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The role of the sun in climate forcing

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Abstract

The Sun is by far the most important driving force of the climate system. However, only little is known how variable this force is acting on different time scales ranging from minutes to millennia and how the climate system reacts to changes in this forcing. Changes of the global insolation can be related to the nuclear fusion in the core of the Sun, the energy transport through the radiative zone and the convection zone, the emission of radiation from the photosphere, and the distance between Sun and Earth. Satellite based measurements over two decades show a clear correlation between the solar irradiance and the 11-year sunspot cycle. The irradiance amplitude is about 0.1%. This is too small to affect significantly the climate. However, there are indications that, on longer time scales, solar variability coluld be much larger. The analysis of cosmogenic nuclides stored in natural archives provides a means to extend our knowledge of solar variability over much longer time periods.

The response of the climate system to solar forcing depends not only on the amount of radiation, but also on its spectral composition (e.g. UV contribution), seasonal distribution over the globe, and feedback mechanisms connected with clouds, water vapour, ice cover, atmospheric and oceanic transport and other terrestrial processes. It is therefore difficult to establish a quantitative relationship between observed climate changes in the past and reconstructed solar variability. However, there is growing evidence that periods of low solar activity (so called minima) coincide with advances of glaciers, changes in lake levels, and sudden changes of climatic conditions. These findings point to an active role of the Sun in past climate changes beside other geophysical factors, internal variability of the climate system, and greenhouse gases. In fact a non-linear regression model to separate natural and anthropogenic forcing since 1850 is consistent with a solar contribution of about 40% to the global warming during the last 140 years. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The Earth receives at the top of the atmosphere an electromagnetic energy flow of about 1365 W m^{-2} from the Sun. Until high-precision satellite data became available, the solar energy output was considered as constant by many scientists. This is nicely reflected in the term "solar constant". All ground-based attempts failed to detect variations of the solar constant due to fluctuations induced by the atmospheric transparency. It was not until radiometers based on satellites outside the atmosphere began to monitor the solar radiation when small changes were discovered. From the minimum of solar cycle 21/22 to the maximum of cycle 22 the variation was in the order of a tenth of a percent. These results clearly showed that the solar constant is not strictly constant and, meanwhile the possibility of larger fluctuations over time scales of decades to millennia became a serious issue in solar physics and climatology.

For climatology, all the factors that affect the energy flow from its source in the core of the Sun through the Earth's climate system to its final sink in deep space are important. On this long way variability on all time scales is generated.

In this paper we concentrate mainly on time scales longer than decades. Since there are no direct observational data to study the solar variability on such long time scales we have to rely on proxy data such as cosmogenic radionuclides.

The Sun is by far the most important driving force of the climate system. But little is known what role solar variability plays in past and present climate change. The main open questions are:

- What are the underlying transport processes of energy and how do they govern the solar variability on different time scales?

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- How does the climate system react to changes in solar forcing?

In spite of all the uncertainties, there is increasing evidence that the variability of the solar constant might indeed have a significant influence on past, present, and future climate changes.

The statement by White (1977, p. 91) is today as true as it was more than 20 yr ago: "Since we do not yet have a firm, quantitative measure of the sensitivity of the earth's climate and weather to changes in the solar constant, however, one very important problem in solar physics continues to be the absolute measurement of the solar constant and its variation with time".

This paper does not intend to provide a comprehensive review of this fast growing field and to cover the huge literature. It is rather a mixture of a general account of possible influences of a changing solar radiation on the Earth's climate from a global perspective with a personal view regarding the relationship between solar and anthropogenic forcing.

2. Variability of the global insolation

The term solar constant is a historical quantity. Its definition has evolved from a quantity characterizing the incident solar radiation to a quantity of the radiation flux density in a given distance (e.g. the mean Sun–Earth distance). A more unique quantity is the total solar irradiance defined as the density of energy flux through an area of 1 m^2 oriented towards the Sun at the top of the Earth's atmosphere at the distance of 1 AU. The integral of the flux density over a sphere around the Sun yields the solar luminosity. This quantity cannot be measured from the Earth. In contrast to this, the term insolation is a quantity mostly used in connection with a specific site on the Earth, a specific season, and a specific angle of incidence.

In this paper we will use the term global insolation for the total (integrated over all wavelenghts) electromagnetic solar radiation at the top of the atmosphere in units of W m^{-2}. This global insolation is a function not only of the properties of the Sun itself but also of the changing transmission conditions between Sun and Earth including the Sun–Earth distance.

There are several types of processes that can generate variability of the global insolation:

- nuclear fusion in the core of the Sun,
- transport through the radiative and convective zone of the Sun,
- the emission of radiation from the photosphere towards the Earth,
- changes of the mean distance between Sun and Earth (changes in eccentricity).

These different sources of variability act on very different time scales from seasons to billions of years. In the following the different sources of variability and their significance for climate forcing are discussed.

2.1. Fusion processes in the core

The long-term energy flow from the sun (luminositiy) is determined by the fusion rate of hydrogen to helium in the solar core on a billion year time scale and follows a hyperbolic trend (Fig. 1) (Gough, 1977). The deviations from this trend are extremely small. From physical models of the Sun's evolution it was computed that the early solar radiation output 4 billion years ago, was only about 75% of its value of today (Newman and Rood, 1977; Gough, 1981). Since then the energy output steadily increased and will continue to do so for another 4 billion years. At this time the hydrogen in the core of the Sun will be exhausted and the solar luminosity will be higher by about 35% compared to today (see Fig. 1). The long-term evolution of the Sun leads to a change of the temperature in the photosphere, which results in a shift of the Planck spectrum.

The steady increase of the luminosity is a consequence of the decreasing number of particles generating the pressure for the equilibrium conditions of the Sun, and the shrinking of the burning core. Later on an outwards moving shell of burning hydrogen will further accelerate the increase in luminosity.

