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Variation of cosmic ray flux and global cloud coverage—a missing link in solar-climate relationships

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Abstract—In the search for a physical mechanism that could account for reported correlations between solar activity parameters and climate, we have investigated the global cloud cover observed by satellites. We find that the observed variation of 3–4% of the global cloud cover during the recent solar cycle is strongly correlated with the cosmic ray flux. This, in turn, is inversely correlated with the solar activity. The effect is larger at higher latitudes in agreement with the shielding effect of the Earth's magnetic field on high-energy charged particles. The observed systematic variation in cloud cover will have a significant effect on the incoming solar radiation and may, therefore, provide a possible explanation of the tropospheric and stratospheric 10–12 year oscillations which have been reported. The above relation between cosmic ray flux and cloud cover should also be of importance in an explanation of the correlation between solar cycle length and global temperature, that has been found. © 1997 Elsevier Science Ltd

INTRODUCTION

The Earth's climate is a manifestation of how the radiation from the Sun is absorbed, redistributed by the atmosphere and the oceans, and eventually re-radiated in to space. Any variation in the energy received at the surface of the Earth and radiated from the surface will therefore have an immediate effect on climate. The composition of the atmosphere is one parameter that influences the energy balance of the Earth. The various atmospheric constituents may reflect or absorb radiation, from space as well as from the re-radiated (thermal) energy from the Earth's surface. One of the main issues, in scientific discussions as well as in public debate, is the size of the climatic effect of man-made contributions to greenhouse gases and aerosols. Estimation of the natural climate variability is therefore of decisive importance for a credible assessment of the man-made signal and hence for possible political initiatives to mitigate the effects of the increased amount of greenhouse gases. Natural climate variability includes possible changes in the radiation balance of the Earth caused by external sources related to the varying solar activity. A vast number of reports have proposed a direct link but, since no satisfactory physical theory has been proposed, these results have never been taken really seriously. In this article we have investigated whether one of the proposed mechanisms, namely an effect through the varying cloud cover of the planet could be supported by actual measurements.

Recently, the variation of the global temperature, particularly the northern hemisphere land air temperature, has been found to be closely associated with the long-term variation of solar activity during the entire interval for which systematic temperature measurements are available (Friis-Christensen and Lassen, 1991). It was concluded that the length of the solar cycle is a possible indicator of long-term changes in the total energy output of the Sun. A subsequent comparison with the temperature series reconstructed from proxy data prior to 1880 revealed that there is a good association between the variations in this temperature series and in the solar cycle length record for more than four centuries (Lassen and Friis-Christensen, 1995).

The most immediate plausible physical explanation of this correlation is the existence of variations in the total solar irradiance that are sufficiently large to have an observed temperature effect on climate. Eddy (1976) hypothesized that an apparent relationship between long-term variations in solar activity and global climate might be due to changes in the solar irradiance. Satellite measurements over approximately one solar cycle have shown that the irradiance is not constant. However, it varies too little (about 0.1% during a solar cycle) to be of major importance for climate. This does not exclude the possibility of larger variations in total irradiance over a longer period of time. Based on empirical relationships between total solar irradiance measurements and CaII solar emissions, Lean *et al.* (1992) estimated that in the absence of surface solar magnetism during the Maunder sunspot minimum period around 1700 the total solar irradiance may be have been reduced by about 0.25%. Studies of sun-like stars indicate that larger irradiances of up to 0.6% since the Maunder minimum may be applicable (Zhang *et al.*, 1994) but even this magnitude is less than the enhanced greenhouse forcing estimated to amount to 2.5 W/m^2 since the pre-industrial era. Of this amount, CO_2 is estimated to contribute with 1.5 W/m^2.

Labitzke and van Loon (1993) have investigated possible effects of solar activity variations on the Earth's temperature and on the height of constant pressure levels in the stratosphere. They emphasize the fact that the dynamics of the general circulation pattern play a major role in the spatial distribution of the atmosphere's response to solar variability. Using temperature profiles from radiosonde measurements they find that the average temperature difference between solar maximum and solar minimum years is largest just below the tropopause. Numerical general circulation models are presently not able to reproduce the observed results assuming a solar forcing over an 11 yr cycle of only 0.1%. Hence it has been argued that the postulated correlations are purely coincidental.

