

III. Earthshine and the Earth's Albedo: Long-Term Variations in Reflectance

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ABSTRACT

Subject headings: Earth : albedo, global climate — Moon: reflection

Continuous observations of the earthshine have been carried out from Big Bear Solar Observatory since December 1998, with some more sporadic measurements made during the years 1994 and 1995. In this paper, we determine the annual albedos both from our observations and from simulations utilizing the ERBE scene model and various datasets for the cloud cover. With these, we look for inter-annual and longer-term changes in the earth's Bond albedo. We find that both our observations and simulations indicate that the albedo was significantly higher 1994-1995 than for the more recent period covering 1999-2001. However, the sizes of the changes seem somewhat discrepant.

Possible solar influences on the earth's Bond albedo are discussed to emphasize that our earthshine data are already sufficiently precise to detect, if they occur, any meaningful changes in the earth's reflectance. Still greater precision will occur as we expand our single site observations to a global network.

1. Introduction

It has been known for some time that the so-called solar constant varies. In particular, data from the Active Cavity Radiometer (ACRIM I) on board the Solar Maximum Mission have revealed that for the last two ~ 11 -year cycles, the solar irradiance is about 0.1% greater at activity maximum than activity minimum (Willson and Hudson 1988, 1991 and Fröhlich, 2000). The precise origin of the changing irradiance is usually attributed to a competition between two components of the sun's magnetic field – dark sunspots and bright faculae. However, the exact physical origin remains unknown. The latest results covering the twenty years of satellite observations of solar irradiance are shown in Figure 1 (Fröhlich, 2000). The conventional wisdom is that a 0.1% variation is several times too small to be climatologically significant over a solar cycle, so why are there terrestrial footprints of the solar cycle? It has also been argued that there may have been two to three times larger, sustained excursions in the recent past (Lean, 1997), like during the so-called little ice age when a sunspot was rare. Still, there is strong evidence from ice core data of a wandering solar cycle, with a period of ~ 11 years, going back more than 100,000 years (Ram and Stoltz 1999). If the 0.1% increase in the mean solar irradiance between the mid-1980's and 1990's were typical, it leads one to ask if it is the direct effect of varying solar magnetism on the irradiance that causes the dominant terrestrial signature of the solar cycle.

Instead an indirect mechanism may be amplifying the solar signal influence on the terrestrial climate. Several mechanisms have been proposed in the literature to produce this amplification, ranging from changes in EUV radiation tied to ozone (Haigh, 1994), to changes in storm-tracks and atmospheric circulation (Bromage and Butler, 1997), or changes in the earth's global electric circuit (Tinsley, 1989). However so far, the possible causal role of each mechanism remain ambiguous at best. Another mechanism that has received some attention in the past few years was proposed by Svensmark and Friis-Christensen (1997). They studied satellite cloud cover data from the International Satellite Cloud Climatology Project (ISCCP) and measured a 3-4% greater cloud cover at solar activity minimum. They argued that the source of the excess cloud cover is the relatively greater galactic cosmic radiation (GCR) at activity minimum which arises from the sun's

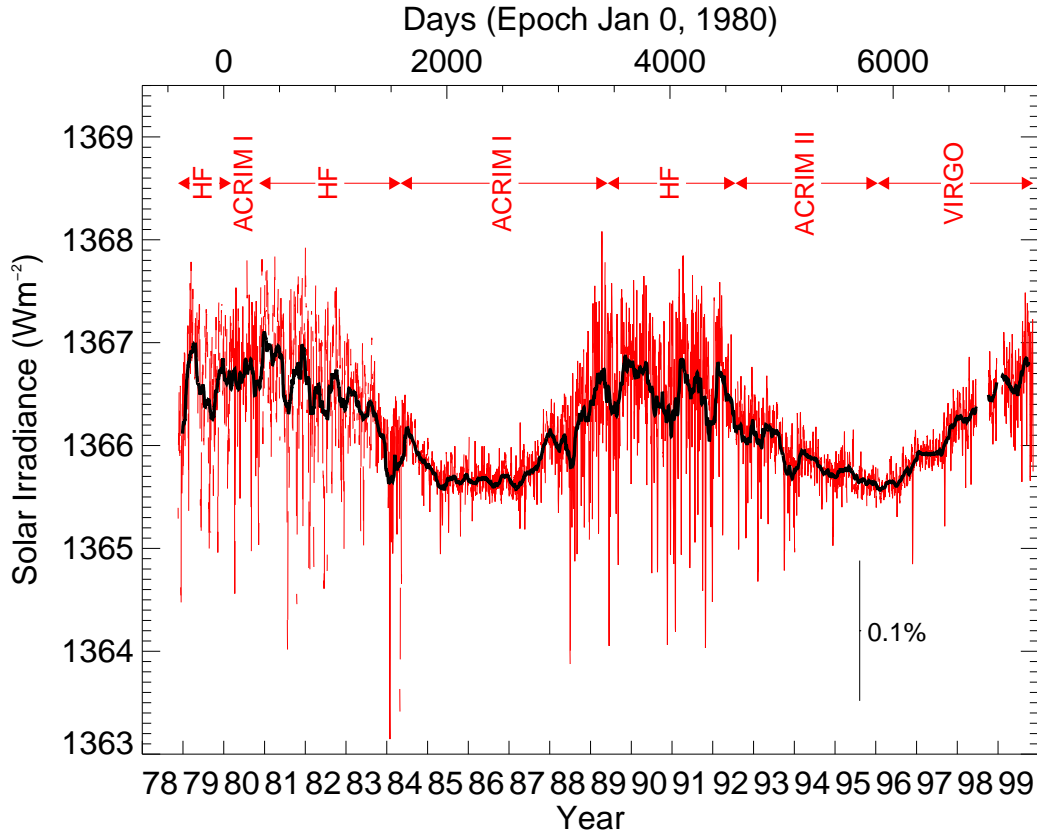


Fig. 1.— Measured solar irradiance (in watts per m²) vs. time (Fröhlich 2000)

magnetic field being weaker at activity minimum and, thereby, being less effective in shielding the earth from cosmic radiation. According to their argument, the relatively greater cosmic radiation creates relatively more ions, which somehow have a correspondingly greater cloud-seeding effect.

