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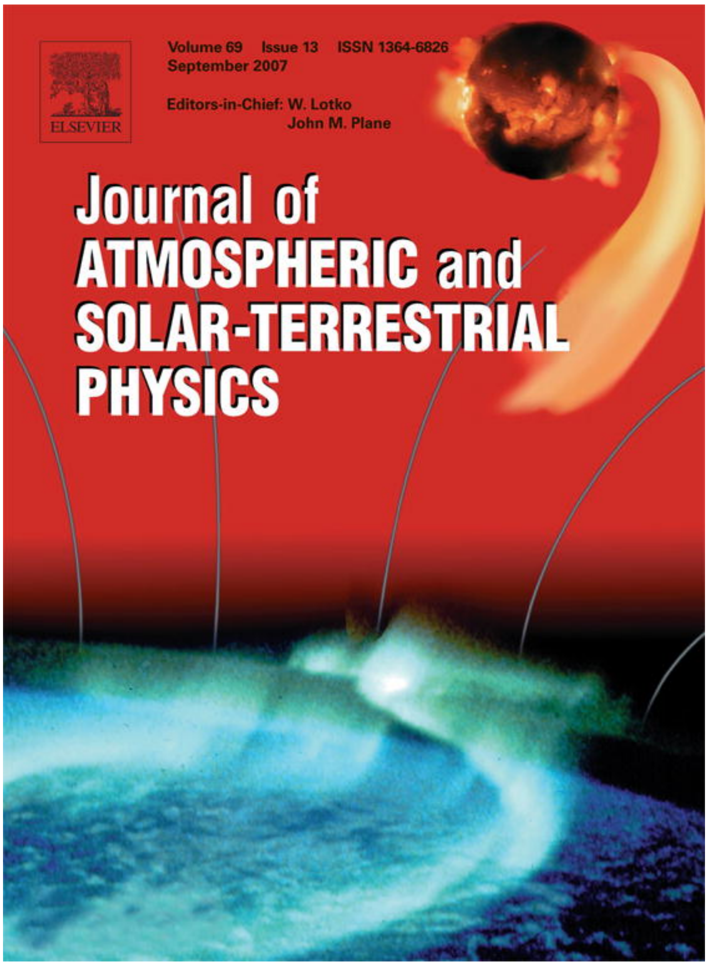

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Shortwave forcing of the Earth's climate: Modern and historical variations in the Sun's irradiance and the Earth's reflectance

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Abstract

Changes in the Earth's radiation budget are driven by changes in the balance between the thermal emission from the top of the atmosphere and the net sunlight absorbed. The shortwave radiation entering the climate system depends on the Sun's irradiance and the Earth's reflectance. Often, studies replace the net sunlight by proxy measures of solar irradiance, which is an oversimplification used in efforts to probe the Sun's role in past climate change. With new helioseismic data and new measures of the Earth's reflectance, we can usefully separate and constrain the relative roles of the net sunlight's two components, while probing the degree of their linkage. First, this is possible because helioseismic data provide the most precise measure ever of the solar cycle, which ultimately yields more profound physical limits on past irradiance variations. Since irradiance variations are apparently minimal, changes in the Earth's climate that seem to be associated with changes in the level of solar activity—the Maunder Minimum and the Little Ice age for example—would then seem to be due to terrestrial responses to more subtle changes in the Sun's spectrum of radiative output. This leads naturally to a linkage with terrestrial reflectance, the second component of the net sunlight, as the carrier of the terrestrial amplification of the Sun's varying output. Much progress has also been made in determining this difficult to measure, and not-so-well-known quantity. We review our understanding of these two closely linked, fundamental drivers of climate.

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Keywords: Albedo; Solar irradiance; Climate; Earthshine

1. Introduction

The Earth's climate is driven by the net sunlight deposited in the terrestrial atmosphere, and so, climate is critically sensitive to the solar irradiance and the Earth's albedo. These two quantities should be linked in any proxy effort to understand the role of a varying Sun in climate change. We need to understand why studies using solar activity as a proxy for net sunlight seem to have real value, even though we know that there are terrestrial imprints of the solar cycle when the implied changes in solar irradiance seem too weak to induce an imprint. These two climate fundamentals appear somehow linked, and it would seem that knowing the relative variations and connectivity of the irradiance and terrestrial reflectance is at the heart of understanding

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the Sun–Earth connection. We review data that shed light on these two fundamental parameters of climate change.

Considering the Earth to be in radiative equilibrium (i.e. power in equals power out), the planet's surface temperature, T_s, would be

$$T_s^4 = \frac{C}{4\sigma(1-g)}(1-A), \tag{1}$$

where C is the solar constant, A is the Bond albedo, σ is the Stephen–Boltzmann constant and g is the normalized greenhouse gas content of the Earth's atmosphere (Raval and Ramanathan, 1989). This means that the Bond albedo, together with solar irradiance and the greenhouse effect, directly control the Earth's temperature. Global warming would result if either A decreases or g or C increases.

The increasing greenhouse forcing due to an anthropogenic increase of atmospheric CO_2 over the past century has been treated in detail in scientific literature in recent years (Intergovernmental Panel on Climate Change or IPCC, 1995; IPCC, 2001; Houghton, 2002 and references therein). However, the variability in the Earth's net short-wavelength forcing could also play a critical role in the Earth's climate change.

Here, we first discuss the physical origin of the Sun's varying irradiance, and the implied limitations on variations over historical times. These times are a minuscule timestep in solar evolution with the Sun being about a sixth brighter than it was at the dawn of complex life on Earth about 600 million years ago. Our second, but closely connected topic is understanding the Earth's varying reflectivity of which recent variations, as measured from earthshine, may or may not be connected to solar variability (Pallé and Butler, 2000; Pallé et al., 2004a). If they are, they might provide the answer to the origin of the large solar influence on climate change implied by the times like the Maunder Minimum (Solanki and Fligge, 1999; Lean, 2000; Fröhlich, 2006, as well as references in all three papers). Nevertheless, regardless of the degree of connection between terrestrial climate change and solar variations, whether due to amplified/indirect changes in irradiance or solar activity, we will see that albedo variations are a much more plausible influence on the Earth's climate change than the direct effect of solar irradiance variations.

