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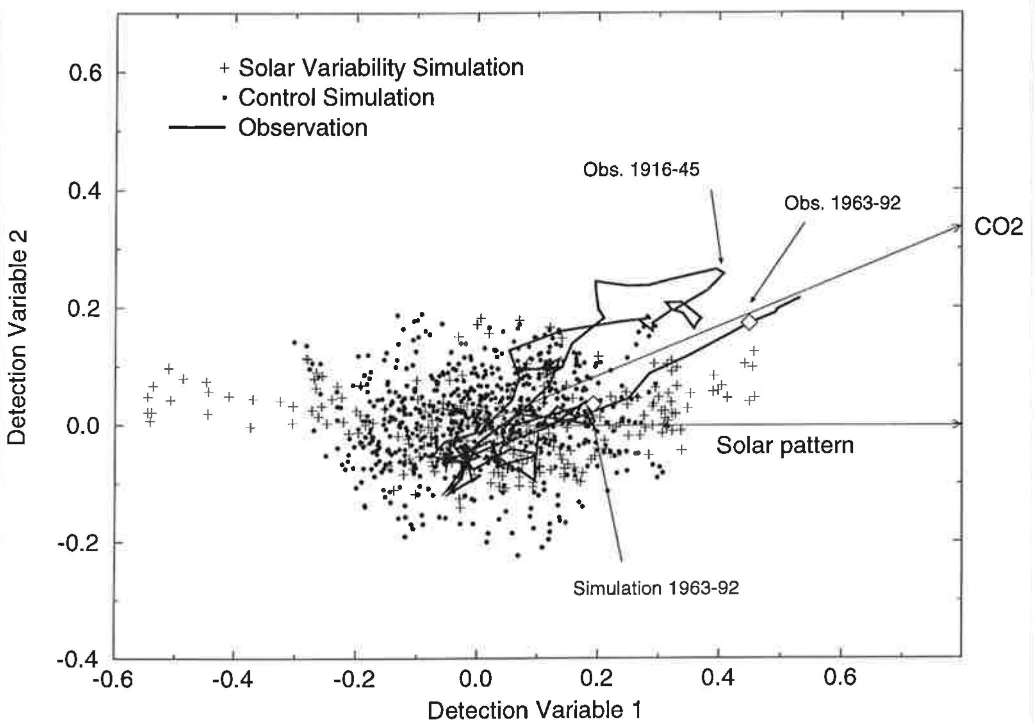

SIMULATION WITH AN O-AGCM OF THE INFLUENCE OF VARIATIONS OF THE SOLAR CONSTANT ON THE GLOBAL CLIMATE

by

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Simulation with an O-AGCM of the influence of variations of the solar constant on the global climate

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Abstract

Two simulations have been carried out with a global coupled ocean-atmosphere circulation model to study the potential impact of solar variability on climate. The Hoyt and Schatten estimate of solar variability from 1700 to 1992 has been used to force the model. Results indicate that the near-surface temperature simulated by the model is dominated by the long periodic solar fluctuations (Gleissberg cycle), with global mean temperatures varying by about 0.5 K. Further results indicate that solar variability induces a similar pattern of surface temperature change as the increase of greenhouse gases, i. e. an increase of the land-sea contrast. However, the solar-induced warming pattern over the ocean during Northern Hemispheric summer is more centered over the Northern Hemisphere subtropics, compared to a more uniform warming associated with the increase in greenhouse gases. Finally, the magnitude of the estimated solar warming during the 20th century is not sufficient to explain the observed warming. The recent observed 30-year trends are inconsistent with the solar forcing simulation at an estimated 90% significance level. Also, the observed trend pattern agrees better with the greenhouse warming pattern.

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Introduction

The potential role of solar variability as an agent for climate change has long been discussed. Although solar variability associated with the 11-year cycle is associated with only a 0.1% change in the solar constant, longer term variations in the sun could conceivably cause larger climate variations. Such changes could complicate the interpretation of the 20th century warming in terms of greenhouse forcing.

In the last few years evidence has accumulated for some level of significant impact of solar variability on climate on decadal-centennial time scales (e.g., Wigley and Kelly 1990; Friis-Christensen and Lassen, 1991; Reid, 1991; Hoyt and Schatten, 1993; Lean et al., 1995; Crowley and Kim, 1993, 1996). Research interest has also been heightened by new estimates from solar models of potential changes in solar variability on centennial time scales of 0.24-0.30% (Hoyt and Schatten, 1993; Lean et al., 1995). Calculations with energy balance models (Reid, 1991; Crowley and Kim, 1996) and an atmospheric general circulation model (AGCM, Rind and Overpeck, 1993) suggest that such changes could potentially cause surface temperature changes on the order of several tenths of a degree centigrade.

Although the AGCM study of Rind and Overpeck (1993) examined the surface temperature response to a reduction of the solar constant during the Maunder Minimum (1650-1710), to date no one has published a study illustrating the time dependent response in a coupled ocean-atmosphere GCM (O-AGCM). Due to the different response times of land and sea, and the extra degree of freedom with a varying ocean, the time varying response to solar variability could be significantly different from the mean response.