Reports on correlations between solar activity variations and climate have persisted to appear in the literature in spite of the almost classical objection that the energy variations caused by solar variations are much too small to have any significant effect on the lower atmosphere. Therefore, other mechanisms may be invoked. Dickinson (1975) realized that the most plausible source of notable changes in the lower atmosphere due to solar activity changes would be significant changes in the absorption of solar radiation or the emission of infrared radiation by the lower atmosphere and Earth's surface. Along these lines he pointed out the possibility of changes in the distribution of cloudiness through processes by which the ionization effects of galactic cosmic rays affect sulphate aerosol formation and cloud nucleation in the vicinity of the tropopause. He estimated that an 8% increase in cloud cover would be equivalent to a 2% decrease in the solar constant. This figure arises as a combined effect of reflected incoming radiation and a decrease in infrared cooling. Tinsley (1994, 1996) proposes that micro-physical changes in the lower atmosphere, which affect nucleation and growth of ice particles, may be involved. This would enhance precipitation and latent heat transfer.

From satellite measurements of Earth's radiation budget it is known that during the present conditions clouds reflect more energy than they trap, leading to a net cooling. The exact value of this cooling is still under debate and ranges from 17 to 35 W/m^2 (Ohring and Clapp, 1980; Ramanathan *et al.*, 1989; Ardanuy *et al.*, 1991). This energy balance is fragile and the effect of an increase of cloud cover depends on the type of clouds that are increased. An increase of low altitude clouds will result in a cooling, whereas an increase of high altitude clouds will warm the planet. An increase of the total amount of clouds without changing the fractions of the different cloud types is, however, believed to give a cooling of the Earth.

The role of cloud effects is one of the major uncertainties in climate models (IPCC, 1992). In addition to the difficulties associated with the parameterization of these effects in general circulation models, the formation of clouds may also be influenced by processes related to the distribution of aerosols from volcanoes and the burning of fossil fuels. Pudovkin and Veretenenko (1995, 1996) report that local decreases in the amount of cloud cover seem to be associated with short term changes in the cosmic ray flux due to increased solar activity (Forbush decreases). If these local results were systematic and could be confirmed to be present on a global scale they would indicate the existence of a very effective amplifying mechanism for climate forcing because the energy needed to change cloudiness is small compared with the resulting changes in solar radiation received at the Earth's surface.

CLOUD COVER AND COSMIC RAY FLUX

Since the effect of solar activity on cloud formation most plausibly is related to the associated variation of the cosmic ray flux, an appropriate representation of this flux must be used. Cosmic rays consist mainly of protons (90%) and of alpha-particles (9%) plus a smaller amount of heavier elements (Lal and Peters, 1967). The cosmic ray data are being recorded at ground-based neutron monitors, which detect variations in the low energy part of the primary cosmic ray spectrum. The lowest energy that can be detected (rigidities of primary particles) at the top of the atmosphere depends on the geomagnetic latitude, and ranges from 0.01 GeV at stations near the geomagnetic poles to about 15 GeV near the geomagnetic equator. In Fig. 1, normalized neutron counting rates from five stations are shown. The cosmic ray intensity shows the well-known inverse relationship to the sunspot cycle. This is caused by the interplanetary medium which has a larger shielding effect on the cosmic rays

