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Signatures of solar activity variability in meteorological parameters

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Abstract

Solar radiation (both total and in various wavelengths) varies at different time scales—from seconds to decades or centuries—as a consequence of solar activity. The energy received from the Sun is one of the natural driving forces of the Earth's atmosphere and since this energy is not constant, it has been argued that there must be some non-zero climate response to it. This response must be fully specified in order to improve our understanding of the climate system and the impact of anthropogenic activities on it. However, despite all the efforts, if and how subtle variations of solar radiation affect climate and weather still remains an unsolved puzzle. One key element that is very often taken as evidence of a response, is the similarity of periodicities between several solar activity indices and different meteorological parameters. The literature contains a long history of positive or negative correlations between weather and climate parameters like temperature, rainfall, droughts, etc. and solar activity cycles like the 27-day cycle, the prominent 11-year sunspot cycle, the 22-year Hale cycle and the Gleissberg cycle of 80–90 years. A review of these different cycles is provided as well as some of the correlative analyses between them and several stratospheric parameters (like stratospheric geopotential heights, temperature and ozone concentration) and tropospheric parameters (like temperature, rainfall, water level in lakes and river flooding, clouds) that point to a relationship of some kind. However, the suspicion on these relationships will remain as long as an indisputable physical mechanism, which might act to produce these correlations, is not available.

Keywords: Sun: activity; Sun: fundamental parameters; Solar–terrestrial relations; Earth; Climate

1. Introduction

It is now well established that our Sun is a fairly typical star, nothing more than one of the variable stars of the Universe. The Sun undergoes changes characterized by variations in its output of electromagnetic and particle radiation over a wide range of temporal scales due to the different degrees of activity. Whether these changes have anything to do with the Earth's atmosphere and, especially, with weather and climate, has been debated for more than 150 years. In 1982 a National Academy of Sciences (NAS) Panel on Solar Variability, Weather and Climate studied the issue in detail and concluded that "it is conceivable that solar variability plays a role in altering weather and climate at some yet unspecified level of significance" (National Research Council, 1982). Since 1982 explosive growth in our knowledge on the Sun's variability and the responses of the different layers of the Earth's atmosphere to it has been made due mainly to Earth satellite observations. The most important discovery is that the total solar irradiance (TSI from now on) varies by about 0.1% over the 11-year solar activity cycle being higher during the maximum of the cycle. Not just the TSI, but also the entire solar spectrum exhibits variations which are strongly wavelength dependent. Larger changes occur at shorter UV wavelengths. Radiation at these wavelengths, which is responsible for stratospheric ozone production, is now known to vary as

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much as 10% with the 11-year solar cycle and causes changes in the total column ozone at a level which is comparable to the decadal depletion by increasing chlorofluorocarbons. Variations also occur at the solar energetic particle outputs which impact primarily the high latitude terrestrial upper and middle atmosphere. These variations provide evidence of a solar-forced climate change and have been acknowledged by a subsequent NAS study (National Research Council, 1994). But like its 1982 predecessor this report too was unable to give a definitive answer to the age-old question of the Sun–climate connection. Apart from the above two referred NAS studies special conferences were devoted to this subject, like “The Solar Engine and its Influence on Terrestrial Atmosphere and Climate” (Nesmes-Ribes, 1995) or “The Solar Cycle and Climate” (Wilson, 2000). A recent excellent book which considers the possible meteorological effects of solar activity is that of Hoyt and Schatten (1997), while several reviews and papers of interest can be found dispersed in nearly every kind of scientific journal due to the truly multidisciplinary character of this subject.

Despite the more than 150 years scientific work supporting the view that meteorological phenomena must respond to variations of solar activity, this subject is far from being settled. On the other hand it is, nowadays, widely assumed that increase of the aerosols and greenhouse gases (especially the carbon dioxide), which result from human activities, will have as a result significant warming of the Earth during the next years. This warming should be accompanied by dramatic changes affecting life on it and having several ecological, social and economic consequences. In this context, the improvement of our understanding of the climate system is not only a challenging endeavour of the current scientific research, but also a subject of paramount concern. It is obvious, that in order to isolate a greenhouse footprint of climate change, we must be able to make distinctions between the contributions that arise from anthropogenic impacts and those that are due to natural influences and particularly the one due to the solar variability. Lack of knowledge of solar influences will limit our ability to clearly gauge the possible impacts of our own activities on the present and future climate.

One key element that has been largely used to prove the Sun–climate/weather connection is the search for possible influences of solar activity on the different meteorological or climatological parameters. Purported correlations are based on the analyses of long-term records of different indicators of solar activity and different historical data of meteorological parameters. Many parameters are found to exhibit cyclic variations of 11, 22, 80 and 200 years common in both records. Several of the analyses of these records are fraught with problems in the methods used, bias in data selection, or questionable statistical significance of the reported correlations. There exists, on the other hand, such voluminous literature with well established correlations showing apparent effects of the variable solar activity to climate that one may think that they would not be the result of a coincidence. The partial acceptance, however, of the potential impact of solar variability to our local environment relies mainly on the lack of an acceptable physical linking mechanism and only its achievement will lead to a complete acceptance. In this review, we will not, of course, include all the ingredients of the subject. We shall discuss the different characteristics of the solar variations in Section 2 (both transient and periodic), while in Section 3 we will review several reported responses of the Earth’s stratosphere and troposphere to these variations.

2. Variability of solar inputs to the Earth’s system

Global weather and climate develop depending on the solar energy reaching our planet’s surface. The solar energy input to the Earth’s system is not constant. Changes in its amount are caused by three main mechanisms: (i) geometric factors related to the inclination of the Earth’s axis and its year after year orbit around the Sun, (ii) processes related to the Earth’s system itself (like albedo changes, volcanic influences, etc.) and (iii) variations in the activity of the Sun. An important element in solar–terrestrial coupling is the understanding and, if possible, forecasting of the solar variability and its effects on the Earth’s atmosphere. In the subsequent sections we will deal only with the solar variability and its influences.

2.1. Variability due to solar activity

The Sun’s output varies on an wide range of time scales, from minutes in the case of some transient events to the billion year time scale of solar evolution. These variations reflect the inhomogeneous emission of radiation due to the presence or absence of active regions on the solar disk. They appear usually quasi-periodically and could be divided into short, intermediate and long-term variations.

Short-term variations include the transient episodes of solar activity like flares or Coronial Mass Ejections (CMEs), those due to the 27-day apparent rotation period of the Sun, and a 154–158 day cycle which exists in many solar phenomena. *Intermediate term variations* include the 16-month cycle discovered quite recently by SOHO (not much is known about it). *Long-term variations* include the 11-year solar cycle which is by-far the more well established cycle of solar activity together with the 22-year Hale cycle of magnetic activity, the 80 to 90-year Gleissberg cycle, the ∼180 to 200-year de Vries cycle, etc. The de Vries cycle is evident indirectly in cosmogenic isotopes like ^{14}C and ^{10}Be, which are both produced by galactic cosmic rays. Cosmic rays are modulated by changes in the interplanetary magnetic field (IMF) and are inversely related to solar activity (Hoyt and Schatten, 1997).

