

# Earthshine and the Earth's Albedo III: Seasonal and long-term variations in the earth's reflectance

E. Pallé, P.R. Goode, J. Qiu, V. Yurchyshyn, J. Hickey, P. Montañés-Rodríguez  
Big Bear Solar Observatory, New Jersey Institute of Technology, Newark, NJ 07102, USA

M-C Chu

Department of Physics, The Chinese University of Hong Kong, Shatin N.T., Hong Kong

E. Kolbe

Department für Physik and Astronomie, Universität Basel, Basel, Switzerland

C.T. Brown, S.E. Koonin

W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

## Abstract.

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 characterize the seasonal cycle of the earth's reflectance. We find that our precision, with the steady observations since December 1998, is sufficient to detect a seasonal cycle, which does not show a fixed pattern from year to year. We have also determined the annual albedos both from our observations and from simulations. The simulations utilize the Earth Radiation Budget Experiment (ERBE) scene model with snow/ice cover and two 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 our observations hint at an increasing albedo since 1999. Further, both the observations and simulations indicate that the albedo was significantly higher in 1994-1995 than for the more recent period covering 1999-2002, although the differences are somewhat discrepant perhaps, at least in part, due to a calibration problem. 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

This paper is the third of a series of three papers dedicated to the earthshine measurements taken from Big Bear Solar Observatory (BBSO) during the past four years. In Qiu et al. (2003) and Goode et al. (2003), hereafter 'Paper I' and 'Paper II' respectively, a detailed methodology to measure and model the earth's Bond albedo has been developed and discussed. We have demonstrated that we can determine an effective albedo with a precision of about 1% on individual nights. Further, our terrestrial measurements of the earth's Bond albedo on yearly time scales have a precision comparable to that of satellite measurements (Paper I). We have also seen in Paper II how we can model these observations using Weather Services International (WSI) daily cloud cover maps taken from the Internet and ERBE scene models. In this paper, we focus on the seasonal and long-

term changes in albedo and their possible global climatic impact.

The earth's climate is driven by the net sunlight deposited in the terrestrial atmosphere, and so, is critically sensitive to the solar irradiance and the earth's albedo. In the formulations detailed in Paper I, under the supposition that the planet is in radiative equilibrium, we derived the following formulation for the surface temperature,

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

where  $T_s$  is the temperature of the earth's surface,  $C$  is the solar constant,  $\sigma$  is the Stefan-Boltzmann constant,  $A$  is the albedo and  $g$  is a normalized greenhouse effect (Ramanathan et al, 1989) - see Paper I for a detailed formulation.

This means that the Bond albedo, together with solar irradiance and the greenhouse effect, directly controls the earth's temperature. By measuring the earth's reflectance and the spectrum of the light reflected by the earth, one can determine  $A$  and  $g$ , respectively. A change in  $A$ ,  $g$  or  $C$  will affect the earth's radiative budget producing a global warming or cooling, depending on the sign and the strength

Copyright by the American Geophysical Union.

Paper number .  
0148-0227/03/\$9.00

of the change, and on the possible climate feedbacks (Paper I). We note that since  $A$  is determined from the ratio of the earthshine to the moonshine, it is independent of  $C$  and any changes in  $C$ .

In recent years, many have argued about a possible change in  $g$  produced by the anthropogenic increase of  $CO_2$  and other greenhouse gases in the atmosphere (see ISCCP, 2001 and 1995; and references therein). An increase in  $g$  would lead to an increase in the surface temperature of the planet by reducing the amount of long-wave (far infrared) radiation emitted to space. However, the range of efforts to characterize the forcing from the short-wave (visible) band of the spectrum (i.e., the solar irradiance and earth's albedo) has not been so prolific, particularly for the albedo. Here we focus on the variability of the latter two parameters, which may also have contributed to climate change.

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, and its successors, have revealed that for the last two  $\sim 11$ -year cycles, the solar irradiance is about 0.1% greater at activity maximum than activity minimum (Willson and Hudson 1988, 1991 and Fröhlich, 2000). Considering the ocean's thermal inertia, it is widely accepted that this 0.1% ( $0.3 \text{ W m}^{-2}$ ) is several times too small to be climatologically significant over the solar cycle (Lean, 1997; IPCC, 2001). Still, there is strong evidence from ice core data of a wandering solar cycle, with a period of  $\sim 11$  years, going back more than 100,000 years (Ram and Stoltz, 1999). If the 0.1% modulation of the mean solar irradiance during the mid-1980's and 1990's were typical over longer time scales, it leads one to doubt a direct role of the varying irradiance in the terrestrial signature of the solar cycle.

