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Inter-annual variations in Earth's reflectance 1999-2007.

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Abstract.

The overall reflectance of sunlight from Earth is a fundamental parameter for climate studies. Recently, measurements of earthshine were used to find large decadal variability in Earth's reflectance of sunlight. However, the results did not seem consistent with contemporaneous independent albedo measurements from the low Earth orbit satellite, CERES, which showed a weak, opposing trend. Now, more data for both are available, all sets have been either re-analyzed (earthshine) or re-calibrated (CERES), and present consistent results. Albedo data are also available from the recently released ISCCP FD product. Earthshine and FD analyses show contemporaneous and climatologically significant increases in the Earth's reflectance from the outset of our earthshine measurements beginning in late 1998 roughly until mid-2000. After that and to-date, all three show a roughly constant terrestrial albedo, except for the FD data in the most recent years.

Using satellite cloud data and Earth reflectance models, we also show that the decadal scale changes in Earth's reflectance measured by earthshine are reliable, and caused by changes in the properties of clouds rather than any spurious signal, such as changes in the Sun-Earth-Moon geometry.

1. Introduction

Earth's global albedo, or reflectance, is a critical component of the global climate as this parameter, together with the solar constant, determines the amount of energy coming to Earth. Probably because of the lack of reliable data, traditionally the Earth's albedo has been considered to be roughly constant, or studied theoretically as a feedback mechanism in response to a change in climate. Recently, however, several studies have shown large decadal variability in the Earth's reflectance.

Variations in terrestrial reflectance derive primarily from changes in cloud amount, thickness and location, all of which seem to have changed over decadal and longer scales (Pallé and Butler, 2002). Global compilations from ground-based radiometer data (Liepert, 2002), covering the period 1960-1990, suggest a substantial decrease in solar irradiance reaching the ground. More recently, Wild et al (2005) have brought up-to-date the Global Energy Balance Archive (GEBA), which is a long-term series of ground-based measurements of the solar radiation incident upon the Earth's surface. These data, together with newly available surface observations from the Baseline Surface Radiation Network (BSRN) from 1990 to present, show that the decline in solar radiation reaching land surfaces seen in earlier data disappears in the 1990's. Instead, a brightening is observed since the late 1980's. This large, long-term variability in the shortwave surface radiation budget would seem to imply that the Earth's albedo has also undergone substantial changes at decadal time scales. However, a long-term, global albedo database does not exist.

Direct measurements of the Earth's albedo from satellite platforms did not start until the 1980's. However, ground-based observations of the albedo by means of earthshine observations go back further in time (Danjon, 1928 and 1954; Dubois, 1947; Bakos, 1964).

These are measurements of the brightness ratio between the bright and dark portions of the lunar surface, from which the instantaneous large-scale Earth reflectance can be estimated. More recently, since the mid 1990's, modern earthshine observations, using CCD cameras have been continuously recorded (Qui et al, 2003; Pallé et al, 2003). Pallé et al (2004a) correlated the earthshine data with International Satellite Cloud Climatology Project (ISCCP) cloud data to construct from the latter a proxy record of the Earth's reflectance. They showed from that proxy that the Earth's albedo decreased by about 6 W/m^2 from 1985 to 2000, while direct earthshine observations from 1999-2003 revealed that the decline had stopped and even reversed to an increasing trend in reflectance. The ISCCP project however, recently released the FD product, which contain estimates of the top of the atmosphere (TOA) albedo. These data are based on ISCCP cloud properties, plus some modeling estimates to derive shortwave and longwave fluxes, and they indicate a more muted long-term albedo decrease from 1983 to 2000. A more apparent difference showing opposing trends between albedo estimates was found between the earthshine data and the CERES dataset over the period 2000-2003 (Wielicki et al, 2005). However, when compared to other direct and indirect albedo indicators, a simple answer as to how the global albedo behaved did not emerge (Pallé et al, 2005b). Meanwhile, data collection has continued, and in the past couple of years, all datasets in the aforementioned literature have been re-calibrated and/or re-analyzed, so it is now proper to make a new comparison, which also benefits from a longer time line.