In spite of the extreme consequences a doubling of the solar luminosity over 8 billion years has on the living conditions on Earth, the rate of change is extremely small (10^{-4} Wm^{-2} kyr^{-1}). Therefore, the variability potential of the fusion process is completely negligible for the present climate change. However, it is an exciting question how the Earth has managed to remain a habitable

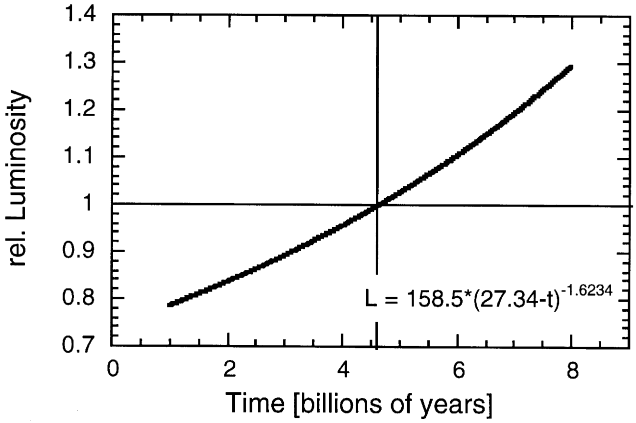

Fig. 1. Hyperbolic model of the long-term trend of the solar luminosity according to the output of a standard solar model from Kippenhahn (personal communication). (Rel. Luminosity = 1 corresponds to 1365 W m^{-2} at 1 AU) (modified hyperbolic model by Gough, 1977).

planet with globally distributed liquid water during the past 4 billion years and why it did not turn neither into an icy nor a hot planet. This question was investigated by Sagan and is known as the "The early faint sun paradox" (Sagan and Chyba, 1997). It illustrates the huge long-term stability of the Earth's climate despite the extreme changes in solar forcing.

2.2. *Variability in the energy transport through the sun's interior*

Another possible source of a changing global insolation is related to the energy transport through the interior of the Sun and the emission of radiation from its surface. The energy transport through the radiative zone (0.3 – 0.7 solar radii) is probably very stable on a million year time scale and does not generate any measurable variability. However, the heat transport through the convective zone (0.7 – 1.0 solar radii) is related to convective and magnetic structures. It is probably a significant source of variability of the solar radiation on time scales of years to 100 kyr (Nesme-Ribes, 1994, #879).

2.3. *Emission of radiation from the photosphere towards the earth*

The measured variability in total solar irradiance (TSI) is a superposition of stochastic and periodic phenomena. Some of them are related to individual features in the photosphere like sunspots, plages, magnetic network, etc. Other variability comes from the photospheric background. All this variability is modulated by the recurrent activity regime during the solar rotation. So, the TSI is a mixture of all these temporal and spatial phenomena and it is difficult to attribute the observed irradiance variations to a single feature in the photosphere. The observed irradiance variability is essentially the response of the outer solar layers to thermally or magnetically driven excitation near the bottom of the convection zone. This excitation generates also the conspicuous photospheric features as sunspots and faculae. So, irradiance and solar surface features have a common cause which explains their high correlation. Attempts have been made to model these irradiance variations by the mentioned features (sunspots, faculae etc.) of the solar surface. (see Fontenla et al., 1999; Fröhlich et al., 1997; Fligge et al., 1998; Solanki and Unruh, 1997; Unruh et al., 1999). The models describe about 95% of the solar irradiance variability. However, the remaining 5% could cause a significant impact on the long-term variability of the Earth's climate.

Fig. 2 shows a composite of TSI measurements from 1980–1997 together with a 2 yr low-pass filtering. During solar cycle 21/22 the maximum daily variation of the total solar irradiance was 0.37%. In the 2 yr low-pass filtering the difference in TSI between solar maximum and solar minimum is 0.14%, which is close to the commonly cited value of 0.1%.

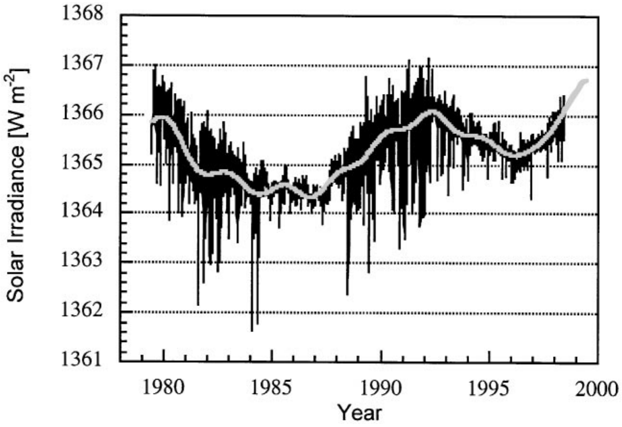

Fig. 2. Compilation of solar irradiance measurements from NIMBUS 7, ACRIM II, and VIRGO.

The composite was made from NIMBUS 7, ACRIM II, and VIRGO data using narrow overlapping intervals of high correlation to flange the three data sets. The difference in the levels between the two solar minima is, if real, a hint to an intercyclic long-term evolution of TSI. Moreover, the u-shape of the solar minimum 21/22 is remarkably different from the v-shape of the minimum 22/23. A similar shorter composite has been published by Willson (1997). Another composite using slightly different data sets with very detailed corrections has been published by Fröhlich and Lean (1997). This composite does not show the level difference between the minima. The main reason for this is a correction applied by these authors to the NIMBUS 7 data to remove two jumps. The discrepancy between different composites illustrates the difficulties involved in combining different TSI satellite records. The achievement of highly accurate long-term TSI measurements is a high priority goal for the future.

2.4. *Variability due to anisotropic emission*

As a consequence of the Sun's rotation we cannot exclude that the energy transport to the surface and its emission into space is anisotropic. Anisotropy is therefore an additional potential source of variability. Some anisotropy is caused by the 27 d solar rotation as visible in the spectral excess (cf. Fig. 3).

2.5. *Kolmogorov spectrum*

Due to the limited time of direct measurements from satellite-based radiometers only changes of solar irradiance on time scales of minutes to decades could be observed so far. The spectrally ordered variance shows