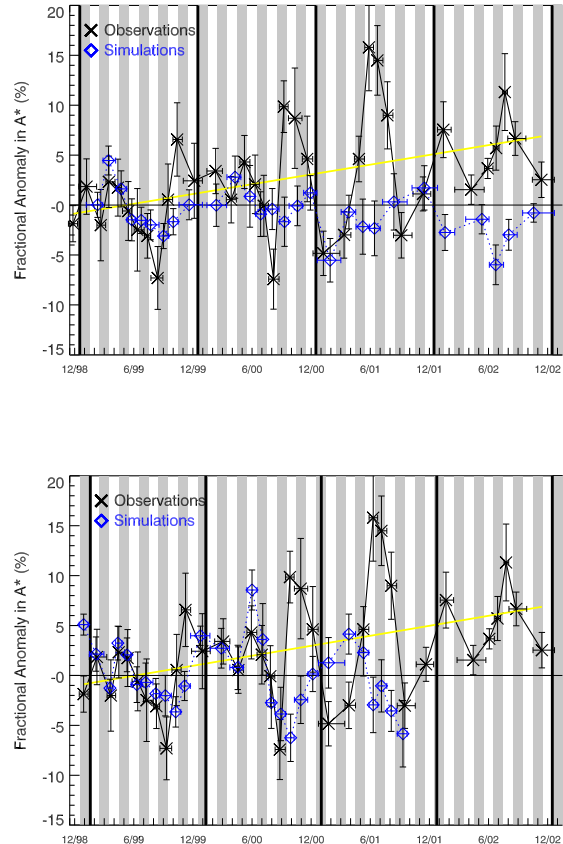
Instead, an indirect mechanism may be amplifying the solar signal influence on the terrestrial climate. Several mechanisms have been proposed in the literature to produce this amplification, ranging from changes in EUV radiation tied to ozone (Haigh, 1994), to changes in storm-tracks and atmospheric 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 remains 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. 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), which may have an impact on the variability of the earth's albedo.

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). We have measured the earthshine with sufficient precision to detect changes that would be climatologically significant (Paper I and Paper II). 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. Seasonal Changes in effective albedo, $A^*$

We have nearly 400 nights of observations covering the period from December 1998 to January 2003. 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. Here we use observations and simulations to probe the earth's albedo by determining its seasonal variability (or anomalies). The seasonal variation of the earth's reflectance is not well known. In fact, Goode et al. (2001) have shown that over a year and a half (1999.0-2000.5), the earth's seasonal variation is more than 10%. This surprisingly large value was twice that determined from the simulations covering the same nights and the same parts of the earth.



**Figure 1.** Seasonal anomalies in the effective albedo,  $A^*$ . From December 1998 through January 2003, there are nearly 396 nights of observations with 11 nights in each of the bins. From January 1999 onward, there are 308 nights for which we have both observations and contemporaneous WSI satellite cloud cover data, which have been averaged in 28 bins with 11 nights in each. We also have ISCCP daily cloud data for the 308 observation nights since December 1998 and ending in September 2001. The  $\times$ 's show the mean of the observations, with the vertical bars being the standard deviation of the mean. The size of the latter stems from the large night-to-night variations in the cloud cover, rather than from uncertainties in the observations. The horizontal bars indicate the temporal span of each average. The diamonds indicate the corresponding simulated results. Anomalies are with respect to the mean for 1999. Top: Observed anomalies are compared to WSI models. Bottom: Same but for the ISCCP simulations, which end with the to-date release of those data. The straight line in both panels represents a linear fit to the observational anomalies

**Table 1.** 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
2002	6	5	5	2	5	12	13	15	4	5	3	3

To determine seasonal 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 lunar phase) and the mean value given by the fit to all nights is determined; this constitutes the anomaly for that night.