Solar activity is controlled by magnetic fields that are generated by a self-exciting magnetohydrodynamic (MHD) dynamo in the interior of the Sun. The combination of convective motions and differential rotation of the Sun is responsible for the changing character of the magnetic fields which in turn generates the different degrees of activity. Their manifestation is observed through the existence and variability of the large number of solar features in the different layers of the solar atmosphere, but also through the variability of the solar electromagnetic and corpuscular radiation. Transient events on the Sun cause dramatic variability, especially in the Earth's upper atmosphere, ionosphere, and magnetosphere. Eruptions such as flares and CMEs frequently give rise to fluxes of energetic particles, which can arrive at the Earth within a few hours to some days. They interact with the solar wind to form the IMF, which impinges on the Earth to cause geomagnetic storms and also deflects galactic cosmic rays. The different consequences of these structures on the interplanetary space and the Earth are just beginning to be studied and understood.

Three major manifestations of solar variability can be observed. These are variations of solar structures, electromagnetic radiation, and energetic solar particles. Examples of these manifestations can be seen in data with increasing time scales as shown in Fig. 1.

2.1.1. Variation of the solar structures

Many different indicators have been employed as measures of solar activity. The basic indicator and also the most commonly used parameter in many correlation studies for Sun–weather relationships is the number of sunspots visible on the solar disk at any given time. The solar 11-year cycle was first noticed in the number, pattern and magnetic polarity of sunspots. Schwabe, in 1843, was the first to announce the discovery of a 10-year cycle in the number of sunspots. Wolf, in 1852, could affirm that the sunspot cycle was not 10-years but rather 11.1 years, but he also noted that some cycles were only about 8 years long while others appeared to last 17 years. This cyclic behavior is followed by many other structures on the solar disk and many other solar characteristic quantities. The magnetic cycle of 22 years, also called the Hale cycle, is the true cycle of solar activity. Bipolar active regions on the Sun are composed by preceding and following magnetic polarities. With the commencement of a new cycle the polarity reverses. Thus the original polarity is restored every second 11-year cycle. The Gleissberg cycle seems fairly clear in the sunspot record although it is not strictly periodic. When one connects the peaks of the quasi-periodic sunspot record by an enveloping curve, minima, which constitute the Gleissberg cycle, emerge around the years 1670, 1810, and 1895. Each of these sunspot minima coincided with cool climate in the Northern hemisphere the two first known as the Maunder minimum and the Dalton minimum. Today, we know that the number of faculae, plages, flares, radio bursts, coronal disturbances, etc., all different manifestations of the solar magnetic field, also show this 11-year cyclic behavior. We also know that the 22-year Hale cycle or the 80–90-year Gleissberg cycle are apparent not only in sunspots, but also in several other solar structures. The existence of this periodicity has also been detected in the aurorae records and is present in the ^{14}C record. The solar activity is also modulated on longer time scales. The proxy records of cosmogenic isotopes (^{14}C and ^{10}Be) show that episodes of reduced activity have a prominent 200-year periodicity for the past 50 000 years (Beer, 2000).

2.1.2. Variation of the solar electromagnetic radiation

Variation of the above mentioned features is the cause of the radiated solar output variability both total and in various wavelengths. Before the launch of satellites the most popular opinion among scientists was that the TSI, i.e. the solar output in all wavelengths, was constant and invarying; indeed, it was called the "solar constant", until recently. Direct measurements of the TSI by Earth satellites have been made with reasonable accuracy only since 1978. The lack of intercalibrated although continuous observations by different radiometers on-board different satellites did not allow a unambiguous result concerning its variations. Fortunately, Frohlich and Lean (1998) have constructed a composite record which proves conclusively that the TSI is not constant and that it varies ∼0.1% from the minimum to the maximum of the solar cycle. Moreover, solar activity and solar irradiance parallel each other. These cyclic variations of the TSI have been tentatively explained in terms of a combination of decreases due to sunspot blocking deficits and increases due to facular and network emission. Bright magnetic features of smaller sizes dispersed on the solar disk (Tsiropoula, 1998) must also contribute to the enhanced emission during the solar cycle. The two effects, e.g. emission depletion and excess tend to cancel each other and the net positive correlation of the TSI with solar activity is explained as a slight excess of facular plus network brightening over sunspot darkening. Apart from this 11-year solar cycle, which is by far the most familiar, the TSI varies at different time scales. The largest variations shown up directly in the irradiance records as a dip (see e.g., Tsiropoula and Argiriou, 2000), could be ∼0.5% when a large sunspot passes across the solar disk. Observations from space reported variations of up 0.2% from one month to the next. These short-term variations are consistent with the Sun's 27-day apparent period of rotation. A longer term irradiance variability component of the order of 200 years is also implied from indirect indices like the cosmogenic radionuclides (Beer, 2000).

The second category of the solar radiance variability involves variations in spectral irradiance, which, furthermore, are not uniformly distributed across the electromagnetic spectrum. These variations occur because of the changing impacts of the solar features whose opposing influences depend on the wavelength. Solar flares are the most prominent examples of the radiated energy of time scales of seconds to hours. Although even the largest of them do