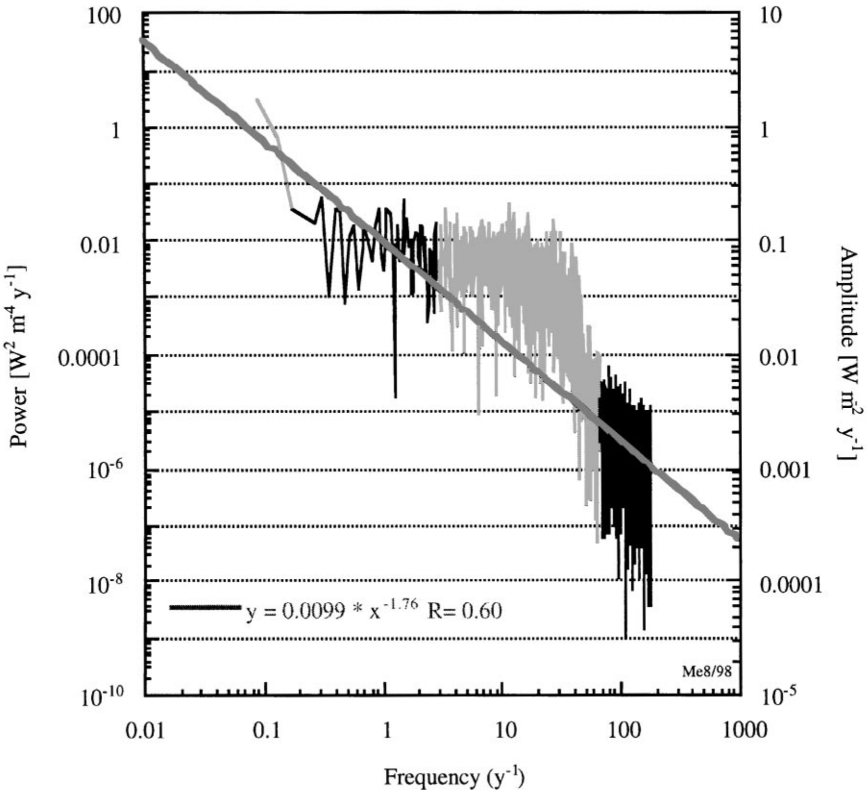

Fig. 3. Solar irradiance spectrum and a hyperbolic fit through the data excluding the rotational frequency band. The fit gives an exponent of -1.76 which is close to the Kolmogorov slope $-5/3$. At the right-hand side a scale of variational amplitudes is given.

coloured noise spectra (Fröhlich et al., 1997). The power spectrum of TSI (Fig. 3) exhibits a broad band excess caused by the solar rotation and its harmonics in the period length from 27 d down to 8 d. If one excludes the rotational frequency and a few harmonics the slope in the observed time range from a few days to 20 yr is comparable with a Kolmogorov 5/3 - spectrum. This spectrum can be used to extrapolate the linear scaling behaviour toward longer time scales. This leads to variability amplitudes of several percent on time scales of $10^3 - 10^4$ yr. The implicit assumption in this estimation is the real existence of physical variability machanisms which extend the coloured noise spectrum. A theoretical limit for these processes is the Kelvin–Helmholtz time (energy content of the convection zone divided by the luminosity) which is 200 kyr for the convection zone (Stix, 1991, p. 295). Beyond the Kelvin–Helmholtz time of the convection zone the solar variability should be again zero (Stix, 1991, p. 295). This puts a lower limit on the variation frequency that the solar convection zone can produce from the thermodynamical point of view. This is in good agreement with the variability estimations from sun-like stars.

The existence of very low-frequency luminosity fluctuations on millennial time scales produced by the Sun is a fundamental issue for paleoclimate studies.

2.6. *Variability of the energy distribution on different wavelengths* (*spectral variability*)

Changes of the global insolation can act very differently depending on the spectral and temporal distribution. The spectral composition of the radiation changes considerably during a solar cycle (Lean, 1991; Rottman et al., 1993). Fig. 4 shows the solar spectrum over a wide range of wavelengths (Handbook of atmospheric Physics complemented in the centre of the spectrum by more recent data from the World Radiation Center Davos). The spectral variability of the continuum is sketched for the same wavelength range neglecting all spectral excesses or variable line structures. The variability is measured by the extreme values of daily measurements ((maximum value – minimum value)/minimum value) independent of where the extreme values occur within a solar cycle. This measure of variability is different from the one used by Lean (1991).

Our variability measure uses daily averages and yields in general much higher variabilities than Lean's values. Due to the lack of long-term measurements in the infrared region we posted the minimum variability in the vicinity of the spectral maximum. Independent of the precise point the smallest relative variation is probably not far off the visible light. The absolute variation of the

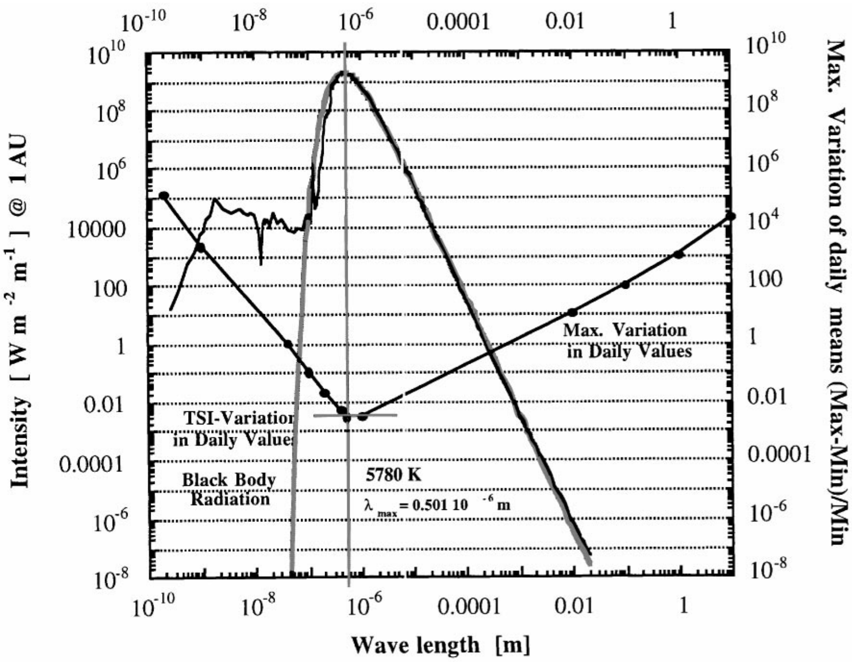

Fig. 4. Dependence of the irradiance and variability on the wavelength. The variability is based on daily values. For details see text.

energy flow is given by the product of relative variation with the absolute spectral intensity. It follows that the largest absolute variation is near the minimum relative variation and near the spectral intensity maximum. Model calculations (Solanki and Fligge, 1998) yield a relative variability minimum near the opacity minimum in the photosphere at 1.6 μm. But this minimum is not confirmed by observations as a relative variability minimum until now. These models show considerable changes of variability in certain spectral regions which is due to the different opacity of the solar atmosphere and to the origin of the radiation in different atmospheric heights.