Several indirect mechanisms have been proposed in the literature to produce an amplification of the solar signal to account for the terrestrial imprint of the solar cycle, as well as longer term wanderings in climate with a solar signature. The putative mechanisms range from changes in EUV radiation tied to ozone (Haigh, 1994), to changes in cosmic rays and atmospheric ionization tied to cloud formation (Svensmark and Friis-Christensen, 1997), to changes in storm-tracks and atmospheric circulation (Bromage and Butler, 1991), or changes in the Earth's global electric circuit (Tinsley et al., 1989). Each has its strengths and weaknesses, but, so far the possible causal role of each mechanism remains ambiguous, at best.

2. The Sun's variable radiative output

The variations in solar irradiance have been carefully measured from space for more than two decades, see Fig. 1. Note that the two activity minima have the same irradiance. We shall see that this is a lower limit. From the figure, one can see that the solar irradiance is about 0.1% (0.3 W/m^2) greater at the solar magnetic activity maxima than at the minima. This variation is generally regarded as being climatologically small (for a review, see Lean, 1997 with more recent results from Solanki and Fligge, 1999; Lean, 2000; Fröhlich, 2006); still the physical origin of these changes has defied explanation.

The variation over the last two cycles has been small, and one is led to ask whether this defines a band to which solar luminosity is confined. On the other hand, many have assumed that larger changes have occurred over historical times (again see Lean, 1997). In particular, the sunspot number (or some effective geomagnetic measure) has been taken as a proxy for irradiance and it has been argued, for instance, that the Sun was as much as 0.5% 1.7 W/m^2) less irradiant during the deepest part of the Maunder Minimum (the time in the 17th century when a sunspot was rare), which coincided with a widespread low temperatures over Europe and other parts of the planet, a time known as 'The Little Ice Age'. Reconstructions of solar irradiance have used the measured terrestrial magnetic *aa* index variations over the last century as a proxy for irradiance from Lean et al. (1995). The *aa* index is an indirect measure of the solar wind and interplanetary magnetic field at Earth. Lean et al. (2002) used the correlation of the sunspot number and *aa* index over the past century to develop a proxy irradiance, which they extrapolated back further in

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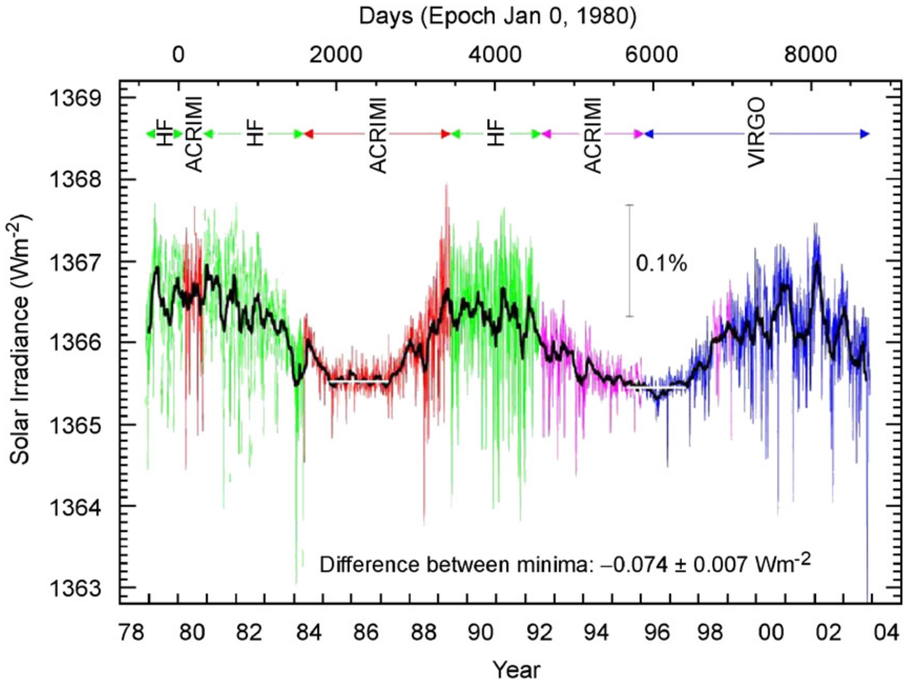

Fig. 1. Measured solar irradiance (in Watts per m^2) vs. time (Fröhlich, 2004, 2006). The two activity minima period centered in 1986 and 1996, are marked by flat white solid lines. Note that they both have the same irradiance level.

time using earlier sunspot numbers to develop a proxy irradiance back to 1600. Foukal et al. (2004) have put forward strong phenomenological arguments to criticize invoking such large drops in irradiance. In particular, they state that if the irradiance deduced from the *aa* index proxy were correct, then the Sun's web-likechromospheric magnetic network (an easily visible solar structure seen through a Ca II K filter) would have looked very different a century ago. However, there is a century of Mt. Wilson Ca II K data which reveal that the early 20th century network is indistinguishable from that of today. Reinforcing arguments against the proxy are put forward in the first half of this paper. These arguments use helioseismic data showing the physical origin of irradiance variations and place limits on possible irradiance variation.

A physical model consistent with the helioseismic data answers basic questions that have persisted, like whether the Sun is hotter or cooler at activity maximum when it is most irradiant. The competing models are ones in which the Sun is hotter at higher activity (e.g., Kuhn, 2000), and ones in which the Sun is cooler at higher activity (e.g., Spruit, 2000). In the latter picture, higher irradiance is explained by a corrugated surface rendering the Sun a more effective radiator.

3. The seismic probe of changing solar activity

The changing solar oscillation frequencies provide the most precise measures of cycle dependent changes in the Sun. Solar oscillations are the normal modes of vibration of the Sun. The real challenge is to make a useful connection between these global, seismic measures and characteristics of the dynamic Sun. We review and expand on the results of two recent papers by Dziembowski and Goode (2004 and 2005, hereafter DGA and DGB) that could solve the problem of the connection and allow one to place limits on solar irradiance over historical timescales, such as concluding that the Sun cannot have been dimmer over recent times than it is now at activity minimum. In our review, we study the seismic data to understand the origin of irradiance variations as detailed in DGA and DGB. Broadly, the frequency of solar oscillations increases with rising solar activity and falls with declining activity.