In this paper, we study in detail the inter-annual trends in the Earth's reflectance over the modern period of earthshine observations 1999-2007. In section 2, we examine the long-term trends of reflectance from earthshine and compare them to satellite estimates from ISCCP and CERES. Finally, in section 3, we describe our observational data and we also model it to determine whether long-term changes in the orbital parameters of the Earth and the Moon can induce a false long-term signal in our earthshine reflectance data.

2. Inter-annual reflectance changes

The *earthshine* is sunlight reflected from the Earth and then reflected back from the Moon back to the nighttime Earth. Global albedo can be determined by measuring the earthshine's intensity relative to that of the *moonshine* (sunlight directly reflected from the Moon to Earth, i.e., the bright of the Moon). Continuous earthshine observations from Big Bear Solar Observatory (BBSO) in California, have been performed from November 1998 to October 2005 (7 complete years). Earthshine data collection stopped for a period of eight months, from November 2005 to July 2006, due to the refurbishment of the Big Bear dome for the new solar telescope. When observations were resumed in mid-2006, two telescopes were used simultaneously, the old manual telescope and a new improved, robotic telescope, the first of a global network (see Pallé et al, 2005a).

When simultaneous data from both earthshine telescopes were compared to calibrate the two datasets, the new telescope data were found to be superior to the older data. This led to our decision to implement a more systematic way to select "good nights". We did this by plotting the nightly albedos as a function of lunar phase, and making fits that were $\pm 3\sigma$ from the fit to the data. Outliers were cast out and the process repeated until it converged (after about five iterations). This had the consequence of systematically casting out about 10% of the nights, which is only a few percent more than were cast out in our old, night-by-night evaluation. The systematic approach is robust in the sense that it is reasonably insensitive to varying how tight we make the fit in iterative process of casting out relatively poorer nights. Implementing the automated selection process had its most apparent impact on the earthshine annual anomaly trend in reducing the size of the large 2003 albedo anomaly (Pallé et al, 2004a), although the result for each year changed. The new annual mean anomalies are compared in Figure 1 to those published in earlier papers. Over the 1999-2007 period, there is an increasing reflectance trend from 1999 to 2003, but after that year the reflectance does not seem to vary. In fact, except for 2003, the Earth's reflectance as measured by earthshine has not changed since 2001. These data also imply a more modest trend than the old 1999-2003 data suggested (Pallé et al., 2004a). Over the common period of 1999-2004, the new analysis of the earthshine data indicates an increase of about $2W/m^2$, which is about half what the earlier analysis indicated.

The old earthshine data, shown in black in the top panel of Figure 1, were found to be in strong contradiction to TOA albedo anomalies as measured by the CERES instruments onboard the Terra and Aqua satellite (Wielicki et al, 2005). These data showed a decreasing trend of $2W/m^2$ over a period of just 4 years. However, since the publication of the earlier results, a calibration error in one of the SW filters was identified and the CERES TOA albedo anomalies have been re-analyzed using an improved six year-long climatology (Takmeng Wong, priv. comm.). As a result, the improved TOA CERES albedo dataset show now no statistically significant trend in reflectance over the 2000-2006 period. See the lower panel of Figure 1.

To further investigate the trends seen in earthshine data, we have compared our measurements with another state-of-the-art TOA albedo dataset, the ISCCP FD product

(Zhang et al, 2004). These data have recently been extended and cover the period from July 1983 to December 2006. In the next section, we make use of these improved datasets to compare the different observing methodologies.

2.1. Multi-data comparison

The yearly changes in Earth's albedo from the most recent analysis of three datasets is plotted in Figure 2. The top panel shows the 24-year period from 1983 to 2006, for which ISCCP FD data are available. Earthshine data are also plotted showing a strong agreement with ISCCP FD estimates. In the lower panel, the temporal scale is truncated to the most recent period, 1999-2006, for which earthshine and CERES observations (starting March 2000) are available.