Subsequent ISCCP satellite data showed that the correlation between total cloudiness and GCR is not maintained over longer period, however the correlation is preserved in the low-lying clouds (Pallé and Butler, 2000; Marsh and Svensmark, 2000). Low clouds have a much greater albedo than any other cloud type, and if the correlation with solar activity were been maintained over the past century this would have contributed, with a strong positive forcing, to global warming.

The details of the interpretation of the cloud and other climate data may or may not be

correct, but the apparent terrestrial magnification of solar effects emphasizes the importance of looking for long term trends in the albedo as an indicator of global climate change. Measuring changes in the albedo gives us a determinant of the net energy contributing to the climate, without parameterizing any climate variable (such as clouds). One can measure the earthshine with sufficient precision to detect changes that would be climatologically significant (Papers 1 and 2 and Goode et al. 2001). If sufficient long-term changes in this quantity were present, they would have a significant impact on the earth’s radiative budget and climate.

2. Inter-annual changes in the albedo

In ‘Paper I’ and ‘Paper II’ (REFERENCES), a detailed methodology to measure and model the earth’s Bond albedo has been developed and discussed. In this paper, we focus on probing the long-term changes in albedo and their global climatic impact.

We have more than 340 nights of observations covering the period from December 1998 to May 2002 (a time of high solar activity). We also have 73 nights of earthshine data covering 1994-1995 (a time of low solar activity).

For each of these nights, a mean effective albedo, A^* , is measured. A^* is the reflectance of the sunlit part of the earth visible from the moon at any particular lunar phase. However, to determine the Bond albedo of the earth, we need to integrate over all lunar phases (see Papers I and II).

$$A = \frac{2}{3} \int_{-\pi}^{\pi} d\theta A^*(\theta) f_L(\theta) \sin \theta. \quad (1)$$

At the present rate of earthshine measurement from our single station, we have realized that we cannot determine a precise *monthly* albedo without a global network. For this reason, we concentrate our efforts here on calculating annual albedos for each of the five years of available data. During the last three, year-to-year changes in the earth’s albedo of order of 3-4% are observed. The results are plotted in Figure 2 and tabulated in Table 1.

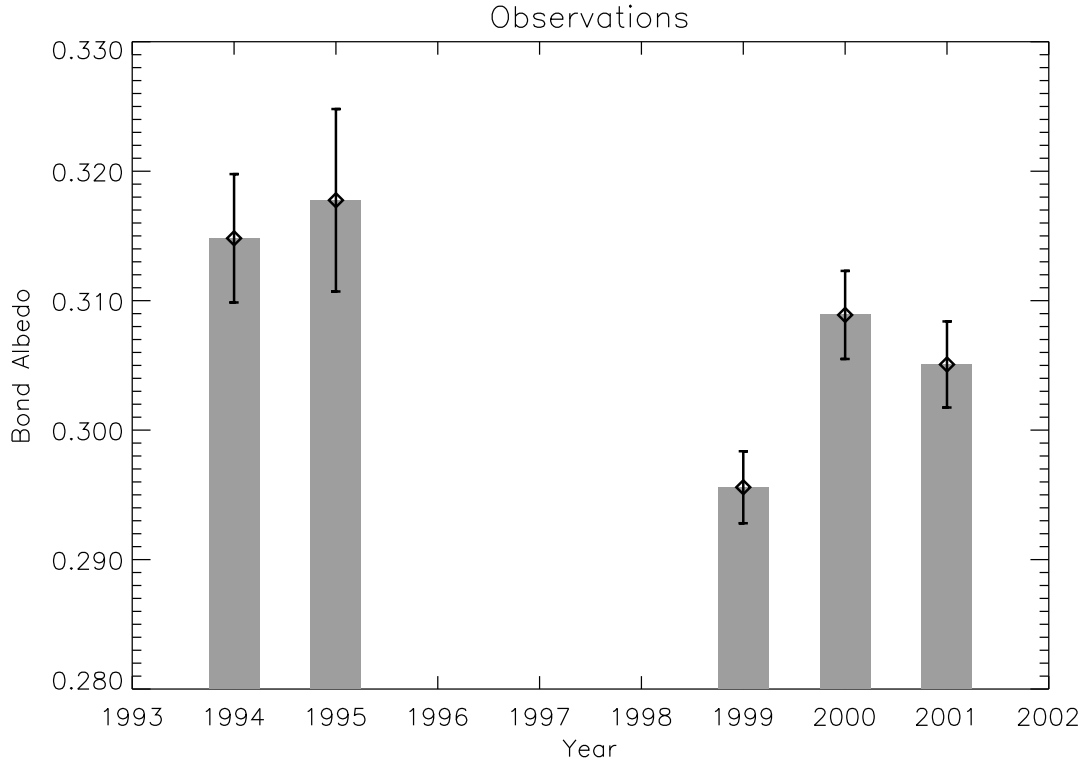


Fig. 2.— The earth’s mean annual Bond albedo for each year in our observational earthshine record. The number of nights included in each year are tabulated in Table 1. Error bars represent $\pm 1\sigma$ deviation from the mean.

A series of straightforward corrections are applied to our daily $[A^*]$ measurements (see Paper I), so that our Bond albedo measurements are insensitive to natural variations, such as astronomical distances or lunar libration. Also, included is the systematic effect of the polar regions that are sometimes in the sunshine, but not in the earthshine. Since the polar regions are quite shiny, we must add 0.006 to the earthshine values. This point was developed in detail in Paper II. Only the effect of lunar precession of the plane of the moon’s orbit is not included, but this effect is quite small compared to, say, the effect of anisotropy (about five times smaller). The effect of precession serves to increase the measured Bond albedo from 1999 to 2000 and from 2000 to 2001. However, during this period, the effect is at least an order of magnitude smaller than the observed year-to-year changes (see Paper II). Also, the effect cannot explain the change from

1994/95 to the present times, since at that earlier time the moon’s orbital plane was approximately in the same precessional phase as during 1999/01.