Starting from Equation (2) in Paper II, the fractional seasonal variation depends only on the observed intensities corrected for airmass. That is,

$$\sum_{i=1}^N \frac{A_{\text{seas}}^*(\theta_i) - \overline{A^*}(\theta_i)}{\overline{A^*}(\theta_i)} = \sum_{i=1}^N \frac{\left(\frac{I_a/T_a}{I_b/T_b} \frac{R_{e,m}^2 R_{s,s}^2}{R_{m,s}^2}\right)_{\text{seas},i} - \left(\frac{I_a/T_a}{I_b/T_b} \frac{R_{e,m}^2 R_{s,s}^2}{R_{m,s}^2}\right)_i}{\left(\frac{I_a/T_a}{I_b/T_b} \frac{R_{e,m}^2 R_{s,s}^2}{R_{m,s}^2}\right)_i}, \quad (2)$$

where  $N$  is the number of nights for which we have data in a particular season,  $\theta_i$  is the lunar phase on the  $i^{\text{th}}$  night of that season, and  $\overline{A^*}(\theta_i)$  is the fit shown in Figure 10 of Paper II. The average for a particular season is computed from each night's data by determining the fractional change for that night's phase angle with respect to the mean for that phase angle for all nights, irrespective of season. With this formulation, possible systematic errors associated with the moon's geometric albedo have been largely eliminated. In the formulation of Equation (2), we minimize the dependence on lunar phase by removing effects, in the mean, arising from the fact that  $A^*$  is a strong function of lunar phase.

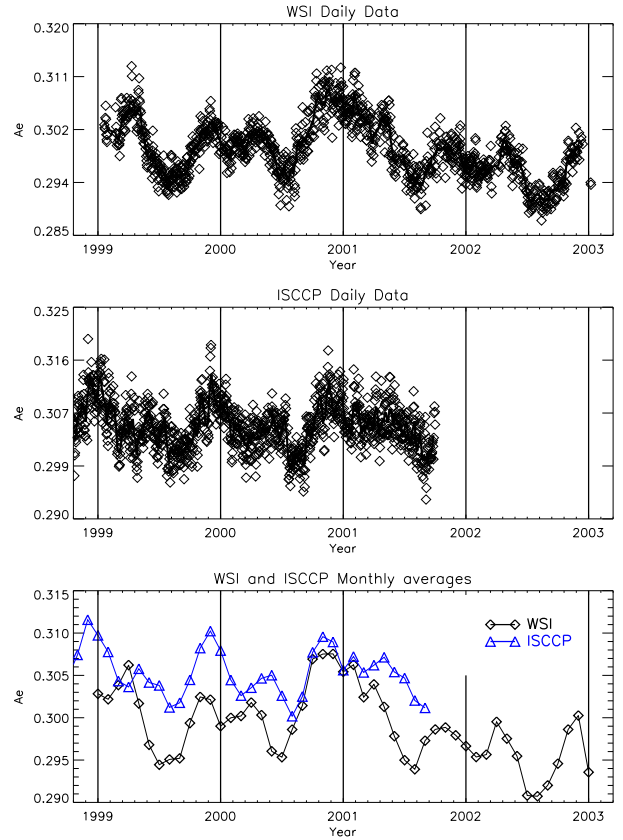
In the next step, the data are averaged in time in bins containing 11 nights each to get a mean anomaly for each period. With this method, we cannot derive an absolute measurement of the Bond albedo, but rather we obtain a measurement of its variability.

These seasonal anomalies, which are formulated as fractional changes in  $A^*$ , carry information about variations in weather, climate and surface type. The fractional seasonal variation of the earth's reflectance over four years (1999-2002), as determined from our earthshine observations, is shown in Figure 1, together with our simulations from WSI and ISCCP data. ISCCP data is derived from measurements in the visible and infrared channels of a series of different and inter-calibrated satellites. The present release of the ISCCP D1 and D2 series used here extends from July 1983 to September 2001. Both the WSI and ISCCP data are introduced in more detail in Paper II of this series. An increasing trend in the albedo of about 1%/year is apparent and significant during the full period of measurements.

One can see in Figure 1 a clear seasonal trend for 1999 and 2000, with the earth being brightest in the spring and fall generally, when it is also the cloudiest (according to WSI satellite data). We see the seasonal trends in spite of the fact that the night-to-night variations are a significant fraction

of the seasonal trends. We emphasize that the large vertical error bars in Figure 1 arise from the large night-to-night variations in the cloud cover, rather than from any errors in the data. In fact, the night-to-night variations are large compared to the formal error bars for one night. With all of this, we see about 15-20% variation in  $A^*$  from season to season. However 2001 and 2002 do not show the same seasonal pattern. In the early months of the year, they show a dip in the albedo that is also visible in the simulations (WSI), and it has a maximum in summer time, although this is not reflected in any of the simulations.

