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Solar-induced versus internal variability in a coupled climate model

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Abstract. A series of experiments is conducted in which a variable solar irradiance is imposed for a range of frequencies and amplitudes in a simplified coupled General Circulation Model. For realistic amplitudes solar forcing dominates over internal variability in global mean surface air temperature (GM-SAT) beyond decadal timescales. Its impact increases with period up to 50 years. Evidence is found for interactions between climate variations with different timescales. A weak 22-yr solar irradiance variation excites a significant spectral peak with a 70-yr period in GM-SAT. On the regional-scale the internal variability dominates at all timescales. Patterns of internal variability and their associated variance are robust for a variable solar forcing. The temporal spectra, however, are sensitive to such forcing. Some preferred decadal timescales of the internal modes of the coupled system disappear when the solar forcing varies.

Introduction

Direct measurements of irradiance variations have revealed a 0.1–0.2% change associated with the 11-yr cycle [*Wilson and Hudson*, 1991]. Such variations are unlikely to have significant climate effects, both due to the small amplitude (0.3–0.7 Wm^{-2}), and due to the damping by the thermal inertia of the oceans [*Reid*, 1991]. Reconstructions of solar variability [*Hoyt and Schatten*, 1993; *Lean et al.*, 1995] suggest that longer term (50–100 yr) variations are associated with greater amplitudes on the order of 1–2 Wm^{-2}. The attenuation caused by the oceans will be less for century-scale fluctuations. As a result, these may have a larger impact on climate. Correlations between estimates of solar variability and the observed change in SAT and SST have been interpreted as indicating that internal variability and/or greenhouse forcing plays a minor role compared to solar forcing [*Friis-Christensen and Lassen*, 1991; *Lassen and Friis-Christensen*, 1995]. However, model calculations of the climate response to external forcings show that it is unlikely that solar forcing dominates greenhouse gases in contributing to the observed temperature change [*Hansen and Lacis*, 1990; *Kelly and Wigley*, 1992; *Cubasch et al.*, 1997]. The relative importance of solar-induced variability versus the internal variability has not been established yet and is the subject of this paper.

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Model description

We use a coupled atmosphere-ocean-sea ice model of intermediate complexity [*Opsteegh et al.*, 1998]. The atmospheric component resolves 21 wavelengths around the globe. It contains 3 levels in the vertical. The dynamical part is an extended quasi-geostrophic model [*Marshall and Molteni*, 1993]. The neglected ageostrophic terms are included in the vorticity and thermodynamic equations as a time and spatially varying forcing. With this forcing the model simulates the Hadley circulation qualitatively correct. Also, the strength and position of the jet stream and transient eddy activity become fairly realistic. The model contains simple physical parameterisations [*Held and Suarez*, 1978], including a full hydrological cycle. The cloud coverage is prescribed. The atmospheric component is coupled to a coarse resolution (5.6 degrees) ocean model [*Lenderink and Haarsma*, 1994] and a thermodynamic sea-ice model. The coupled model is two orders of magnitude faster than state-of-the-art models. No flux correction has been applied. The model displays realistic internal climate oscillations on the decadal timescale [*Selten et al.*, 1998].

We have integrated the model towards a quasi stationary steady state in which the solar forcing has been kept constant (apart from the seasonal cycle). The internal variability is analysed from a 2000-yr control simulation. The variability of the annual mean SAT in the tropics is largely underestimated due to the quasi-geostrophic dynamics. In the extratropics the spatial pattern of this variability compares rather well with observations, although the amplitude is on the average a factor of 2 too small. In the remainder we will confine ourselves to the extratropics. Wherever we discuss globally averaged quantities we have computed averages over the area poleward from 22.5 degrees latitude.

