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What do we really know about the Sun-climate connection?

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ABSTRACT

The Earth's climate has always been changing. This is documented in historical as well as in geological records. The reasons for these changes, however, have always been subject to discussions and are still not well understood. In addition to natural climate changes the risk of human influence on climate has recently been seriously considered by the Intergovernmental Panel on Climate Change. Any factor that alters the radiation received from the Sun or lost to Space will affect climate. The Sun's output of energy is known to change over an 11-year cycle, and variations over longer periods occur as well. A number of correlations between solar activity variations and climate changes, some more significant than others, have been reported but they have traditionally been accompanied by a considerable skepticism among scientists because a plausible physical mechanism to account for these correlations has not yet been found. The most immediate cause of climate changes would be changes in the total irradiance of the Sun. This, however, would either imply unrealistically large variations in total solar irradiance or a higher climate sensitivity to radiative forcing than normally accepted. Therefore other mechanisms have to be invoked. The most promising candidate is a change in cloud formation because clouds have a very strong impact on the radiation balance and because only little energy is needed to change the cloud formation process. One of the ways to influence cloud formation might be through the cosmic ray flux that is strongly modulated by the varying solar activity.

INTRODUCTION

The Sun is the source of the energy that causes the motion of the atmosphere and thereby controls weather and climate. Any change in the energy from the Sun received at the Earth's surface will therefore affect climate. During stable conditions there has to be a balance between the energy received from the Sun and the energy that the Earth radiates back into Space. This energy is mainly radiated in the form of long wave radiation corresponding to the mean temperature of the Earth.

From historical and geological records we know that the Earth's climate has always been changing. Sometimes such changes have been relatively abrupt and have apparently had large sociological effects. It is therefore natural that our society is interested in future climate changes and in particular is concerned about a possible influence on climate of society itself. This concern is associated with the effect of the increasing amount of greenhouse gases, in particular CO_2, which is due to human activities related to the burning of fossil fuel.

The determination of the natural climate variability is therefore of decisive importance for a credible estimation of the man-made signal and hence for possible political decisions regarding initiatives to mitigate the effects of the increased amount of greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environmental Program (UNEP). This Panel in 1990 published a report about the scientific basis for the assessment of the found climatic changes and their causes. The report concluded that it was presently not possible to ascribe unequivocally the found changes in climate to the enhanced greenhouse effect since the size of the global warming is of the same magnitude as natural climate variability. In the 1992 IPCC supplement (Houghton et al., 1992) the major conclusions were not altered although the predicted rate of warming of 0.3° C per decade was estimated to be reduced, significantly in the Northern Hemisphere, by the cooling effect due to sulphate aerosols and to stratospheric ozone depletion. In their latest report the IPCC (Houghton et al., 1995) for the first time stated that the observed increase of the global average temperature during this century is unlikely to be due to natural variations in the climate only. Hence some, although still not quantified, part of the temperature rise is now believed to be the effect of the increase in the concentration of CO_2 and other manmade greenhouse gases.

There exists, however, another possible cause of a change in the radiation balance, namely a variation in the energy from the Sun received at the Earth's surface. This possibility has attracted much less attention, although many observations in the past have pointed at striking correlations between changes in climatic parameters and different manifestations of solar activity. One of the problems with these hypotheses has been the lack of a plausible physical mechanism that could explain the observed correlations. Eddy (1976) provided the first thorough study of long-term (century scale) variations in solar activity and climate. This study indicated a very strong link which he hypothesized could be accounted for by small changes in the solar total irradiance. Subsequently studies of palaeoclimate and historical solar activity inferred by its modulation of ^{14}C in tree rings and ^{10}Be in ice cores provided evidence that long-term minima in solar activity seems to be associated with climate on Earth that is colder than average.

The climate variations prior to the industrial era may thus be strongly influenced by variations in solar activity. After the start of the industrial era and the associated increasing concentration of greenhouse gases in the atmosphere we are faced with at least two simultaneously operating mechanisms, both possibly contributing to the observed global warming of about 0.5° since 1890. Because of the significant economic aspects associated with possible political interventions based on estimated effects on society of emissions of greenhouse gases, there is a considerable interest in a precise evaluation of future climate changes. If the reported correlations between solar activity variations and climate changes are indeed associated with a physical mechanism that could be understood and predicted, this would probably mean a major reduction of the uncertainty associated with the natural climate oscillations. Thereby the quality of our evaluation of the increased greenhouse effect would be considerably improved.