In this paper we examine the potential effect of solar variability on climate by forcing the Hamburg O-AGCM with the Hoyt-Schatten (1993) solar index. Specific objectives of the study involve determining of the potential magnitude and spatial and temporal patterns of temperature change and evaluating the implication of results for interpretation of the 20th century warming trend. Note that due to the high uncertainty associated with the estimate of solar forcing, we emphasize that we are evaluating the potential change in forcing. By choosing an estimate of solar forcing that might be considered generous by some, we are therefore testing the response "in the limit". This represents a standard approach to evaluating mechanisms whose significance have not been fully confirmed.

Model and Experiment Design

All simulations were carried out using a new version (ECHAM3 + LSG; see Voss, 1996), of the Hamburg O-AGCM (Cubasch et al, 1992; Maier-Reimer et al, 1993; Roeckner et al, 1992), with a resolution of T21 and with 19 levels in the atmosphere and 11 levels in the ocean. The models comprehensive physical parameterization includes cloud liquid water as prognostic variable and resolves the diurnal cycle (DKRZ, 1994). This model has been used for a number of climate and climate change experiments (Cubasch, 1995; Hasselmann et al, 1995; Hegerl et al, 1996), whose results have been included in the most recent IPCC report (IPCC, 1996). The model's sensitivity to a doubling of CO_2 is estimated to be 3.2 K (Roeckner, pers. com.).

The experiment discussed in the present study consists of three simulations:

a) a control simulation (CTL) with fixed solar constant of 1365 W/m^2, which has been run for 500 years. During the first 160 years of the control simulation there is a drift of 0.5 K, which is caused by adjustment processes of the coupled model at the Antarctic sea-ice edge. This response is likely to be caused by imbalances of the fluxes exchanged between ocean and atmosphere (von Storch et al, 1996). In order to remove this drift, the climate change has been calculated by subtracting the respective year of the control simulation from each year of the climate change simulation ("definition 2" of Cubasch et al; 1994). Other techniques to remove the trend, such as fitting and subtracting EOF functions, have only be used for the spectral analysis (Fig.2) and do not give substantial differences for the other results;

b) two solar variability experiments which started in the year 1700 and were integrated up to 1992. The solar constant in the latter experiments has been prescribed following the estimates of Hoyt and Schatten (1993). The solar constant has been normalized in a way that its average value equals the solar constant in the control simulation. Since the solar constant at 1700 starts with a lower than average value at 1700, a 20 year spin-up run has been carried out in which the solar constant has gradually been reduced from the average value to the 1700 value. The two experiments were started from two different initial conditions (160 years apart) of the control simulation.

Although solar studies indicate that UV variability is proportionately greater than variability in the visible band, no attempt has been made to adjust the model forcing to changes in solar variability by wavelength. We consider such an approach justifiable at this stage of assessment of the sun-climate linkage because Lean et al. (1995) estimate that peak-to-trough changes in UV radiation in the 200-300 µm band represent only 7% of the total irradiance change. Such an amount should not greatly affect our calculation of the response of near-surface temperature, but it could affect the changes with height calculated by the model (see below).

The time series of estimated solar irradiance changes (Hoyt and Schatten, 1993) is derived from five different proxy measures which are considered a measure of secular changes in solar convective energy transport and thus of solar irradiance changes. The time series of estimated solar irradiance changes is clearly subject to high uncertainty imposed by the uncertainties in the proxies and additionally in the relation of these proxies to solar irradiance change. Note that there are also some differences between the estimates of solar variability by Hoyt and Schatten (1993) and one derived by Lean et al. (1995). The former is about 20% larger than the latter and timing of changes is also phase-shifted 20 years (see further discussion in Crowley and Kim, 1996).

Results

Differences in the surface temperature response to solar forcing are illustrated in Fig. 1. Fluctuations of about 5 W/m^2 in the solar constant are translated into global mean temperature changes of ca. 0.5 K. This response is approximately the expected value for a model with an equilibrium sensitivity of about 0.75 $K/(W/m^2)$. The Little Ice Age response in the model is comparable to a substantial fraction of the estimated temperature change (0.5-0.6 K) between 1700-1850 (Groveman and Landsberg, 1979; Bradley and Jones, 1993; Crowley and Kim, 1996). The model responds more to a decrease in the solar constant (max. 0.3 K) than to an increase (max. 0.2 K). This is likely to be caused by the strong sign dependency of the ice-albedo feedback (Roeckner et al, 1995), which has also been found in other simulations (Spelman and

Manabe, 1984; Manabe et al, 1991). There is an indication that the model response to solar forcing changes also deviates from linearity, in the sense that warming tends to peak earlier in the response than in the forcing (for example around 1730) in both experiments. Further simulations would have to be conducted to determine whether this response represents a realistic system response to the change in the rate of solar forcing.