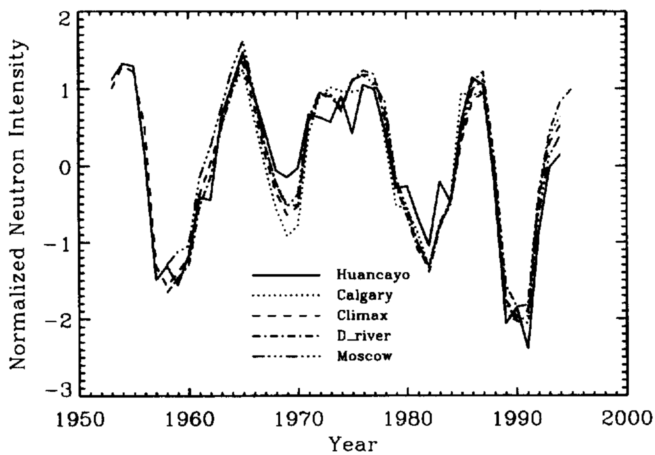

Fig. 1. Annual cosmic ray intensities for five stations. For all the individual stations, the mean counting rate is subtracted and normalized with the variance. The stations are: (1) Huancayo, Peru: S12 W75, Alt = 3400 m, Cutoff Rigidity = 12.92 GV; (2) Calgary, Canada: N51 W114, Alt = 1128 m, Cutoff Rigidity = 1.09 GV; (3) Climax, Colorado: N39, W106, Alt = 3400 m, Cutoff Rigidity = 2.99 GV; (4) Deep River, Canada: N46 W77, Alt = 145 m, Cutoff Rigidity: 1.02 GV; (5) Moscow, Russia: N55, E37, Alt = 200 m, Cutoff Rigidity = 2.42 GV. Notice that the general features are very similar. Only at solar maxima and minima are there individual variations.

during high solar activity. Further it is seen that general features of the five stations are very similar, when plotted using a normalized scale. Only at solar maxima and minima are there minor individual variations. It should be realized, of course, that the percentage variations in absolute counting rates during the solar cycle are different for different geomagnetic latitudes.

Clouds vary on time scales from 10 min to 10 yr and possibly even longer with a spatial range in scales from 30 m to the circumference of the Earth. Monitoring clouds with high accuracy is therefore a difficult task and can only be done by satellite. Ideally a monitoring system should have a uniform global coverage with a spatial/temporal sampling interval of less than 50 km and a sampling frequency of at least six times a day (Rossow and Cairns, 1995). Unfortunately a dataset fulfilling all these requirements does not yet exist. However, there are several satellite cloud datasets, one of which partially fulfills the above requirements.

This dataset, which is one of the longest, and most comprehensive series of cloud cover data, has been compiled in the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer, 1991). It covers the period July 1983 to December 1990, which is a considerable part of one solar cycle. However, even this combined ISCCP—C2 data set is a compilation based on different satellite instruments with different observational coverage. In order to increase the homogeneity of the data set we looked at the observation statistics of the cloud cover for the ISCCP—C2 data (monthly data) and found that the geostationary satellites provide the absolute highest observation frequency. We further found that the cloud cover over sea behaves markedly differently from the cloud cover over land. This could be partly caused by the different atmospheric processes but it could also be related to increased difficulties with the interpretation of the satellite data in terms of cloud cover over land, which tends to be too low in the ISCCP—C2 data (Rossow *et al.*, 1993). For these reasons, in our analysis we restricted the data set of global cloud coverage to include only data from the geostationary satellites over the oceans.

With the compilation of global cloud data observed on geostationary and polar orbiting satellites over more than one solar cycle it has now been possible to study whether this important parameter regarding the Earth's radiative balance does in fact show systematic variations associated with the solar cycle.

Regarding a possible solar modulation we first looked at variations on time scales of the order of one year. We therefore smoothed the data series by applying a running mean filter of 12 months in order to remove seasonal variations. In Fig. 2 it is seen that a pronounced variation (corresponding to 3%–4%) takes place during this period with a maximum around 1986–1987, close to the minimum in solar activity. It has been reported (Kyle *et al.*, 1995) that the outgoing longwave radiation is strongly negatively correlated with total cloud cover for the mid-latitudes, whereas