VARIATIONS IN SOLAR ACTIVITY AND CLIMATE

In search of a physical mechanism it is important to examine in detail the basis for the suggested link between solar activity variations and climate. In this search it must be realized that it is not possible to define climate in a simple and unique way. Even a simple number like the yearly global average temperature is subject to variations without any immediate cause in terms of a change in the radiative forcing because the existence of internal oscillations in the atmosphere and the complex coupling to the oceans. Similarly, solar activity can not be characterized by a simple number, at least not until we have identified the exact physical mechanism that is involved. Different solar activity parameters show different solar cycle variations and different long term trends. Therefore it is not surprising that studies dealing with different climate and solar activity parameters do not always agree. These studies may not all be particularly credible in their methodology and use of data. Beyond all these caveats, however, there continues to appear new and strong evidences, which indicate that the apparent effect on climate of variations in solar activity cannot just be coincidental.

The idea of a relationship between long-term changes in solar activity and climate published by Eddy (1976) was re-examined in detail by Reid (1987). He looked at the record of the globally averaged sea surface temperature (SST) and noticed a striking similarity between this and the long-term variation of solar activity represented by the 11 year running mean Zürich sunspot number. Among the particular features he pointed out, was the prominent minimum in the early decades of this century, the steep rise to a maximum in the 1950s, a brief drop during the 1960s and early 1970s followed by a final rise. Based on model calculations Reid suggested that the solar irradiance may have varied by approximately 0.6% from 1910 to 1960 in phase with the 80-90 year cycle (the Gleissberg period) of solar activity represented by the envelope of the 11 year solar activity cycle.

One problem with this interpretation was that the SST is highly influenced by the thermal inertia of the oceans which may imply a considerable delay in the temperature response. That this is the case was demonstrated by Friis-Christensen and Lassen (1991) who demonstrated that the smoothed land surface temperature of the Northern Hemisphere preceded both the smoothed sunspot number and the smoothed SST curve by nearly twenty years. If a causal relationship between solar activity variations and temperature was to be maintained, the smoothed sunspot number could not be an appropriate representation of solar activity. Instead they pointed at another fundamental solar activity parameter, namely the length of the sunspot cycle. On the average the period is about 11 years, but it is known that it does vary from cycle to cycle. It had been demonstrated that the length of the sunspot cycle is usually shorter during strong activity cycles than during low activity cycles. Since the sunspot cycle is related to the varying solar surface magnetic fields it was not quite inconceivable that the period length contained information about some, still not well understood, processes on the surface related to the energy output of the Sun. In fact a comparison with the Northern Hemisphere land temperature during the last 130 years did show a remarkably good correlation with the smoothed curve of the varying solar cycle length (see Figure 1) indicating that this parameter was possibly a better indicator of a solar activity variations that could affect the Earth's climate (Friis-Christensen and Lassen, 1991).

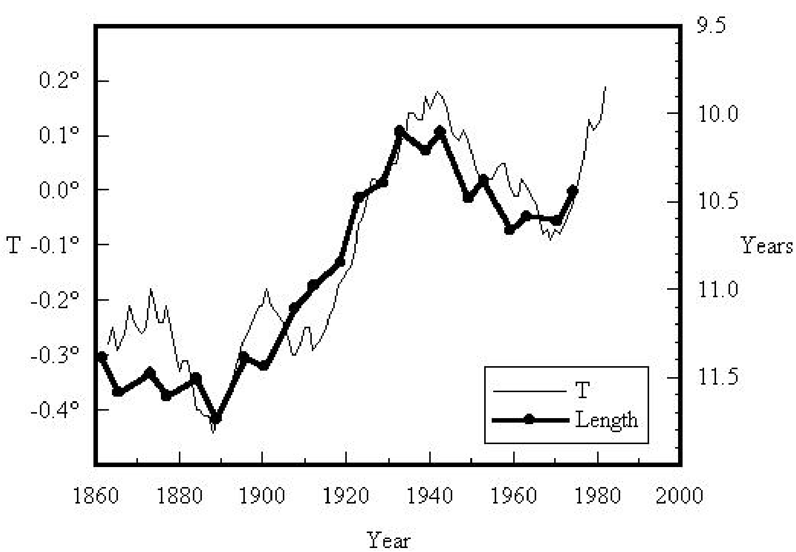

Fig. 1 11-year average values of the Northern Hemisphere Land temperature (T) and the length of the solar cycle (L).