The simulated 20th century warming (0.20 ± 0.04 K) represents only about one-third of the observed change (0.53 ± 0.07 K) over the latest 100 years (Jones et al., 1992). During the last 30 years the rise in the solar constant by 2.3 W/m^2 (at the top of the atmosphere) causes the temperature to rise by about 0.16 ± 0.08 K, compared to 0.54 ± 0.11 K of the simulated global warming by greenhouse gas forcing (Hasselmann et al., 1996) and 0.40 ± 0.12 K for the observations. We used linear trends fitted to the time series of the last 30 and 100 years (restricted to areas where enough observed data are available), the uncertainties refer to a 90% confidence interval. Note that, as mentioned above, our simulations give a rather large estimate of the possible influence of solar variability due to the use of a generous estimate of solar forcing variations.

Figure 1 also shows a large quasi-cyclic response of around 90 years that is associated with the Gleissberg cycle in solar forcing. The solar variability boosts the standard deviation of the global mean near surface temperature of the CTL simulation by about 60%. A spectral decomposition shows that the ECHAM3/LSG control simulation (Fig. 2) has a similar variability as an earlier version, the ECHAM1/LSG model (von Storch et al., 1996, Hegerl et al., 1996). However, in the solar variability experiments, the model generated long-term variability with periods of longer than 50 years is significantly enhanced. This response coincides with the spectral interval where the

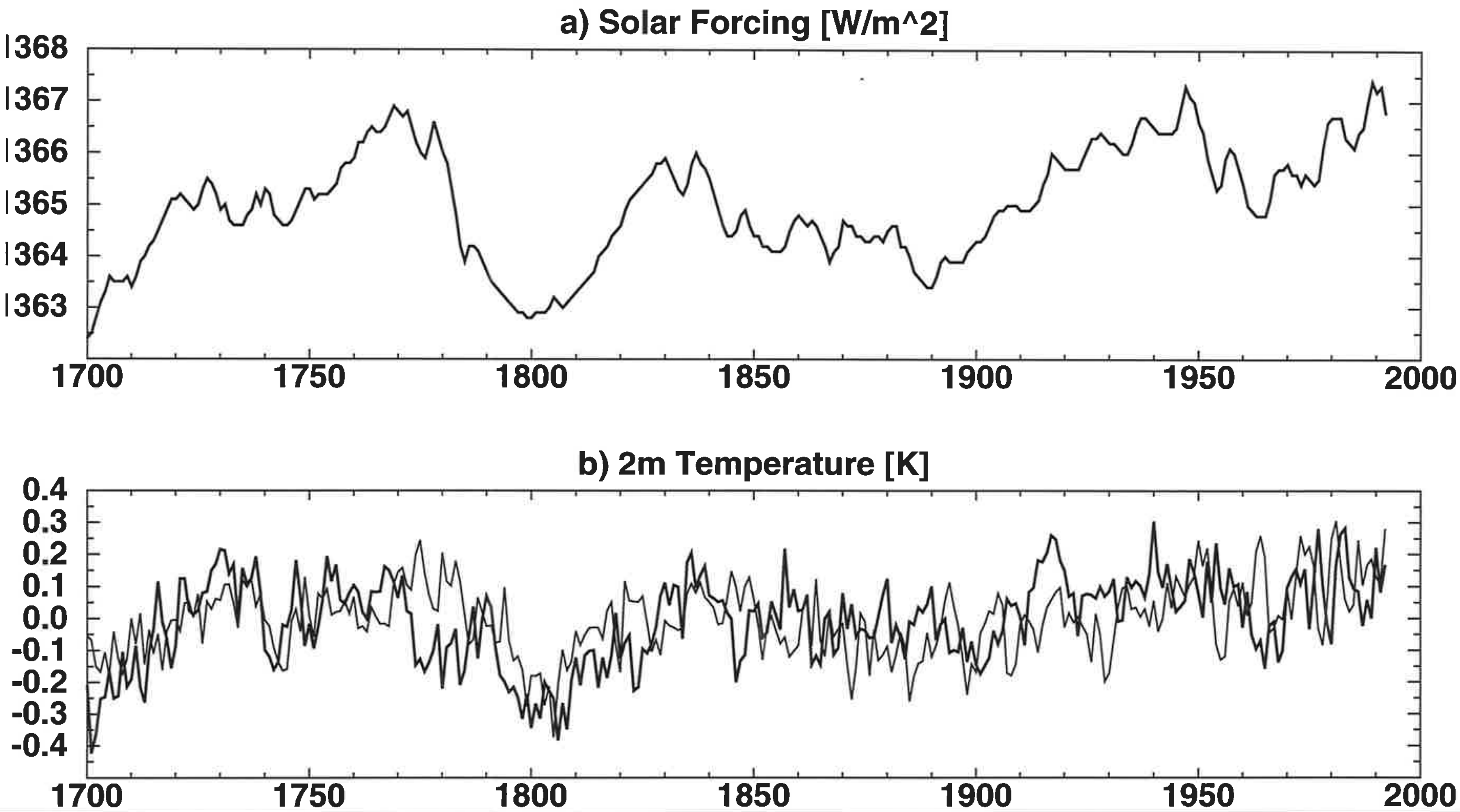


FIGURE 1. a) The solar constant after Hoyt and Schatten (1993), normalized so that its average value is 1365 W/m^2, b) the global mean near surface temperature response to the solar variability for both experiments.

solar variability provides the largest input. This increased variance at lower frequencies may explain some model - data discrepancies previously discussed by Barnett et al (1996a, 1996b). However, there is little indication that the short term variability is enhanced, even though some solar variability can be found at the frequency range of 11 years. This muted response may reflect buffering of the weak 11-year solar signal by the ocean-atmosphere system. Furthermore, the parameterization of physical processes within the stratosphere, and the vertical resolution might be not adequate to respond realistically to the prescribed radiative fluctuations on this time scale.