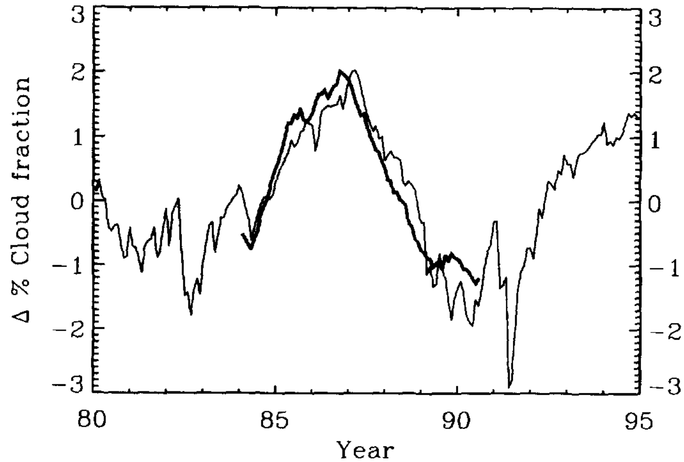

Fig. 2. The thick curve displays the 12 months running average of total cloud cover given as changes in per cent (ISCCP—C2 monthly data). The data are from the area over the oceans covered by geostationary satellites. The end points of the ISCCP—C2 curve (first and last 6 points) have been discarded. The thin curve represents the normalized monthly mean counting rate of cosmic ray intensity from Climax, Colorado, drawn to the same scale.

this correlation drops significantly in the Tropics. In Fig. 3 we have therefore displayed the cloud cover excluding the latitude band from 22.5°S to 22.5°N. A strong seasonal effect is present in the unaltered monthly average cloud data which is also shown. The seasonal variations are probably related to the North-South asymmetry in ocean coverage.

Although the data set displayed in Figs 2 and 3 is the longest homogeneous data set, it may be possible to include three additional data sets which illustrate that the effect is present also at other time intervals. These data sets comprise the NIMBUS-7 CMATRIX project (Stowe *et al.*, 1988), which covers the period April 1979 to March 1985. The second data set is provided by Defense Satellite Meteorological Program (DMSP) Special Sensor Microwave/Imager (SSM/I). This cloud data set (Weng and Grody, 1994; Ferraro *et al.*, 1996) covers the period July 1987 until November 1995 with data gaps in December 1987 and from July 1990 to December 1991. Finally the ISCCP—D2 data set comprising the years 1990–1992 is included. The difference between the data sets

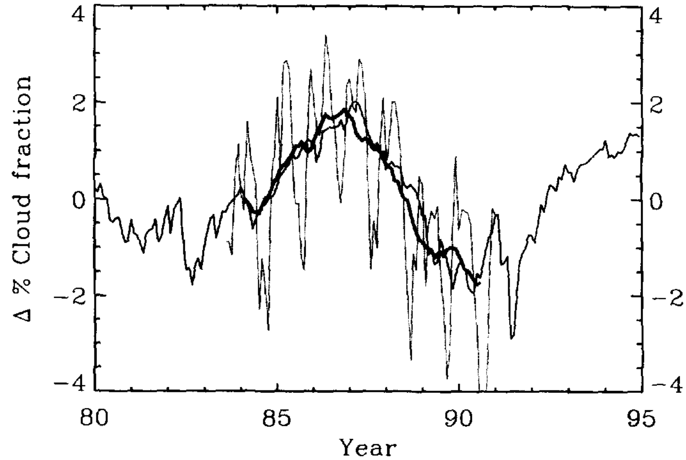

Fig. 3. Same as Fig. 2 except that the cloud data exclude the tropical zone 22.5°S to 22.5°N and that the unsmoothed monthly values of cloud cover are included (thin line).

