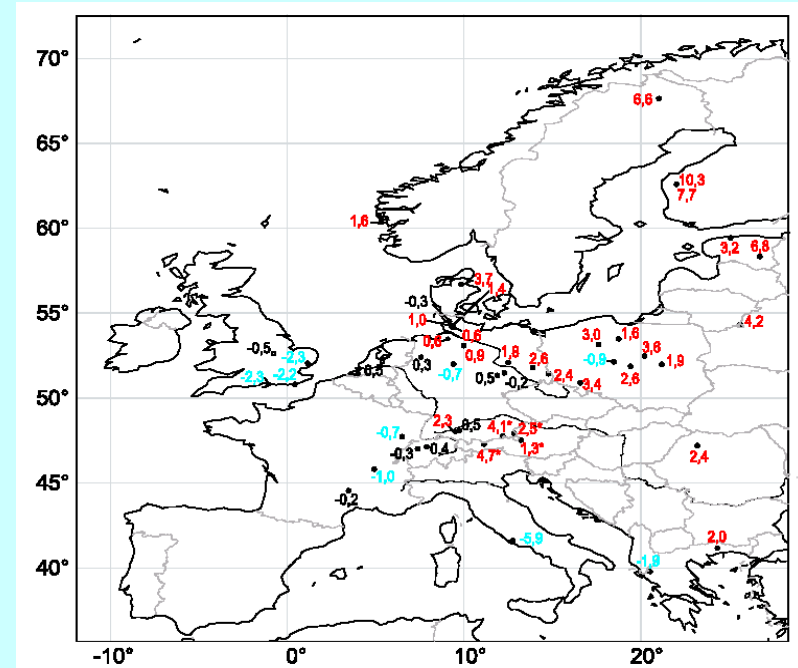
Orbital Forcing and Glaciation

January temperatures of the early Eemian (Corylus-phase)
(differences from observed present-day values)