The global model enables us to calculate the regional effect of solar variability. Even though the input is spread evenly around the globe, clouds and the different distribution of land and sea can translate the response into a differentiated warming at the surface and in the atmosphere. The spatial covariance between the solar variability and the mean temperature response of both solar forcing simulations (each relative to the instantaneous state of the control simulation) at the surface is displayed in Fig. 3. It has been normalized by the variance of the forcing.

Contrary to analyses of global warming simulations (Cubasch et al, 1992), an EOF analysis did not yield a stable response to changes in solar variability, since the climate change signal in this case is weaker and thus dominates less over the internal fluctuations of the model. In the high latitudes of both hemispheres the natural variability is so large that a significant link between solar variability and temperature change cannot be established (Fig. 3). On the whole, the land areas react stronger to the solar forcing change than oceanic regions due to the higher thermal inertia of the ocean. This response is similar to that obtained in greenhouse gas simulations. If the global response pattern is considered, the difference between the solar forcing pattern

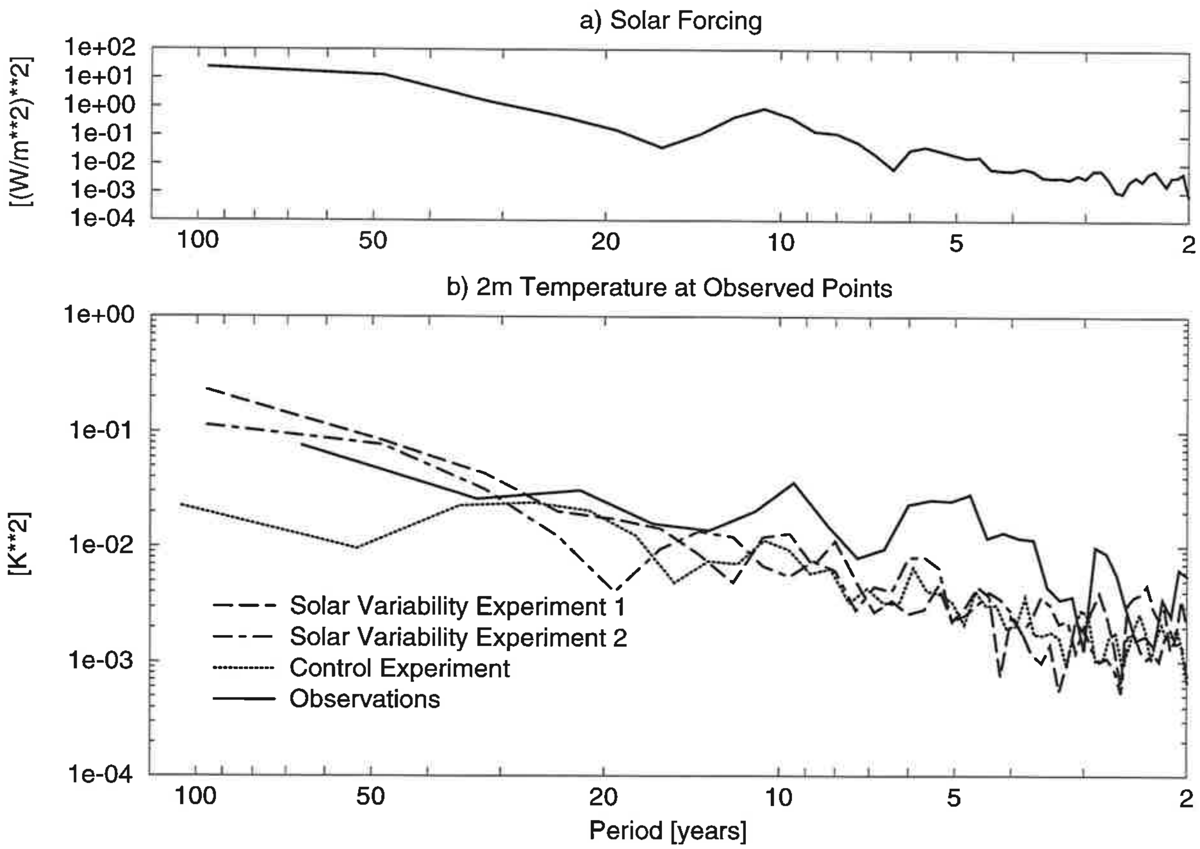


FIGURE 2. Spectra of (a) the solar variability time series and (b) of global mean near surface temperature for the solar variability experiments, the control experiment and the observations. To allow comparisons, all global averages have been computed using only areas where enough observed data are available after 1949 (c.f. Hegerl et al., 1996).