Objections that the good correlation could be just coincidental were met by a subsequent paper in which Lassen and Friis-Christensen (1995) examined a considerably longer series of temperature and solar activity data. Available information about the Northern Hemisphere temperature based on proxy data going back to the second half of the sixteenth century was compared with a new derivation of solar cycle lengths based on auroral observations prior to 1750 when systematic solar observations were not available. Except for a short interval including the Maunder minimum when auroral observations were too scarce to allow unambiguous determination of auroral activity extrema, the 400 year long period confirmed the good correlation between solar activity and the Northern Hemisphere land temperature as indicated in Figure 2.

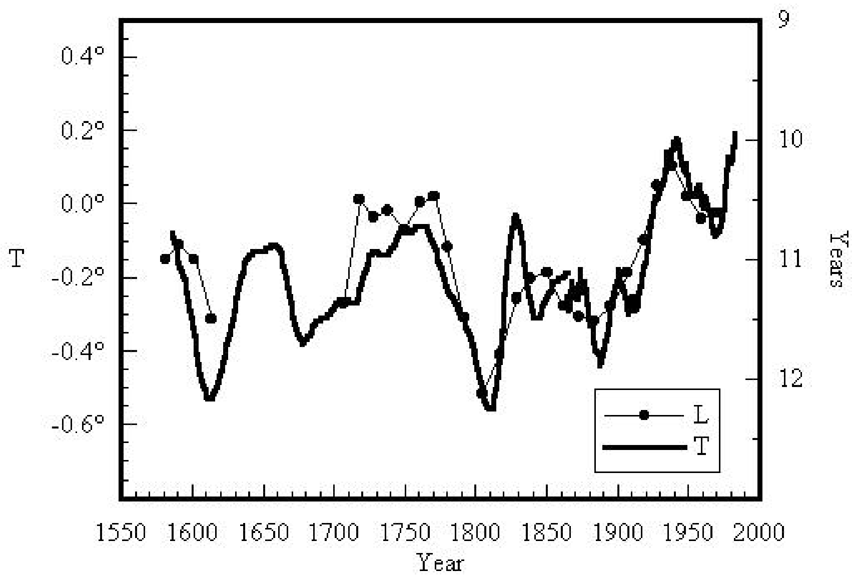

Fig. 2 11-year running average of Northern Hemisphere land temperature, (before 1860 estimated by means of tree-ring analyses, and long-term variation of solar activity expressed by means of auroral observations)

A similar conclusion was reached by Lean et al. (1995) who made a reconstruction of the solar total and UV irradiances since 1610. They found a correlation of 0.86 between the total solar irradiance and the Northern Hemisphere surface temperature from 1610 to 1800, implying a predominant solar influence. Extending the analysis to present indicated that solar forcing may have contributed to about half of the 0.5 ° C surface warming since 1860.

Since the most pronounced feature of solar variability is the nearly 11 year period it is obvious to search for a direct physical mechanism associated with this variation. Labitzke and van Loon (1993) have reviewed recent investigations of possible effects of solar variations on the Earth's temperature and on the height of constant pressure levels in the stratosphere. They find that the correlations between solar activity and climate parameters for the stratosphere on a decadal scale have a specific spatial distribution over the globe, and that they have the highest values between 20° N and 45° N in the Pacific-Atlantic area during most of the year but especially high and statistically significant during summer. Only during winter the correlations are not statistical significant but this could be improved by grouping the data according to the phase of the Quasi-Biannual Oscillation (QBO). The dynamics of the general circulation pattern play a major role in controlling the spatial distribution of the atmosphere's response to solar variability. They also find that the average temperature difference between solar maximum and solar minimum years is largest just below the tropopause.

PHYSICAL MECHANISMS

The abundance of good correlations between solar activity and climate parameters indicates a physical link. Immediately one would think that the most likely one must be associated with a variation in total solar irradiance. A suggestion of a 0.6% change (Reid,1987) could not, however, be confirmed when direct measurements in space of solar irradiance became available. Although the satellite data did show a clear reduction at solar minimum, the effect was only about 0.1% during a solar cycle. Solar irradiance variations may not, however, on longer time scales be limited to this amount. Lean et al. (1992) used correlations between total solar irradiance measurements and Ca II solar emissions to simulate the solar irradiance during the Maunder sunspot minimum probably associated with nearly complete absence of solar surface magnetism. For this case they found that total solar irradiance may have been reduced by about 0.25%. Even this magnitude, however, is small compared to the estimated enhancement of the greenhouse forcing to date.