Note that the agreement between measured and modeled anomalies is remarkable from the beginning of the measurements until the end of 2000, particularly for the ISCCP simulations, for which all nights coinciding with observa-



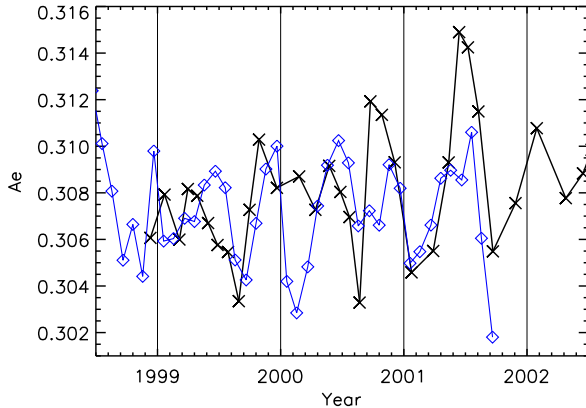
**Figure 2.** Top Panel: Daily mean Bond albedo over the entire earth, simulated using daily WSI cloud data maps. Middle panel: Same as top but, this time using daily mean ISCCP cloud cover maps as input to our models. Bottom Panel: The daily means in the two upper panels are averaged to monthly values of the earth's albedo for the whole earth (24-hour).

tions have data available. However, since the end of 2000, although the simulations maintain the same seasonal cycle, the observations start to deviate; we will come back to this point.

The observations show about twice the variability as the simulations, with the differences being greatest at the extremes. The muted seasonal amplitude of the simulations may well derive from the coarse binning of the scene models and/or the use of simulated snow and ice cover. But the oversimplified treatment of the clouds is a stronger candidate than any other climate parameter that may contribute to changes in albedo. Our model contemplates only 12 different scenes and 4 cloudiness levels (0-5%, 5-50%, 50-95% and 95-100%). Beyond the appreciable binning of the cloud cover, changes in cloud type or optical thickness for example, will also affect the albedo, but it is not accounted for in the models. Thus, our albedo models need to be considered only as an initial exploration of the problem.

In Figure 2, we plot the daily modeled 24-hour Bond albedo simulations for the whole earth. The bottom panel of the figure reveals a clear offset between albedos obtained using different data sets. The WSI albedo is significantly lower than the ISCCP one. The computed averaged ISCCP (1983-2001) albedo  $\bar{A}$ , is 0.313 and the WSI (1999-2002) averaged albedo  $\bar{A}$  is 0.300. This difference is well within what we can measure. However, ISCCP data for 1999 and 2000 are the lowest of the 1983-2001 period in cloudiness and albedo,  $\bar{A} = 0.307$ , and so the offset between the two datasets in the common years is reduced by half (0.007). This offset changes with time (Figure 2), even disappearing for short periods. Here we need to remind the reader that the WSI data posted on the Internet are uncalibrated from one day to the next, while the ISCCP data undergo a detailed calibration process.

It is also seen in Figure 2 how the seasonal variation of the two cloud (or deduced albedos) datasets are not equivalent. While the WSI simulations show the expected seasonal variation with an August minimum and November and May



**Figure 3.** Bond albedo simulations of the whole earth. In this case we use monthly mean ISCCP cloud cover maps as input to our monthly simulation, as opposed to Figure 2 where we used daily values which were then averaged to form a daily value. The observed seasonal anomalies are overplotted (crosses), and arbitrarily scaled for comparison. Note the good agreement on both curves for the year 2001.

maxima (Danjon, 1928; Dubois, 1942; Dubois, 1947, Gibson et al, 1990), the ISCCP data has a more broad peak during the summer months, which generally increases the albedo for the year. The dominant source of the seasonal variability is the interplay of the annual cycle of cloud cover and snow/ice cover; the greater land fraction in the northern hemisphere plays only a direct small role. The seasonal cycle of our modeled 24-hour Bond albedo of the earth and that of our modeled effective albedo at the time of observations are closely similar.

In Figure 3 we have repeated the 24-hour whole earth simulations of the earth's Bond albedo, but this time, rather than averaging daily means into monthly means, we have used for our model input monthly mean cloud cover maps given by the ISCCP D2 dataset. The observed seasonal anomalies have been also plotted in Figure 3. It is surprising that the ISCCP-derived Bond albedo from Figure 2 and Figure 3 is different, particularly in 2001. It is also striking that during 2001, our  $A^*$  observations do not agree with our simulations, but agree with the Bond albedo derived in Figure 3.