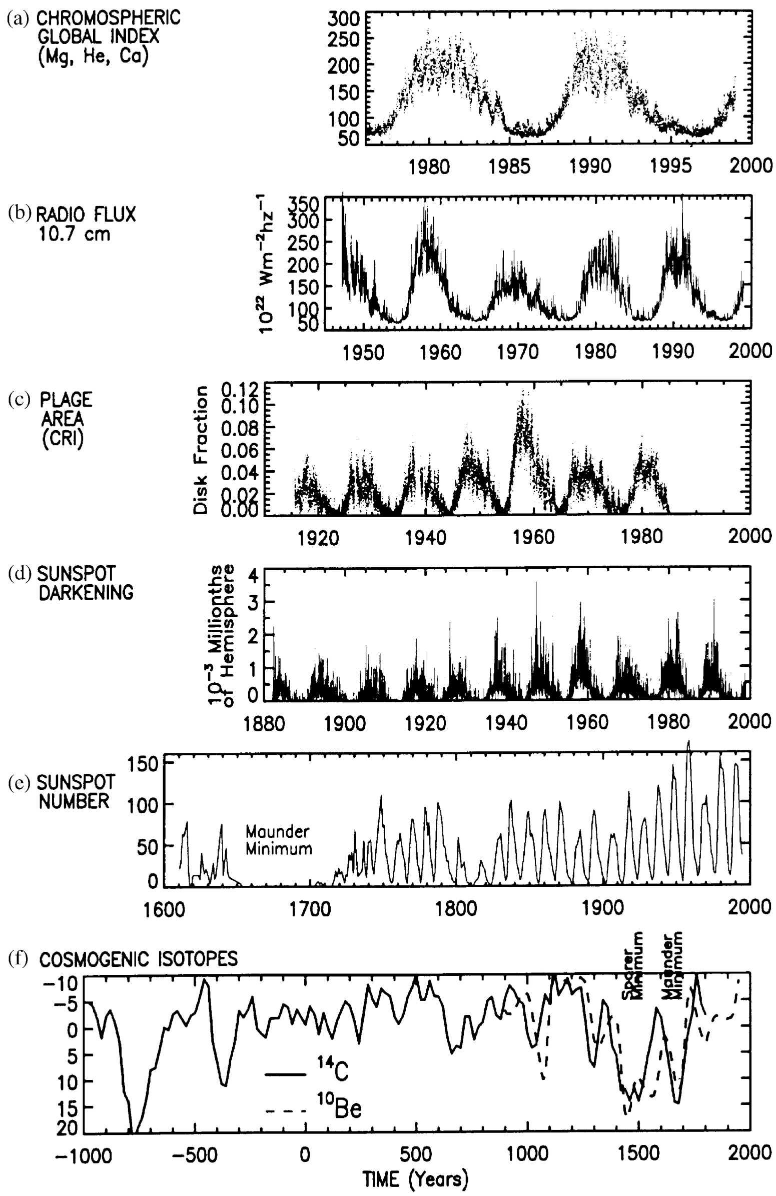

Fig. 1. Solar activity variability on increasing time scales as indicated by solar structure, radiation, and cosmogenic isotopes (adapted from Lean, 1997).

not enhance the TSI more than a hundredth of a percent, they temporarily enhance the solar output at UV, radio and X-ray wavelengths (and sometimes gamma-rays) by several orders of magnitude. Sunspots, on the other hand, have a significant role at the visible and negligible role at the UV wavelengths. The variable radiated energy at different wavelengths is now clearly demonstrated by observations made by satellites or ground-based instruments (solar mesosphere explorer (SME) and upper atmosphere research satellite/solar stellar irradiance comparison experiment (UARS/SOLSTICE) for the UV, Yohkoh/SXT (Soft X-ray Telescope) for the X-rays, radiotelescopes for the radio). UV and X-ray records show clear episodes of the 27-day rotational modulation and also variations in phase with the 11-year solar cycle. The UARS data suggest changes of 20%, 8% and 3% near wavelengths of 140, 200 and 250 nm, respectively, from solar maximum to solar minimum (Lean et al., 1997). The extremes in wavelength, i.e. X-ray and radio, show stronger, more transient fluctuations than the spectrum from the Lyman continuum edge

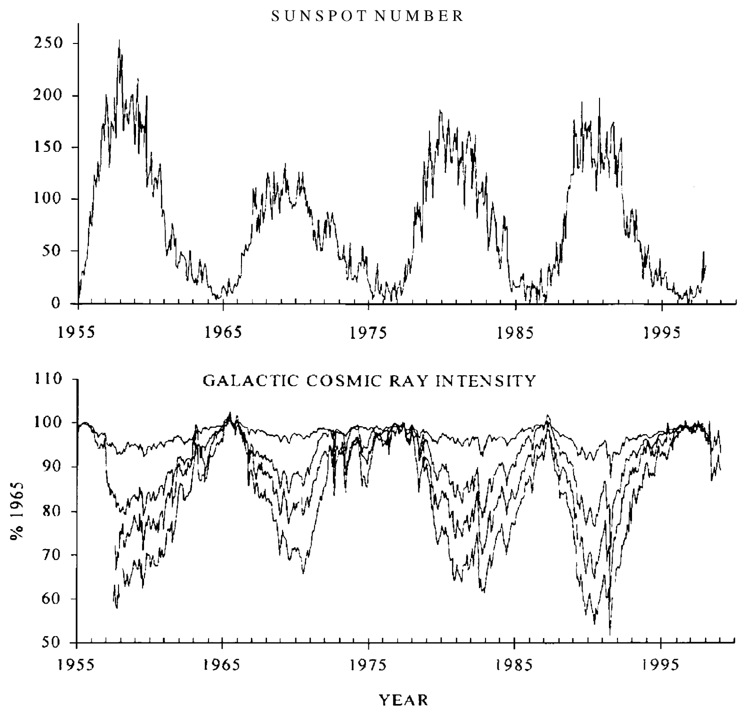

Fig. 2. Long-term changes in solar activity (upper panel) and galactic cosmic ray intensity (lower panel) as recorded by balloon detectors and by neutron monitors (adapted from Bazilevskaya, 2000).

at 91.2 nm to the far IR at 1 cm. This mid-range spectrum varies more slowly and carries 99.9% of the solar radiant energy. Variations in the different spectral regions could have a major impact on climate change since the Earth's atmosphere, land and oceans respond differently to the different wavelengths. In particular, the UV radiation below 300 nm varies by an order of magnitude more than the TSI with the 11-year solar cycle and it contributes more than ~10% of the TSI irradiance variations. Absorbed in the Earth's upper atmosphere solar UV radiation is very important because it controls ozone processes.

2.1.3. Variation of the solar particles (solar wind, high energy accelerated particles)

Along with variations of the electromagnetic energy emitted by the Sun, highly energetic particles originating from active regions also undergo large changes. Often particles (mainly protons and alpha particles) are accelerated to high energies during a flare process, while during CMEs large amounts of solar material are suddenly injected into the solar wind and are usually accompanied by magnetic disturbances. Solar proton events can occur any time, but there is a definite preference for occurrence during sunspot maximum.

Relativistic electron fluxes (2–15 MeV) are also observed. Their presence or absence is controlled largely by high speed solar wind streams, which in turn show a strong solar cycle dependence. A 27-day periodic enhancement of the relativistic electrons is observed in association with concurrently measured solar wind streams in excess of 600 km s^{-1}. The solar wind is also highly variable and its properties impede the flux of high energy cosmic rays coming from the interstellar space and entering the Earth's atmosphere. Cosmic ray flux modulation manifests itself on a wide range of time scales and closely mirrors the solar activity time history. Their range of energy is from tens of MeV to hundreds of GeV. Low energy cosmic rays are recorded at high altitudes and latitudes with rockets and spacecraft, while high energy cosmic rays are easily monitored at the Earth's surface with muon telescopes and neutron monitors (Bazilevskaya, 2000). Their most impressive modulation is the 11-year variation that shows a clear anticorrelation with the 11-year solar cycle (Fig. 2). Longer cosmic ray modulation is also imprinted as cosmogenic nuclei abundance in different terrestrial archives, such as polar ice cores and tree rings.