Table 1: The mean annual albedos for each of the years available in the earthshine record. Also given are the standard deviation of the mean, percentage deviation and number of nights involved in each albedo determination. Mean values for the periods 1994/95 and 1999/01 are also given. Note: a value of 0.006 has been added to all the albedos to account for the polar regions (see Paper II)

Year	Mean Albedo	St. Dev. Mean	% Deviation	Days
1994	0.316	0.005	1.6%	44
1995	0.319	0.007	2.2%	29
1999	0.297	0.003	1.0%	117
2000	0.310	0.003	1.1%	105
2001	0.306	0.003	1.1%	89
1994/1995	0.316	0.004	1.4%	73
1999/2001	0.301	0.002	0.6%	311

The major change in albedo occurred between the early measurements and those that are the most recent. For the 1994/1995 period, we obtain 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 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 $4.97\% \pm 1.66\%$ decrease in the albedo between the two periods. We note that this result implies a positive climate forcing, thus going in the same direction as the picture in which the earth’s albedo is lower when the cosmic ray flux is lower, i.e., times of high solar magnetic activity. But is this result significant or correlated with the flux of galactic cosmic rays, the Zurich sunspot number (R_z) or the global mean temperature of the earth? Although we have only five annualized temporal points, a linear correlation analysis between the observed Bond albedo gives

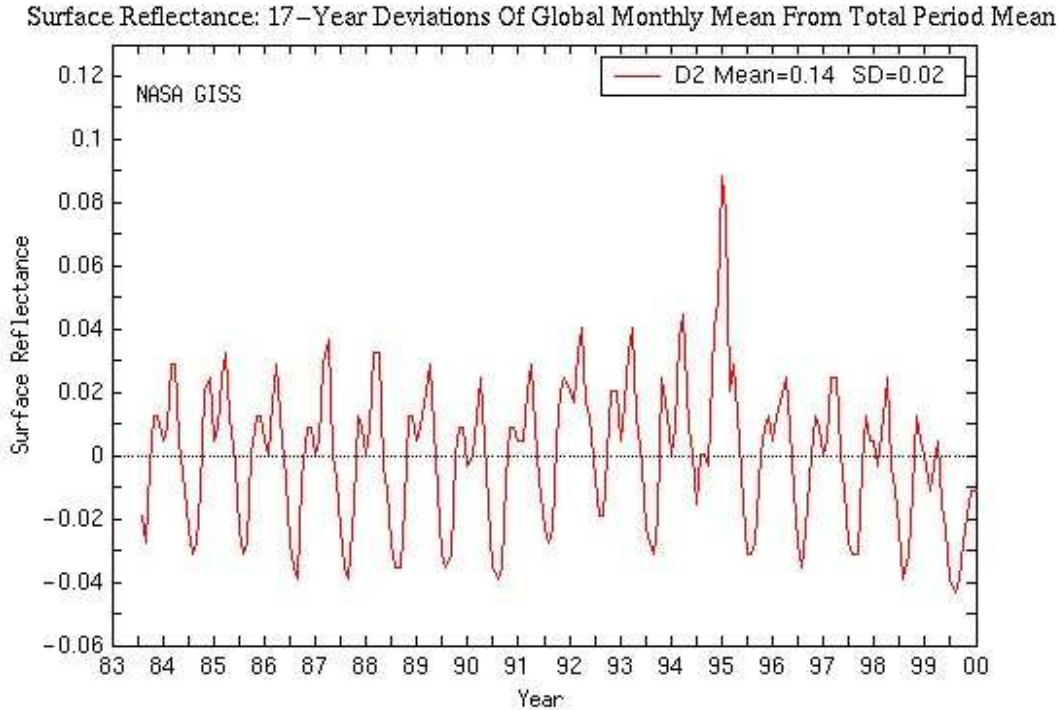


Fig. 3.— Variation of the surface reflectivity (with respect to a mean of ~ 0.14) for the period 1984-1999 derived from ISCCP data. Adapted from: <http://www.isccp.com>

correlation coefficients of 0.34, -0.7 and -0.2, respectively. Thus, none reaches a 95% confidence level.

At this point, however, we stress that we do not have the same confidence in the mid-90's measurements, as we do in the more recent ones. So far, we have not been able to identify a reason, but we worry that there might be a calibration problem between the old and new data. In particular, a different field stop and a different camera was used in the 1994/95 telescope setup. In Paper II, the crucial importance of an accurate filter transmission determination was shown. Uncertainties in this area can produce strong offsets between different observations. For the 1994/95 data, we do not have enough nights to perform an accurate filter test, so we rely on the nominal transmission of the filters. WHAT ABOUT THE LUNAR PHASE FUNCTION TEST RESULTS COMPARED TO THE FILTER TRANSMISSION INPUT TO THE ANALYSIS???

It is difficult to determine whether this 5% change in albedo is real or an artifact. However, we note that the surface reflectance (the reflectance of the cloud-free regions of the earth) data provided by the ISCCP dataset (Figure 3) shows its highest spike in 1995, with 1994 being the second highest peak of the whole record (1983-2000). In the next section, we will see how simulations of the Bond albedo using ISCCP cloud cover also result in a higher albedo for the 1994/95 period than for 1999/01, albeit the change is only about a third ($\delta A = -0.005$) of what the observations seem to indicate ($\delta A = -0.015$).