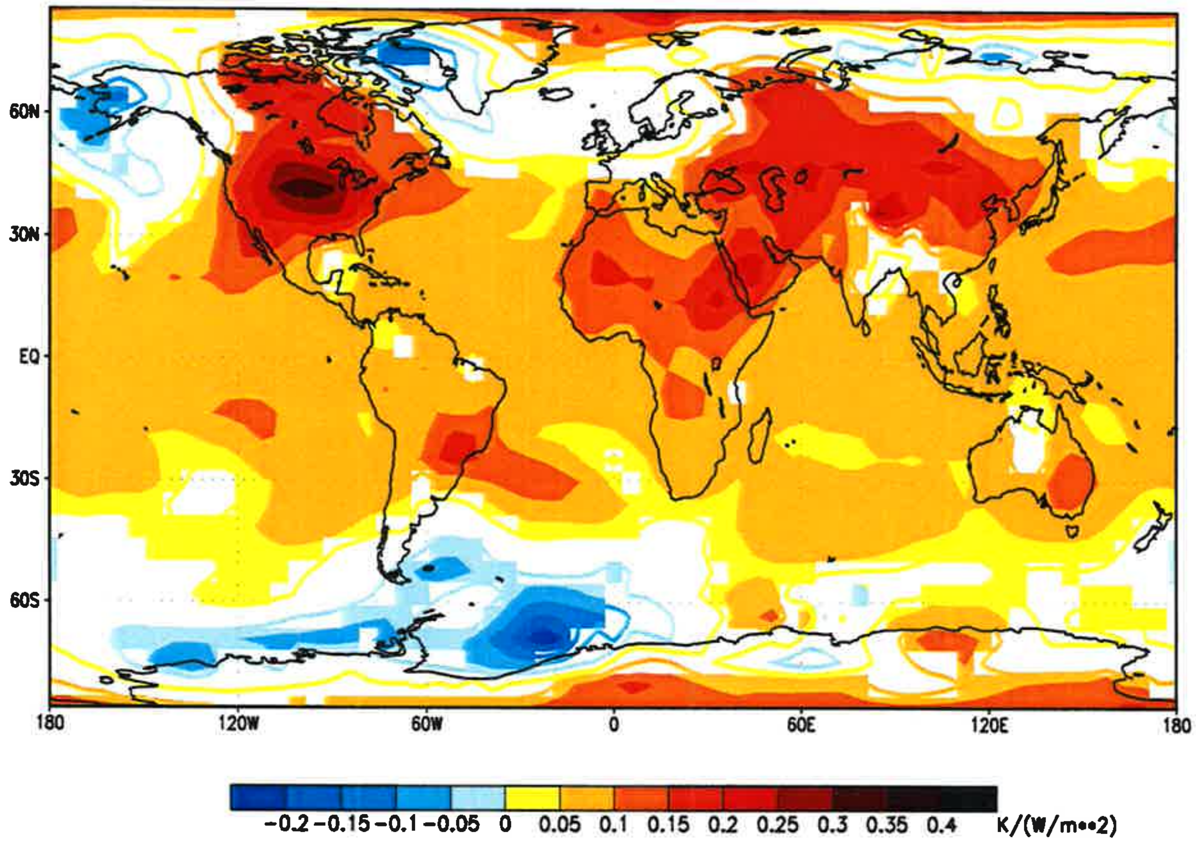


FIGURE 3. Horizontal response pattern of annually averaged near surface temperature to changes in solar forcing (mean of both solar variability experiments). White areas indicate regions with a non-significant correlation between solar variability and surface temperature response.

and the 1. EOF of a greenhouse gas climate change experiment (Cubasch et al, 1996) is dominated for both patterns by the land-sea contrast (Table 1), where DJF denotes the northern hemispheric winter and JJA denotes the northern hemispheric summer.

	annual	DJF	JJA
land and sea	.61	.54	.49
land only	.60	.54	.51
sea only	.39	.36	.25

If the response to solar variability is analyzed separately for land- and sea-areas, and for winter and summer seasons, and then compared to the greenhouse gas response pattern, the patterns in the ocean during JJA hardly correlate. This response suggests that it might be possible to separate the greenhouse gas increase and the solar variability signal in the observed climate change records (see below). Although the exact reason for such a separate response requires more examination, a plausible mechanism might be that the heating due to the increased CO_2 concentration is caused by an enhanced absorption of infrared radiation, while the solar variability heats the atmosphere via an increased flux of shortwave radiation, which can only reach the ground in cloud-free regions. The link of solar variability and surface temperature might therefore be strongest in the subtropical belt, where cloudiness is low. Such a difference would explain the tendency for a relatively strong temperature response in the subtropics (Fig. 3). However, this response would have to be examined with further simulations.