Important for the discussion of different sources of variability is the low variability of the spectral continuum near the visible range and the increase of variability towards both ends of the spectral window following approximately a power law. These features are independent of the applied measure of variability. It is important to note that the huge variability changes at the far ends of the spectrum contribute only little to the absolute total energy flow, but nevertheless their effects on the climate system can be important, if there exist mechanisms that are specifically sensitive to certain spectral bands (for example ozone absorption of UV) (Haigh, 1994). The short-wave part of the spectrum (< 400 nm) contributes only about 7% to the total irradiance. The variability measured by the maximal level in certain UV bands during one solar cycle can be several times higher than the normal UV level. Such a high variability can strongly affect the ozone layer in the stratosphere (Haigh, 1994). At the long-wave side of the solar spectrum the irradiance exhibits a variability of about 2 orders of magnitude at 10 cm and 4 orders of magnitude at wavelengths beyond 10 m. This illustrates the enormous variability at both ends of the spectrum.

2.7. *Variability of the earth's orbital parameters (Milankovich theory)*

The Earth's orbit and the tilt of the Earth's rotational axis are changing slowly with time. This is caused by gravitational forces of the other planets which affect the eccentricity, the obliquity and the precession. These orbital parameters vary mainly with oscillation periods of 100, 41 and 23 kyr, respectively. The same periodicities have been found in δ^{18}O records from deep-sea sediments (Imbrie, 1993, #141) (Fig. 5). These δ^{18}O records reflect the global ice volume on a millennial time scale and point to a connection between ice ages and orbital forcing.

The final orbital forcing theory was worked out by Milutin Milankovich during the 1930s (Milankovich, 1930) based on earlier work by Croll (1867) and others. It is important to note that only changes in the eccentricity affect the globally and yearly averaged insolation. Changes in the obliquity and precession on the other hand cause a different latitudinal distribution of the insolation during the seasons. Orbital changes are purely geometrical. They are independent of the solar radiation and do not affect their spectral composition.

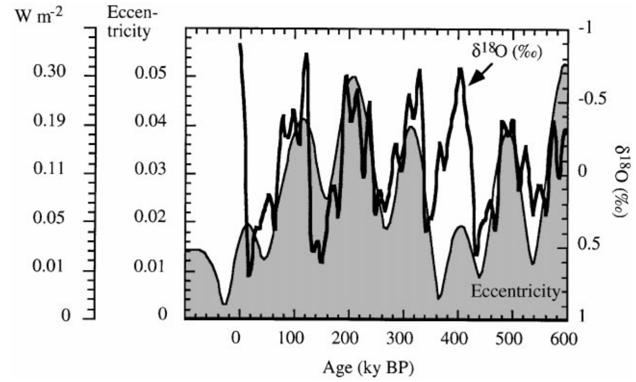

Fig. 5. Comparison of the calculated eccentricity with the SPECMAP δ^{18}O record (Imbrie, 1993).

The sequence of glacials and interglacials revealed by the δ^{18}O SPECMAP curve (Fig. 5) shows a strong 100 kyr periodicity (except for the glacial period 400 kyr BP and the last 20 kyr). It is remarkable how dominant the 100 kyr eccentricity signal is. This is in contrast to the induced small radiation changes (1–2‰) which are comparable to the changes of irradiance measured during one 11-yr Schwabe cycle. We will come back to this point later when we discuss the sensitivity of the earth system.

Currently the orbital forcing has small amplitudes (Berger, 1997, #2391). Obliquity and precession are approaching a half-million year minimum in the next 10 kyr. The eccentricity has a deep minimum in about 30 kyr. So, for the next 50 kyr orbital forcing will probably not strongly affect the climate evolution.

2.8. *Solar-type stars*

An elegant way to study the solar variability is to observe stars that are very similar to the Sun. The investigation of 30 solar-type stars over the past 30 yr shows that cyclic variability is typical for solar-type stars Radick et al., 1990. The observed periodicities range from 7 to 20 yr as in the case of the solar Schwabe cycle. Most of these stars exhibit much larger brightness changes with peak-to-peak amplitudes of up to 1% compared to the 0.1% irradiance amplitude for solar cycle 22.

This leads to the conclusion that the variability potential of the Sun could be much larger than the variability observed during the satellite-based observational period of two solar cycles.

It is remarkable that the brightness of most monitored stars shows significant intercyclic variations, especially the minimum levels change from cycle to cycle in the order of several percent. Eventually the Sun shows a similar intercyclic variation of the minimum level as it is suggested by our composite of solar irradiance (see Fig. 2).

2.9. *Periodicities*

The sun is a variable star that shows variability on time scales from less than a minute up to more than billions of years. The first detected periodicity in solar activity was the famous 11 yr Schwabe cycle (Schwabe, 1844). Magnetic measurements revealed an alternating polarity of sunspot groups in a contiguous 22-yr cycle, the so-called Hale cycle. Longer periodicities cannot be observed directly but they can be clearly identified in the ^{14}C tree ring record (Stuiver and Braziunas, 1993). The most prominent "long" cycles have period lengths of 88 and 208 yr, respectively. Later on all these cycles could be detected in other proxy data (e.g. Sonett and Suess, 1984). These records contain also some hints to considerably longer cycles, for example of 2000 yr (Mayewski et al., 1997). Cosmogenic radionuclides reveal periods of low solar activity, e.g. the so-called Maunder (1645–1715), Spoerer (1416–1534), and Wolf-minimum (1282–1342). The solar origin of the Maunder minimum is confirmed by historical observations of the absence of sunspots (Eddy, 1976). Modern observations confirm that amplitude and spectral distribution of the solar irradiance change in phase with the solar activity. However, the observed changes during the last two cycles are relatively small (0.1%). But, as we discussed above, there is a potential for much larger variability amplitudes on longer time scales.

3. Indications of changes in global insolation

We now address the question of how much the Sun made use of its potential to change the irradiance. There are only a few pieces of direct and indirect information that shed some light on this difficult problem.

The energy generation in the core of the Sun can be calculated for any time in the past and in the future over millions of years. Unfortunately beyond the hyperbolic trend on the billion year time scale (Fig. 1) this is not the case for the variability of the solar luminosity at the surface of the Sun and the irradiance at the top of the Earth's atmosphere. An important question is therefore how solar forcing has changed in the past on centennial-to-millennial time scales.