3. Evidence for solar influences on meteorological parameters

Numerous and various processes appearing on the Sun due to different degrees of activity propagate through the interplanetary medium producing disturbances which can be detected at the magnetosphere, the ionosphere and even at the Earth's surface. Inputs of solar energy produce at times intense geomagnetic storms in the magnetosphere during which energized electrons bombard the upper atmosphere producing aurorae and depositing energy locally. The ionosphere, upper and middle atmosphere and probably troposphere of the Earth also respond to rapid changes in energetic particle precipitation that accompany transient solar events. Some ionospheric disturbances are thought to be initiated by the deposition of protons and relativistic electrons to low altitudes that enhance ionization and cause plasma instabilities. Penetration of an energetic proton into the stratosphere (i.e. altitudes below about 50 km) requires energies in excess of 30 MeV, while penetration into the high-latitude troposphere requires energies greater than 1 GeV. Solar proton events have a direct influence on the levels of the HO_x and the NO_x, which are of central importance to the understanding of stratospheric ozone variations and its global balance. Relativistic energetic electrons like energetic protons are capable of penetrating to the middle atmosphere. The depth of their penetration is a strong function of the electron energy. Some of these precipitating electrons may contribute to the odd-nitrogen budget of the middle atmosphere and thus to the modification of the mesospheric ozone (Baker et al., 1993).

Apart from these responses to transient solar events a wide range of cyclic changes in the Earth's atmosphere seems to be linked with the solar cycle. The 27-day solar variations seem to be more persistent at the shorter wavelengths. Radiation at these wavelengths (especially the UV radiation) reacts most strongly with the Earth's upper atmosphere and thus most of the 27-day responses are to be found in the Earth's stratosphere and mesosphere. No report on a meteorological response to the 154/158-day solar cycle is found. A significant number of studies show that some meteorological parameters, such as storms and droughts show a good correlation with the 22-year Hale magnetic cycle. Many meteorological parameters seem to occur in a 80–90-year cycle, which parallels the Gleissberg solar cycle. But by far the more familiar cycle of solar activity is the 11-year cycle and it is this cycle that is mostly used for correlative analyses with meteorological parameters, due also to the limited historical record of the latter ones.

The literature contains a long history of variations in meteorological parameters which parallel some aspect of solar variability expressed very often by the sunspot number for which we have the most extensive record dated back to 1600. Several other indicators both direct and indirect (like sunspot cycle length, irradiance variation (both total and in various wavelengths), cosmic ray flux, cosmogenic radionuclides, etc.) have been used for correlation analysis with varying degrees of success.

The first observation of such a relationship dates back about 2400 years BP. As it is reported by Theophrastus, Meton used to climb the hill Lycabettus, in Athens, to record the Sun's location on the horizon. After 20 years of observations Meton examined his records and surprisingly noticed that when the Sun had spots the weather tended to be wetter and rainier. In the recent past the coincidence of the Sun's Maunder Minimum with the lowest temperatures of the 17th century Little Ice Age is the best documented of such associations. In the last century—in 1885—Meldrum, a British meteorologist in India, published a paper where he presented a comparison between Indian cyclones and group sunspot numbers (see Hoyt and Schatten, 1997). The striking relationship he found was the cause for a surge of publications. Several papers appeared relating changes in the Sun to variations not only in the Earth's temperature, rainfall, droughts, but also in wheat prices, wine harvests, forest fires, etc. The poor statistical analysis used in some of these papers and the confusing and controversial results were the reason that the whole field received a bad reputation. These last years, however, the field has been revitalized because of three interesting findings. Labitzke and van Loon (1988) suggested an association between the 11-year solar cycle and a wide range of stratospheric parameters like the geopotential heights and the temperature. Friis-Christensen and Lassen (1991) pointed out a striking relationship between northern hemisphere surface temperatures and the variation of the solar cycle length over the past 130 years. Finally, Reid (1991) found a striking similarity between sea-surface temperature (SST) anomalies and the 11-year running mean of the sunspot number.

In the following we will review several of the reported associations between stratospheric and tropospheric parameters and the different cycles of solar activity.

3.1. Stratospheric parameters

Solar UV radiation plays a major role in the temperature, dynamics and photochemistry of the stratosphere. Between 120 and 300 nm it is absorbed in the Earth's outer atmosphere by ozone and molecular oxygen. Increased levels of UV radiation heat the stratosphere and mesosphere due to absorption by ozone and oxygen. It produces atomic oxygen by photodissociation of molecular oxygen, which, in turn, by recombination with atomic oxygen generates ozone. In this way, the variation of UV affects the ozone concentration. Satellite observations have documented ozone and temperature perturbations at the 27-day period. It also seems that ozone presents a similar variation as the 11-year UV variations (Hood and McCormack, 1992). Ozone measurements obtained from satellites and by ground-based instruments suggest a variation of 2% in global ozone content between solar minimum and maximum, a level comparable to the decadal depletion by increasing chlorofluorocarbons. Labitzke and van Loon (1997) examining the spatial correlations between the total column ozone data obtained by total ozone mapping spectrometer (TOMS) with the 11-year solar cycle found that they show high correlations at latitudes between 5° and 30° in both hemispheres (Fig. 3). Surprisingly, the correlation is low in the equatorial region,