Results

In order to evaluate the model's sensitivity to a variable solar forcing we calculated the response to an estimate of the variation since 1700 [*Hoyt and Schatten*, 1993] and compared it with a comprehensive model

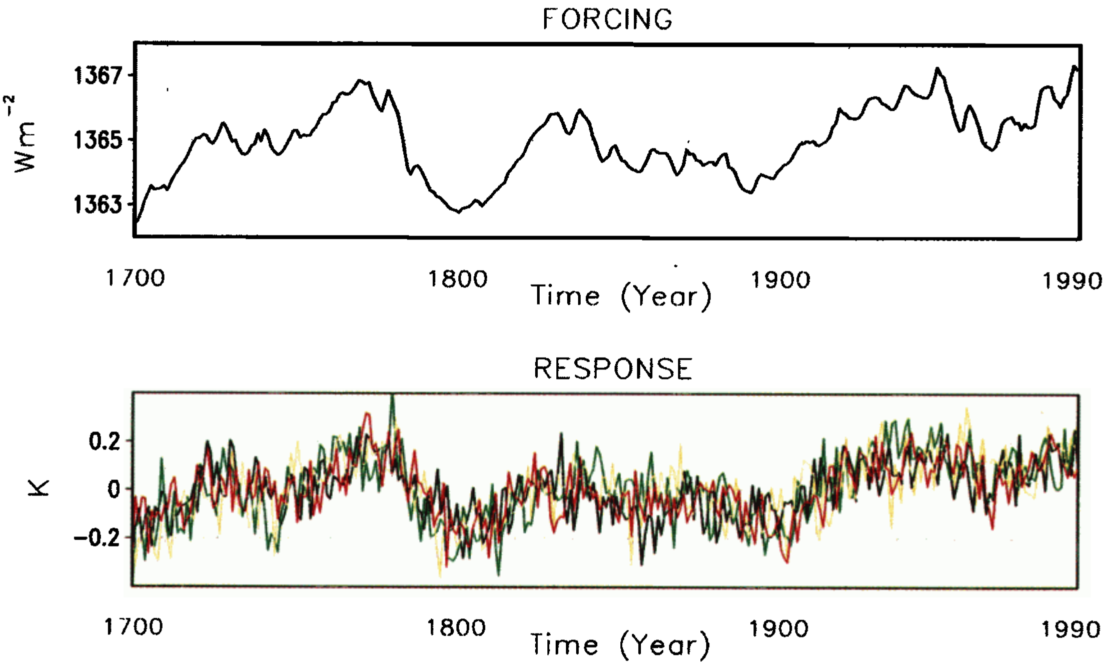

Figure 1. Time series of an estimate of the solar irradiance since 1700 by Hoyt and Schatten (a), and time series of GM-SAT of 4 simulations starting with different initial conditions taken from the control simulation and forced with this estimate of the solar irradiance (b).

[*Cubasch et al.,* 1997]. The time series of GM-SAT are well correlated on the decadal timescale with the solar forcing, (Fig. 1). The spatial pattern of the response compares well with the pattern obtained by Cubasch et al., but the amplitude is a factor of 2 smaller in the extratropics. The ratio between internal variability and solar-induced variability, however, is comparable to Cubasch et al. Significant spectral peaks in both the solar forcing and the response in GM-SAT are apparent at a period of 80 years. At this period the variance in GM-SAT is typically 10 times larger compared to the control simulation.

To obtain a statistically robust estimate of the effect of variations in solar irradiance on climate we performed a series of 1000-yr integrations in which the solar constant has been modulated with a periodic signal. The periods range from 11–160 yrs, the amplitudes from 0.5–6.0 Wm^{-2}. With a forcing period of 80 years and a typical amplitude of 2 Wm^{-2} [*Hoyt and Schatten,* 1993; *Lean et al.,* 1995], the variance in GM-SAT