The rise of solar activity is characterized by increasing sunspot number, as well as increases in various related measures of solar magnetic fields. The rising field spawns a number of indirect responses, like changing flow, thermal and mass profiles near the surface of the Sun. Goldreich et al. (1991) were the first to try to calculate the frequency changes, and the frequency dependence, of

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solar p-mode oscillation frequencies with increasing solar activity. The solar p-modes are acoustic normal modes. Intuitively, one can imagine a frequency increase with an increasing field, due to the increase in magnetic pressure raising the local speed of sound near the surface where it is cooler and, thus, where the p-modes spend most of their time. Of course one can also imagine higher frequencies may result from an induced shrinking of the sound cavity and/or an isobaric warming of the cavity.

Goldreich et al. (1991) calculated changes in the superficial, random magnetic field, which they identified as the primary cause of the centroid frequency shifts. They were able to successfully describe the p-mode frequency changes in terms of the direct effect of the evolving near-surface, small scale field. Over the years more data have become available, which enabled Kuhn (1998) to criticize this attribution. He pointed out that Goldreich et al. (1991) require an rms, quadratic, near-surface magnetic growth from activity minimum to maximum, $\langle B^2 \rangle$, of around $(250\,\mathrm{G})^2$, while the observations of Lin (1995) and Lin and Rimmele (1999) show a significantly weaker increase of the mean surface field ($\langle B^2 \rangle \sim (70\,\mathrm{G})^2$). Instead, Kuhn sees a critical role for the variations of the Reynold's stresses (field induced changes in the convective flows, which are only appreciable very near to the solar surface), or turbulent pressure, through the solar cycle. The turbulent pressure is about 10% of thetotal pressure at the photosphere, but is a negligible fraction at 2 Mm depth, and therefore has no dynamical effect beneath a depth of about 1 Mm. The same can be said for the corresponding changes in the thermal structure.

Clearly, we have been lacking a basic understanding of how the frequency changes arise, and so, have not been able to understand the origin of the aforementioned dynamical changes in the Sun through the activity cycle. Lacking a clear understanding of the origin of oscillation changes and their relation to dynamical changes in the solar output over the solar cycle, we are unable to place any limits on variations of the Sun's output, and this has left an open path to various proxies for irradiance. However, the seismic data from SOHO/MDI (SOlar and Heliospheric Observatory/Michelson Doppler Imager) satellite now have a rich complement of f-mode oscillation data to complement their p-mode data, and the data enabled DGA and DGB to resolve the aforementioned ambiguities. The f-modes are the eigenmodes of the Sun having no radial null points and these modes are asymptotically surface waves.

3.1. Spherically symmetrical changes in oscillation frequencies over a solar cycle

Libbrecht and Woodard (1990), who first determined the activity related p-mode frequency shift for modes over a broad range of angular degrees, ℓ, noted that most of the frequency dependence of the shift is described by the inverse of the mode inertia, $I_{\ell n}$, which they called mode mass (the solar density weighted integral of the probability density of the mode). Here we follow DGA and DGB, and references therein, to express the frequency shifts for p-modes and f-modes in the form

$$\Delta\bar{v}_{\ell n} = \frac{\gamma_{\ell n}}{\tilde{I}_{\ell n}}, \qquad (2)$$

where $\tilde{I}_{\ell n}$ is dimensionless mode inertia and the γ's are the near-surface perturbation due to the effect of solar activity. Asymptotically, f-modes are normal-mode, surface waves. The SOHO/MDI p-mode data extend up to $\ell = 200$ and cover a frequency, v, range of $1.1 - 4.5\,\mathrm{mHz}$. For more details, see DGA and DGB, who treated the f-modes separately because even in the outer layers these modes have vastly different properties than those of p-modes at the same frequency, hence we cannot expect the same $\gamma(v)$ dependence for both types of modes. The kernels for calculating γ's resulting from changes in the magnetic field, turbulent pressure, and temperature as calculated in DGA, are indeed very different for these two types of modes. Both types of $\gamma(v)$-dependence are helioseismic probes of the averaged changes over spherical surfaces in the subphotospheric layers during the activity cycle. However, they are independent probes.

The plots in Fig. 2 show the frequency averaged γ's, against date, for all available data sets from SOHO/MDI measurements calculated from frequency differences relative to the first set from activity minimum of cycle 23. The similarity in the behavior seen in the three panels might suggest that the source of the changes is the same for both f- and p-modes but, as we shall see, this is not true.

3.2. The frequency dependence of the f- and p-modes

The frequency dependence yields a critical clue to the physics of frequency change. Fig. 3 shows