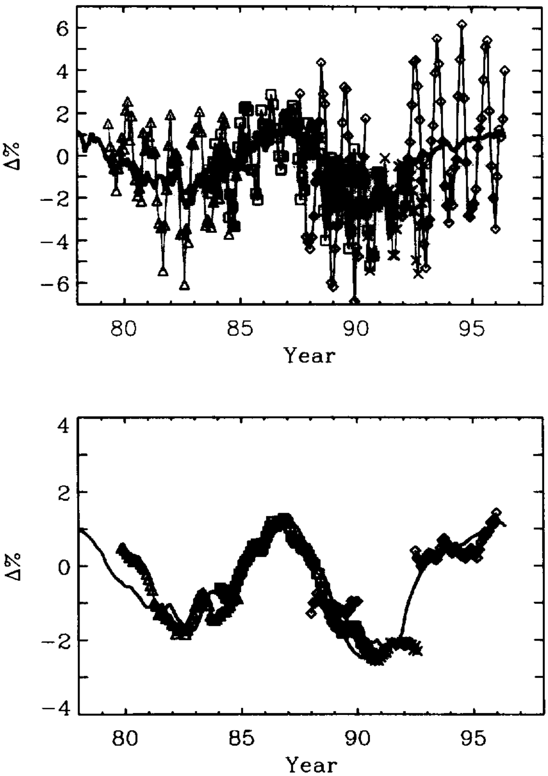

Fig. 4. Composite figure showing four satellite cloud data sets and normalized cosmic rays fluxes from Climax (thick curve). Triangles are the Nimbus-7 data, squares are the ISCCP—C2 data, diamonds are the DMSP data, and crosses are the ISCCP—D2 data. The top panel of the monthly values illustrates the noise level in the cloud data sets. The bottom panel displays the data smoothed using a 12 months running mean. The Nimbus-7 and the DMSP data are total cloud cover for the Southern Hemisphere over oceans, and the ISCCP data have been derived from the geostationary satellites over oceans with the tropics excluded.

reflects the different satellite coverage, instrumentation, and algorithms used to derive the cloud cover. Therefore a detailed comparison of absolute levels is difficult (Rossow *et al.*, 1985). However, assuming that the different data sets can be connected without any rescaling of the individual curves, we have in Fig. 4 constructed a composite cloud curve, which shows a variation in phase with the cosmic ray flux from 1980 to 1995. The top panel corresponds to the monthly values, and is therefore an indication of the noise level in the data sets. The bottom panel is the annual smoothed data. The Nimbus-7 and the DMSP data are from single satellites of which the DMSP only provides data over water. These satellites have a temporal and spatial resolution which is relatively low (Rossow and Cairns, 1995) and in order to get the best unbroken large scale cloud structures we have restricted these two data sets to the Southern Hemisphere over oceans. The ISCCP data represent the geostationary satellites over oceans, excluding the tropics.

In all three figures the cosmic ray flux has been represented by the normalized monthly average neutron monitor data observed at Climax station, Colorado. The calculated correlation coefficient between 12 months running mean values of the mid-latitude cloud cover for the ISCCP—C2 data and the monthly averages of the cosmic ray flux in Fig. 3 is as high as 0.95. If, also, 12 months running mean values of the cosmic ray flux are used the correlation coefficient increases to 0.97. For the total cloud cover in Fig. 2 the correlation coefficients are not much less, 0.92 and 0.93, respectively.

The statistical significance of the correlation coefficient is of course influenced by the fact that it was calculated using the the running mean values over 12 months. This leads to a reduction of the number of degrees of freedom from 90 to say 7 or 8 independent data points. In this case the above correlations are significant at the 0.01 level if the correlation coefficient is above 0.83. The statistical significance will also depend on possible persistence in the cloud data. If such a persistence were to reduce the effective number of independent data to 4, the statistical significance becomes marginal. The consistency in the combined set of four cloud records, however, indicates that the good correlation is not just caused by persistence.

DISCUSSION

The results indicate that there is a direct connection between cloudiness and the intensity of cosmic radiation. The actual microphysical explanation of such a relationship is still lacking. Several possibilities exist, which all depend on free charges or ions located in the lower stratosphere and in the troposphere produced by the energetic cosmic radiation. In 1912, C. T. R. Wilson observed that super-saturated vapour tends to condense on ions, an effect which he used to visualize tracks of alpha particles (in the Wilson cloud chamber). Such a direct mechanism is, however, not likely to be present in the atmosphere since, in the above experiments, the vapour is supersaturated by several hundred per cent. This highly exceeds the level of supersaturation found in the atmosphere, typically a few percent. However, the possibility that cosmic rays might affect weather and climate was suggested by Ney (1959). He pointed out that ions produced by cosmic rays was the variable in the lower atmosphere which had the largest modulation through a solar cycle.