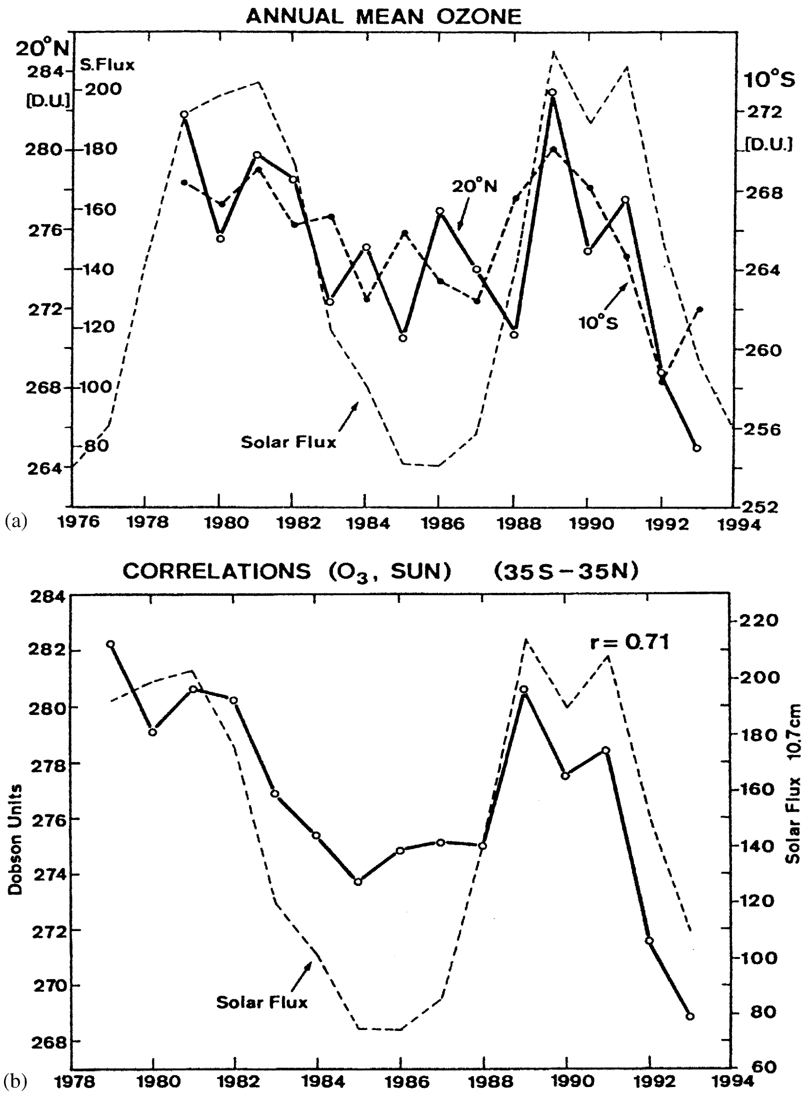

Fig. 3. (a) Time series of the annual means of the 10.7 cm solar flux (short dash) and the zonally averaged total column ozone (in Dobson units) at 20°N and 10°S (long dash). (b) The same for the area 35°N–35°S (adapted from Labitzke and van Loon, 1997).

where ozone is produced and in the subpolar regions, where the largest amounts of ozone are found. They suggested, that this effect may be due to solar induced changes on the poleward transport of ozone rather than be the result of direct radiative interaction between the Sun and the ozone. Ozone concentration changes alter also the vertical temperature profile and modify the radiative and dynamical coupling of the stratosphere and troposphere. Analysis of the temperature response of the stratosphere and mesosphere to the 11-year solar cycle observed in the last decades by different instruments (radars, lidars, rockets, satellites, radiosondes) suggests that there is a solar signature, although it is highly variable in amplitude and in sign and depends on latitude and altitude.

Another interesting finding concerns the influence of the 11-year solar cycle on the stratospheric geopotentials and temperatures. Labitzke and van Loon (1992) reported a clear correlation between the 30-hPa geopotential heights and temperatures in the lower stratosphere on the Northern hemisphere and the 11-year solar cycle. Later, van Loon and Labitzke (1998) using global data from NCEP/NCAR re-analyses for the stratosphere at levels as high as the 10-hPa geopotential heights were able to show the existence of the 11-year solar signal on both hemispheres (Fig. 4). They found that the signal is strongest in the northern summer, and that the highest correlations between solar cycle signal and temperatures in the stratosphere move from one summer hemisphere to the other, while the highest correla-

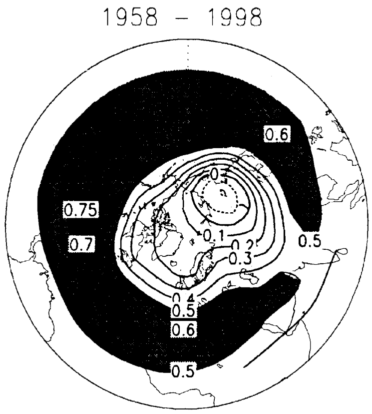

Fig. 4. Correlation coefficients between the 10.7 cm solar flux and annual mean 30-hPa heights. Data from the NCEP/NCAR re-analyses, 1958–1998 adapted from van Loon and Labitzke (1998).

tions between the solar cycle and the stratospheric geopotential heights move poleward from winter to summer in both hemispheres. They also found that the correlations are weakest over the whole globe in the northern winter. They attributed this to the quasi-biennial oscillation (QBO) in the tropical stratospheric winds, which may modulate the solar signal. When grouping the data into years when the QBO in the lower stratosphere was westerly and years when it was easterly, the correlation coefficient becomes highly positive in the Arctic in the west years and negative in the east years. Beyond the Arctic, and as far as the Antarctic, this coefficient approaches zero in the west years, whereas it is positive and high in the subtropics and tropics in the east years. Understanding the role of the QBO in modulating the solar signal is of enormous importance. Results of recent modeling efforts (see e.g. Balachandran and Rind, 1995) indicate that variations in the middle atmospheric temperature and wind structure associated with the QBO and solar UV irradiance may have a direct impact to the troposphere primarily through alteration in the generation and propagation of the planetary waves. Planetary wave activity is found to be more important during the western phase of the QBO and solar maximum and less pronounced during the eastern phase and solar minimum and may play a principal role in the variations of the tropospheric geopotential height, temperature and wind.

3.2. *Tropospheric parameters*

The two most common meteorological parameters used to define climate have been temperature and rainfall and these two also have been used mostly in Sun–weather correlation studies. Other popular parameters include surface pressure, winds, droughts, storms, cyclones, clouds, etc. It is of interest, to review some of the results over the years that attempted to relate some of these climatic variables to the solar cyclic variations.

During the past 100 years many studies have attempted to correlate temperature measurements and solar activity. The reported results are mixed, i.e. maximum temperatures are related to maximum activity (positive correlation) or to minimum activity (negative correlation), but also sometimes no correlation at all was found depending on the location, the time interval and the analysis technique. At the beginning of this century a paper by Koppen (1914) appeared which discussed sun and climate. Koppen examining global mean annual temperature data for the years 1804–1910 concluded that a negative correlation exists between the 11-year solar cycle and the Earth's surface temperature. Many authors confirmed later the results of Koppen for this time interval. Lawrence (1965) analyzing more than 130 years of temperature data (1830–1965) for three places in England (Edinburgh, Greenwich and Wakefield) found that temperatures showed negative correlation with solar activity from 1880 to 1930 and positive correlation for the other years. King et al. (1974) indicated that for two 11-year cycles (1938–1958) London temperatures had strong positive correlation with the solar cycle. Currie (1993) examining temperature records of 1197 sites in the US found cyclic variations at almost every site, which were in phase with the 11-year solar cycle. Recently, a decadal component identified in globally averaged SST anomalies compiled from bathythermographs that tracks TSI during the past few 11-year cycles add further support. Indeed, in the search for the source of global-average upper ocean temperature changes, White et al. (1997, 1998) found that decadal and interdecadal signals in the Earth's ocean–atmosphere–terrestrial system are phase locked to decadal and interdecadal signals in the Sun's irradiance. They have shown the existence of temperature variations amounting to a few hundredths of a degree in all the major ocean basins and also that these variations are of the magnitude expected as a response to the 11-year TSI variations. They also strongly emphasized that the amplitude of the observed decadal SST response is 2 to 3 times that expected from the transient Stefan–Boltzmann radiation balance. SST are probably better indicators of the global temperature variations than land or air temperatures since the first ones are less subject to regional variations and, furthermore, oceans cover the 70% of the Earth's surface.