For the pretelescopic period there are no continuous and reliable records of direct solar observations. The only continuous information is based on indirect proxies such as cosmogenic radionuclides (^{10}Be, ^{14}C, ^{36}Cl). The production rate of these nuclides in the atmosphere is modulated by the solar wind (Masarik and Beer, 1999). Their analyses in natural archives such as ice cores (^{10}Be, ^{36}Cl) and tree rings (^{14}C) allow reconstructing their production history and deriving conclusions about the solar variability in the past (Beer et al., 1994a; Stuiver and

Braziunas, 1993). The main result is the persistence of the solar activity cycles, especially the so-called Schwabe cycle, the Gleissberg cycle and even longer cycles far into the past (Beer et al., 1994b).

3.1. The reconstruction of the past solar irradiance

Solar effects on the climate are usually thought to be connected with changes of the total solar irradiance. To investigate the underlying mechanisms one has to reconstruct the solar irradiance with high accuracy back in time as far as possible. Up to now reliable reconstructions of the TSI with a long-term stability in the range of a tenths of a percent are not available. Even the satellite measurements do not provide a unique determination of irradiance changes with such a high stability during the last two cycles. Even more uncertain are reconstructions over longer periods of time.

For the last 250 yr most reconstructions are based on solar activity data such as the sunspot number (Fig. 6). To estimate the irradiance the amplitude, the solar cycle length or its frequency are often used. Several reconstructions have been proposed (Lean et al., 1995; Hoyt and Schatten, 1993; Solanki and Fligge, 1998). They differ in details but agree in the overall shape, the generally increasing trend with local minima during periods of low solar activity (Maunder minimum: 1645–1715 AD; Dalton minimum: 1800–1820; 1900 minimum: 1880–1900), and a slight decrease between 1940 and 1970. A sharp maximum around 1830 is connected with high solar activity. Superimposed on this long-term trend are short-term fluctuations caused by the Schwabe cycle.

Our own irradiance reconstruction is based on the frequency of the Schwabe cycle because we find a better fit with the temperature data if we assume a linear relationship between cycle frequency and irradiance (Fig. 7). We estimate the frequency change in time by complex demodulation. This provides a continuous frequency modulation function. For comparison with temperature records we use a 14 yr low-pass filtering in order to remove all periodic irradiance changes during one Schwabe cycle. This leads to a relatively smooth frequency modulation function the "Sun Melody". It shows approximately the same general shape as the reconstruction of solar irradiance by Hoyt (Hoyt and Schatten, 1993) and exhibits the described characteristic minima and peaks.

The Sun melody is a good candidate for a proxy of solar irradiance on time scales longer than one solar cycle. The Schwabe bands in the yearly spaced ^{14}C tree ring record (Stuiver and Braziunas, 1993) and in the Dye 3 ^{10}Be record (Beer et al., 1994a). Show frequency modulation with 88 and 208-yr periodicities. The variability

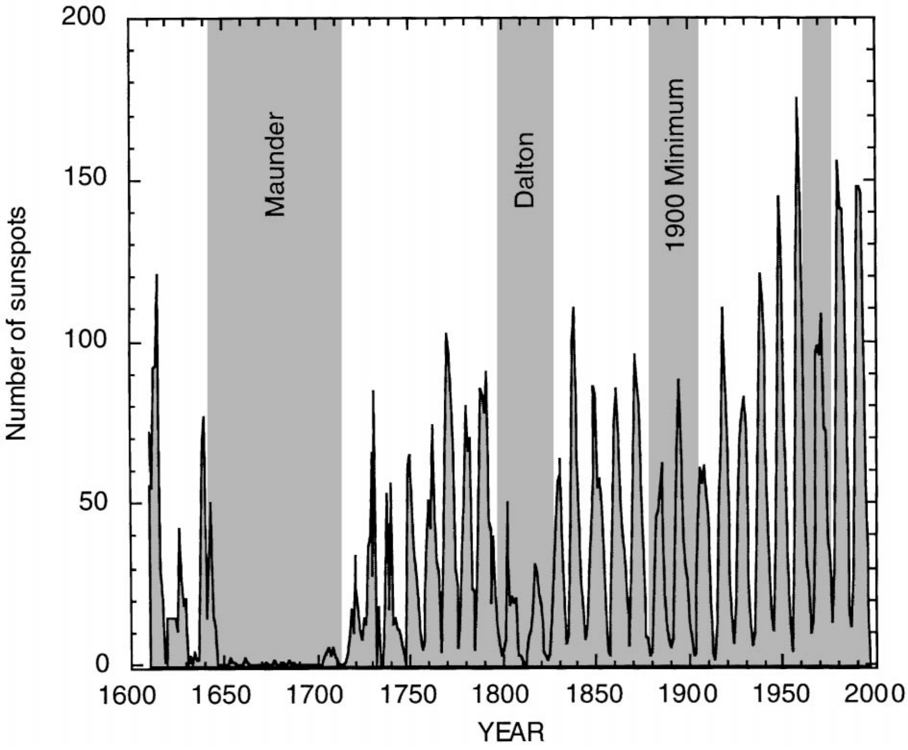

Fig. 6. Sunspot cycle derived from the number of sunspot groups (Hoyt and Schatten, 1998). Periods of reduced solar activity (Maunder, Dalton, 1900 Minimum, …) are shaded. A general increasing trend since the Maunder Minimum is visible.

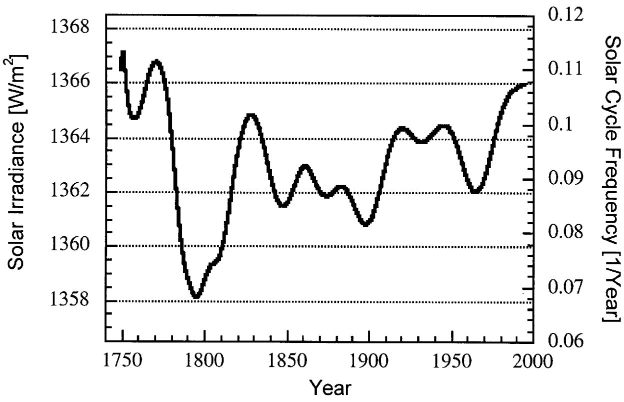

Fig. 7. Sun melody. Frequency modulation of the sunspot Schwabe cycle (14 y low-pass filter).

amplitude connected with these two low-frequency components seems to be higher than the irradiance variability induced by the Schwabe cycle.