The single most important and commonly accepted mechanism for condensation of water vapour into drops is related to the effect of aerosols (Rogers and Yau, 1989). The aerosol particles may initiate the nucleation process in a slightly supersaturated water vapour. When the aerosol is dissolved in a tiny haze particle the vapour pressure of the drop is lowered, increasing the probability of drop growth. However, aerosols are also known to be recombination centres for ions in the atmosphere, thereby making a size dependent statistical distribution of charges on the aerosols (Hoppel *et al.*, 1986; Gringel *et al.*, 1986). The hygroscopic aerosols increase their radius with increasing relative humidity, which makes the aerosols much more effective scavengers of ions. Above 100% humidity some of the aerosols are activated into cloud droplets. Experiments with charged rain drops have also shown that they are 10–100 times more efficient in capturing aerosols than unchanged drops (Barlow and Latham, 1983). This is consistent with the reduced atmospheric conductivity found in fog and clouds, because of the extremely low mobility of the charged droplets and aerosols. It is not unlikely that the combined effects of the aerosol solute (Raoult's law (Rogers and Yau, 1989)) together with charges (Segre, 1953) on the droplets are responsible for the observed cloud modulation (affecting both vapour/liquid and liquid/ice transitions and modulating the effective collision cross-sections), since ions in the troposphere are generated by cosmic rays and hence modulated by solar activity.

Pudovkin and Raspopov (1992) propose that the mechanism is related to change in atmospheric transparency caused by the ionizing effect of cosmic rays (galactic and solar), whereby the relative constituents of the atmosphere change, implying a change in the optical properties. They further report on the possible changes in the cloud coverage in association with these changes. Pudovkin and Veretenenko (1995, 1996) investigate in more detail the response of cloud cover to the cosmic ray flux and find local decreases in the amount of cloud cover related to short term changes in the cosmic rays caused by increased solar activity (Forbush decreases).

If the cosmic ray flux is indeed a cause of cloud cover variations one would expect that the effect is least near the equator, in particular the geomagnetic equator where the magnetic field lines are horizontal and therefore will have a larger shielding effect regarding the ionizing particles. That this effect is present in the total cloud cover data is illustrated in Fig. 5. The figure displays the correlation between the zonal average cloud data and the cosmic ray flux. That the effect is stronger at higher latitudes agrees well with the slightly enhanced response in Fig. 3 where the tropics have been excluded. A net cooling corresponding to the average of 65% cloud cover is assumed to amount to 17 to 35 W/m^2 (Ohring and Clapp, 1980; Ramanathan *et al.*, 1989; Ardanuy *et al.*, 1991). For a variation in cloud cover of 3% during an average 11 yr solar cycle a crude estimate of this effect is 0.8 to 1.7 W/m^2. This is a very significant amount compared to the total radiative forcing of the increase in the concentration of CO_2 since 1750 which is estimated to 1.5 W/m^2 (IPCC, 1995).

CONCLUSIONS

We have presented a systematic variation in global cloud cover during a considerable part of the last solar

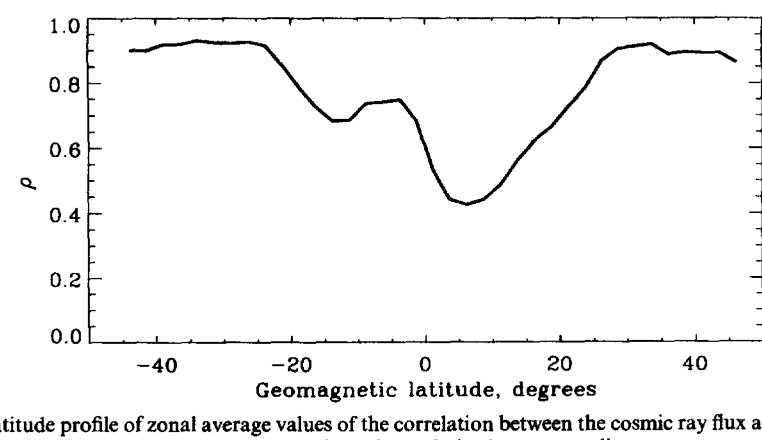

Fig. 5. Latitude profile of zonal average values of the correlation between the cosmic ray flux and the cloud cover over the oceans. The zonal averages have been derived corresponding to geomagnetic latitudes (dipole field with pole at 78.5°N 291°E).