There are several conclusions to be drawn from Figure 2. First, there is an overall agreements between the earthshine measurements and the FD TOA albedo, which begins to break down from 2005 onwards. During 2005 and 2006, FD data indicate an increase in albedo that is not seen either in Earthshine or CERES data. Some authors (Campbell, 2004) have questioned the stability of the long-term calibration in the ISCCP data, thus it is conceivable that deviations at the end of the time series (2005/06) might be due to a calibration bias. Over the two-year period 1999-2000, however, both earthshine and FD data show an increase in reflectance, with very consistent magnitudes. The agreement between the two datasets suggests that the change is real, but there were no CERES data to confirm the measurements.

Comparing the two panels of Figure 1 with the lower panel of Figure 2 makes it apparent that what was a stark disagreement between CERES and Earthshine data has become a reasonable agreement, within the error bars. Now, over the common period of data 2000-

2007, both datasets show no overall significant changes in Earth's reflectance. While the de-seasonalized CERES data has a small year to year variability (Figure 2), the earthshine data seem to present overly large inter-annual anomalies, along with a large size of the error bars associated to the yearly means. This is mostly due to sampling issues, as earthshine measurements are taken from a single station. However the accuracy of the earthshine data will be improved by the deployment of a network of telescopes around the world (Pallé et al, 2005a).

3. The Earthshine Methodology

On a given night, the earthshine measures an apparent albedo value, p^*, defined as the albedo of a Lambert sphere that would give the same instantaneous reflectivity as the true Earth at the same phase angle (Qiu et al., 2003). One can think of it as the albedo at a given reflection angle. To obtain the Earth's Bond albedo, A, we must integrate the p^* values over all phase angles (over all directions).

Earthshine observations take place when the lunar phase ranges approximately between 50 and 140 degrees. This means that during a lunar month (28 days), we observe approximately half of the nights, divided in two periods of about one week, with a week break between observations. Nightly coverage through a month is illustrated in Figure 3. During the first week of observations the Moon is waxing and it is up in the sky at sunset (negative lunar phases), and observations take place from sunset to moonset. During these observations the area of the Earth that is reflecting sunlight toward the Moon is the Australasian region. In the next round of observations the Moon is waning (positive lunar phases) and observations take place from moonrise to sunrise. During these times, the area contributing to the earthshine is the Atlantic region.

As the Moon waxes toward full, the Earth, as seen from the Moon, becomes an ever thinner crescent, but the Moon also stays observable for a longer time period in the night sky. Thus, we note that during an observational round the size of the area contributing to the earthshine at any moment gradually changes, but this is compensated by the time available for observations. Thus, the combined effect is that the area contributing to the earthshine is roughly constant during our observation rounds, see Figure 3. The night of 19th June (4th panel from the top on the left column) is the exception, with only one hour of observations (instead of the possible 2.5-3) due to local bad weather at Big Bear. Goode et al. (2001) and Pallé et al. (2003) found that the mean albedo value of the two geographic regions was practically identical over the 1999-2001 period.

The annual mean long-term trends have been calculated with all the data combined and also for the Australasian and Atlantic regions, separately. Although there is some scatter among the measurements, there is a general agreement between the year-to-year anomalies for the Australasian and Atlantic regions. However, the long-term evolution of the position of the Moon in the sky for the same lunar phase changes the parts of the Earth contributing to the earthshine. Does this lead to a false long term trend in reflectance?

3.1. Modeling albedo changes with time

Earthshine measurements are corrected for periodic variations in the Sun-Earth-Moon geometry (Qiu et al., 2003; Pallé et al., 2003 and 2004b). However, with the earthshine technique, one can only observe on certain days and at certain times, thus, one should wonder if the aforementioned spatial variations (see Figure 3) and temporal gaps in our measurements can lead to false long-term trends in our earthshine data. To this end, it is essential to determine the effects of changes in the orbital parameters on the retrieved albedo estimates. For this, we used our albedo models (see Pallé et al, 2003 for a detailed description) to estimate such changes in terrestrial reflectance.