4. Response of the terrestrial system to changes in the global insolation

4.1. Sensitivity of climate forcing

The next question to be addressed is how the climate system reacts to changes of solar forcing. Often, when different forcing factors are compared only the annually and globally averaged mean forcing (in W m^{-2}) is considered and the following concept of climate sensitivity is applied: The climate sensitivity λ defines the response of the climate system to a special forcing F:

$$\Delta T = \lambda \Delta F.$$

The sensitivity can be very different for various variability sources and is dependent on the resolution in time and space. Even the effect of the well-defined electromagnetic radiation cannot be adequately described by a constant sensitivity over long periods. The sensitivity is also influenced by changes of the spectral distribution of solar radiation in different phases of solar activity (cf. Fig. 4).

The large variability of the UV part of the solar spectrum affects considerably the atmospheric chemistry in general and the ozone production in particular which in turn affects the radiation balance and the atmospheric circulation (Haigh, 1994; Brasseur and Solomon, 1986). There are also considerable differences in the sensitivity depending on whether the forcing is connected with long-wave IR radiation or short-wave UV radiation. Moreover, solar forcing and greenhouse gas forcing are not the same: the latter is very efficient in infrared backscattering from clouds and water vapour and it is acting 24 h a day whereas solar forcing takes place only during daytime. This leads to quite different effects in the climate system.

The climate response to a given forcing is strongly dependent on feedback mechanisms connected with clouds, water vapour, ice-cover, albedo, atmospheric and ocean circulation, etc. It is possible that the interaction of the solar wind with the cosmic ray flux and the Earth's magnetosphere affects the atmosphere in different ways (Tinsley, 1996; Svensmark and Friis-Christensen, 1997).

A lower limit of sensitivity can be obtained by considering the Earth as a black body and neglecting any atmospheric feed back mechanism. Using the law of Stefan Boltzmann it can be calculated that a change in spherical forcing of 1 W m^{-2} should cause an increase of the mean global temperature of 0.26 K. This forcing of the Earth energy balance by 1 W m^{-2} is equivalent to 5.7 W m^{-2} change in the global solar radiation flux with an albedo of 30%. The other extreme is the sensitivity one obtains for the 100 kyr Milankovitch cycle if one assumes that the temperature changes between glacials and interglacials are caused by eccentricity-induced forcing. This already mentioned Milankovitch forcing (see Section 2.7) can be calculated very precisely because it is based on celestial mechanics. If one computes the global and annual mean of solar forcing caused by the 100 kyr period of eccentricity one gets an amplitude of 0.12 W m^{-2} in the spherical mean. This value is too small to be detected in climate records. But, despite the tiny global forcing value, we can observe the 100 kyr frequency during the last 800 kyr in most paleoclimatic records (cf. Fig. 5). The global mean temperature changes between glacial and interglacial periods are large: about 20°C for polar (Johnsen et al., 1995) and 5° for tropical regions (Stute et al., 1995). As a consequence the sensitivity for the 100 kyr Milankovitch forcing formally turns out to be about a 100 times larger than the values obtained from GCMs. This result illustrates that using global and annual averages to estimate the climate sensitivity can be very misleading, especially when seasonal and local effects are significant. E.g. in the case of glaciers strong melting during the summer cannot be compensated by ice accumulation during the rest of the year. Beyond a certain threshold the winter temperatures have a vanishing influence on ice accumulation. So, constant small differences can be accumulated to large effects over long periods of time (10 kyr or half a period of the precessional cycle). This is similar to resonance effects in mechanics.

The sensitivities can be masked by different time constants and other variability sources of the climate system. As a consequence of the different heat capacities of land and sea and different time constants of feed back mechanisms (ice, vegetation) the system does not always reach equilibrium which leads to smaller sensitivities for high-frequency forcing.

Moreover, there is a great difference between sea surface and land temperatures regarding the homogeneity of their spatial distribution. This explains why in most land temperature records the Schwabe cycle forcing is completely masked by the natural variability of the climate system.

In view of these difficulties the climate sensitivity factor λ has to be applied with caution especially for longer time periods.

4.2. Comparisons of terrestrial with solar records

There are numerous publications dealing with correlations between solar variability and various parameters measured in the environment. It is beyond the scope of this short article to review them all (see e.g. Hoyt and Schatten, 1997).

For example, a recent investigation of sea surface temperature data detects the Schwabe cycle for the last 100 yr (White, et al., 1997). The amplitude of the ocean response is obviously damped by a factor of 2 or 3 due to the heat capacity of the oceans.

Reid (1991) compared the long-term trend of the sea surface temperature with the corresponding trend of solar activity. He found a good agreement between the shapes, especially during the minima periods. A more quantitative approach is to invoke climate models for deriving the role of solar forcing in the climate history. Schlesinger and Ramankutty (1992), Kelly and Wigley (1992), and Crowley (1996) used energy balance models and induced different combinations of forcing factors. They all found effects from solar forcing but with rather different sensitivities. There were several model experiments carried out with GCMs after implementation of a variable solar forcing. Rind and Overpeck (1993) found an increase of about 0.6°C for the period 1600 – 1950 in good agreement with the observations. Cubasch, Voss, Hergerl, Waskewitz and Crowley (1997) also found in model simulations a significant contribution of solar forcing to the global warming for the time before 1940.

Finally in Fig. 8 we compare the ^{10}Be concentration record from Dye 3, Greenland, with the combined temperature record of Groveman and Landsberg (1979b) and Jones (1993). Keeping in mind that both records are proxies that are affected by many different variabillity sources the correlation is fairly good.

As far as changes on time scales of millennia are concerned there is no quantitative information available about the solar forcing. However, the Δ^{14}C record exhibit earlier periods of quiet sun intervals similar to the Maunder minimum (Fig. 6). These periods, which occur about every 200 yr and last between 70 and 100 yr, are generally related to advances of glaciers (Denton and Karlen, 1973), water levels in lakes (Magny, 1993), and sudden detoriations of climatic conditions (van Geel and Renssen, 1998).

4.3. Other sources of climate variability

There are many other forcing factors beside solar forcing to be considered when discussing climate change. For example volcanic dust can reduce significantly the solar insolation leading generally to a cooling. A famous example for this effect is the eruption of Tambora in 1815 which caused a serious global climate detoriation in 1816 ("year without summer"). However, the mean residence time of dust in the stratosphere is in the order of a few years (Minnis and Harrison, 1993). As a consequence, dust forcing due to volcanic eruptions can be responsible for episodic cooling events, but not for long-term trends (Crowley et al., 1993).