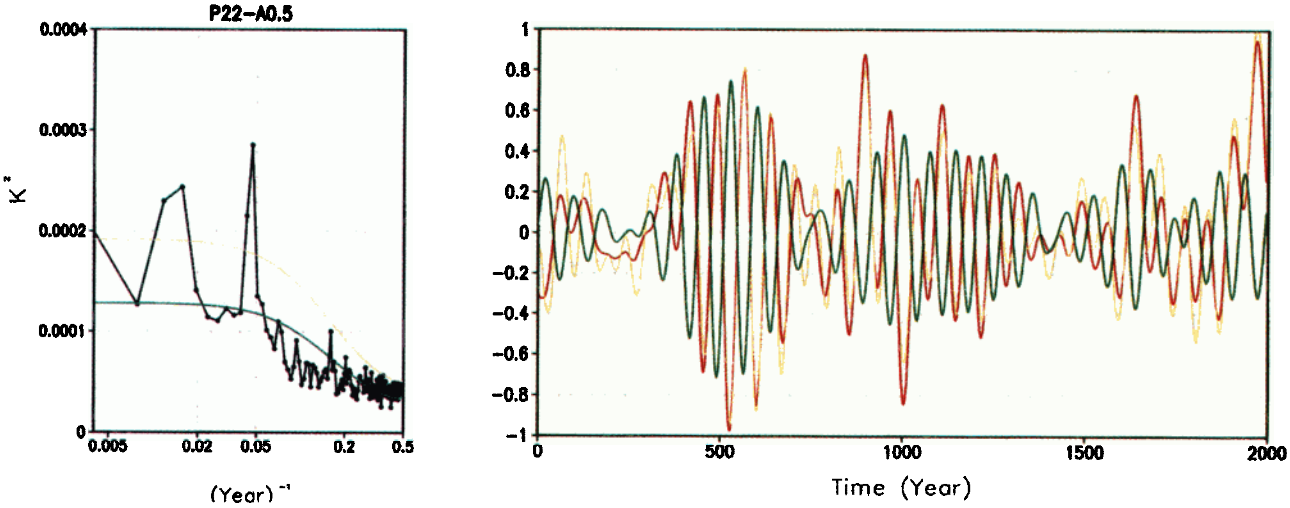

Figure 2. Variance spectrum of GM-SAT when the model is forced with a solar irradiance variation of 0.5 Wm^{-2} with a 22-yr period. Additionally, a red noise fit (green line) and the 95% confidence limit that the variance spectrum is significantly different from red noise (yellow line) are plotted (a). Filtered time series of area averaged SAT (yellow line), SST (red line) and sea-ice distribution (green line) for the same experiment, each normalized by 3 times the standard deviation (b).

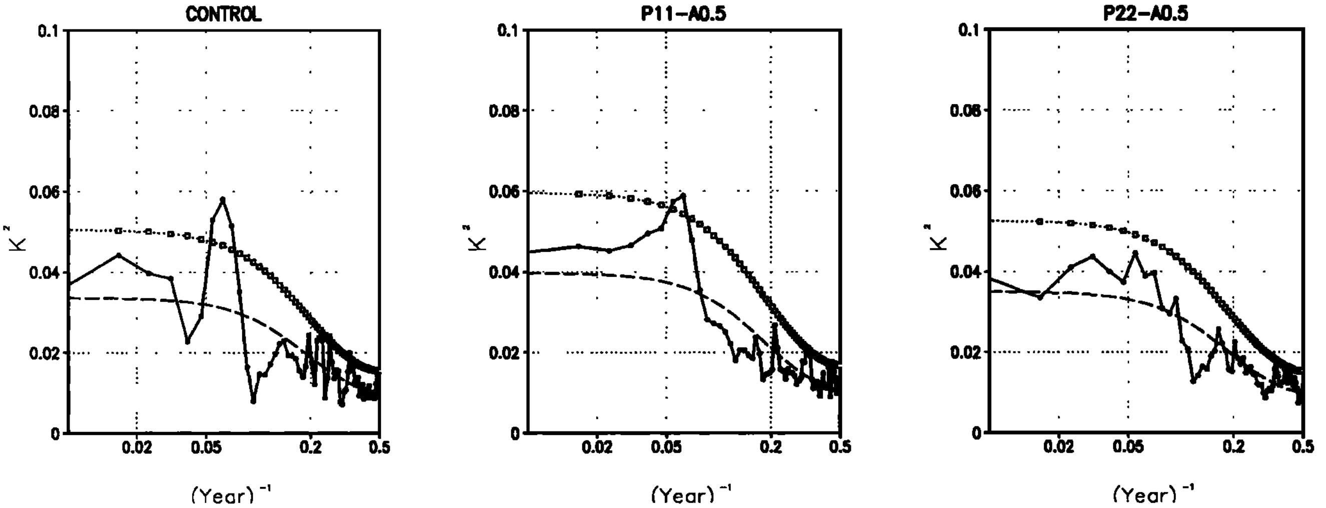

Figure 3. Variance spectrum of North Atlantic SST belonging to the second SVD of wintermean SST and geopotential height at 800 hPa: the control simulation (a), the experiment forced with solar irradiance variations with a 0.5 Wm^{-2} amplitude and a period of 11 years (b), the same experiment, but with a period of 22 years (c).