Could the difference between the two periods be terrestrial in origin? The years 1994/95 were in the midst of an El Niño event, while during the years 1999/01 a La Niña event was in progress (<http://www.cdc.noaa.gov>). The ISCCP global cloud coverage cloud indices seem to have an El Niño component with more clouds during the event. In principle, a greater cloud cover would imply a higher albedo, however there are strong regional trends (as opposed to global) in the cloud indices (Farrar, 2000). A fact that argues against El Niño events being responsible for our higher albedo during the period 1994/95 is that our albedo simulations using ISCCP total cloud cover do not show a higher albedo during the period around 1998, when the strongest El Niño event on record took place (next section). In fact, the ISCCP-derived albedo for 1998 is lower than for 1994 or 1995.

So, we cannot confidently conclude whether the $5\% \pm 2\%$ excess in the Bond albedo is a change tied to the systematic variation in solar activity, a spike in our record due to a relatively short-lived climate phenomenon like El Niño, a calibration problem, or most probably some combination of the three. The size of the anomaly is apparent in Figure 4.

We can also see from Table 1 that the uncertainty in the albedo determination strongly depends on the number of nights for which we have data. In this sense, we expect that increasing the number of earthshine stations (a process already underway), and judiciously spacing them in longitude will significantly reduce this uncertainty. The fact that the morning and evening earthshine measurements are almost identical (Paper II) suggests that data from different stations may be easily combined to derive a 24-hour, annual Bond albedo with a precision far better

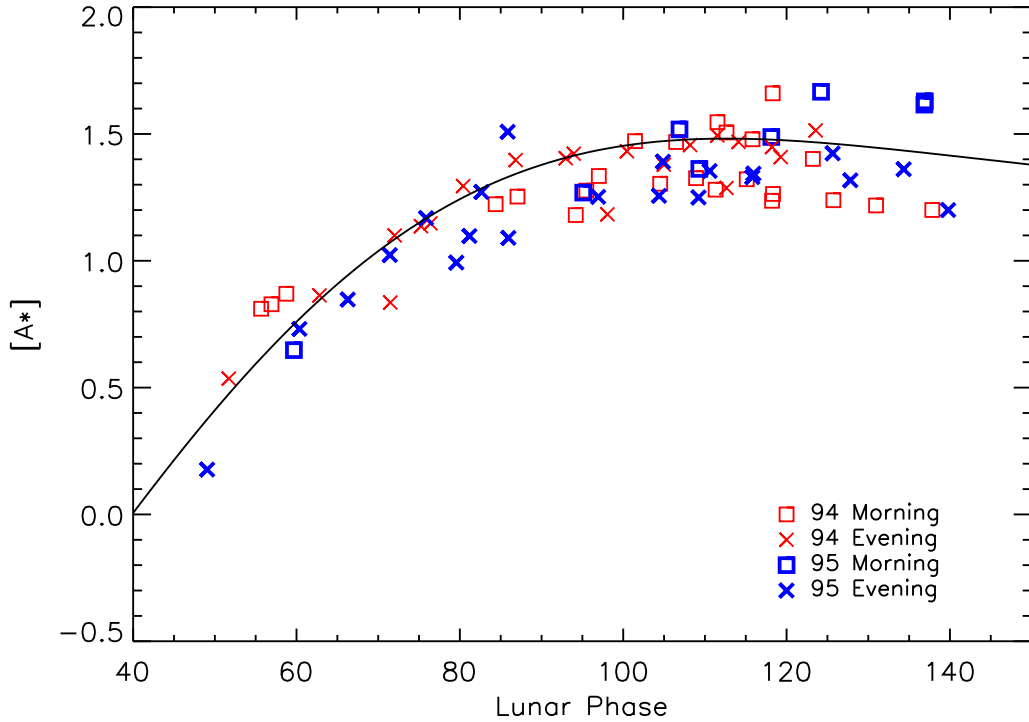


Fig. 4.— Plot of $[A^*]$ observed during 1994 and 1995. The symbols are shown separately as morning and evening observations for each of the two years. The fit shown is that from the observations for 1999-2001. Notice that the preponderance of the points are below the fit, implying a higher albedo for 1994-1995.

than a percent, and monthly albedos with a precision closer to a percent. Further, we anticipate determining regional albedos, of large slices of the the earth, to about a percent. These will allow us to confidently distinguish between changes in the albedo arising from variations in solar activity from variations in weather phenomena, while reducing, or even eliminating calibration problems.

2.1. Calculated anomalies in the effective albedo, A^*

Another way to probe the changes in the earth's albedo is by calculating the anomalies, as done in Paper II (see in particular Figure 7 therein, showing the seasonal anomalies). For the