Modelled

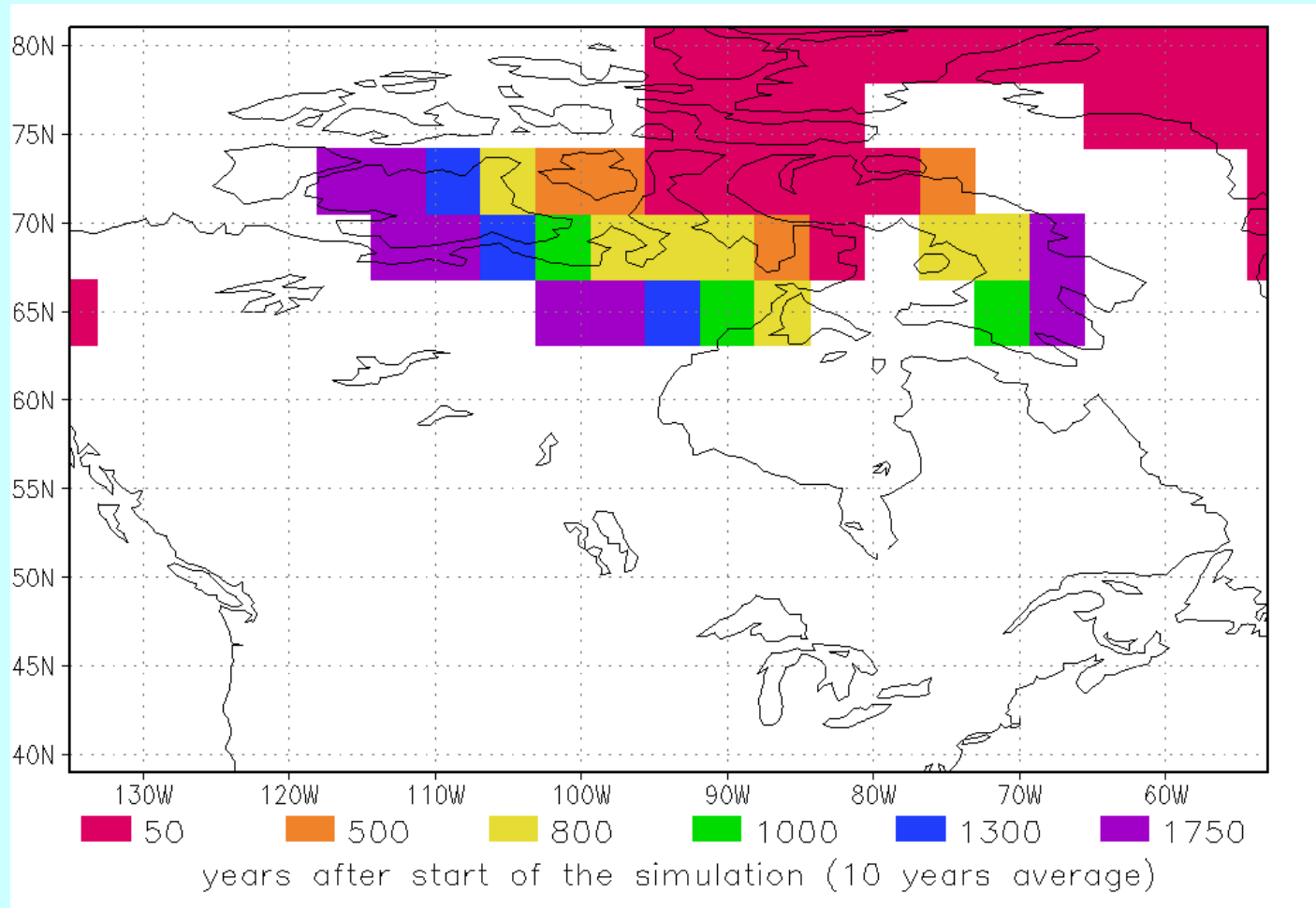


Reconstructed

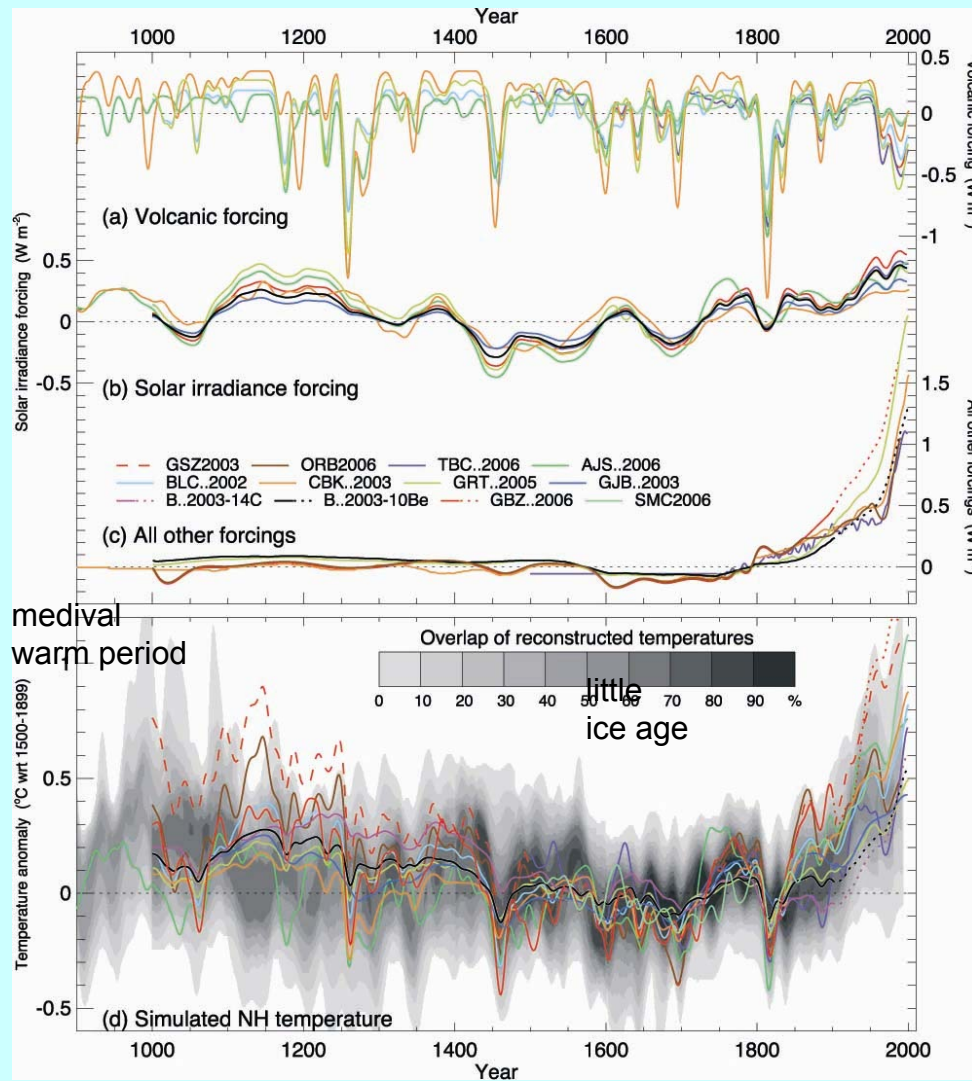


Orbital Forcing and Glaciation

Permanently snow-covered areas in the simulation for 115 kyr BP



Simulations of Climate over last 1 ky



Volcanism

Solar variability

Greenhouse Gases

Temperature

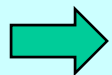
Climate Change 2007
(IPCC)