around the 80-yr period becomes 40 times larger compared to the control simulation, completely dwarfing the background internal variability. When the forcing period decreases, the spectral peak of the response in GM-SAT also decreases due to a stronger damping by the inertia of the ocean. Nevertheless, even when the model is driven with a weaker amplitude of 0.5 Wm^{-2}, which is more typical for the shorter periods of 11 and 22 years, at these periods the response in GM-SAT is still significantly larger than the background internal variability.

A new and unexpected feature arises when the model is weakly forced (0.5 Wm^{-2}) with periods of 11 and 22 years. A significant peak in GM-SAT is excited with a period of about 70 years (Fig. 2a). We have isolated the 70-yr oscillation from the timeseries and reconstructed the associated patterns with a Singular Spectrum Analysis. The associated patterns of SST and sea-ice distribution show a signal confined to the Ross Sea, indicating a local coupling between sea-ice, convective overturning and SST. The associated SAT response consists of a Rossby wave train with standing components which are resonantly amplified by the large-scale land-sea distribution. As this wavy-signal is more strongly damped over the oceans than over land it contributes to the GM-SAT. The time series for the isolated 70-yr oscillation in both SAT, SST and sea-ice distribution are very well correlated (Fig. 2b). [*Jacobs and Giulivi,* 1998] document oscillatory behavior of the Ross Sea ice coverage.

The role of internal variability is different on the regional-scale. With a variable solar forcing the dominant patterns of atmospheric variability do not change and neither does their associated variance. The spectra, however, are sensitive. The robustness of the patterns implies that at a particular location the variance in SAT associated with the solar forcing is only a small part of the total variability. When averaging over a larger domain, the contribution of the internal variability to the variance in SAT decreases, while these patterns primarily redistribute heat. A contribution to the GM-SAT remains, as the dominant patterns redistribute heat between ocean and land, and the anomalies above the ocean are more strongly damped than those over land. As a result, that part of the internal variability that optimally correlates with GM-SAT can be described as a Cold Ocean Warm Land pattern [*Wallace et al.,* 1995] and its reverse. [*Hurrell,* 1996] showed that the correlation between the internal variability and the hemispherically averaged SAT is larger in the winter hemisphere. In winter, the internal variability is strong and the solar forcing is weak. Averaged over the year the contribution of the internal variability to the GM-SAT appears to be less important than the response to solar forcing which is much more homogeneous and single-signed.

The sensitivity of the spectra is associated with multiple timescale interactions between forcing frequency and the internal modes. The coupled mode associated with the North Atlantic Oscillation [*Selten et al.,* 1998] shows a significant peak at 18 years for SST and SAT. With a variable solar forcing this peak disappears in most runs. Only when the forcing is weak (0.5 Wm^{-2}) and the period short (11- yrs) the mode remains robust (Fig. 3).

Conclusions

Our results indicate that the response to variable solar forcing will dominate the internal variability in GM-SAT at decadal periods. This is in accordance with analyses of historical records of SST [*White et al.,* 1997] and SAT [*Mann et al.,* 1998]. We have calculated only the direct effect of variable solar insolation. Indirect forcings due to ozone [*Haigh,* 1996], or cloud cover [*Svensmark and Friis-Christensen,* 1997] are probably in phase with the solar forcing, so their effect can be included by specifying the forcing appropriately [*Hansen et al.,* 1997].

It is unclear to what extent the simplifications made in the model have affected the results. To evaluate this, experiments are needed with a comprehensive climate model. At present, however, such a model can not be run long enough to ensure statistical robustness of the results. Our main conclusion is that the observed multiple timescale interaction between forcing and internal variability implies that the spectra of climate variables cannot be properly understood without considering external forcings and nonlinear aspects of climate dynamics.

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