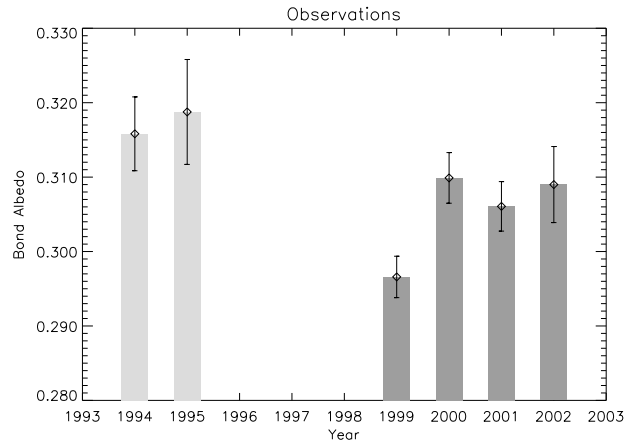
### 3. Inter-annual changes in the albedo

To determine the Bond albedo of the earth,  $A$ , we need to integrate the effective albedo,  $A^*$ , over all lunar phases (see Papers I and II).

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

where  $\theta$  is the lunar phase angle,  $f_L(\theta)$  is the moon's Lambert phase function and  $A^*$  is the effective albedo associated with a particular night (Paper I).

At the present rate of earthshine measurement from our single station, we realize 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 year of available data. Since 1999, year-to-year



**Figure 4.** 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 2. Error bars represent  $\pm 1\sigma$  deviation from the mean. We have less confidence in the 1994/95 data than the recent data, and so show them as faded.

**Table 2.** 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
2002	0.309	0.005	1.5%	75
1994/1995	0.316	0.004	1.4%	73
1999/2001	0.301	0.002	0.6%	311

changes in the earth's albedo of order of 3-4% are observed. The results are plotted in Figure 4 and tabulated in Table 2.

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) - see Paper II for a discussion on this effect. The effect of precession serves to increase the measured Bond albedo from 1999 to 2000, from 2000 to 2001 and from 2001 to 2002. However, during this period, the effect is at least an order of magnitude smaller than the observed year-to-year changes (see Paper II).

#### 4. The 1994 and 1995 measurements

We also have 73 nights of earthshine data covering 1994-1995, which we analyze in the same way as the more recent data. However, we stress at this point, 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 were used in the 1994/95 telescope setup. In Paper I, the crucial importance of an accurate filter transmission determination was shown. Uncertainties in this area can produce offsets between different observations. For the 1994/95 data, we do not have enough nights to perform an accurate filter test, so we are forced to rely on the nominal transmission of the filters.

With all this in mind, a major change in albedo occurred between the early measurements and the most recent ones (Figure 4). For the 1994/1995 period, we obtain a mean albedo of  $0.310 \pm 0.004$ , while for the more recent period, 1999/2001, the albedo is  $0.295 \pm 0.002$  (with a 0.6% precision in the determination). The combined difference in the mean  $A$  between the former and latter periods is of  $-0.015 \pm 0.005$ , 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 to 2001 because these are the 3 years around the solar activity maximum (2000), which we will discuss in section 6.

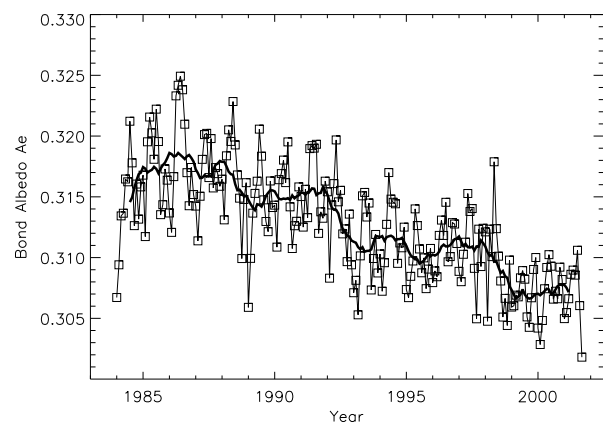
It is important to note that 1999 is by far the year with the lowest albedo value in our record. While that year is in the present measurement period and we have no worries in

the calibration from 1998 onward, this is a lower than usual albedo value. If we do not take into account this year in our measurements, the discrepancies between the 1994/95 and the 2000/01 period are reduced by half, i.e.  $2.5 \pm 2\%$ .