Our models use ISCCP mean cloud amount data as an input to ERBE scene models (Goode et al., 2001) from which we retrieve apparent and Bond albedo values. The ISCCP cloud amount data indicates that the Earth's mean cloud amount decreased from 1994-95 to 2000. Some earthshine measurements were made during the 1994-95 period, and also seem to indicate a higher albedo at that time, although the spectrum of data is not as rich as that since 1999 and the older data were not reanalyzed. Nonetheless, it is informative to apply our reflectance models to these two periods: 1994-95 and 1999-2001 to probe for possible deficiencies, while reaching for a clearer exposition of the earthshine data.

Since we use ISCCP data in the reflectance models, it is worth mentioning that the ISCCP cloud data might be subject to some observational biases, which seriously challenge the reliability of their long-term trends (Campbell, 2004). However, this challenge is not directly germane to the experiment we are performing in this section. Here we are about to compare the changes introduced into the albedo due to planetary geometric effect as contrasted to those due to cloud properties (whether or not changes in clouds have taken place in reality).

In Figure 4, we have plotted the 24-hour runs of modeled p^* values for several consecutive days during the month of June (those in the right column of Figure 3), over several years, for the positive (Atlantic region) round of observations. For all panels, the data have a 30-minute time resolution. In panel a, the dominant variation in p^* is due to changes in the lunar phase (the exponential-like curvature), but there is also a modulation due to the Earth's 24-hour rotation, which makes the albedo vary as brighter or darker Earth regions enter or leave the earthshine-contributing area.

From 1994-95 to 1999-2001, the Moon's orbital parameters changed, but the changes in the simulations of earthshine albedos, see panel *a*, are not due to the changing orbital parameters, but rather to the varying cloud maps from day to day, and year to year. This fact is demonstrated in Figure 4 (panel *b*) where the exact same simulations are plotted as in panel *a*, but in this case the cloud maps are fixed and all the simulations use the cloud data for June 13th 2000. In Figure 4 (panel *b*), each simulation of a round of observations uses the orbital parameters and earthshine-contributing areas for that date, and only the cloud maps are fixed. From inspecting panel *b*, we find that the mean apparent albedo does not change from year to year, when the clouds are fixed. Maximum and minimum envelope curves would be the same for all the simulated curves. The year-to-year offsets among the oscillating simulated curves arise because in consecutive years, when the lunar phase is the same, the Universal Time (UT) is different.

Each of the middle panels of Figure 4 show the same data as the top two panels immediately above, except this time they are plotted against UT. The albedo peaks in the middle panels occur at exactly the same time and with the same amplitude when the cloud data are fixed (panel *d*), but not when the real cloud maps are used (panel *c*). To understand this difference, one must bear in mind that the daily variations in the Earth's albedo is caused by the Earth's rotation as various areas come into view and then disappear from the earthshine. But from a given location, we always observe the same areas of Earth, so if we are simulating BBSO observations at around 11:00 UT with fixed cloud cover, when a supposed maximum in daily reflectance occurs, we will see the same bump for each night of the observing round and each subsequent year at that time. The differences from year to year in these panels are due to the fact that the lunar phase and time (UT) are de-coupled variables. Thus, for smaller phases where effective albedo is most sensitive to small changes in phase, the year-to-year differences are larger. However, this does not introduce any annual trend in the effective albedos because we are always comparing our albedo anomalies normalized against lunar phase.

Our models also calculate the Bond albedo, A, over the whole sunlit half of the Earth. The values of A for the same dates as the panels above them are also plotted in the two lower panels of Figure 4. Note that the Bond albedo is higher for the 1994-95 period than for 1999-2001 (panel e), and so is the apparent albedo p^* (panel a), because of different cloud properties during 1994-95. But the albedo values are exactly the same for all years when the cloud data are fixed (panel f).