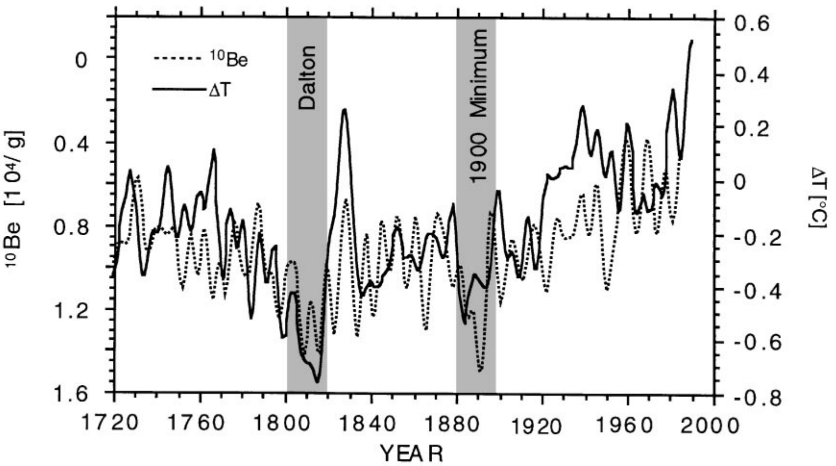

Fig. 8. Comparison of the ^{10}Be concentration in the Dye 3 ice core from Greenland (Beer et al., 1994a) as a proxy of solar activity with a combined filtered temperature record of the northern hemisphere (Groveman and Landsberg, 1979a; Jones et al., 1986).

Other possible causes of climate change are internal variations within the climate system itself which affect the global distribution of heat. A possible way to detect such internal climate variations is to compare the synchroneity of temperature records from the northern and the southern hemisphere. Fig. 9 shows a plot of the two 13-yr low-pass filtered hemispheric temperature records for the period 1856–1998 (Jones, 1993). In this filtering fast natural variability processes such as the El Nino are removed. A slope of -1 represents interhemispheric heat exchange for which internal processes of the climate machine are responsible. Stronger interhemispheric heat exchange takes place only around 1870 and between 1960 and 1970. The trajectory moves mostly along the slope of about 1 pointing to a simultaneous warming or cooling of both hemispheres. Fig. 9 shows that in general temperature changes between 1856 and 1998 follow the slope $+1$ pointing to a global warming caused by external forcing. Relatively fast simultaneous warming on both hemispheres is found for the periods 1910–1940 and 1970–1990. Global cooling is observed around 1890 and 1950. These times coincide with minima in the sunspot record (Fig. 6) and with minima in the Beryllium record (Fig. 8).

On a time scale longer than 13 yr synchroneity between both hemispheres is remarkable. This clearly points to an external forcing of the climate machine either due to solar or anthropogenic effects.

4.4. Separation of solar and greenhouse gas forcing

Finally, an attempt is made to assess the relative importance of solar and greenhouse forcing. For a separation of greenhouse gases and solar effects it is necessary to compare the historical records of temperature, solar variability, and greenhouse gases.

A large number of investigations using energy balance models and GCMs has already been published about this question (e.g. Kelly and Wigley, 1992; Wigley and Jaumann, 1998; Santer and Taylor, 1995; Kacholia and Reck, 1997).

A rather different approach is based on a comparison of the temperature history with the reconstruction of solar irradiance and the greenhouse gases using a nonlinear regression model (Mende and Stellmacher, 1994). In view of all the limitations in the available data and the uncertainties involved in forcing functions and sensitivities a highly aggregated regression model with only a few components and a minimal number of parameters is used.

Our regression model expresses the 14 yr filtering of the hemispheric near-ground temperature anomalies $T(t)$

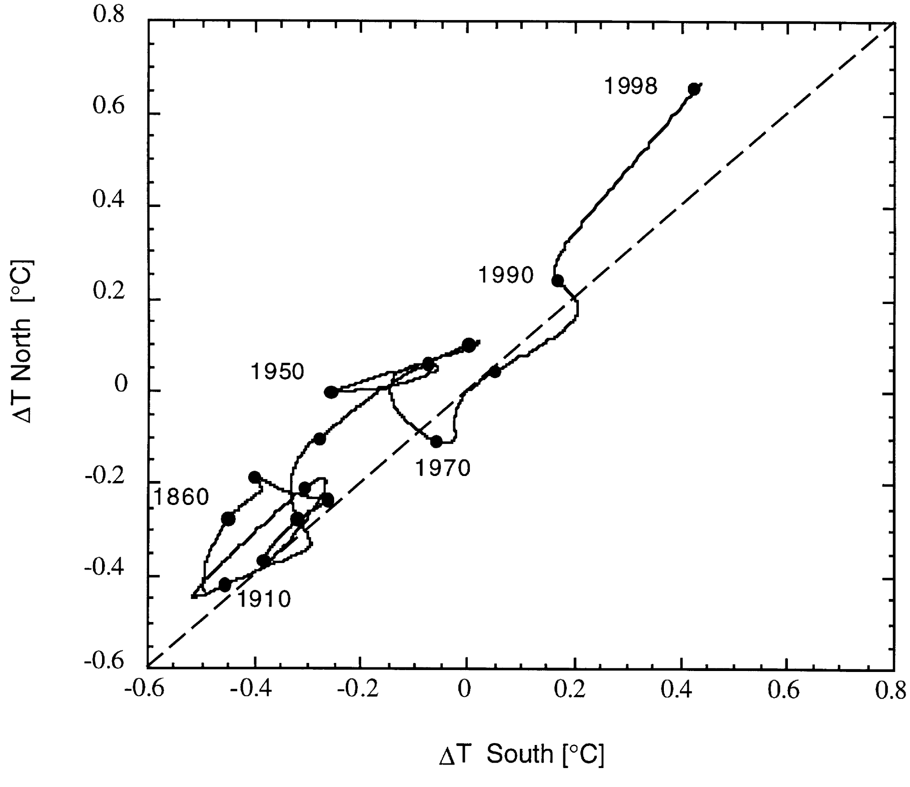

Fig. 9. Comparison of the mean hemispheric temperatures (Jones, 1993) after applying a low-pass filter of 13 yr for the period 1856–1998 to remove variability induced by volcanism or ENSO.