It is difficult to determine whether this 2.5-5% change in albedo is real or an artifact. 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 ([www.cdc.noaa.gov](http://www.cdc.noaa.gov)). The ISCCP global cloud cover 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 centered on 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.

The precession effect cannot explain the change from 1994/95 to the present times either, since at that earlier



**Figure 5.** Monthly averages of  $A$  are represented by the boxes. The averages derive from monthly average cloud cover data from the ISCCP data as input to the scene model. The averages are plotted against time. The solid line represents the 12-month running mean of the monthly averages.

time the moon's orbital plane was approximately in the same precessional phase as during 1999/01.

So, we cannot confidently conclude at this point whether the  $2.5 - 5\% \pm 2\%$  excess in the Bond albedo is real, 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.

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 1, 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 a maximum (according to our ISCCP simulations for that period). Data for 1995 has 10 nights for February, a usual period of minimum earthshine brightness (again from ISCCP simulations), and no data for the last 4 months. So the compensating seasonality of the data would not seem to account for the higher  $A^*$  values for 1994/95, but it would seem to affect 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.

## 5. Simulating the earth's albedo, 1984-2001

In Paper II, we compared the results from our daily observations to those of our simulations using WSI daily cloud maps. 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 calculate a 30-minute resolution, global Bond albedo for the earth (see Paper II). In Figure 5, the earth's Bond albedo for the full period 1983-2001 is plotted. A general decreasing trend is apparent over the whole period. This decrease appears to support the observational result of a higher albedo in the period 1994/95 than there is at present.

The lack of a solar modulation in the ISCCP total cloud cover data 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. At the same time, mid and high 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 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.

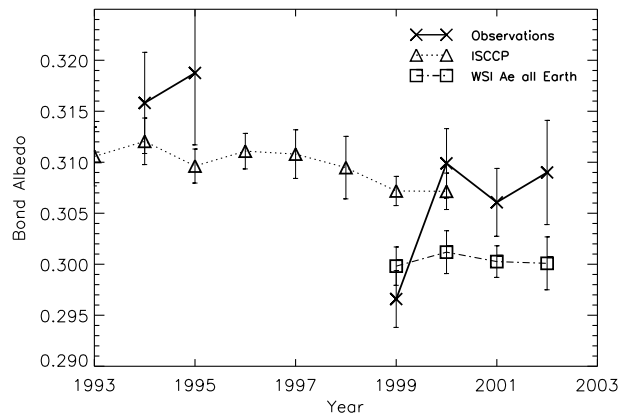
In the future, we are planning to include the distinction between cloud heights in our model parametrization. Low

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 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 5.

In Figure 6, 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 more muted seasonal variability of the latter, while the inter-annual variability between observations and modeled Bond albedo from WSI and ISCCP are in fair agreement. It is unfortunate that at this time there are only two full years (1999 and 2000) of overlapping results from all data types.

## 6. 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 goals to determine whether or not the earth's reflectance varies with solar activity. 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.



**Figure 6.** Summary of annual mean albedos determined from observations and simulations. Crosses are our observational results, squares are the WSI model of the 24-hour Bond albedo for all the dates for which we have cloud data, and triangles are our modeled Bond albedos from ISCCP data. For observational determination 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 apparent in the overlapping years of 1999 and 2000.

Nonetheless, suppose the differences in reflectance were tied to the cycle. What size change in the net sunlight reaching the terrestrial atmosphere 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?

To see the relative roles we use

$$P_{\text{in}} = C\pi R_e^2(1 - A), \quad (4)$$

where  $R_e$  is the earth's radius, and under the assumption that the  $A$ 's scale with the  $A^*$ 's, we find that

$$\frac{\delta P_{\text{in}}}{P_{\text{in}}} = \frac{\delta C}{C} - \frac{\delta A^*}{1 - A^*}, \quad (5)$$

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 to variations in the solar irradiance. The  $2.5\% \pm 2\%$  change in our observed reflectance translates to  $\frac{-\delta A^*}{1 - A^*} \sim 0.010 - 0.021 \pm 0.007$ . 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.

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 the 1994/95 and the 1999/02 periods, they imply an effective increase in the solar irradiance of  $10.92 \pm 5.96 \text{ W/m}^2$ , or a surface averaged (i.e., divide by four) increase of  $2.73 \pm 1.36 \text{ W/m}^2$  over the five year span, or  $3.8\text{-}7.5 \pm 2.4 \text{ W/m}^2$ , 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.