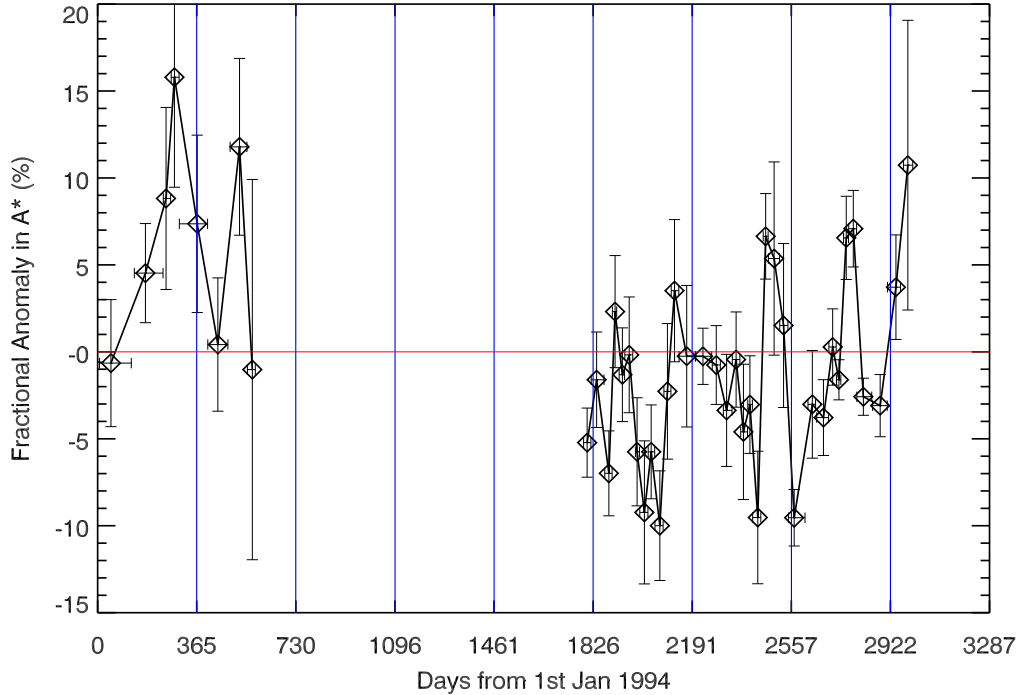


Fig. 5.— Fractional anomalies in the earth’s effective albedo for the period 1994-2001. Each of the diamonds represents the average of 10 nightly earthshine measurements. The horizontal error bars represent the period of time contained in each average and the vertical error bars represent the standard deviation of the mean, $\pm 1\sigma$. The last bin in both epochs contains fewer points than the rest.

anomalies, a fit to the lunar phase dependence of $[A^*]$ is calculated for all the available data. Then, for each night the difference between the $[A^*]$ for that night and the mean value given by the fit to all nights is determined; these constitute the anomalies. In the next step, the data are averaged in time in bins containing 10 nights each to get a mean anomaly for this period. With this method, we cannot derive an absolute measurement of the Bond albedo, but rather we obtain a measurement of its variability. The anomaly plot for 1994-2001 is given in Figure 5.

An increasing trend is apparent for the 1999/01 period, but not for the 1994/95. The mean albedo difference between the two periods is about the same as obtained with the annual albedos.

This change is comparable in size to the observed seasonal changes in the effective albedo, which can be as high as 15%.

The seasonal cycle of the ashen light has been discussed in Paper II. Although the 1999 seasonal cycle appears to repeat itself in 2000 - with the earth being brighter in Spring and Fall - 2001 is an ‘anomalous’ year. The 73 nights covering 1994/95 do not help us in the determination of this seasonal cycle, since few data are available. However, a spike in the earth’s albedo in the Fall of 1994 and Spring 1995 seems to agree with the seasonal changes observed in 1999/2000.

One might think that the seasonal variations could be a key factor in interpreting the change in albedo from 1994/95 to 1999/01. A preponderance of measurements in one of the seasons could bias the Bond albedo to a higher (or lower) value for the year. In Table 2, the number of measurements per month is given. Data for 1994 are greatly biased toward the fall (Sep-Oct) a period when the earthshine is typically at its brief, but greatest maximum. Data for 1995 has 10 nights for February, a usual period of minimum earthshine brightness, and no data for the last 4 months. So the compensating seasonalities of the data would not seem to account for the higher A^* values for 1994/95, but it would seem to effect the absolute measurements suggesting that the 1994 value should be smaller and the 1995 result should be even larger. For the recent period, 1999/01, the number of available nights per month is only limited by the lunar phase and weather conditions in Big Bear.

3. Simulating the earth’s albedo, 1984-1999

In the previous section, we compared the observed effective albedo between the present time (1999-2001) of high solar activity and the most recent previous time of low solar activity (1994-1995). Further, in Paper II, we compared the results from our simulations to those from our observations. Here, we use the monthly averaged ISCCP-D2 data as input to compare and contrast our simulations of albedo for the present solar cycle to those for the previous cycle. The simulations make use of cloud and snow and ice cover together with ERBE scene models to

Table 2: Number of nights per month for which we have observations. Clearly, the measurements are more evenly distributed in the latter period 1999/01 than for 1994/95 when measurements were scarce for the majority of the months.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	6	-	1	2	3	4	1	5	9	10	2	-
1995	-	10	2	4	2	6	3	2	-	-	-	-
1999	6	8	14	11	9	13	10	9	11	14	6	6
2000	6	3	8	8	7	11	13	9	12	9	11	8
2001	6	1	10	5	10	14	12	10	7	3	5	6

calculate a 30-minute resolution, global Bond albedo for the earth (see Paper II). In Figure 6, the earth’s Bond albedo for the full period 1984-1999 is plotted. A general decreasing trend is apparent over the whole period. This decrease supports the observational result of a higher albedo in the period 1994/95 than there is at present. However, a solar cycle modulation of the albedo is not present. In particular, 1986 was a time of activity minimum, showing higher albedo than the 1990-91 maximum, but there is no increase in albedo going to the next activity minimum.

The lack of a solar modulation in the ISCCP total cloud cover data however, does not necessarily mean that there is no relationship between solar activity and cloudiness. There are many complex, and some apparently contradictory issues surrounding cloud cover detection. ISCCP D2 *total* cloud data uses visible (VIS) and infrared (IR) radiances to determine a percentage global coverage. Pallé and Butler (2000) already demonstrated that this parameter is correlated to solar activity only during the restricted period 1983-1991. However, ISCCP D2 products also include a distinction between high-, mid- and low-level cloudiness based on IR radiances only. When using these data, the correlation between low cloudiness and solar variability (or galactic cosmic rays) is maintained at least over the period 1983-1994 (see Figure 7). At the same time, high and mid-level cloudinesses are almost invariant during this period (Pallé and Butler, 2000), so that the sum of the 3 IR cloud types does not equal the total cloudiness using