by (1) a monotonic hyperbolically growing component (Hyp(t)) as a proxy for anthropogenic influences, (2) a non-monotonic component derived from the Sun melody (Sun(t)) as a proxy of solar irradiance and (3) a residual component (Resid(t)) including all other forcings:

$$T(t) = a_0 + a_1 \,\mathrm{Hyp}(t - t_1) + a_2 \,\mathrm{Sun}(t - t_2) + a_3 \,\mathrm{Resid}(t).$$

The hyperbolic term is a minimal parametric representation of the overall industrial activity and other anthropogenic influences. The exponent of the hyperbola is derived from a global growth function of greenhouse gases. This is justified by supplementary investigations which show that other anthropogenic gases (e.g. methane and CO_2 from ice cores) and other industrial indicators exhibit hyperbolic growth behaviour with similar exponents. The solar component is the frequency modulation function of the Schwabe cycle (Sun melody) using the sunspot record. The Sun melody is supposed to be linearly connected with the solar irradiance (cf. Fig.7). For comparison with temperature records we use a 14-yr low-pass filtering in order to remove all irradiance changes during one Schwabe cycle. By minimizing the residual component the three components of the model and their scaling with temperature are determined.

Fig. 10 shows the result of the regression procedure. The upper thin curve depicts the 14 yr filtered northern hemispheric temperature anomalies and the thin lower curve shows the hyperbolically detrended temperature anomalies, which represents the temperature history after subtracting the anthropogenic component. It contains the solar and other natural variability components. This curve can be compared with the Sun melody (thick line) as a proxy of solar irradiance. The hyperbolically detrended temperature curve shows a good correlation ($r = 0.\ 7$ taking into account the filter correlation) with the Sun melody. In the frame work of this regression model we can attribute nearly half of the temperature variance of the last 140 yr to the solar variability.

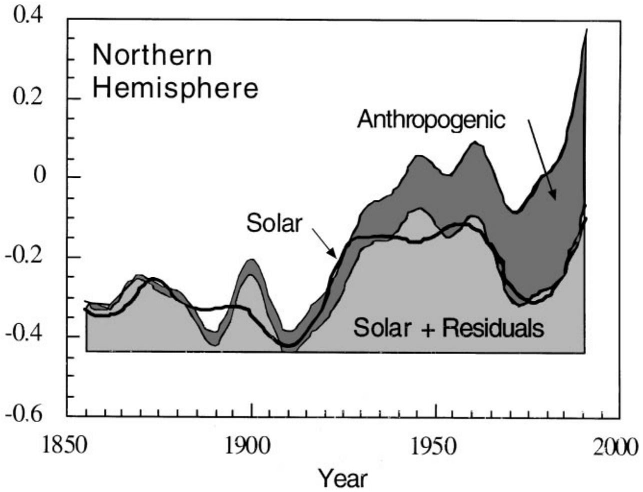

Fig. 10. Separation of the different components contributing to the northern hemispheric warming since 1850. The upper dark band represents the anthropogenic contribution to the warming. The lower band reflects the combined effects of solar and other forcings. The solar forcing itself is depicted by the thick line.

With an increase of the solar irradiance of 2.2 W m^{-2} during the last 140 years on the basis of our solar irradiance reconstruction, we get a solar forcing at the top of the atmosphere of 0.55 W m^{-2} and corrected for short-wave reflections 0.4 W m^{-2}. In case of an assumed sensitivity of 0.5 K/(W m^{-2}) which includes all feedbacks solar variability accounts for an increase of 0.2 K for the global mean annual temperature during the last 140 yr. This is in good agreement with the results of the separation of the solar forcing component based on the regression model. In contrast to the estimation of the solar forcing component by Friis-Christensen and Lassen (1991) who attributed almost all variability of the northern hemisperic temperature anomalies between 1865 to 1985 to the Sun leaving no room for the anthropogenic greenhouse effect and other forcings (aerosols, internal climate variability) our separation approach provides a more realistic balance between the anthropogenic and the solar component and leaves room for other variability sources as well. According to the model at present about half of the temperature variability is attributable to greenhouse gases, somewhat less to solar forcing and 10–20% to internal climate variability.

The separation of the anthropogenic component from a solar forcing component in the framework of this separation approach gives, despite its simplicity, a relative consistent picture of the interrelationship between the main forcing components of the climate system on a global aggregated level. The separation shows that the anthropogenic forcing component is steadily growing. Even now the continuing influence of solar forcing should not be neglected in the evolution of the Earth's climate.

5. Conclusions and outlook

The sun is the engine that drives the climate system. Any change in the global insolation is therefore expected to affect the climate evolution. Since 1978 satellite-based measurements show that the solar irradiation fluctuates in phase with the solar activity. The observed changes are small, but there are good arguments that larger variations may occur on time scales of decades to millennia. Modern analytical techniques allow us to measure radioactive and stable isotopes in natural archives and to significantly improve our ability to reconstruct the history of solar activity and climate.

Comparisons of climate forcing and climate change based on paleodata indicate that the simple concept of climate sensitivity 'based on annually and hemispherically averaged temperature anomalies only' is not adequate to describe correctly solar forcing.

Based on the analysis of historical data we conclude that solar forcing indeed plays an important role in past and present climate change. However, it is still premature to quantify this role on centennial and millennial time scales. The two main uncertainties involved are related to the history of solar forcing caused by solar variability and the sensitivity of the climate system to this forcing. To make progress these two main fields should be addressed jointly by solar physicists and Earth scientists. The goal on the solar side is twofold:

- We have to improve our understanding of the mechanisms responsible for changes in the emission of the total solar radiation and its spectral composition as a function of solar activity.
- We have to calibrate our tools (cosmogenic radionuclides) to reconstruct the solar activity and also the solar irradiance for at least 10,000 yr back in time.

The goal on the terrestrial side is threefold:

1. We have to improve our understanding and quantify the reaction of the climate system to forcing including spectral and frequency dependencies.
2. We have to consider possible climatic effects related to the interaction of solar wind particles and magnetic fields with the Earth system.
3. We have to separate solar from non-solar induced climate changes in the past in order to reliably quantify the increasing anthropogenic effects at present and in the future.

Although the first steps have been made successfully there is still a long way to go. However, we believe it is worth the effort.

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