3.2. Cloud changes and albedo trends

There is a quite different way, using all observing nights, to demonstrate that sampling errors in Sun-Earth-Moon orbital changes could not have introduced our reported drift in the p^* observations. Using six years of ISCCP data 1999-2004 when uninterrupted earthshine observations exist, we have simulated (following Pallé et al, 2003) the p^* values seen at the same times and days when observations were made. We have performed the simulations using the real ISCCP data for each date/time of observation during that period, and next by fixing the ISCCP data to that of the same day of the year but for the year 2000, i.e., effectively removing any long-term trends in the cloud data. We have then processed these synthetic p^* sets in exactly the same way as the real p^* data to generate the anomalies. Further, we have also repeated these two analyses using the same dates as our observations, but averaging the modeled p^* values over the 24-hour daily interval.

The resulting four sets of annual time series' are plotted in Figure 5. When the clouds for each year are fixed to those of a single year, no long-term trend in albedo is visible in either synthetic time series. The error bars on both series imply consistency with no anomaly. However, when real ISCCP data are used, there is an increasing trend for both the synthetic time series using the earthshine observing period and the earthshine daily means (always restricted to the earthshine observing dates). Moreover, the magnitude of these synthetic trends are similar to the observed anomalies in p^* (Figure 1). Thus, the lack of a significant trend in the simulated p^* when cloud data are fixed, demonstrates that the increase in the observed p^* has not been produced by any changes in the Sun-Earth-Moon geometry, but rather by evolving cloud properties.

4. Conclusions

In this paper, we have demonstrated that the agreement between earthshine and CERES reflectances have shown a dramatic improvement after CERES data were re-calibrated and earthshine data were re-analyzed. In the common period, earthshine, CERES along with ISCCP-FD data show a trendless albedo. However, preceding CERES, earthshine and ISCCP-FD reflectances show a significant increase before flattening and holding the increase. This implies a reduction in the net sunlight reaching Earth. In the context of the recent climate change, it is important to point out that the physical causes behind these large decadal variations in albedo are still unknown, and that we just don't know yet whether we should expect the albedo changes observed during the modern period to persist into the future.

Further, we have demonstrated that the trend toward an increasing terrestrial albedo seen in the earthshine is due to evolving cloud properties, rather than sampling problems or issues arising from the Sun-Earth-Moon geometry.

Future observations of the earthshine from a planned global network of robotic telescopes will provide an even more valuable tool, complementary to satellite data, for the study of changes in the short-wave forcing of the Earth's climate. The first robotic telescope is already in regular operation.

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Figure 1: Top: Inter-annual Earth albedo anomalies as measured by earthshine. In black are the albedo anomalies published in 2004, following Palle et al. (2004), and in blue are the updated albedo anomalies after our improved data analysis, which also included more years of data. Bottom: Inter-annual Earth albedo anomalies as measured by CERES. In black are the albedo anomalies published in 2005, following Wielicki et al. (2005), and in red are the updated albedo anomalies after their improved re-calibration of the on-board sensors (Loeb et al., 2007). To evaluate the recalibration effects, a linear fit is applied to both datasets within each panel using only the data over the common period of 2000-2004. For both, Earthshine and CERES, the linear fit to the full dataset up to 2006 would not differ much.

Figure 2: Top panel: Annual mean Earth albedo anomalies, as derived from ISCCP FD data, over the period 1984-2006 are plotted in black. Also, plotted in blue, are the annual mean anomalies measured by earthshine (note that annual means are only plotted for the years with complete data coverage). Bottom panel: Annual mean albedo anomalies, as derived from ISCCP FD (black), earthshine observations (blue) and CERES data (red). For the earthshine data, annual means are calculated from November to October to take advantage of the full database (see main text). For the CERES data, de-seasonalized anomalies are used, which reduces the size of the error bars. However, it is worth noting that the scatter of the CERES points in the lower panel of Figure 1 is comparable to the error bars of the ISCPP FD and earthshine points in the lower panel of this figure.