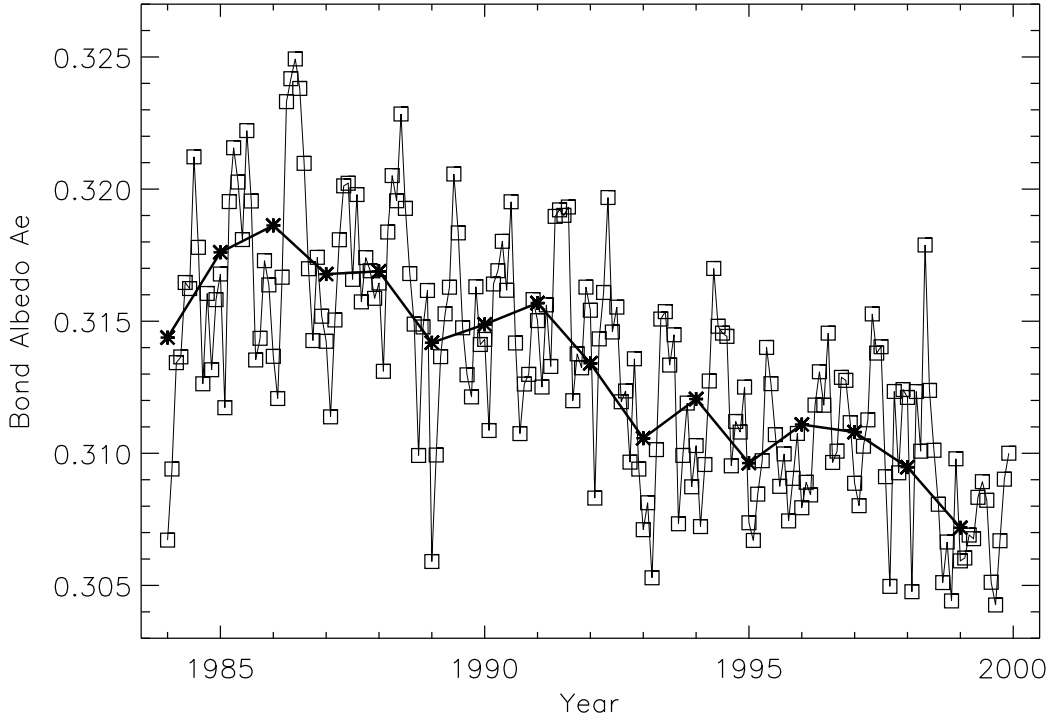


Fig. 6.— Using monthly average cloud cover data from the ISCCP data as input to the scene model, we calculate monthly averages of A that are represented by the boxes. We also show the annual averages of A as stars. The averages are plotted against time.

IR+VIS radiances. ISCCP data are a combination of many satellite datasets subject to spurious changes and calibration problems. It is difficult then, not only to ascertain the reasons for the discrepancies, but also to decide which dataset should be used to study long-term trends in the earth’s global radiation budget.

In the future, we are planning to include the distinction between cloud heights in our model parametrization. Low clouds are optically thick, and will have a bigger impact on the earth’s albedo than mid- or high-level clouds. At present, we use only total cloud cover in our simulations (see Paper II for details of the models). It is quite possible then, that with the introduction of independent treatments of the different cloud types in our models, the Bond albedo variability

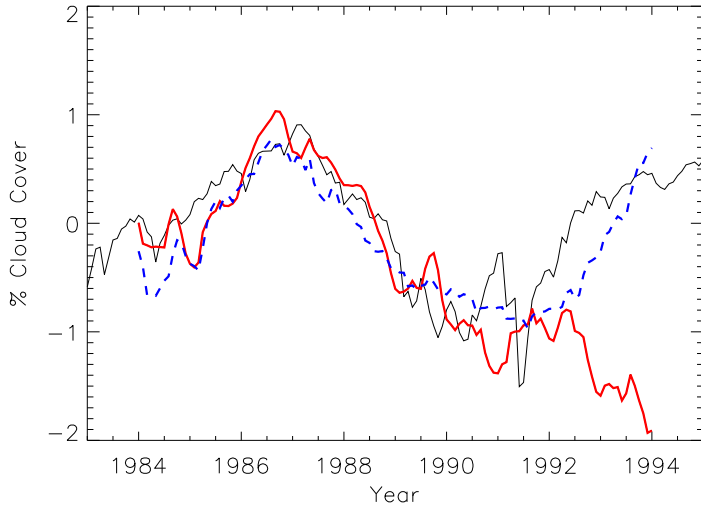


Fig. 7.— Globally averaged total cloud cover (thick solid line) and low cloud cover (dashed line) as obtained from the D2 dataset from infrared (low cloud) and visual plus infrared (total cloud) observations. The thin solid line represents the Climax cosmic ray flux (REFERENCE???) scaled for comparison. Note how the previously good correlation between total cloud cover and the cosmic ray flux breaks down after 1992, but is maintained for the low clouds, Pallé and Butler (2000).

will become more correlated with solar variability. Bluntly, there is an inconsistency between the treatment of the cloud cover that could, when resolved, yield model results having quite different temporal variation than appearing in Figure 6. The earthshine project circumvents all of these problems by directly measuring the earth’s albedo without the need for parameterizing cloud quantities.

In Figure 8, we show a comparison between observed and simulated annual albedos over the past eight years. The observed albedos are more variable than those in the models due to the muted seasonal variability of the latter (see Paper II), while the inter-annual variability between observations and modelled Bond albedo from WSI are in fair agreement. It is unfortunate that at this time there is only one year (1999) of overlapping results data from all data types. The sizeable offset between the two simulations of 1999 albedo most likely arises because of problems