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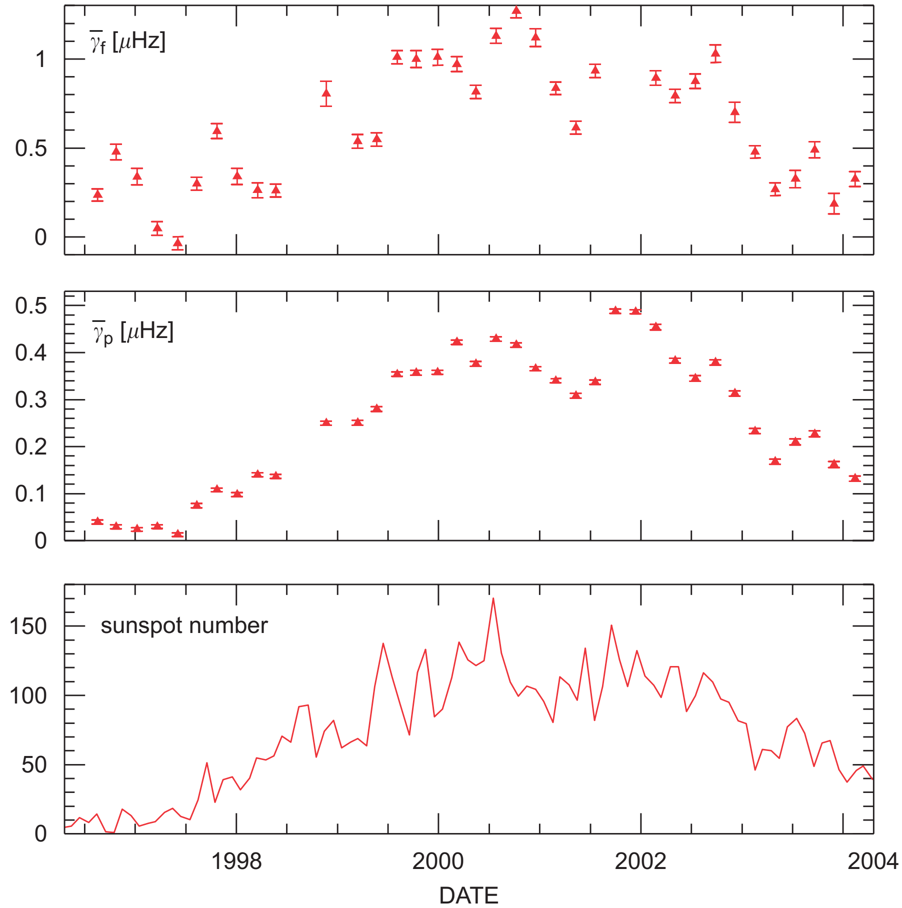

Fig. 2. The values of the averaged γ's from DGB, which are global helioseismic measure of solar activity, are derived from 38 SOHO/MDI data sets compared to sunspot number (lower panel)for Solar Cycle 23. The p-mode γ's (middle panel) very closely track the sunspot number. The behavior of the f-modes (upper panel) is similar, but the values are less significant. The larger errors are mainly a consequence of an order of magnitude fewer f-modes.

individual $\gamma_{\ell n}$ values with their individual 1σ error bars, as well as the Legendre polynomial fit to the ensemble. The robust feature of the $\gamma(\nu)$ dependence for the f-modes is the gradual decrease of γ between $\nu = 1.37$ and 1.74 mHz. The robust feature of the $\gamma(\nu)$-dependence for the p-modes is the steady increase beyond $\nu = 2$ mHz. For both p- and f-modes, higher frequency means a stronger sampling of the outermost layers. Therefore, the opposing behavior of the two types of modes at the high frequency end of the spectrum is a critical clue implying that different physical effects are responsible for the frequency increase correlated with rising solar activity.

The question is what dynamics are in play to cause the opposite behaviors for the f- and p-modes with increasing frequency?

The SOHO/MDI f-modes lie immediately beneath a 2–3 Mm depth in the Sun, above which the frequency changes in the p-modes are driven. Only the dynamical effect of the rise of the magnetic field can act at these depths to change the γ's, and thus, are the only possible explanation for the observed f-mode frequency behavior in Fig. 3. DGB found that the f-mode frequency increase between solar minimum and maximum requires an average field increase of some 0.5–0.7 kG at a depth of about 5 Mm and a much smaller increase closer to the photosphere. Thus, the required field growth at the photosphere is consistent with observations.

Changes in the magnetic fields inferred from f-mode data have only a very small effect on p-mode frequencies. This suggests that the averaged dynamical effect of the magnetic field rise at a depth of a few Mm is responsible for an appreciable part of the frequency increase of low frequency p-modes. However, DGB stressed that, as we may see in Fig. 3, the significance of $\gamma(\nu)$ in this part of the p-mode spectrum is questionable. In any case, most

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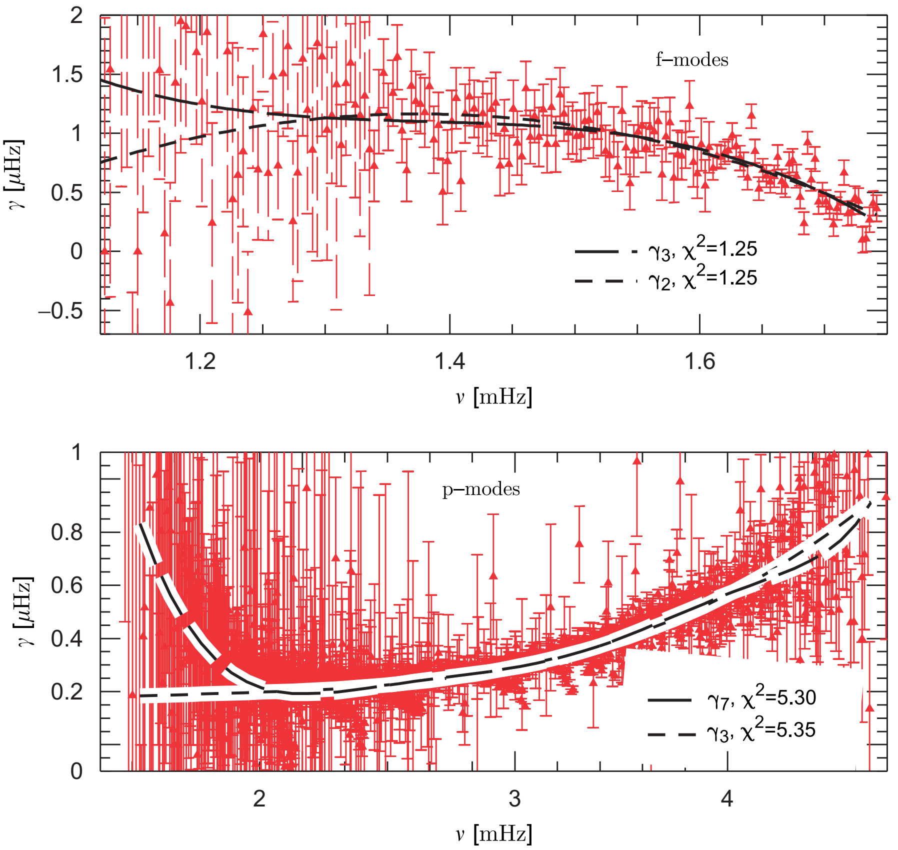

Fig. 3. Frequency dependence of the γ's derived from the frequency difference between averaged frequencies from solar maximum phase (2000.4–2002.4) and the minimum phase (1996.3–1997.3). The lines represent fits using truncated Legendre polynomial series. Subscripts at γ's denote the order at which the series was truncated. The quoted values of χ^2 are calculated per degree of freedom.

of the p-mode frequency increase with rising activity requires a different explanation.