Figure 3: A plot of the total earthshine-contributing Earth regions for the observed nights in June 1999. The color scale within the sunlit regions represents the mean cloud amount at each point of the Earth. The numbers over-plotted on the maps indicate the

number of hours of observation for the night. Right: The six nights correspond to the observing round of 5th, 6th, 7th, 8th, 9th and 10th June 1999 (positive lunar phases, or waning Moon), from bottom to top, respectively. The region covered is the Atlantic region. Left: The six nights correspond to the observing round of 17th, 18th, 19th, 20th, 21st and 22nd June 1999 (negative lunar phases, or waxing Moon), from bottom to top respectively. The area covered is the Australasian region.

Figure 4: Apparent and Bond albedo simulations for each positive lunar phase (Atlantic region) round of simulated observations during the month of June (for the nights shown Figure 3for the years 1994-95 and 1999-2001. Left panels represent the Atlantic apparent and Bond albedo values simulated using real orbital parameters and appropriate cloud cover maps for the given date of the observations. The models in the right panels also use real orbital parameters, but the cloud maps in all models have been fixed to that of June 13th 2000. Top panels: 30-minute resolution modeled Atlantic apparent albedo values plotted against lunar phase angle. Each year has its own color, and approximately 8 days of consecutive simulated observations are plotted for each year. Middle panels: Same as top panels, but in this case the Atlantic's apparent albedo values are plotted against universal time. Bottom panels: Bond albedo simulations for the same dates as in the two previous panels. Bond albedo simulations cover the whole sunlit Earth. Note that Bond albedo is independent of lunar phase, and it turns out to be identical for each year when the same cloud map is used for all nights: in panel f, five Bond albedo values are represented, but they all fall onto the same curve.

Figure 5: Modeled annual mean p^* anomalies. In black are the simulated δp^* time series using fixed cloud amount data from the year 2000 and in blue using the real ISCCP

cloud data 1999-2004. The solid (blue and black) lines indicate simulations of δp^* for the same dates and during the earthshine observing hours. The broken (blue and black) lines indicate simulations of δp^* of the 24-hour daily average for the same dates as earthshine observations. Note that for both black lines (fixed cloudiness), there is no trend in the δp^* time series. Contrariwise, a positive albedo trend occurs for the two blue lines (real, variable cloudiness) of the same magnitude as the trend in our earthshine observations. For clarity, the 1σ error bars are plotted only for the models calculated at the same dates/times as the observations.