A test of the hypothesis of an effect on climate through a variation in total solar irradiance may be performed using relatively simple energy-balance climate models that can take into account various radiative forcing factors, including the concentration of greenhouse gases, sulphate aerosols and solar forcing. Such models were applied by Kelly and Wigley (1992) and Schlesinger and Ramankutty (1992) using the solar cycle length as a proxy for total solar irradiance. They both found that variations in solar irradiance have been contributing to the observed global temperature change since 1860 but their calculations also indicated that since the nineteenth century, greenhouse gases have been the dominant contributor.

It should be noted that the energy-balance models, contrary to the large general circulation models (GCMs), do presume a prescribed value of the climate sensitivity, i.e. the climate response to a given radiative forcing. The climate sensitivity may be provided in terms of the change in the Earth's equilibrium temperature in response to a change in radiative forcing corresponding to a doubling of the CO_2 concentration. Also the solar radiative forcing corresponding to the change in solar cycle length is an unknown factor in the model runs. With estimated concentrations of greenhouse gases and sulphate aerosols and with various choices of climate sensitivity and solar forcing factors the observed temperatures since 1860 may be reasonably simulated. Surprisingly though, the best simulation was obtained for the case where only solar forcing was considered (Kelly and Wigley, 1992). The authors immediately discarded this solution because it was physically unrealistic, implying either solar irradiance changes much larger than observed or a very high climate sensitivity. The latter would mean that the effect of the increased concentration of CO_2 should be large and should already have been clearly identified in the temperature observations.

This apparent contradiction between the results of climate models and the observations implies that either the models are fundamentally wrong or the assumption of a large change in total solar irradiance is not valid. The simple climate models rely on the assumption that the global climate can be calculated simply by means of global averages of radiative forcings, some of which are assumed to be relatively well described. As a first-order approximation these models may be appropriate but global mean values may not necessarily provide an adequate description of the very complex atmospheric processes that determine the average global temperature. Although energy-balance models are only intended to consider the global-mean response to different forcings, a global-mean climate sensitivity is not necessarily applicable, taking into account the multitude of non-linear effects that is characteristic of the Earth's climate. The different radiative forcings, including solar irradiance, greenhouse gases, and anthropogenic sulphate aerosols, all have different spatial distributions and, in case of the latter, a particularly inhomogeneous distribution. On the other hand, results of the existing GCM experiments do indicate a similar climate sensitivity, regardless of the nature of the radiative forcing, be it solar luminosity or long-wave radiative forcing. A reason for this is that both forcings act through a warming of the surface and that the major effect on the temperature is caused by the feed-back mechanisms primarily due to water vapour and clouds. The feed-back mechanisms are assumed to be independent of the nature of the primary warming.

If the hypothesis of a link through the total irradiance is abandoned another mechanism has to be invoked. In fact, the solar cycle variation is much larger in the ultraviolet part of the spectrum of solar radiation. Recently an attempt has been made to study the climatic effect of solar cycle variations based on measured changes in the solar radiation in various spectral bands thus taking into account also the modulating effect of the varying ultraviolet radiation on the lower stratospheric ozone. Although this model did not take into account the effects of the ocean the experiments show an increased tropospheric Hadley circulation during high solar activity consistent with observations (Haigh, 1994).

Finally, the solar variations are even more pronounced in the variations in the emission of particles and fields from the solar surface. Although the energy in the solar wind is negligible compared to the energy in the ultraviolet and visible spectral bands, the relative variations are considerable. One of the effects of the varying solar wind is the modulation of the cosmic ray flux. Figure 3 shows the cosmic ray flux observed at Climax Neutron monitor station in Colorado. Note the reversed scale indicating a clear solar cycle modulation nearly in antiphase with the variation of the sunspot number. The possibility of an effect on weather and climate of variations in the cosmic ray flux was already discussed by Ney (1959). He pointed out that the most pronounced solar modulation which is seen also in the lower atmosphere is the variation of the cosmic ray flux. Dickinson (1975) noted that the most plausible source of notable changes in the lower atmosphere due to solar activity would be significant changes in the absorption of solar radiation or the emission of infrared radiation for example by changes in the distribution of cloudiness.