The high frequency end of the $\gamma(\nu)$ dependence, which is the truly significant part, may be explained only by invoking an effect acting preferentially very close to the Sun's photosphere. The dynamical effect of the growing magnetic field is excluded by measurements of the averaged photospheric field and by the f-mode data. What remains to be considered is an inhibiting effect of the field on convection leading to a lower turbulent velocity and temperature and shrinking Sun in the outermost layers. The three effects are expected to be significant only very close to the photosphere. The question to answer is how much of a reduction is required to account for the observed frequency changes.

The turbulent pressure helps support the solar radius, and the effect of rising activity is to block the flows near the surface, which shrinks the radius and leads to higher frequencies in the normal modes. The blocking of the heat flow also shrinks the radius and leads to higher frequencies because the effect of the shrinking overcompensates for the frequency reduction caused by cooler temperatures. Both the changing turbulent pressure and heat flow alter the thermal structure, but the thermally induced changes in frequency are secondary to the changes induced by shrinkage.

DGB first considered the effect of lowering the turbulent velocity very close to the surface. In fact, only the vertical component of it matters because the horizontal components hardly affect p-mode frequencies. They showed a less than 1.3% decrease in the rms vertical component of the turbulent velocity very close to the surface was sufficient to account for the evolution of the p-mode frequencies during the rise from activity minimum to maximum. This small change is not in conflict with observations.

According to the estimate by DGB, a 1% decrease in the convective velocity is associated with a relative temperature decrease ranging from roughly 1×10^{-3} at a depth of 1 Mm to roughly

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3×10^{-3} at the photosphere. The cooling causes a shrinking (about 1 km from activity minimum to maximum), which over compensates the frequency decreases caused by cooling. The net of these two values are about one half of what is needed to account for the p-mode frequency increase solely by the temperature effect. Therefore, the required velocity reduction is smaller. Thus, DGB argued that the inhibiting effect of the magnetic field on convection is the cause of p-mode frequency increase correlated with increasing activity.

3.3. Limits on variations of solar irradiance

From the helioseismic data, we now have an internally consistent picture of the origin of frequency changes that implies a Sun that is coolest at activity maximum when it is most irradiant. DGB also calculated the changes in the radius of the Sun from minimum to maximum and find that the implied contraction of the outermost layers is about 1 km. Goode and Dziembowski (2003) used the same seismic data to determine the shape changes in the Sun with rising activity. They included shape asymmetries from P_2–P_{40} from the seismic data and found each coefficient was essentially zero at activity minimum and rose in precise spatial correlation with rising surface activity, as measured using Ca II K data from Big Bear Solar Observatory. From this one can conclude that there is a rising corrugation of the solar surface due to rising activity. A cooler and smaller active Sun, whose increased irradiance is totally due to activity induced corrugation, has been advocated for years by Spruit (e.g. 1991, 2000). The valleys of the corrugations may be viewed as functioning like spicules. This interpretation has been recently observationally verified by Berger et al. (2007) using the new Swedish Solar Telescope. They directly observed the corrugations.

We note that various authors have proposed that the Sun's oblateness has changed more than found from the seismic data. One example of a large diameter change over a solar cycle were reported by Nöel (1997) from his measurements with the astrolabe of Santiago. He finds the difference between the 1991 (previous maximum) and 1996 (previous minimum) radii exceeds 700 km. Such a result would be significant for irradiance. Ground-based measurements are notoriously subject to atmospheric problems. Less solid still are proxy data used to argue for large changes in solar diameter (see Ribes et al., 1987; Ribes and Nesme-Ribes, 1993) and solar surface properties between the Maunder Minimum and now. However, the seismic result of Dziembowski et al. (2001) implied a photospheric radius shrinkage of 2–3 km/year with rising activity. This rate is not fundamentally inconsistent with the growth rate of about 5.9 ± 0.7 km/y determined by Emilio et al. (2000) from the direct radius measurements based on SOHO/MDI intensity data. Both of the latter results, however, imply a negligible contribution of the radius change to the solar irradiance variations. The most complete and reliable ground-based data are from the High Altitude Observatory Solar Diameter Monitor (Brown and Christensen-Dalsgaard, 1998), and they are consistent with the space data and seismic data. Such small values are consistent with the picture of rising corrugation being associated with increasing irradiance.

We conclude that the Sun cannot have been any dimmer, on the time steps of solar evolution, than it is now at activity minimum. On the other hand, ever greater solar activity would imply an ever larger mean solar irradiance. This means that, in epochs of minimal solar activity, the solar irradiance is even more constant than it is at the present time.

Thus, to account for the apparent solar-climate link to times like the Maunder Minimum, one must invoke a more subtle linking between the full spectrum of the Sun's output and many possible terrestrial links. This is obviously more complicated than invoking a change in solar irradiance, because the Sun's output is better understood than the terrestrial response. We use Eq. (1) to argue that the Earth's reflectance is the other climate parameter contributing to the net sunlight reaching Earth, so albedo is the logical global quantity to begin any search for an amplified terrestrial response to a changing Sun.

4. The Earth's albedo

In the first half of this paper, we have reviewed the possible changes in solar irradiance on time-scales shorter than that of solar evolution. In the second half, we shall concentrate on the Earth's global reflectance, i.e. on what fraction of the available energy from the Sun is actually entering the climate system.

4.1. The earthshine albedo observations

The earthshine, or ashen light, is sunlight reflected from the Earth and retroflected from the

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Moon back to the nighttime Earth. Global scale albedo can be determined at any moment by measuring the earthshine's intensity. Uninterrupted earthshine data from Big Bear Solar Observatory span from November 1998 to the present, with some more sporadic measurements during 1994 and 1995.