The latest Intergovernmental Panel on Climate Change (IPCC, 1995 and 2001) argues for a comparably sized  $2.4 \text{ W/m}^2$  increase in forcing, which is attributed to greenhouse gas forcing since 1850.

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.

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  $15.5 \mu\text{m}$  if there were no long-wave atmospheric absorption. In those terms, we have from Equation (2) of Paper I,

$$P_{\text{out}} = 4\pi R_e^2 \sigma \epsilon T_e^4, \quad (6)$$

with  $\epsilon$  being the atmospheric emissivity. And combining Equation (6) with Equation (5),

$$\frac{\delta P_{\text{in}}}{P_{\text{in}}} = \frac{4\delta T_e}{T_e}, \quad (7)$$

under the assumption the  $\epsilon$  in Equation (6) doesn't change, and 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 0.6-1.3 K (simulations and observations, respectively) from the albedo. 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.

However, as stated before, there is no compelling reason to attribute the change in albedo from the 1994/95 to the 1999/01 to solar-induced changes. Calibration problems between the two datasets may be an issue. However, we emphasize that there are no calibration problems in the measurements taken from December 1998 to the present. Thus, the planned extension of our observations during the next solar cycle with this consistent dataset will help to either support or dismiss a possible solar cycle change in the earth's Bond albedo.

## 7. The need for a global network

We can see from Table 2 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 than a percent, and monthly albedos with a precision closer to a percent. Further, we anticipate determining regional albedos of large slices of 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.

It is also worth noticing that we get a greater number of observation nights in the summer than in any other period because of local weather at Big Bear, which is cloudier at night in the winter. Thus, locating our new stations in areas where good nighttime conditions are present during the whole year will also increase our data intake.

Currently, we are taking data at about five times the rate we did in 1994-1995, and we have a carefully calibrated uninterrupted time series from December 1998 to the present. We are also building a four-station global network that will quadruple our current data rate and space-time coverage. 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.

## 8. 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 strong seasonal variations and annual trends, as well as a significant decrease in the earth's Bond albedo during the periods 1994/95 to 1999/01 with an

increasing trend during the 1999-2002 period. By extrapolation, the results would seem to suggest some dependence of the earth's albedo on solar activity. However, a calibration problem between the two observing periods may be the cause, at least partially, of this change.

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.

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.

**Acknowledgments.** This research was supported in part by a grant from NASA (NAG5-11007). The cloud D2 datasets were obtained from the NASA Langley Research Center EOSDIS Distributed Active Archive Center.

## References

- Bromage, B.J.I., and C.J. Butler, Local climatic effects of energetic particles impinging on the atmosphere, *Proc. 31st ESA-LAB Symp, Correlated Phenomena at the Sun, the Heliosphere and in Geospace*, ESA SP-415, December 1997.
- Farrar, P.D., Are cosmic rays influencing oceanic cloud coverage - or is it El Niño?, *Climatic Change*, 47, 7-15, 2000.
- Fröhlich, C., Observations of irradiance variations, *Space Science Reviews*, v. 94, 15, 2000.
- Goode, P.R., J. Qiu, V. Yurchyshyn, J. Hickey, M.C. Chu, E. Kolbe, C.T. Brown, and S.E. Koonin, Earthshine observations of the earth's reflectance, *Geophys. Res. Lett.*, 28 (9), 1671-1674, 2001.
- Goode, P.R., E. Pallé, V. Yurchyshyn, J. Qiu, J. Hickey, P. Montañés-Rodríguez, M.C. Chu, E. Kolbe, C.T. Brown, and S.E. Koonin, Earthshine and the earth's albedo II: Observations and simulations over three years, *submitted*, 2003.
- Haig, J.D., The role of stratospheric ozone in modulating the solar radiative forcing, *Nature*, 370, 544-546, 1994.
- Intergovernmental Panel on Climate Change (IPCC), 2001, *The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.), Cambridge University Press, pp 944, 2001.
- Intergovernmental Panel on Climate Change (IPCC), 1995, *Climate Change 1994, Radiative Forcing of Climate Change and an Evaluation of the IPCC 1992 Emission Scenarios*, J.T. Houghton, L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callender, E. Haites, N. Harris and K. Maskell(Eds.), Cambridge University Press, 1994.
- Lean, J., The sun's variable radiation and its relevance for earth, *Ann. Rev. Astron.*, 35, 33, 1997.
- Pallé, E., and C.J. Butler, The influence of cosmic rays on terrestrial clouds and global warming, *Astronomy & Astrophysics*, 41, 18-22, 2000.
- Qiu, J., E. Pallé, P.R. Goode, V. Yurchyshyn, J. Hickey, P. Montañés-Rodríguez, M.C. Chu, E. Kolbe, C.T. Brown, and S.E. Koonin, Earthshine and the earth's albedo I: Precise and large-scale nightly measurements, *submitted*, 2003.
- Ram, M., and M.R. Stoltz, Possible solar influences on the dust profile of the GISP2 ice core from Central Greenland, *Geophys. Res. Lett.*, 26, No. 12, 1763, 1999.
- Ramanathan, V., R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, E. Ahmad, and D. Hartmann, Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment, *Science*, 243, 57-63, 1989.