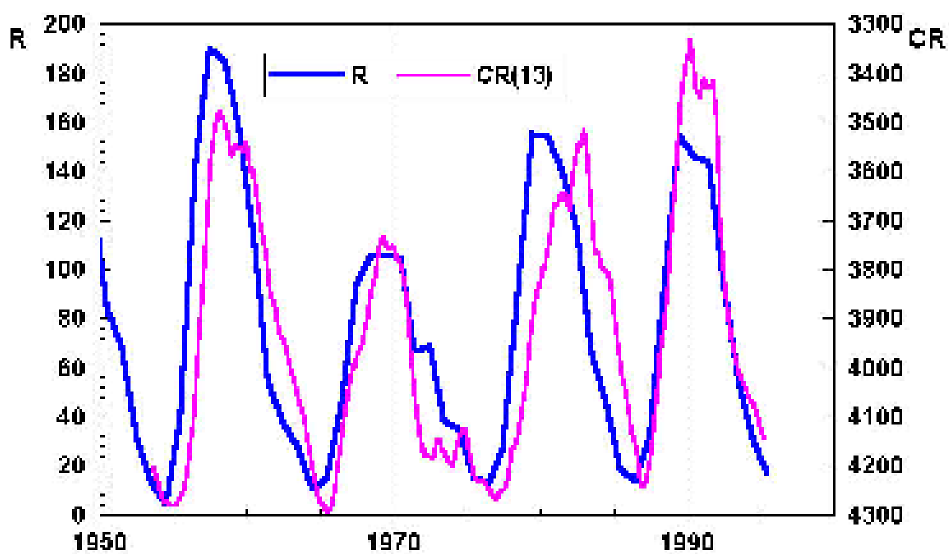

Fig. 3 Sunspot number (R) and Cosmic Ray flux at Climax (CR)

COSMIC RAY FLUX AND CLOUDNESS

One of the major uncertainties in climate models is the role of cloud effects (Houghton et al., 1992;1995). In particular there are large difficulties associated with the parameterization of these effects in general circulation models. Recent studies (Tinsley, 1994) indicate that cloud formation may be influenced by galactic cosmic rays through ionization changes that cause microphysical changes in the atmosphere. Hereby nucleation and growth of ice particles may be affected. Along these lines Pudovkin and Veretenenko (1995;1996) found local decreases in the amount of cloud cover related to short term changes in the cosmic rays due to increased solar activity (Forbush decreases). The effect, however, seemed to disappear at latitudes lower than 55°.

A change in cloud cover would indeed be a very effective amplifying mechanism for climate forcing because the energy necessary to condense water vapour is small compared to the resulting changes in energy of solar radiation received at the Earth's surface. Svensmark and Friis-Christensen (1997) examined the compiled International Satellite Cloud Climatology Project (ISCCP) data. In Figure 4 from Svensmark and Friis-Christensen (1997) is shown the 12 months running mean of the total cloud cover (thick line) together with the 12 months running mean values of cosmic ray intensity measured at the Climax Neutron Monitor station, Colorado. The correlation between the cosmic ray flux and the global cloud cover is 0.93 for the 12 months running means. The effect is larger at higher latitudes in agreement with the increased shielding effect of the Earth's magnetic field at low latitudes. For latitudes excluding the tropics the correlation increases to even 0.97. Svensmark and Friis-Christensen (1997) emphasize that a large seasonal variation exists in the unfiltered monthly average cloud data probably due to the North-South asymmetry in ocean coverage. This effect could account for an apparent slight but not significant time lag of the cosmic ray data relative to the cloud data.