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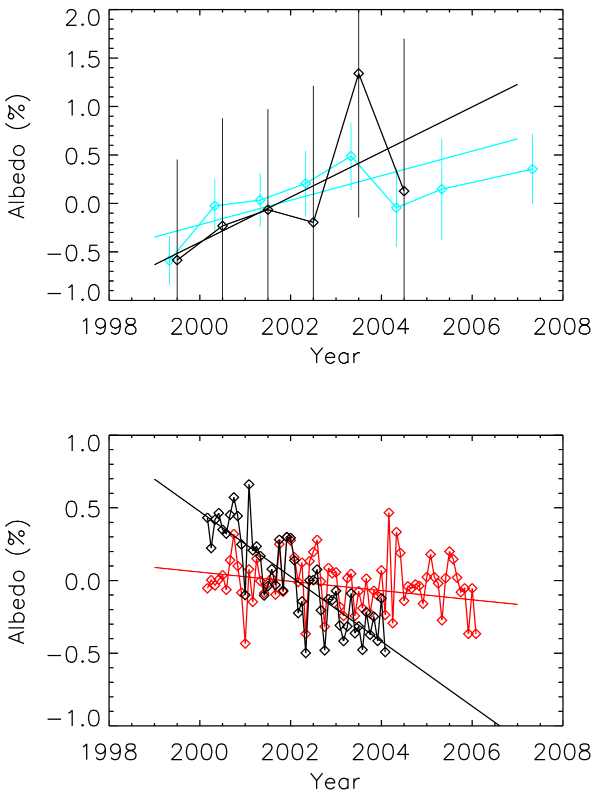
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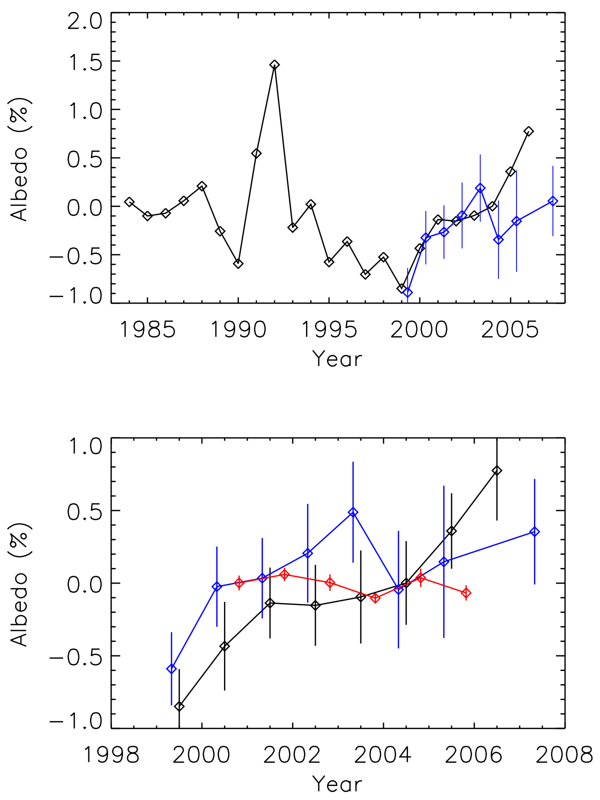
Figure 1.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Year

Figure 2.

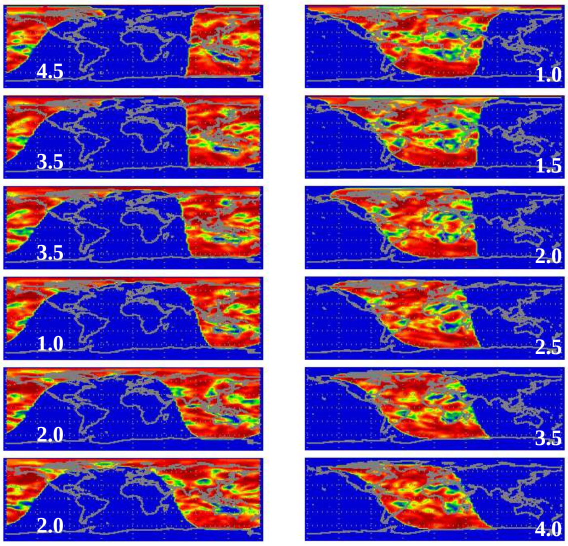

Figure 3.