Perhaps the most compelling Sun–climate relationship is the correlation between surface temperatures and solar activity for the last 1000 years presented by Eddy (1976). The data published by Eddy constitute a strong argument for the reality of the Grand Maximum, or the Spörer and Maunder minimums, which coincided with warm or cold periods, respectively. The high correlation between north hemisphere summer surface temperature anomalies and reconstructed TSI from 1610 (or 1700) to the present (Lean et al., 1995; Solanki and Fligge, 1999), lead to the conclusion that solar variability is a factor that should be taken

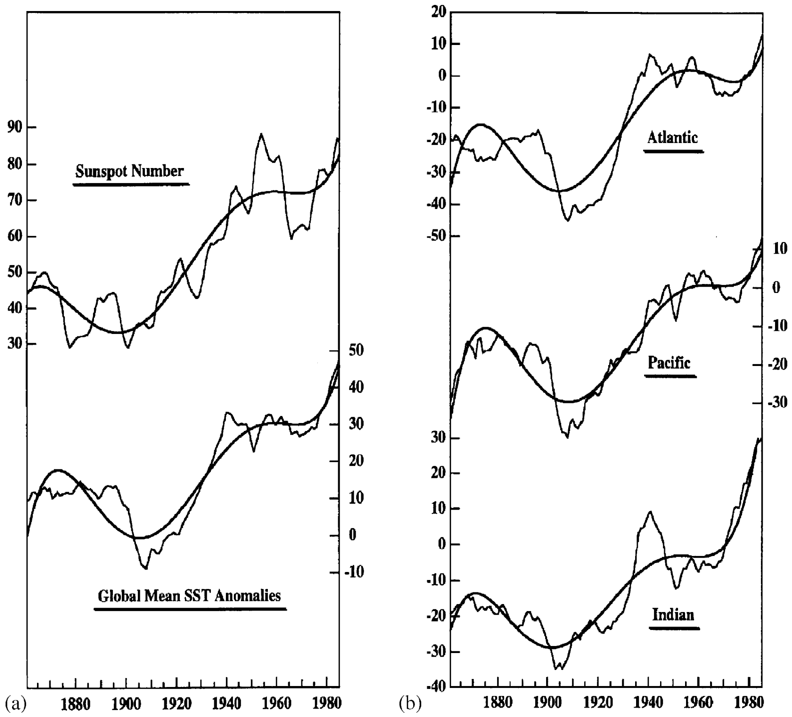

Fig. 5. Elevan-year running mean numbers and departures of sea-surface temperatures (in hundredths of a degree Celsius) from the long-term mean (adapted from Reid, 1999).

into account in the assessment of past and/or future climate change. These reconstruction efforts were able to show that the larger global temperature variations occurring on time scales longer than that of the 11-year cycle in the past could have been caused by larger variations of the TSI. It seems that the long-term average level of solar activity has a positive trend since the Little Ice Age, and the global temperature record seems to have varied roughly in step with the average level of solar activity. Recently, from data of Bottomley et al. (1990), it was shown that 11 year running mean sunspot numbers and departures of SST from the long-term average parallel each other and the same do SST of all three major ocean basins (i.e. Atlantic, Pacific and Indian) (Reid, 1999) (Fig. 5). Furthermore, it is interesting to notice in Fig. 5 that long-term variations shown by the curves, which are the result of least-squares polynomial fits, have almost identical shapes with minima in the early 20th century and in the 1970s. The temperature fluctuations both global and in all three major ocean basins indicate that they are most probably due to an external forcing mechanism and not be the result of the chaotic behavior of the climate system itself.

In addition to the 11-year cycle longer term periodicities are also identified in temperature data for several locations. Thus, e.g., a 22-year periodicity has been found in central England (King et al., 1974) or in Omaha, Nebraska (Willet, 1974) temperatures. Cycles of 80 to 90 years, which are consistent with the Gleissberg solar cycle have also been reported, e.g. central England temperature (Burroughs, 1992).

For rainfall also positive, negative or non-existent correlations to the solar cycle variations have been reported depending on the geographical region or the time interval. At the beginning of this century, Clayton (1923) considering rainfall data from stations at different geographic latitudes and spanning the years 1860–1917 found that increased precipitation exists in the equatorial regions and decreased precipitation in the mid-latitudes during solar maximum. Polar regions may have increased precipitation. Considering seasonal rainfall variations Clayton pointed out that at continental, middle latitude stations winter rainfall is negatively correlated and summer rainfall positively correlated with the solar cycle. He found the inverse correlations for several coastal stations. Xanthakis (1973) investigated annual excess precipitation as a function of the 11-year cycle for 10°-wide latitudinal zones between 40° and 80°N. He found strong positive or negative correlations depending on the latitudinal and longitudinal bands considered and the time intervals.

Indirect indicators of rainfall such as droughts, snowfall, water level in lakes and river flooding are very often investigated. Perry (1994, 1995) examining hydrologic time series in selected regions in the western two-thirds of the

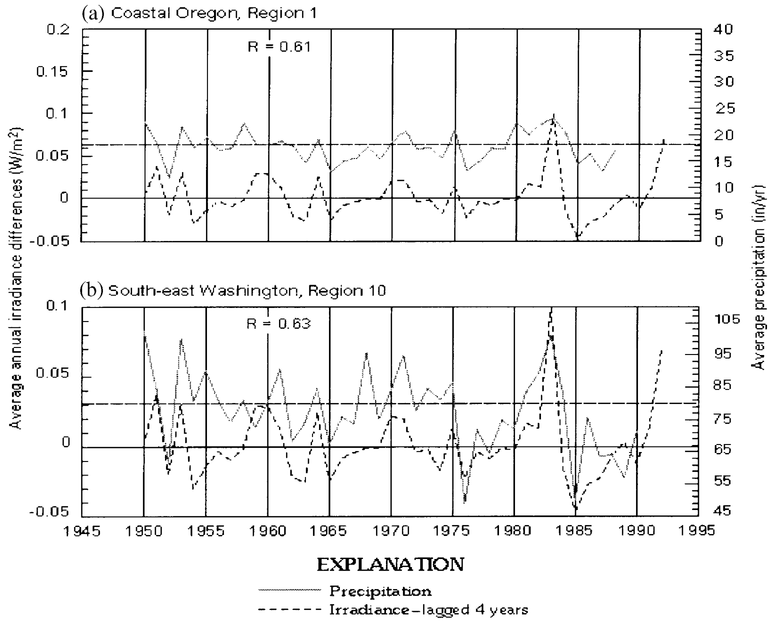

Fig. 6. Three-year running means of south-east Washington and coastal Oregon precipitation and solar irradiance variations lagged 4 years (Courtesy of C.A. Perry).