Climate Response to Solar Forcing: Summary (Cubasch)

- The Sun influences the climate on various timescales by orbital variations and variations of TSI and UV spectral irradiance.
- However, its influence is not sufficient to explain the recent warming.
- The 11-year solar signal in the upper stratosphere leads to circulation changes in the lower stratosphere and down to the troposphere at polar and equatorial latitudes.
- There are indications that it has some influence in the Pacific region, which might give some potential for decadal weather prediction.
- The interplay between direct and indirect effects on the troposphere is not clear.
- The effects of galactic cosmic rays on climate are not yet quantified and therefore are not yet modelled.

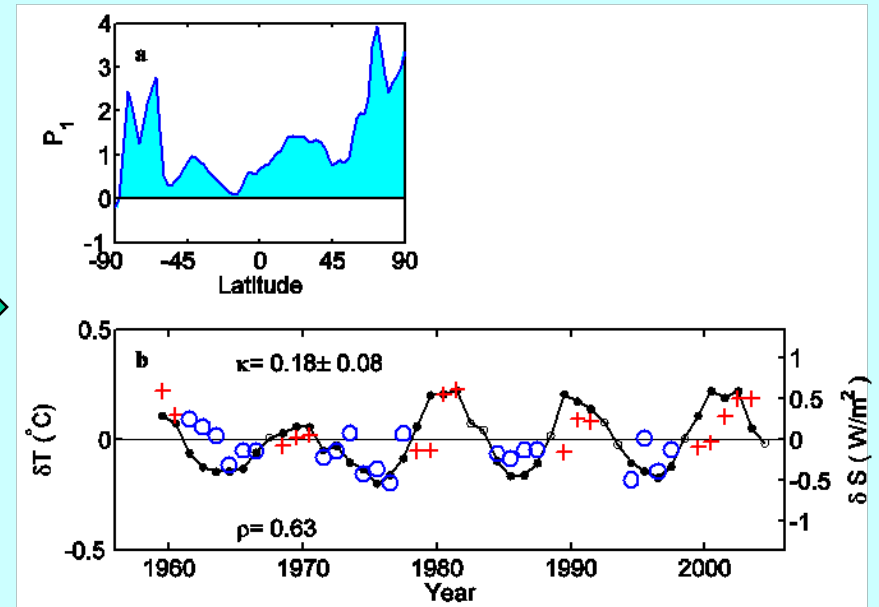
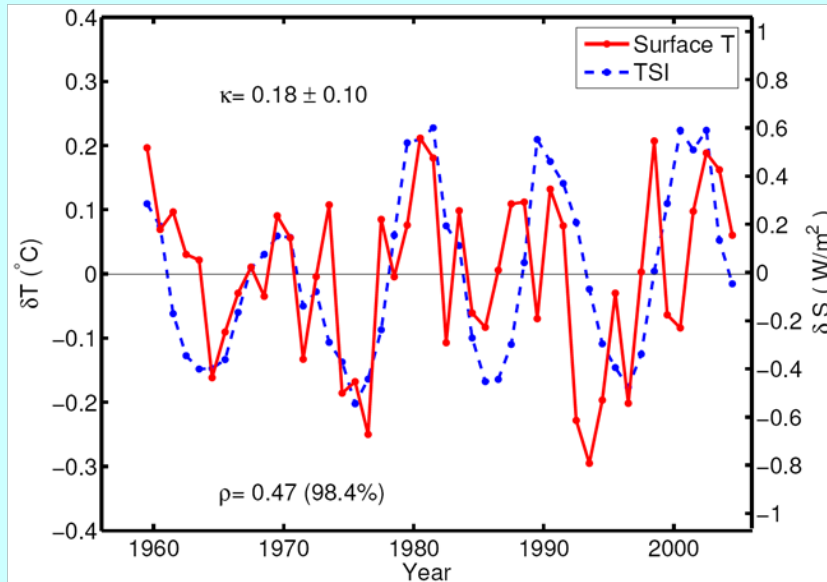
Reasons for past difficulties with observational analysis and modeling of solar-cycle response (Tung)

- Regional versus global response
- Lack of statistical tests
- Using energy-balance models and getting weak response (0.03-0.06 K)
- Using General Circulation Models (GCMs) with fixed sea-surface temperature (SST) and getting weak response
- Thinking that the mechanism is through stratosphere ozone-UV interaction or is more exotic (cosmic rays, atmospheric electricity, etc.) – affected the design of model experiments.