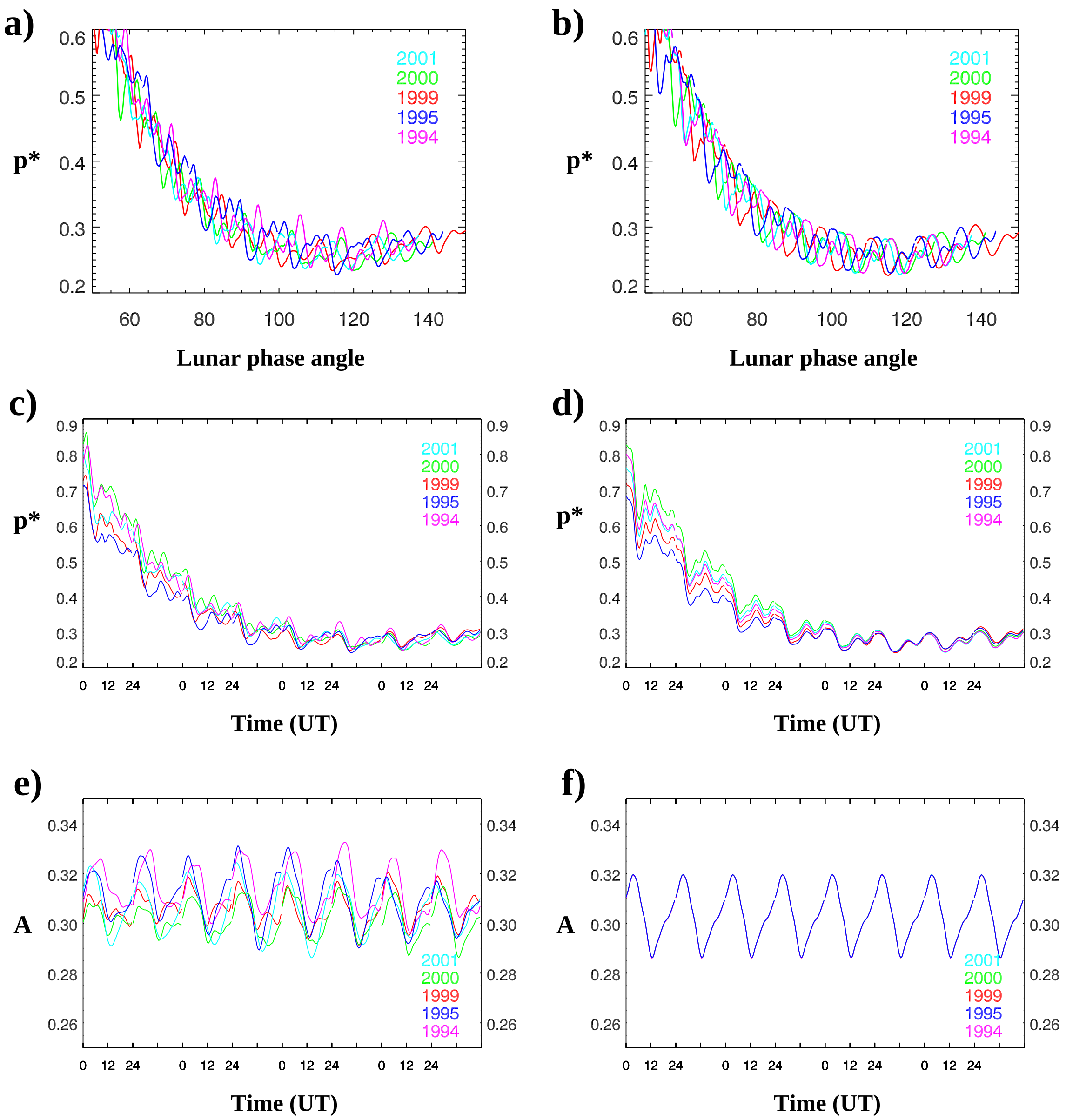

Figure 4.

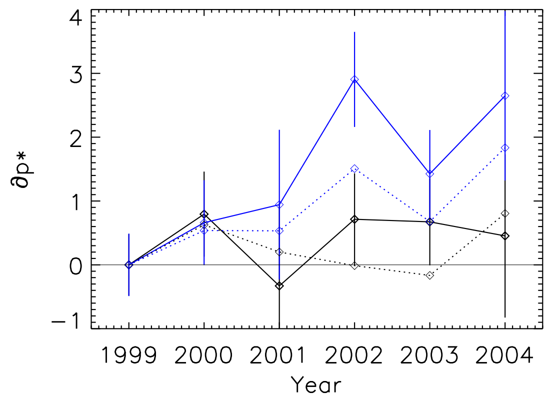

Figure 5.