Stevens, M.J., and G.R. North, Detection of the climate response to the solar cycle, *Journal of the Atmospheric Sciences*, 53, 2594, 1996.

Svensmark, H., and E. Friis-Christensen, Variations on cosmic rays flux and global cloud coverage - A missing link in solar climate relationships?, *J. of Atm. and Solar-Terrest. Physics*, 59, 1225, 1997.

Tinsley, B.A., G.M. Brown, and P.H. Scherrer, Solar variability influences on weather and climate - possible connections through cosmic ray fluxes and storm intensifications, *J. Atmos. Sol-Terrest. Phys.*, 94, 14783-14792, 1989.

Willson, R.C. and H.S. Hudson, Solar luminosity variations in solar cycle-21, *Nature*, 332, 810, 1988.

Willson, R.C. and H.S. Hudson, The sun's luminosity over a complete solar-cycle 1991, *Nature*, 351, 42, 1991.

---

Big Bear Solar Observatory, New Jersey Institute of Technology, Newark, NJ 07102, USA

(Received \_\_\_\_\_)





**Figure 1:** Seasonal anomalies in the effective albedo,  $A^*$ . From December 1998 through January 2003, there are nearly 396 nights of observations with 11 nights in each of the bins. From January 1999 onward, there are 308 nights for which we have both observations and contemporaneous WSI satellite cloud cover data, which have been averaged in 28 bins with 11 nights in each. We also have ISCCP daily cloud data for the 308 observation nights since December 1998 and ending in September 2001. The  $\times$ 's show the mean of the observations, with the vertical bars being the standard deviation of the mean. The size of the latter stems from the large night-to-night variations in the cloud cover, rather than from uncertainties in the observations. The horizontal bars indicate the temporal span of each average. The diamonds indicate the corresponding simulated results. Anomalies are with respect to the mean for 1999. Top: Observed anomalies are compared to WSI models. Bottom: Same but for the ISCCP simulations, which end with the to-date release of those data. The straight line in both panels represents a linear fit to the observationad anomalies

**Figure 2:** Top Panel: Daily mean Bond albedo over the entire earth, simulated using daily WSI cloud data maps. Middle panel: Same as top but, this time using daily mean ISCCP cloud cover maps as input to our models. Bottom Panel: The daily means in the two upper panels are averaged to monthly values of the earth's albedo for the whole earth (24-hour).

**Figure 3:** Bond albedo simulations of the whole earth. In this case we use monthly mean ISCCP cloud cover maps

as input to our monthly simulation, as opposed to Figure 2 where we used daily values which were then averaged to form a daily value. The observed seasonal anomalies are overplotted (crosses), and arbitrarily scaled for comparison. Note the good agreement on both curves for the year 2001.

**Figure 4:** 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 2. Error bars represent  $\pm 1\sigma$  deviation from the mean. We have less confidence in the 1994/95 data than the recent data, and so show them as faded.

**Figure 5:** Monthly averages of  $A$  are represented by the boxes. The averages derive from monthly average cloud cover data from the ISCCP data as input to the scene model. The averages are plotted against time. The solid line represents the 12-month running mean of the monthly averages.

**Figure 6:** Summary of annual mean albedos determined from observations and simulations. Crosses are our observational results, squares are the WSI model of the 24-hour Bond albedo for all the dates for which we have cloud data, and triangles are our modeled Bond albedos from ISCCP data. For observational determination 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 apparent in the overlapping years of 1999 and 2000.