cycle that seems to be caused by the varying solar activity through its 11 yr modulation of the cosmic ray flux. As a result the complexity of the coupled atmosphere–ocean system including the ocean's thermal inertia, the effect on surface temperature during the 11 yr solar cycle, is less direct, as observations also indicate. The existence of a physical mechanism, which is sufficiently strong, indicates that the deduced inverse correlation between the solar cycle length and long term variations in global temperature (Friis-Christensen and Lassen, 1991) may be related to long term variations in the solar modulation of cosmic ray flux.

Our result not only provides an explanation of solar variability effects on climate through the modulating effect of the solar wind magnetic field on the cosmic ray flux. Since the cosmic ray flux and, in particular, its distribution on the Earth is also influenced by the Earth's main magnetic field as demonstrated by the C^{14} record (Damon and Sonett, 1991), any variation in this field may have climatic effects as some palaeoclimate and palaeomagnetic studies indicate (Anderson, 1992).

An external forcing through the cloud coverage will have far-reaching consequences for the design and application of climate models in determining the magnitude of the enhanced greenhouse effect. Taking into account the good correlation between solar activity variations and observed climate parameters in the past, we may be able to model the 'natural' variability of climate far better than hitherto possible. This will provide us with a much more firm baseline from which to estimate the possible climatic effects of human activity. This, of course, needs further studies regarding both the latitude and altitude distribution of the effect.

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REFERENCES

Anderson R. Y. 1992 Possible connection between surface winds, solar activity and the Earth's magnetic field. *Nature* **358**, 51–53.

Ardanuy P., Stowe L. L., Gruber A. and Weiss M. 1991 Shortwave, longwave, and net cloud-radiative forcing as determined from Nimbus-7 observations. *J. geophys. Res.* **96**, 1–2.

Barlow A. K. and Latham J. 1983 A laboratory study of the scavenging of sub-micron aerosol by charged raindrops. *Quart. J. R. Met. Soc.* **109**, 763–770.

Damon P. E. and Sonett C. P. 1991 Solar and terrestrial components of the atmospheric ^{14}C variation spectrum. *The Sun in Time*, ed. C. P. Sonett, M. Giampapa and M. S. Matthews, The University of Arizona Press, Tucson, Arizona, 149 pp.

Dickinson R. 1975 Solar variability and the lower atmosphere. *Bull. Am. Met. Soc.* **56**, 1240–1248.

Eddy J. A. 1976 The Maunder minimum. *Science.* **192**, 1189–1202.

Ferraro R. R., Weng F., Grody N. C. and Basist A. 1996 An eight-year (1987–1994) time series of rainfall, clouds, water vapor, snow cover, and sea ice derived from SSM/I measurements. *Bull. Am. Met. Soc.* **77**, 891–905.

Friis-Christensen E., Lassen K. 1991 Length of the solar cycle: an indicator of solar activity closely associated with climate. *Science* **254**, 698–700.

Gringel W., Rosen J. M. and Hoefmann D. J. 1986 Electrical structure from 0 to 30 kilometers. *The Earth's Electrical Environment, Studies in Geophysics*, ch. III, National Academy Press, Washington, pp. 166–182.

Hoppel W. A., Anderson R. V. and Willett J. C. 1986 Atmospheric electricity in the planetary boundary layer. *The Earth's Electrical Environment, Studies in Geophysics*, ch. III, National Academy Press, Washington, pp. 149–165.