The IPCC AR4 coupled atmosphere-ocean GCMs are adequate for studying solar cycle-climate interaction, even though they do not have much of a stratosphere or interactive ozone.

Take advantage of the spatial pattern associated with the solar cycle response



- LDA analysis; Schneider and Held (2001, J. Climate), Tung and Camp (2008, JGR). Find the optimal spatial weights that best separate the solar max years from solar min years, as measured by the separation index R , which is the ratio of variance between solar groups vs variance within each solar group. More difficult to understand but yields almost the same spatial pattern. The signal is much cleaner, with less than half the error bars.

Should we be able to detect climate response to TSI variability?

Hoyt and Schatten

“From an energy standpoint, a factor of at least 10 is missing in known solar variations that would produce the observed climate fluctuations. Many meteorologists and climatologists remain skeptical about whether solar activity variations are significant at all.”

Tung

- Solar “constant” S varies on 11-year time scale by about $dS \sim 1 \text{ W m}^{-2}$.
- $dQ = dS/4 \sim 0.25 \text{ W m}^{-2}$.
- 30% of that is reflected back to space by clouds and snow and surface. Ozone in the stratosphere absorbs 15%, the remaining absorbed near the surface. Stratospheric warming due to ozone absorption also warms the troposphere through downward long-wave flux.
- Net radiative forcing is $\sim 0.18 \text{ W m}^{-2}$ (Larkin et al. 2000). Response is expected to be small. Can we detect it?

Yes: 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.
- These feedback processes are well-known and intensely studied in global warming research, but often neglected in solar response research.

Solar Cycle and Global Warming

- Radiative forcing from solar-min to solar-max:
~0.18 W m⁻².
 - Periodic warming ~ 0.18 K
 - Transient (periodic) climate sensitivity:
 $\lambda = dT/dRF \sim 1 \text{ K}/(\text{W m}^{-2})$
 - Radiative forcing for 2x CO₂
~ 3.7 W m⁻² (20 times larger than solar cycle RF)
 - Equilibrium warming:
~3.7x $\lambda > 3.7 \text{ K}$ since equilibrium $\lambda >$ transient λ .
- Tung estimate:
~4 K for TCR
~6 K for ECS
- Current model range:
2 - 4.5 K for ECS
1.2 - 2.6 K for TCR

Response to Secular Increase in TSI

- IPCC/AR4: “The estimated direct radiative forcing due to changes in solar output since 1750 is $+0.12[0.06 \text{ to } 0.3] \text{ Wm}^{-2}$...”
- If calibrated against response to solar cycle, the longer-term (equilibrium response) to $\text{RF}=0.12 \text{ Wm}^{-2}$ is approximately $dT\sim 0.18 \text{ K}$ globally averaged.
- The upper bound, $\text{RF} = 0.3 \text{ Wm}^{-2}$, should yield $dT\sim 0.45 \text{ K}$ globally averaged. Arctic warming is $\sim 3x$ higher.
- Not negligible, but probably inadequate to explain warming prior to mid 20th century.
- More research is needed to narrow the solar RF range.
- Solar forcing cannot explain the peak in warming in 1940, because the solar forcing peaked a decade later.

Climate Response to Solar Forcing: Summary (Tung)

- Observational analysis, theory, and model analysis all point to the existence of a solar cycle response at the surface. Statistical significance has been established and there is an energetically consistent explanation.
- This response can be understood as arising from the direct radiative heating of the Sun amplified by positive feedback processes well studied in GHG warming problems.
- The similarity of the solar and GHG responses implies that one can be used to constrain the other, thus reducing model uncertainty.

IPCC models need to be validated against this observational data.
Better than calibrating against volcano-induced cooling ...

Outline

- Introduction
- Helioseismology
- Solar Dynamo
- Solar Cycle Prediction
- Reconstructions of Past Solar Activity
- Climate Response to Solar Forcing
- Where Next?

Where Next?

What should we do to promote scientifically productive interactions between the solar and climate communities?

- Improve reference spectral irradiance and quantify range of spectral variation for different levels of activity
- Use GCMs to investigate effects of solar infrared irradiance variations out of phase with the solar cycle.
- Improve identification and understanding of solar cycle effects in regional climate data, taking care to establish statistical significance in the presence of internal climate variations.
- Continue to investigate indirect stratosphere-troposphere coupling mechanisms.
- Refine reconstructions of past solar activity to bound what the Sun has done, guarding against false convergence due to inbreeding of models.
- Continue to study solar structure to understand what the Sun might be capable of doing; obtain new types of observations (e.g., radius).

Where Next?

What should we do to promote scientifically productive interactions between the solar and climate communities?

-
-
-
-
-
-