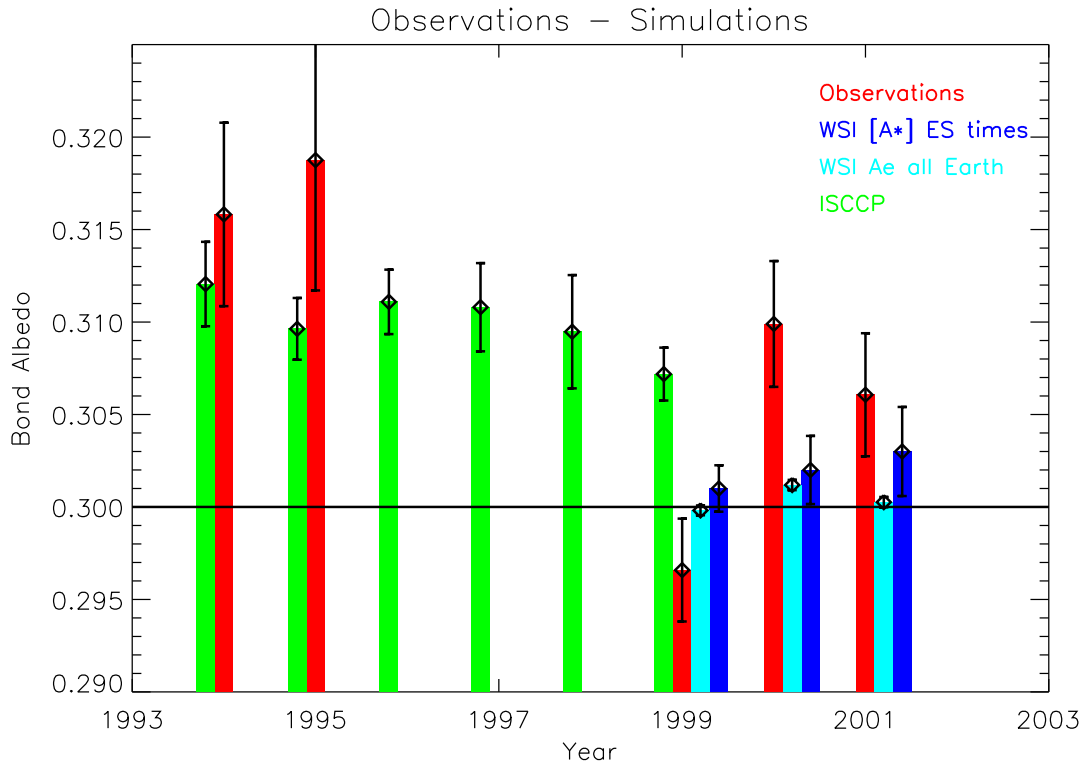


Fig. 8.— Summary of annual mean albedos determined from observations and simulations. In red are our observational results, in cyan are the WSI model of the 24-hour bond albedo for all the dates for which we have cloud data, in dark blue the WSI Bond albedo determined by simulating [A*] for the same days and times for which we have earthshine observations and integrating to obtain a Bond albedo, and finally in green are our modelled Bond albedos from ISCCP data. For observations and WSI simulations of [A*], a value of +0.006 has been added to the albedo in order to account for the polar regions, see Paper II for details. The offset between the albedos calculated with the ISCCP and the WSI data is visible in the overlapping year of 1999. The nature and value of this offset between the two series is also discussed in Paper II. THE LEGEND FOR "OBSERVATIONS" DOESN'T LOOK RED, ARE MY EYES DECEIVING ME???

in calibrating cloud cover in the models. ISCCP data indicate a decrease in albedo from 1994 to 1999, in agreement with our earthshine measurements, although this decrease is only about a third of that indicated by our observations.

4. Solar Cycle Variations in $[A^*]$?

There are many terrestrial signatures with an 11/22 year periodicity that, by default, would seem to be associated with the sun’s magnetic activity cycle. Perhaps the most impressive is the demonstration 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). With such signatures in mind, it is one of our primary goals to determine whether or not the earth’s reflectance varies with solar activity. We have presented sufficient data to do a preliminary probe of this question. From observations and models, we conclude that the albedo has decreased from the period 1994/95 to 1999/01, however we have no compelling reason to attribute this decrease to changes in the sun.

Nonetheless, suppose the difference in reflectance were tied to the cycle. What size change in the net sunlight reaching the climate system would be caused by that change in solar activity? And how would it compare to changes in the sun’s irradiance that are tied to the cycle?

The net sunlight reaching the earth depends on the sun’s irradiance and the earth’s reflectance. As mentioned earlier, it is generally agreed that a 0.1% variation over the activity cycle is too small to be climatologically significant (see Lean (1997) for a review). What about the earth’s reflectance? Taking the aforementioned albedo changes to be real, how significant would they be? To see the relative roles of varying solar irradiance and the varying reflectivity of the earth in the change in the net input of sunlight to the climate system between a time of high solar activity (1999-2001) and one of low activity (1994-1995), we use:

$$P_{\text{in}} = C\pi R_e^2(1 - A), \tag{2}$$

and, under the assumption that the A ’s scale with the A^* ’s, we find that

$$\frac{\delta P_{\text{in}}}{P_{\text{in}}} = \frac{\delta C}{C} - \frac{\delta A^*}{1 - A^*}, \quad (3)$$

where $\frac{\delta C}{C} \sim 0.001$. Our observations of the earthshine take the ratio of the earthshine to moonshine, so they are insensitive variations of the solar irradiance. The $5\% \pm 2\%$ change in our observed reflectance translates to $\frac{-\delta A^*}{1 - A^*} \sim 0.021 \pm 0.007$. Solar and terrestrial changes are in phase and contribute to a greater power going into the climate system at activity maximum. However, the effect of the albedo is more than an order of magnitude greater. Still, whether the earth's reflectance varies with the solar cycle is a matter of controversy, but regardless of its origin, if it were real, such a change in the net sunlight reaching the earth would be very significant for the climate system.

It is always possible that the change derived from the observations have been overestimated, and so we look to a different indicator of this change, which can be derived from the simulations. In this case, we only have the simulations coming from the monthly mean cloud cover from the ISCCP D2 data. To compare, we again use a modified Equation (3) in which A^* is replaced by A , because in the simulations we do not have to assume a proportionality between the A^* 's and the A 's. Using Figure 6, we find a -0.005 ± 0.003 decrease in albedo from 1994/95 to 1999 ($1.6\% \pm 0.8\%$), and so for this period $\frac{-\delta A}{1 - A} \sim 0.007 \pm 0.004$. Comparing with the solar irradiance change during the same period, again the two contributions have the same sign, but the effect of the albedo is several times larger.