In Pallé et al. (2004b, 2006), earthshine measurements of the Earth's reflectance from 1999 through mid-2001 were correlated with satellite observations of global cloud properties to construct from the latter a proxy measure of the Earth's global shortwave reflectance. Cloud data were taken from the International Satellite Cloud Climatology Project (ISCCP).

The reconstructed annual mean albedo anomaly, from 1984–2004 is plotted in Fig. 4. The most evident trend in Fig. 4 is the fairly steady decrease in the reconstructed reflectance from the late 1980s to the late 1990s. Support for this trend comes from BBSO earthshine observations during 73 nights of 1994 and 1995. These data were not used in the regression, but the roughly 2% increase in the Earth's reflectance that they imply relative to 1999–2001 is in good agreement with the reconstruction from ISCCP data. The observational data from 1999 into 2004 indicate a strengthening of the mild reversal that began in 1998.

The decrease in the Earth's reflectance from 1984 to 2000 suggested by Fig. 4, translates into a Bond albedo decrease of 0.02 (out of the nominal value of about 0.30) or an additional global shortwave forcing of 6.8 W/m^2. To put that in perspective, the latest IPCC report (IPCC, 2001) argues for a 2.4 W/m^2 increase in CO_2 longwave forcing since 1850.

The temporal variations in the albedo are closely associated with changes in the cloud cover. In the upper panel of Fig. 5, we see the changes in the cloud cover over the two decades of ISCCP data, which crudely tracks the evolving albedo of Fig. 5. One might think that the increase in cloud cover since 2000 might force a cooling, but the lower panel of Fig. 5 reveals that this is not necessarily true. In the lower panel, low and mid + high lying cloud evolution are separated and binned, and one can see that there is no particular change in the early bins, but the one covering 2000–2004 show an increase in mid + high lying clouds, while low lying clouds decline. Since low clouds cool (reflection dominates) and mid + high clouds warm (heat trapping dominates), it could be that a cloudier Earth warms (or cools), but the sign of the change is not obvious. This presents a clear warning against predicting energy balance change by considering one climate parameter in isolation. It is also worth noting that

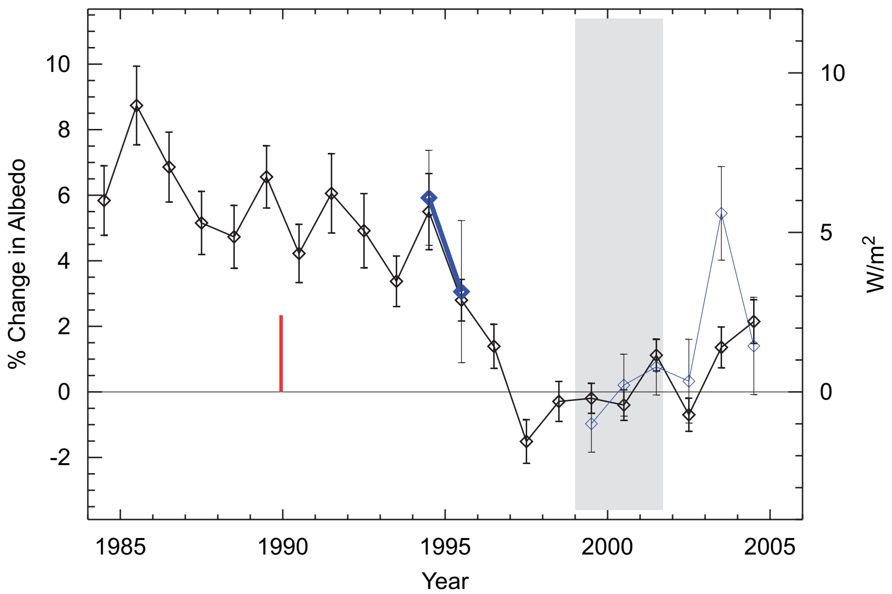

Fig. 4. Globally averaged reconstruction (black) of albedo anomalies from ISCCP cloud amount, optical thickness, and surface reflectance (following Pallé et al., 2006). In blue are the observed earthshine albedo anomalies. All observations agree with the reconstruction to within the 1σ uncertainties, except for the year with sparse ES data, 2003. The shaded region 1999 through mid-2001 was used to calibrate the reconstruction and is the reference against which anomalies are defined. The right hand vertical scale shows the deficit in SW forcing relative to 1999–2001.

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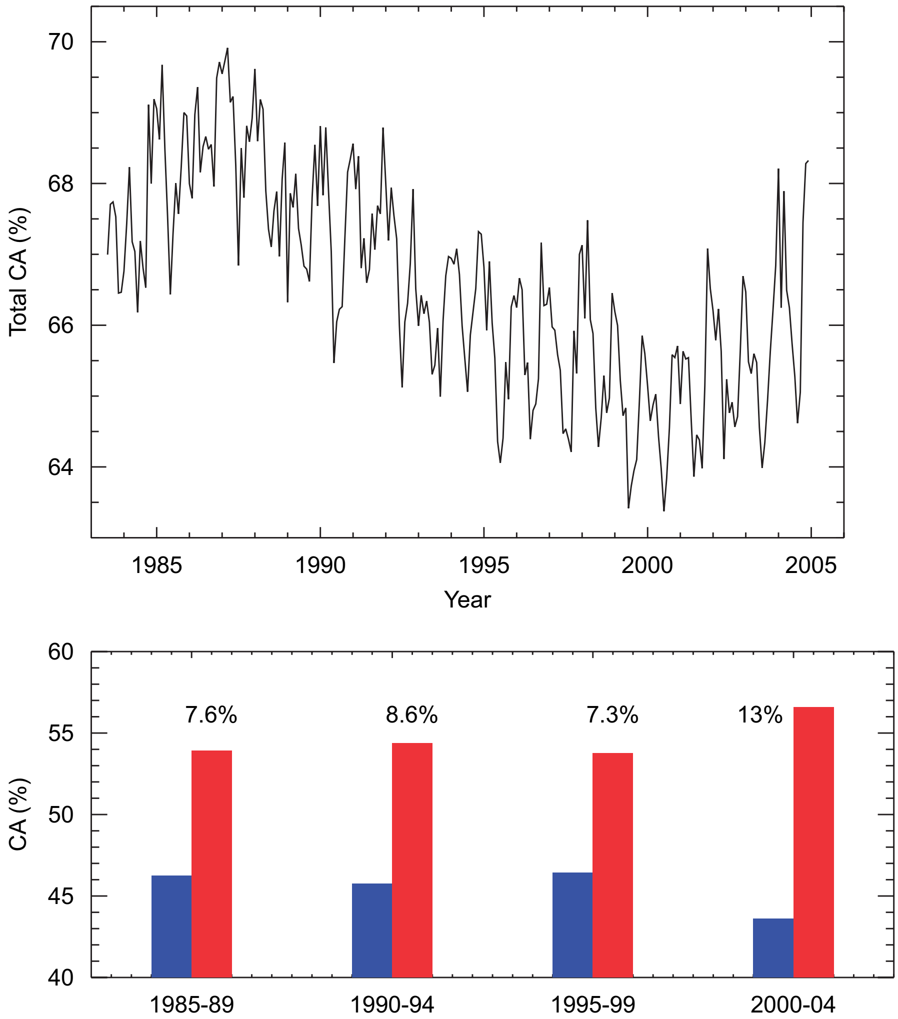