Houghton J. T., Meira Filho L. G., Bruce J., Hoesung Lee, Callander B. A., Haites E., Harris N. and Maskell K. (eds) 1992 *Climate Change* 1992: *The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, U.K.

IPCC 1995 *Climate Change* 1995: *The Science of Climate Change*, WMO & UNEP.

Kyle H. L., Weiss M. and Ardanuy P. 1995 Cloud, surface temperature, and outgoing longwave radiation for the period from 1979 to 1990. *J. Climate* **8,** 2644–2658.

Labitzke K. and van Loon H. 1993 Some recent studies of probable connections between solar and atmospheric variability. *Ann. Geophys.* **11,** 1084–1094.

Lal D. and Peters B. 1967 Cosmic ray produced radioactivity on the Earth. *Encycelopedia of Physics*, Flugge, S., ed. number XLVI in 2, Springer-Verlag, Berlin, Heidelberg, pp. 551–612.

Lassen K. and Friis-Christensen E. 1995 Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate. *J. atmos. terr. Phys.* **57,** 835–845.

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

Ney E. R. 1959 Cosmic radiation and the weather. *Nature* **183,** 451–452.

Ohring G. and Clapp P. F. 1980 The effect of changes in cloud amount on the net radiation at the top of the atmosphere. *J. atmos. Sci.* **37,** 447–454.

Pudovkin M. I. and Raspopov O. M. 1992 The mechanism of action of solar activity on the state of the lower atmosphere and meteorological parameters (a review). *Geomagn. Aeronomy* **32,** 593–608.

Pudovkin M. and Veretenenko S. 1995 Cloudiness decreases associated with Forbush-decreases of galactic cosmic rays. *J. atmos. terr. Phys.* **57,** 1349–1355.

Pudovkin M. and Veretenenko S. 1996 Variations of the cosmic rays as one of the possible links between the solar activity and the lower atmosphere. *Adv. Space Res.* **17**(11), 161–164.

Ramanathan V., Cess R. D., Harrison E. F., Minnis P., Barkstrom B. R., Ahmad E. and Hartmann D. 1989 Cloud-radiative forcing and climate: results from the Earth's radiation budget experiment. *Science* **243,** 57–63.

Rogers R. R. and Yau M. K. 1989 *A Short Course in Cloud Physics*, 3rd edn, Int. Series in Nat. Phil., Pergamon Press, Oxford.

Rossow W. B. and Cairns B. 1995 Monitoring changes of clouds. *J. Climate* **31,** 305–347.

Rossow W. B., Mosher F., Kinsella E., Arking A., Desbois M., Harrison E., Minnis P., Ruprecht E., Seze G., Simmer C. and Smith E. 1985 ISCCP Cloud Algorithm Intercomparison. *J. Climate* **24,** 877–903.

Rossow W. B. and Schiffer R. 1991 ISCCP cloud data products. *Bull. Amer. Meteor.* **72,** 2–20.

Rossow W. B., Walker A. W. and Garder L. C. 1993 Comparison of ISCCP and other cloud amounts. *J. Climate* **6,** 2394–2418.

Segre E. 1953 *Experimental Nuclear Physics*, vol. 1, Wiley, New York, 53 pp.

Stowe L. L., Wellemayer C. G., Eck T. F. and Yeh H. Y. M. the Nimbus-7 Team 1988 Nimbus-7 global cloud climatology, Part 1: Algorithms and validations. *J. Climate* **1,** 445–470.

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

Tinsley B. A. 1996 Solar wind modulation of the global electric circuit and the apparent effects on cloud microphysics, latent heat release, and tropospheric dynamics. *J. Geomag. Geoelectr.* **48,** 165–175.

Weng F., Grody N. C. 1994 Retrieval of cloud liquid water using the special sensor microwave imager (SSM/I). *J. geophys. Res.* **99,** 25535–25551.

Zhang Q., Soon W. H., Baliunas S. L., Lockwood G. W., Skiff V. A. and Radick R. R. 1994 A method of determining possible brightness variations of the Sun in past centuries from observations of solar-type stars. *Astrophys. J.* **427,** L111–L114.