During the restricted period of 1984-1991, the total and low cloudiness variations from ISCCP were strongly related (see Figure 7). Following Willson and Hudson (1991), we compare the simulated albedo changes between 1986 and 1990. These two times correspond to the solar activity minimum and a time near maximum. Actually, 1991 was the maximum, but we chose 1990 because 1986 and 1990 are roughly at the same phase of the El Niño and Mt. Pinatubo erupted in June of 1991. Over the four years between 1986 and 1990, the solar irradiance increased by about 0.1% (see Figure 1), while the simulated albedo decreased by about -0.004 ± 0.005 ($1.3\% \pm 1.6\%$). This translates to a $\frac{-\delta A}{1 - A} \sim 0.006 \pm 0.007$, roughly the same as for the period 1994 to 1999.

The same trend in the albedo holds from 1990 to 1994, and with about the same magnitude ($\delta A = -0.003 \pm 0.002$ or $\frac{-\delta A}{1-A} \sim 0.004 \pm 0.003$). This behavior is opposite to what one would demand from a solar cycle dependence. However, as we have seen there is the very real possibility that the treatment of the clouds is so inadequate that a correct treatment could change the trends, e.g., from a steady decline in albedo, like in Figure 6, to an oscillating behavior like the IR low cloud cover displays in Figure 7. But, we still don't know.

If the latter hypothesis is to be true and there is a solar influence on the earth's albedo, one question remains: would these changes be climatologically significant over the solar cycle? Looking at our simulations, between 1994 and 1999, they imply an effective increase in the solar irradiance of 10.92 ± 5.96 W/m², or a surface averaged (i.e., divide by four) increase of 2.73 ± 1.36 W/m² over the five year span, or 7.5 ± 2.4 W/m², as derived from the observations. We change here to a surface-averaged value, since that is the way in which the climate models are presented. Between 1990 and 1994, the change is 1.02 ± 1.02 W/m² (where during this period $\frac{\delta C}{C}$ is negative), but between 1986 and 1990, data imply a surface-averaged increase of 2.38 ± 2.38 W/m². The latest Intergovernmental Panel on Climate Change (IPCC, 1995) argues for a comparably sized 2.4 W/m² increase in forcing, which is attributed to greenhouse gas forcing since 1850. IPCC also argues that this forcing is larger than changes in the sun's irradiance, aerosols and their effect on clouds, and that greenhouse gasses have dominated climate change since the industrial revolution being ultimately responsible for the increase in global temperatures experienced during the major part of the 20th century.

The change arising from the albedo, over just five years is too abrupt to change the global climate – considering the thermal inertia of the oceans. However, Stevens and North (1996) have used ocean surface temperature data to suggest a subtle variation, with an eleven year period, since 1850. One key to the argument comes from the study of ¹⁰Be concentration in Greenland ice cores by Beer, Raisbeck and Yiou (1991), to show that the cosmic ray flux at activity maximum a hundred years ago was comparable to what it is now at activity minimum. ¹⁰Be is created by cosmic rays and falls to earth in about two years. As such, it is a good proxy for the cosmic ray

flux.

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 emission temperature, as would be seen in the IR near $15.5 \mu\text{m}$. In those terms, we have from Equation (2) of Paper I,

$$P_{\text{out}} = 4\pi R_e^2 \sigma \epsilon T_e^4 \tag{4}$$

and that combining Equation 4 with Equation 3

$$\frac{\delta P_{\text{in}}}{P_{\text{in}}} = \frac{4\delta T_e}{T_e}, \tag{5}$$

under the assumption the ϵ in Equation (4) doesn’t change. Taking $T_e \approx 255\text{K}$, we find a temperature perturbation due to the sun of about 0.1 K from the irradiance changes, but about 0.5 K and 1.3 K (simulations and observations, respectively) from the albedo. We note that the largest variations in Figure 6 correspond to temperature variations of about 1 K for the earth. The temperature changes here are simply related to changes in the earth’s net sunlight, not changes in the temperature of the earth’s surface.

5. Discussion and Conclusions

With our level of precision, we can track long-time frame changes in the earth’s albedo, if they are at a climatologically significant level. Both from our observations and simulations we have found a significant decrease in the earth’s Bond albedo during the periods 1994/95 to 1999/01 and 1986 to 1990 (both ranging from a time of high solar activity to a time of low solar activity), which by extrapolation, would seem to suggest some dependence of the earth’s albedo on solar activity. We have also seen how the change in the earth’s net sunlight from a time of high activity to low activity from varying cloud cover is several times greater than changes in the sun’s irradiance and that the two effects may work in concert. However, the period from 1990 to 1994, for which which we would expect an increasing trend in the earth’s albedo argues against a solar modulation. The

resolution of the apparent conflict may well arise from an inadequate treatment of the cloud cover in the simulations.

Of course, placing solar magnetism at the heart of terrestrial climate change is controversial, but merits consideration based on the results here and in the referenced literature in this paper. Nevertheless, even if those changes are not tied to the solar activity cycle, they deserve attention for their possible climatic implications. Traditionally the earth's Bond albedo has been considered as a roughly invariant parameter in Global Circulation Models. In this study we have shown how, to the contrary, the earth's albedo is quite a variable parameter for which a detailed study of its seasonality, long-term variability and climate implications need to be carefully undertaken, if we are to fully understand the present changes in the earth's climate.

Currently, we are taking data at about five times the rate we did in 1994-1995. We are also building a three-station global network that would triple our current data rate. We also plan an automated network of earthshine telescopes, so that we can have long-term data covering all geographic regions. Thus, during the declining phase of the current activity cycle, we should be able to precisely determine whether or not there is a correlation between the earth's reflectance and evolving solar magnetic activity. We are also aiming to identify and quantify the effect on albedo of other future climatic forcings, such as volcanic eruption or El Niño events.

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