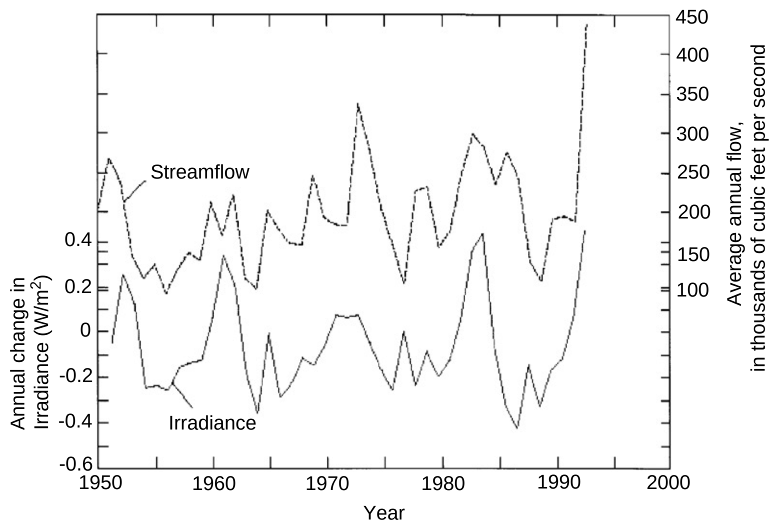

Fig. 7. Average flow of the Mississippi River at St. Louis, Missouri and solar irradiance variations lagged 5 years (Courtesy of C.A. Perry).

USA found a solar/hydroclimate association and pointed out for a tendency for hydroclimatic variables to lag solar irradiance variations by 4–5 years. Considering, e.g., regional annual average precipitation for 344 sites in the USA and solar irradiance variations, Perry obtained a high correlation in the Pacific Northwest with a lag time of 4 years (Fig. 6). He also found that the annual average flow of the Mississippi River basin parallels the solar irradiance variations and the best correlation is obtained with a 5-year lag time (Fig. 7). Perry proposed a mechanism for these time lags based on the different responses of oceans and land due to the thermal inertia of the oceans. According to this mechanism varying amounts of solar energy are absorbed by tropical oceans creating temperature anomalies that move with the ocean currents to locations where they can alter regional atmospheric moisture and pressure patterns, which affect regional precipitation and temperature and, consequently, the hydroclimatology of a region.

Apart from these rainfall and hydroclimate periodicities that show some kind of relationship with the 11-year solar cycle, longer periodicities are also reported. King (1975) suggested that the rainfall at Fortaleza, Brazil (4°S, 39°W) follows the 22-year solar cycle rather than the 11-year cycle. Closely related to rainfall amounts is also the occurrence of droughts. The most known drought regions in the USA are in the High Plains for which a marked tendency to occur in phase with the Hale cycle is found (Mitchell et al., 1979). A 84-year periodicity is reported for Beijing rainfall (Burroughs, 1992) and a 77-year for Nile floods (Hameed, 1984).

Among the most important variables influencing the Earth's radiation budget is cloudiness. Clouds may play an important role as they influence vertically integrated radiative properties of the atmosphere by cooling through reflection of incoming shortwave radiation and heating through trapping of outgoing longwave radiation. Dickinson (1975) first pointed out the possibility that processes by which the ionization effects due to galactic cosmic rays affect sulfate aerosol formation and cloud nucleation would lead to changes in the distribution of cloudiness. Tinsley and Deen (1991), (see also Tinsley, 1996) have developed a more complex idea, known as "electrofreezing" mechanism, according to which the ions created by cosmic rays make the atmosphere more electrically conductive. This should increase the flow of ionosphere-Earth current density in the global electric circuit. The atmospheric response is due to changes in the rate of ice production at the upper surfaces of clouds, caused by the changes in current density into the clouds. This may have consequences for cloud thickness and reflectivity to sunlight and for precipitation rates and latent heat transfer both of which are capable of affecting global atmospheric temperature. Recently a correlation between global average of cloud cover and the flux of cosmic rays incident in the atmosphere (Svensmark and Friis-Christensen, 1997; Svensmark, 1998) has been reported (Fig. 8). The cloud data used to obtain these results were compiled by a variety of sources. Serious criticisms against the quality of the International Satellite Cloud Climatology Project (ISCCP) cloud cover dataset and its suitability for studying the cosmic ray-cloud relation were pointed out by a number of authors (see e.g. Kernthaler et al., 1999; Jorgensen and Hansen, 2000). In a subsequent work Marsh and Svensmark (2000) have shown that there is a strong correlation between low liquid clouds (< 3 km) and galactic cosmic rays. They suggested that since low clouds are warm and comprise water droplets nucleated by aerosols, a link may be found through a galactic cosmic rays (GCR) influence on the atmospheric aerosol distribution. If an increase in GCR can lead to increases in aerosol then this could explain the positive correlation between GCR and low cloud top temperatures over a large fraction of the globe. Here again serious criticisms exist against the

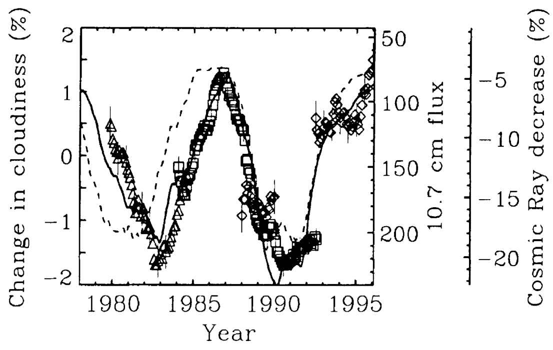

Fig. 8. Composite figure showing changes in the Earth's total cloud cover for four cloud data sets obtained from satellite observations vs. cosmic ray fluxes from Climax (solid line, normalized to May 1965) and 10.7 cm solar flux (dashed line) (adapted from Svensmark, 1998).

use of the ISCCP D2 dataset used by these authors. For example, Schweiger et al. (1999) have shown that the annual cycle of ISCCP D2 total cloud amount over the Arctic is at odds compared to surface observations and the TOVS polar pathfinder data set. It is claimed that this dataset does not properly distinguish between low and high clouds mainly because of the June 91s release of Mount Pinatubo aerosols.