Fig. 5. Upper Panel: Globally-averaged monthly mean total cloud amount from the ISCCP data. The overall decrease in cloud amount from 1985 to 2000 is about 4–5% with a recovery of about 2–3% from 2000 to 2004. Lower Panel: Globally-averaged 5-year mean low (blue) and mid + high (red) cloud amounts. The difference in percent between low and mid + high cloud amounts is also given on top of each of the four 5-year intervals. Note the near doubling of these difference over the 2000–2004 period with respect to the previous means.

ocean heat storage data (including depths from 0 to 750 m) point to a global mean cooling in both 2004 and 2005 (Lyman et al., 2006). This is significant because the oceans are the Earth's primary heat reservoir.

4.2. Other albedo measurements and proxies

Recently other studies using independent techniques have also reported large decadal changes in the Earth's radiation budget. The cloud/reflectance changes deduced from earthshine observations over the past two decades, are consistent with the large trends over the tropical regions in both (increasing) outgoing longwave radiation and (decreasing) reflected SW reported from satellite data (Wielicki et al., 2002; Wang et al., 2002). The decrease in albedo, however, is about half that observed by Pallé et al. (2004b) and by Wild et al. (2005) at global scales.

Wild et al. (2005) have brought up-to-date the Global Energy Balance Archive (GEBA) long-term series of ground-based measurements of the solar radiation incident to the Earth's surface. These data, together with newly available surface observations from Baseline Surface Radiation Network (BSRN) from 1990 till date, show that the decline in solar radiation on land surfaces seen in earlier data starting in the 1960s (and earlier with less reliability) and known as "global dimming", disappears in the 1990s. Instead, a brightening is observed since the late 1980s. Over the period covered by currently

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available BSRN data (1992–2001), the overall change observed at eight individual sites, amounts to 6.6 W/m^2. Although constructing a global mean from only eight stations is a very crude approximation, the changes measured at the surface within the BSRN network are quantitatively in line with the change in the net solar fluxes at the top of the atmosphere estimated by the earthshine method (6.8 W/m^2).

Casadio et al. (2005) have studied the temperature evolution of the instruments on-board the Global Ozone Monitoring Experiment (GOME). The long-term evolution of the on-board temperatures (proxies for the amount of shortwave sunlight reflected to space) are characterized by a small variability throughout the period 1998–2000, and a progressive increase afterwards. This evolution is also consistent with the behavior of the Earth's reflectivity in the visible range as determined from the earthshine.

Clouds could be responding to secular climate change (global warming), providing a strong positive SW feedback (although a simultaneous negative OLR feedback would be expected). However, natural variability in clouds is a much more plausible explanation given the size of the changes and the observed reversal in reflectance to an upward trend during 1999–2004.

5. Past changes in Earth's reflectance

There are no long-term records of the Earth's reflectance. The most important historical program of earthshine measurements was carried out by Danjon (1928, 1954) and Dubois (1942, 1947) from a number of sites in France. Danjon's differential measurements removed many of the uncertainties associated with varying atmospheric absorption and the solar constant, allowing him to achieve his estimated uncertainty of roughly 5%, ignoring his appreciable systematic error from an incorrect determination of the Moon's reflectivity. Modern earthshine measurements are about an order of magnitude more precise than his estimates, in large part because we have better measurement technologies. Therefore, the historical earthshine record is too imprecise to be used to retrieve significant information for climate change. Earth's radiation budget observations from the satellite record are also available only since the early 1980s.

Thus, to explore past changes in the Earth's reflectance one has to rely on proxy measurements. It is clear that the albedo is tightly related to cloud amount and properties, and there are clear indications that these have changed in the past (Pallé and Butler, 2002). During the period 1960–1990 global compilations from ground-based radiometer data (Liepert, 2002) suggest that there has been a decrease in solar irradiance reaching the ground (increase in albedo). From the analysis of sunshine records, this 'global dimming' can be extended back in time to the beginning of the 20th century (Stanhill and Cohen, 2001; Pallé and Butler, 2001), but it is difficult to quantify on a global scale due to the local nature of the few available data sets. Romanou et al. (2007) point to aerosols as the source of varying terrestrial surface irradiance. In summary, and with a large degree of uncertainty, reflectance seems to have increased from 1900 (or at least 1960s) to the mid-1980s, then declined through the late 1990s, and to have increased again during 2000–2004. This late increase however is still a matter of dispute (Wielicki et al., 2005; Pallé et al., 2006). Before 1900, we have no information on what the albedo/cloud changes might have been, although sunshine data are available from some sites dating from the 1880s.