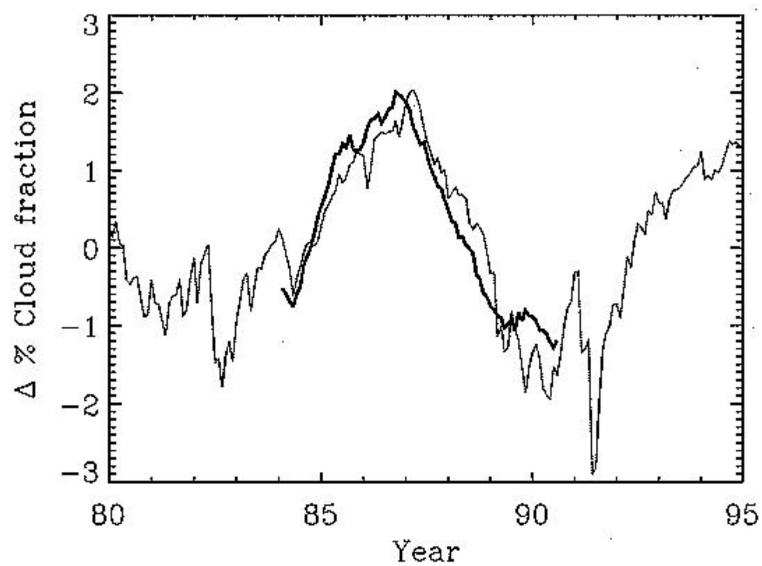

Fig.4 Variation of total cloud cover and cosmic ray flux observed at Climax. (Svensmark and Friis-Christensen, 1997).

The amount of the decrease of cloud cover is considerable. The satellite data documented a decrease of 3% in global cloud cover from the solar minimum around 1987 to the solar maximum around 1990. The effect of a decrease of cloud cover would be dependent on the type of clouds that are affected. A decrease of high clouds would result in lower temperatures while a decrease in the low-altitude clouds would mean an increase in temperature (Manabe and Wetherald, 1967). On the average a decrease in the various cloud types will mean a warming. The effect of a 3% decrease in cloud cover is believed to represent a global warming corresponding to 1-1.5 Wm^{-2} (Rossow and Cairns, 1995). Compared to the 0.1% change in solar irradiance during the same interval which corresponds to 0.25 Wm^{-2} when taking into account the effect of the albedo of the Earth, the mechanism is therefore stronger by a factor of possibly 6. With this amount the solar forcing of long-term variations in global temperature seems plausible and a number of the reported correlations between solar activity variations and climate may then be immediately explainable.

DISCUSSION

Scientific discussions about the possible role of solar activity variations on climate have suffered from the lack of a precise physical mechanism that could account for the vast number of reported correlations. In particular it has not been possible to identify unambiguously neither the important solar activity parameter nor the primary climatic parameter in such relationships.

Solar activity variations have traditionally been associated with the sunspot number although it is well known that solar activity may not be described by a single number. In particular it has been difficult to find a good representation of the long-term variations of solar activity. That solar cycle relationships cannot just be extrapolated to represent long-term behaviour is demonstrated by the relative variations of the sunspot number and the geomagnetic activity index, aa. Although aa is an index specifically associated with the fluctuations in the terrestrial magnetic field, it does represent the result of the continuous interaction between the geomagnetic field and the solar wind, and hence some form of solar activity. In Figure 5 is shown a comparison between the aa-index and the sunspot number R since 1868 when systematic geomagnetic recordings allowed the derivation of the aa-index. The aa-index does show the 11-year cycle but two main differences between R and aa are clearly noticeable. Firstly, the individual cycles are very different with the aa record normally displaying several maxima whereas the sunspot record has only one dominant maximum in each cycle. The second fundamental difference is the different long-term variation seen in aa and R, in particular in the level at solar activity minima. This clearly demonstrates that some long-term change in the solar wind has taken place during this century which is not reflected in the sunspot number at solar minima.

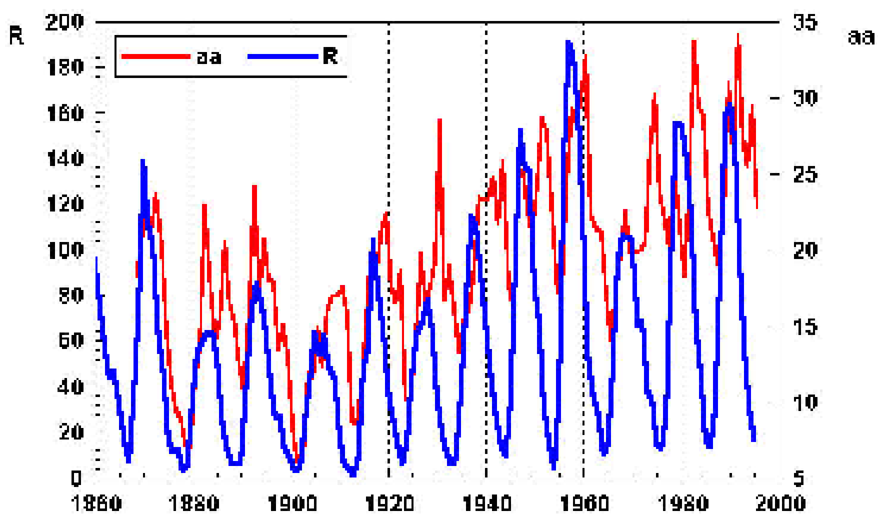

Fig. 5 Yearly values of the sunspot number R and the geomagnetic activity index aa.