The vertical structure of the temperature response to solar variability in the troposphere (Fig. 4) resembles the one obtained by the greenhouse gas increase experiment, i. e. it features a general warming with a maximum in the upper tropical troposphere. The correlation (mean subtracted) between the zonally averaged greenhouse warming pattern and the zonally averaged solar response pattern between the surface and the 250 hPa level is 0.68. In the stratosphere, the zonally averaged response pattern of the solar variability experiments and the CO_2 experiment are uncorrelated (correlation -0.03), yielding an overall pattern correlation of 0.20. In the stratosphere, the CO_2 experiment shows a general cooling which has also been found in the observations (Karoly et al, 1994; Santer et al, 1996), while in the solar variability experiments a warming is visible. However, this latter response should be treated with caution because we did not include a varying UV component to our solar forcing (but because variable UV might amplify the response we obtain, this consideration may not undermine our provisional conclusion). Anthropogenic ozone changes may also significantly modify the stratospheric response (Santer et al., 1996).

The solar runs can also be used for investigating what may have been the cause of the 20th century warming. Hegerl et al. (1996a) showed that the recent observed 30-year trend patterns of near surface temperature deviate significantly from unforced model variability and also from the observed variability with a model-estimated greenhouse warming signal subtracted (Hegerl et al., in prep.). The authors concluded that this climate change is consistent with greenhouse gas induced climate change, but that it cannot be uniquely attributed to the greenhouse gas forcing. To assess what part of the observed warming may have been caused by a change in solar irradiance, we compare the observed 30-year (locally fitted linear) trend patterns synchronously to the solar response pattern and the greenhouse warming pattern. Since both patterns are not orthogonal, the orthogonal pattern to the solar forcing pattern in the plane spanned by both has been computed to enhance the graphical representation. The main difference between the solar forcing pattern and the greenhouse warming pat-