5.1. *Comparison albedo/irradiance variations: a solar-albedo link?*

There are many terrestrial signature with an $\frac{11}{22}$ periodicity that by default, one would have to associate with cycle the solar magnetic polarity cycle. Perhaps one of the most impressive is the detection of a wandering, near 11-year periodicity in the dust in Greenland ice core data going back more than 100,000 years (Ram and Stoltz, 1999). Stevens and North (1996) have used ocean surface temperature data to suggest a subtle variation, with a 11 year period, since 1850. With such signatures in mind, it is crucial to determine whether or not the Earth's reflectance varies with solar activity, since irradiance changes alone would seem to be too small to leave a terrestrial footprint. In fact, the origin of imprints of the $\frac{11}{22}$ year solar cycle on Earth remain a deep mystery.

A major change in albedo occurred between the early earthshine measurements and the more recent ones (Fig. 4). For the 1994/1995 period, Pallé et al. (2003) obtained a mean albedo of 0.310 ± 0.004, while for the more recent period, 1999/2001, the albedo is 0.295 ± 0.002 (with a 0.6% precision in the determination). The combined difference in the

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mean A between the former and latter periods is of -0.015 ± 0.005, assuming the 1994/1995 and 1999/2001 uncertainties are independent. This corresponds to a $5\% \pm 1.7\%$ decrease in the albedo between the two periods. Here, we take the period 1999–2001 because these are the 3 years around the solar activity maximum (2000). The years 1994/95 were near activity minimum, but also in the midst of an El Niño event, while during the years 1999/01 a La Niña event was in progress (www.cdc.noaa.gov). A weak argument against El Niño events being responsible for our higher albedo during the period 1994/1995 is that our albedo reconstruction does not show a higher albedo during the period centered on 1998, when the strongest El Niño event on record took place. In fact, the ISCCP-derived albedo for 1998 is lower than for 1994 or 1995. This argument is weak because a peak in the reconstruction would derive from the indirect effect of El Niño on clouds, since therewas no event during the period used in determining the coefficients of the albedo reconstruction. Further, the bump in albedo in 1994/1995 cannot be attributed to the Mt. Pinatubo eruption of 1991 because the dust had largely settled, as reflected in other cloud properties.

To see the relative roles of irradiance and reflectance changes over the period 1994–2001, we define the power into ($P_{\rm in}$) Earth by

$$P_{\rm in} = C\pi R_{\rm e}^2(1 - A), \quad (3)$$

where $R_{\rm e}$ is the Earth's radius, to find that

$$\frac{\delta P_{\rm in}}{P_{\rm in}} = \frac{\delta C}{C} - \frac{\delta A}{1 - A}, \quad (4)$$

where $\delta C/C \sim 0.001$. Our observations of the earthshine take the ratio of the earthshine to moonshine, so they are insensitive to variations in the solar irradiance. The $5\% \pm 2\%$ change in our observed reflectance translates to $-\delta A/1 - A \sim 0.021 \pm 0.007$. Negative variations in albedo have an effect of the same sign as a positive variation in irradiance. Thus, solar and terrestrial changes are in phase, and contribute to a greater power going into the Earth at activity maximum. However, the effect of the albedo is more than an order of magnitude greater. In other words, the solar irradiance changes over this time period are dwarfed by the concurrent changes in Earth's reflectance.

Relating these changes in radiative flux to changes in the Earth's surface temperature is problematic. We focus here on changes in the Earth's effective temperature (the temperature of the blackbody that would emit the same energy per unit area). In that case, we have the power out of ($P_{\rm out}$) Earth being

$$P_{\rm out} = 4\pi R_{\rm e}^2 \sigma \varepsilon T_{\rm e}^4, \quad (5)$$

with ε being the atmospheric emissivity, σ being the Stefan–Boltzmann constant and $T_{\rm e}^4$ being the Earth's effective temperature. And combining a variation applied to Eq. (5) with Eq. (4),

$$\frac{\delta P_{\rm in}}{P_{\rm in}} = \frac{4\delta T_{\rm e}}{T_{\rm e}}, \quad (6)$$

under the assumption the ε in Eq. (5) does not change, and taking $T_{\rm e} \approx 255\,{\rm K}$, we find a temperature perturbation due to the Sun of about 0.1 K from the irradiance changes, but about 1 K from the albedo. The temperature changes here simply relate to changes in the Earth's effective temperature, not changes in the temperature of the Earth's surface.

However, over the full period 1984–2003 shown in Figs. 4 and 5, as mentioned above there are clear solar cycle-like variations in the albedo. However, the phasing is different. Thus, the preceding discussion cannot be used to argue for a solar cycle dependence. On the other hand, it is also difficult to dismiss the possibility of a solar–albedo link. The Earth's albedo record is too short and one relies on too many proxies to investigate in detail such a possibility. Especially if other natural or man-made climate variations are superimposed on the modern reflectance record.

Our purpose here was to illustrate the possibilities of a Sun–albedo link. Reflectance changes like the ones observed during the past two decades, if maintained over longer time periods, are sufficient to explain climate episodes like the 'Little Ice Age' without the need for significant solar irradiance variations. Thus, continuing precise albedo observations over another solar cycle or two will be crucial to establish or not a solar–albedo link. Either way, apparent appreciable variations in the albedo bear study on their own merit.

6. Conclusions

In this paper we have reviewed the physical mechanisms behind solar irradiance variation, and we have reviewed how on the timescale of solar evolution, the Sun cannot have been any dimmer than it is at the most recent activity minima. We have also shown how concurrent changes in the

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Earth's reflectance can produce a much larger climate impact over relatively short time scales. Thus, a possible Sun–albedo link, would have the potential to produce large climate effects without the need for significant excursions in solar irradiance. These could provide an explanation for the apparently large climate response to apparently small solar changes, as well as how the $\frac{11}{22}$ year solar cycle is imprinted on Earth.

Regardless of its possible solar ties, we have seen how the Earth's large scale reflectance—and the short wavelength part of the Earth's radiation budget—is a much more variable climate parameter than previously thought and, thus, deserves to be studied in as much detail as changes in the Sun's output or changes in the Earth's atmospheric infrared emission produced by anthropogenic greenhouse gases. Long-term records of the Earth's reflectance will provide crucial input for general circulation climate models, and will significantly increase our ability to assess and predict climate change.

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