The above presented various results concerning Sun–weather relationships are only a small number of the many others reported by numerous investigators. We tried to present different cases where positive, negative or no correlation at all is reported. This conflicting evidence gives a confusing and contradictory picture. It is apparent that before rejecting the whole field of solar influences on global change the identification of all relevant reasons should be considered. It is, e.g., argued that solar influences on the meteorological parameters are manifested differently in different geographical regions and in different time periods. This might explain the several breakdowns or reversals of correlations. It is also suggested that measurements at single sites are usually very noisy, while mean hemispheric and global observations present better results. It is necessary to unravel the competing effects of statistical methods used in the various analyses, different types of measurements, etc. in order to resolve the conflict evident in the various results. One must always have in mind that improper use of statistics can lead to false conclusions. Thus, for the detection of a solar induced signal in meteorological data not only careful selection of the data, but also careful statistical considerations must be performed. The use, e.g., of some modern spectral analysis techniques—like the wavelet analysis—useful for detecting cyclic variations and also breakdowns seems very appropriate. Classical Fourier analysis allows the study of a signal only in the frequency domain, whereas wavelet analysis yields information in both time and frequency domains. A classical paradigm of how different methods applied in the same set of data can yield inconsistent results is the following: Mann and Park (1994) analyzed a data set of global land and sea surface temperature anomalies with singular value decomposition and found significant decadal and interdecadal signals over northern hemisphere continents. Allen and Smith (1994) analyzed the same data set with Monte Carlo singular-spectrum analysis and found significant decadal signals in the equatorial Atlantic Ocean, but no significant interdecadal signals. Lau and Weng (1995), on the other hand, analyzing the global-average northern hemisphere portion of this data set applying the wavelet analysis found significant decadal and interdecadal signals. It is also worth noting that Dettinger et al. (1995) in contrast to Currie's findings failed to find a significant correlation between the temperature variation and the 11-year solar cycle using a singular-spectrum analysis.

4. Discussion

That the Sun has at least the potential to affect climate is indisputable. However, although the question of Sun–weather relationships has been studied for such a long time many people remain unconvinced of the reported correlative relationships. Their objections reside mainly on the following 3 facets: (a) despite the large number of striking correlations several breakdowns and reversals between solar activity parameters and meteorological/climatological responses abound in the literature; (b) the fluctuations of the solar energy output are relatively minor and their potential impacts on the Earth's low atmosphere may be easily masked from the intrinsic short-term variability of the weather system; (c) physical processes and/or linking mechanisms for this association are as yet unclear and (d) current GCM simulations do not attribute a special role to the solar input variations on the climate change of the 20th century.

However, before rejecting the empirical associations because we lack an explanation, there are some aspects of the subject that are fascinating and point to a closer examination. First of all, both the Sun and the climate, change continuously, over all time scales. Solar radiation emergent from the Sun's atmosphere exhibits significant variability throughout the entire spectrum from X-rays to radiowaves. On the other hand, the dynamical atmosphere of our planet is a complicated, chaotic system responding strongly to several varying internal factors, like volcanic eruptions, anthropogenic greenhouse gases, land changes (deforestation, albedo, etc.) and to external stimuli of varying solar radiation. There are, however, some variations of solar activity and of meteorological parameters that exhibit well-defined periodicities. Several of these periodicities are in phase. These parallelisms suggest, although do not prove, a causal connection between the Sun and the weather/climate and thus they deserve further consideration.

Furthermore, even a reversal or breakdown of a correlation could contain a physical explanation. For example, perhaps during low levels of activity sunspot blocking dominates over facular emission. It is also very often argued that the 0.1% decadal variation of the TSI is insufficient not thought to drive a significant direct response in the climate system. For this reason different amplification mechanisms have been sought. In this context the understanding of the detail physics behind the findings of White et al. (1997, 1998), i.e. that the amplitude of the observed decadal SST anomalies is 2 to 3 times that expected from the transient Stefan–Boltzmann response to changes in the Sun's irradiance, could provide the amplification mechanism needed to explain the observed internal decadal mode in the Earth's ocean–atmosphere system. A change in cloud cover, e.g., as reported by Marsh and Svensmark (2000) would also be a very effective amplifying mechanism for climate forcing. Other amplification mechanisms are mainly based on the large variations that take place in the UV, X-rays and energetic particle emissions, the role of which may be important in all the layers of our atmosphere and must be investigated. Especially, the 11-year large variations of the UV radiation are sought to cause significant changes in stratospheric chemistry and dynamics.

However, the question of the stratospheric influences on the troposphere remains debatable and somewhat controversial. Some GCM results have shown significant tropospheric effects resulting from variations in solar UV. Haigh (1996, 1999), e.g., using realistic solar-cycle variations of the UV radiation and ozone in a GCM simulation for January conditions found significant changes in the dynamics of the lower stratosphere and troposphere. During solar maximum, warming of the lower stratosphere gives rise to stronger easterly winds in the summer hemisphere and penetration of these winds into the upper troposphere cause the Hadley circulation to weaken and broaden. Shindell et al. (1999), on the other hand, although reported a similar effect found the Hadley circulation to increase. Following up on the problem of different and sometimes contradictory findings, which result from the use of the existing GCMs, it is reasonable to ask about the perfection of the current climate models. The issue of model validation has been reviewed recently by Soon et al. (2000). It seems that although numerical simulations are a useful tool in the evaluation and understanding of how the Earth's climate responds to a remarkable number of forcing agents, there is still much work to be done and much physics to be understood. Several effects leading to the refinement of the existing models must be included in order to obtain a comprehensive, ideal, global climate model, giving consistent and unambiguous results. In such a model, e.g., the formation of clouds and the formation and distribution of aerosols, changes in the solar spectral radiation including the more variable UV, vertical inhomogeneities, stratospheric–tropospheric coupling, ozone variations, global wind and ocean circulation patterns, must be introduced.

Of course, the significance of any correlation is difficult to assess as long as the physical mechanism has not been established and formulated. However, we have today some promising steps towards the physical connections that might link the variations seen on one with the variability occurring in the other. A serious basis for a linking mechanism is the one proposed by Tinsley and his colleagues (Tinsley and Deen, 1991; Tinsley and Heelis, 1993), where it is assumed that electrically induced changes in the microphysics of clouds (electrofreezing) enhance ice nucleation and formation of clouds, and can lead to large scale changes in tropospheric circulation. An answer to the problem of the connection between cosmic ray flux and cloud radiative forcing may be provided by a team of atmospheric, solar–terrestrial and particle physicists, which has joined together to construct the cosmics leaving outdoor droplets (CLOUD) experiment. A beam of charged particles from Centre Européenne pour la Recherche Nucléaire (CERNs) proton synchrotron will pass through a cloud chamber, where the atmosphere is to be represented realistically by moist air charged with condensation nuclei and trace condensable vapors and chilled by expansion. It is noteworthy, that a successful mechanism will improve our basic understanding of fundamental physical processes that influence our climate system.

Of course, part of the recent upsurge of interest in the evaluation of Sun-climate relationships is due to the fact that man-produced substances are believed to be altering our environment and this subject has raised the public and scientific concerns. An important issue in the global warming and ozone depletion matter is the extent to which solar variability can influence them. In that spirit the detection of cycles in both solar and climatic variables is important because it may provide an impetus to develop physical theories to better quantify the terrestrial relevance of the Sun's variability. Thus research in this area is important not only because it will lead to the improvement of our understanding of the climate system, but also for protecting life and environmental quality. It is noteworthy, that the influence of solar variable inputs on climate is only a side branch of the general field of climate modeling and should not be understood to suggest that anthropogenic changes are not important.

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