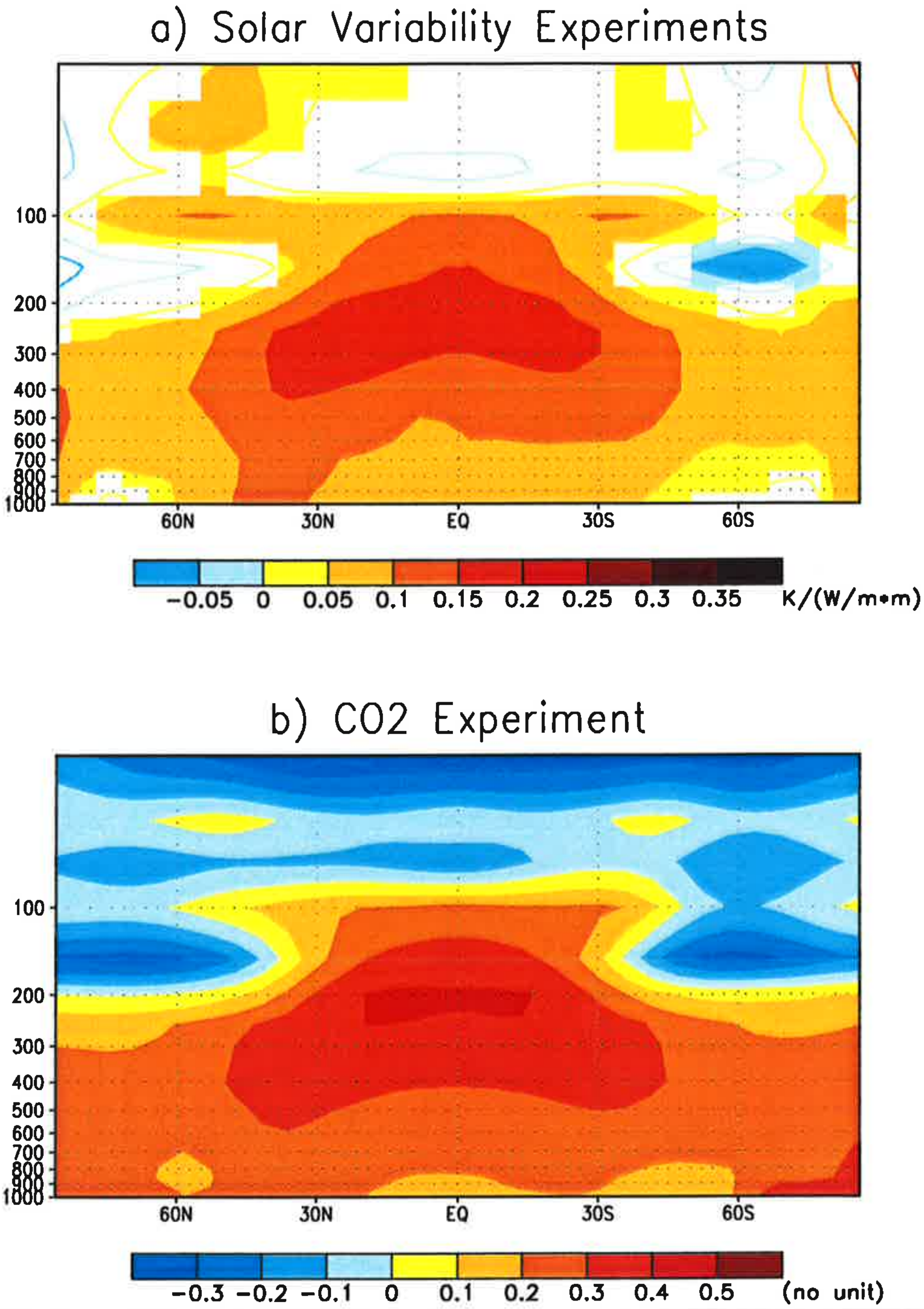
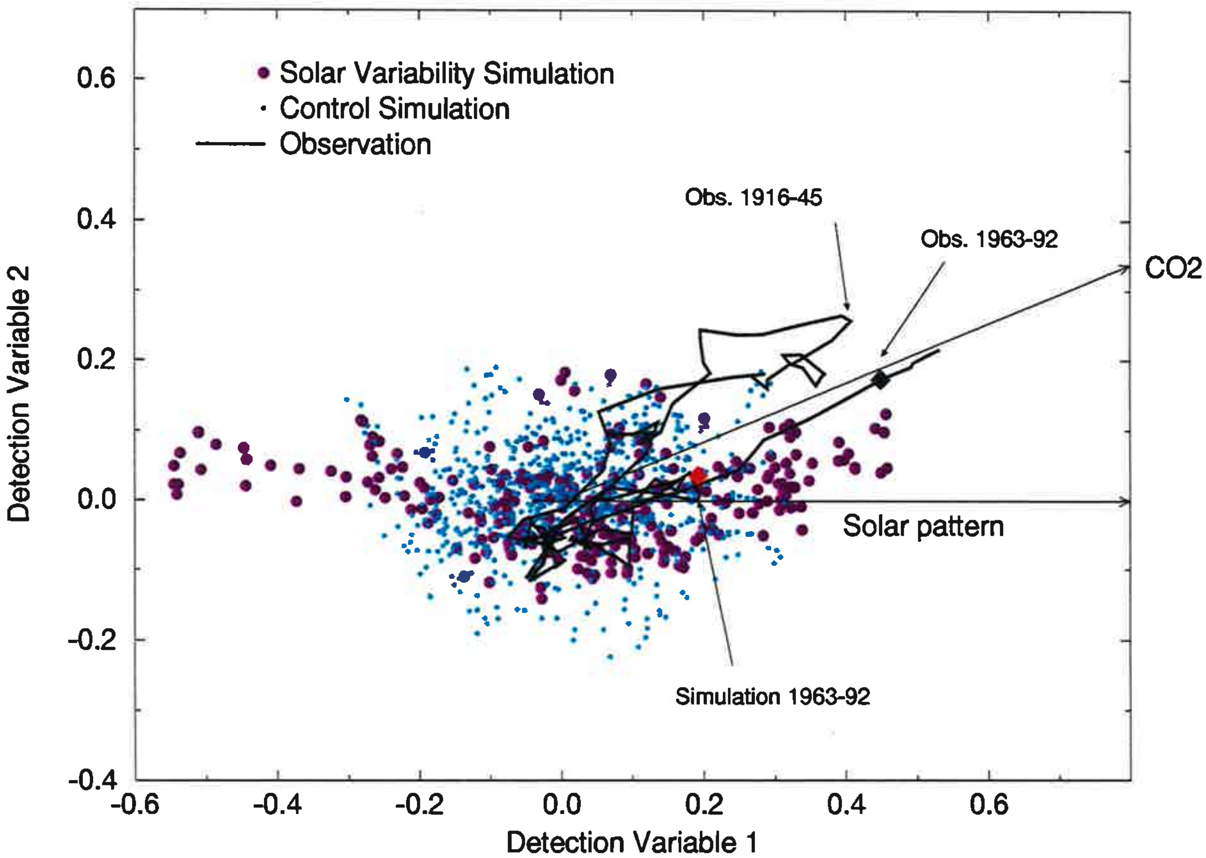


FIGURE 4. (a) Response of zonally averaged atmospheric temperature to changes in solar forcing (mean of both solar variability experiments) compared to (b) zonal mean of the first EOF of greenhouse-gas-induced climate change simulated with the same climate model (Hasselmann et al., 1995). White areas indicate regions with a non-significant correlation between solar variability and the zonally averaged temperature response.

tern (if both are normalized to the same mean warming to allow a comparison of pattern only) occurs in the low latitudes, especially over the Pacific (result not shown), where the solar response shows a more enhanced warming.