The formation and radiative effect of clouds is one of the major uncertainties in climate modeling (Houghton et al., 1995). Due to the large radiative effect of clouds, any insufficiency in the parameterization of clouds will introduce major uncertainties in the results of the climate models. Recent results have indicated strong correlations between the total cloud cover and the cosmic ray flux, indicating that this could be the missing link between solar activity variations and climate changes. If this relationship can be confirmed and understood, a major obstacle in our understanding of natural climate variations may be removed and our chances of a credible estimate of the effects of manmade greenhouse gases could be significantly improved.

REFERENCES

Dickinson, R., Solar variability and the lower atmosphere, Bull. Am. Met. Soc., 56(12), 1240-1248 (1975).

Eddy, J.A, The Maunder minimum, Science, 192, 1189-1202 (1976).

Friis-Christensen, E. and K. Lassen, Length of the solar cycle: an indicator of solar activity closely associated with climate, Science, 192, 1189-1202 (1991).

Haigh, J.D. , The role of stratospheric ozone in modulating the solar radiative forcing of climate, Nature, 370, 544-546, (1994).

Houghton, J.T., B.A. Callander., and S.K. Varney (eds.). Climate Change 1992: The Supplementary Report to the IPCC 1991 Scientific Assessment, Cambridge University Press, Cambridge, UK. (1992).

Houghton, J.T., L.G. Meira Filho, B.A. Callander., N. Harris, A. Kattenberg and K. Maskell (eds.)., The science of climate change. Cambridge University Press, Cambridge, UK. (1995).

Kelly, P.M. and T. M. L. Wigley, Solar cycle length, greenhouse forcing and global climate, Nature 360: 328-330 (1991).

Labitzke, K. and H. van Loon, Some recent studies of probable connections between solar and atmospheric variability, Ann. Geophysicae, 11: 1084-1094 (1993).

Lassen, K. and E. Friis-Christensen, Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate, J. Atmos. Terr. Phys., 57(8), 835-845 (1995).

Lean, J., A. Skumanich, and O. White, Estimating the Sun's radiative output during the Maunder minimum, Geophys. Res. Lett., 19, 1591-1594 (1992).

Lean, J., J. Beer, and R. Bradley, Reconstruction of solar irradiance since 1610: Implications for climate change, Geophys. Res. Lett., 22, 3195-3198 (1995).

Manabe, S., and R.T. Wetherald, Thermal equilibrium of the atmosphere with a given distribution of relative humidity, J. Atmos. Sci., 24, 241-259 (1967).

Ney E.R, Cosmic radiation and the weather, Nature, 183, 451-452 (1959).

Pudovkin, M. and S. Veretenenko, Cloudiness decreases associated with Forbush-decreases of galactic cosmic rays, J. Atm. Terr. Phys., 57, 1349-1355 (1995).

Pudovkin, M. and S. Veretenenko, Variations of the cosmic rays as one of the possible links between the solar activity and the lower atmosphere. Adv. Space Res., vol. 17, No. 11, (11)161-(11)164 (1996).

Reid, G.C, Influence of solar variability on global sea surface temperatures, Nature, 329, 142-143 (1987).

Rossow, W.B., and B. Cairns, Monitoring changes of clouds, J. Climate, 31. 305-347 (1995).

Schlesinger, M.E., and N. Ramankutty, Implications for global warming of intercycle solar irradiance variations, Nature, 360: 330-333 (1992).

Svensmark, H. and E. Friis-Christensen, Variation of cosmic ray flux and global cloud coverage - a missing link in solar-climate relationships, J. atmos. sol.-terr. Phys., 59, 1225-1232, (1997).

Tinsley, B. A. ,Solar wind mechanism suggested for weather and climate change, EOS, 75(32), 369 (1994).