Fig. 5 shows the evolution of the observations in the two-dimensional phase space of the solar and greenhouse gas pattern compared to 30-year trend patterns from the mean of both solar variability simulations and the control simulation. The analysis is restricted to areas where enough observed data are available since 1949 (Hegerl et al., 1996). Points in the phase space close to the arrow denoted by "Solar pattern" show a pattern which is more similar to the solar response pattern, points close to the diagonal arrow denoted by "CO2" are more similar to a greenhouse warming pattern. The results indicate that changes in the solar forcing increase the spread of the 30-year trend patterns compared to the control simulation. The amplitude of the solar signal (detection variable 1) of the observed temperature trends in the early part of this century (Fig. 5) is similar to amplitudes in the solar simulations in the respective period (some of the high excursions of the solar pattern in Fig. 5). However, the phase diagram (Fig. 5) shows that the observed trends in this period are more similar to the greenhouse warming pattern. This may be partly due to a developing greenhouse warming signal in the observations. However, the pattern separation in the early part of the century is not reliable, since there are very few observed data in areas where the strongest differences between both model patterns occur (e.g. the low-latitude Pacific Ocean). Qualitatively similar results as shown in Figure 5 are obtained if the analysis is restricted to 45N to 45S, is applied to ocean data only or to JJA data (where the difference in pattern is largest). Thus, the evolution of the observations in the phase space of solar forced and greenhouse gas forced climate change patterns is not dependent on the choice of data.

FIGURE 5. Evolution of observed (1889 - 1995) and simulated (1729 - 1992) annual mean 30-year temperature trend patterns in a phase space spanned by the solar variability pattern (horizontal axis, denoted by "Solar pattern") and the greenhouse warming pattern (diagonal axis, denoted by "CO2"). An orthogonal pattern is introduced to enhance graphical representation. The observed and simulated trend patterns are projected onto the solar variability pattern (detection variable 1) and the orthogonal pattern (detection variable 2). The comparison is restricted to areas covered by observations (c.f. Fig. 2). The purple dots denote 30-year trend patterns from the average of both solar simulations. Note that the solar forcing increases the variability compared to pure internal climate variability (blue dots) and that the observed trend ending in 1992 (black diamond) diverges from the trend pattern predicted if the warming was due to solar irradiance changes only (red diamond).



Clearly, the most recent observations resemble more the greenhouse warming pattern. The latest model trend pattern 1963-1992 and the respective observed trend pattern are also shown in Figure 5. If projected onto the greenhouse warming pattern, the observations and the mean of both solar forcing simulations disagree at an estimated 90% confidence level. In other words, the probability that such a disagreement can be caused by the internal variability of the simulations and the observations (both estimated by the control run variability) is less than 0.10. Although the difference between both amplitudes is relatively large, the confidence level is quite small due to the uncertainty associated with the model simulated amplitude. Also, the internal variability of this climate model may be underestimated (c.f. Hegerl et al., 1996), furthermore the estimate is subject to sampling uncertainties (the natural variability level of the 30-year trend pattern has been estimated from 700 years of control simulation).

In order to check the above result, we have additionally analyzed observed global mean temperature trends. We have subtracted the climate response to the estimated solar forcing change as computed by an energy balance model (EBM; Crowley and Kim 1996) from the observations, since different from a O-AGCM, an EBM yields an estimate of the noise-free system response to solar forcing. The climate sensitivity of the EBM was scaled to the same climate sensitivity as the coupled model prior to comparison. Results (not shown) show that the 30-year trend of global mean near surface temperature ending in 1992 is significantly different (this time beyond the 95% confidence level) from internal climate variability estimates computed from different model simulations (in the same way as used in Hegerl et al., 1996). This and the further evolution of the observations towards the greenhouse warming pattern between 1992 and 1995 (Fig. 5) enhances our confidence in the finding that solar forcing alone does not explain the recent observed climate change.

Summary and Conclusion

A coupled ocean-atmosphere model has been forced with an estimate of solar variability since 1700 in order to assess its potential impact on temperature. The coupled model transfers the variations of the solar constant into changes of the near-surface temperature with only a small time lag. The dominant response in the model is at the centennial-scale Gleissberg cycle, with peak-to-trough changes in global temperature on the order of 0.5 K with a stronger response to a decrease of the solar intensity than to an increase. The prime response to an increase of solar forcing is an increase in the land-sea contrast, similar to the effect of an enhancement of the greenhouse gases. The vertical structure of the heating is similar for the greenhouse gas and the solar warming in the troposphere, but in the stratosphere considerable differences appear. The greenhouse gas response pattern generally shows a cooling in the stratosphere, while an increase in solar radiation tends to increase temperatures there. The observed stratospheric cooling cannot be explained by solar variability. However, other effects, like volcanic aerosols and ozone variations, also have to be considered at this layer of the atmosphere.

During recent years, the modeled global warming due to the solar constant increase explains only a fraction of the observed global warming. The pattern and the amplitude of the observed warming is different from that predicted by the solar simulations. However, the significance level of this conclusion is only 90%, and also subject to uncertainty associated with the estimate of internal climate variability. Nevertheless, the fact that this conclusion was obtained using a rather generous estimate of solar variability changes and a model with a moderately high climate sensitivity give some confidence that the present warming cannot be explained by changes in solar irradiance alone.

Experiments with the coupled climate model provide a wealth of additional information which we will report on in future studies. Future investigations of such effects may better enhance our understanding of climate change in the 20th century and the potential effect of solar variability on the instrumental and paleo-climatic record.

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