New developments in using solar cells as remote sensors to gauge climate change

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ABSTRACT

Earth's albedo is the fraction between the radiation reflected outside and the incident solar radiation, and regional albedo is this parameter obtained in the nadir point of a satellite. This work describes a new self-calibrated method for the assessment of albedo using the telemeterized data from the solar cell experiment of the second data collection satellite, second "Satelite de Copeta de Dados" (SCD2), launched on October 1998. A numerical simulation shows that the albedo data of this experiment is a function of the local weather condition (clouds). The continuous monitoring of this data permits one to infer climate change. This work shows and makes analysis of albedo in three cities of Brazil (South America) during 1999 and 2000, which have different climate conditions. The albedo graphics help explain the climate behavior in these regions. The experiment and the method of this work may establish a cost-effective innovation for space programs.

INTRODUCTION

Deforestation, the greenhouse effect, pollution-caused inversions, and other suspected causes of shifting global climate patterns demand that scientists develop practical ways to keep a close watch on changes in the Earth's atmosphere. One important measure is albedo, the percentage of solar energy that is reflected back to space by clouds and the Earth's surface. For example, the albedo is expected to be significantly higher during the summer months in heavily forested areas such as the Amazon, where there is much evaporation of water from the soil. Consequently, higher amounts of radiation are reflected back from Earth toward space. With significant deforestation, the seasonal albedo from the Amazon probably will be lowered.

Recently, Brazil's Instituto Nacional de Pesquisas Espaciais (INPE, National Institute for Space Research) in São José dos Campos, Brazil, developed methods that make ongoing study of albedo

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practical. Prior studies involve relatively expensive CCD (charge-coupled device) cameras and similarly costly calibration methods. This research relies on automated data analysis software, Origin (OriginLab, Northampton, Massachusetts), to interpret readings from solar cells on the second satellite of the Brazilian Complete Space Mission. This new method does not require sensor calibration, but instead makes use of an algorithm that allows global albedo measurements to be self-calibrated during each complete spin of the satellite.

SCD2/MECB, the second satellite of the Brazilian Complete Space Mission, launched in October 23, 1998, has a circular orbit of 750 km high and a spin of 35 rpm. It transmits meteorological data in real time to a ground station in Cuiabá, Brazil (16°S and 56°W). The satellite's orbit is inclined 25° in relation to the plane of the equator. During each orbit, the satellite is illuminated by the sun for 65 min, with the remainder of its 100-min orbit eclipsed by the Earth's shadow. Aboard the satellite are homojunction monocrystalline silicon solar cells that respond to spectra between 400 and 1100 nm, representing two-thirds of the solar spectra. The photogenerated current from these solar cells is directly proportional to the power of the solar radiation (Rauschenbach, 1980). The solar cells are located on the lateral panel of the satellite, such that there is a 180° angle view. The pair of solar cells used for the albedo experiment connects to a load resistance of 1 ohm, and its voltage is amplified to a maximum value of 5 V (Veissid et al., 1997). The amplifying circuit reads any point on the half-sine signal. These data are then transmitted by satellite telemetry to the ground station.

This configuration of solar cells for space research is similar to how many radiometers work and is not new. Instead, the breakthrough is in the development of an algorithm to interpret the luminosity in an instantaneous angle view from the satellite, in lieu of a collimated optical system.

REFLECTIVITY MEASUREMENT

Because the satellite has its spin axis normal to the plane of the solar eclipse, it lets us observe the two peaks of solar radiation that comprise albedo measurements. The higher peak is radiation coming directly from the sun. The lower peak shows the radiation reflected back from the Earth. Both of these graphs, the calculations of peak heights and all the data analysis tasks in these solar cell experiments, were handled by importing files into Origin software. Because the Origin software allows to automate graphing, albedo values during the life of the satellite can easily be obtained.

Figure 1 shows the current generated from the solar cells at 0.5-s intervals on November 21, 1998 at 4:02 p.m. Greenwich Mean Time with the satellite positioned at 3°52″S and 73°17″W. This same current plotted in relation to the satellite's spin phase is shown in Figure 2.

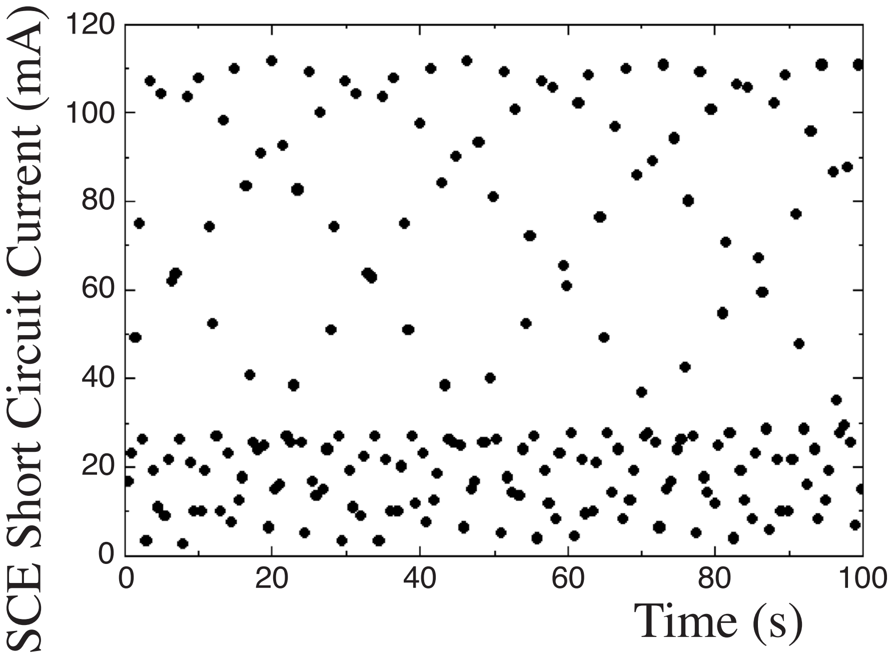


Figure 1. Sample of solar cell experiment data received by SCD2 satellite telemetry.

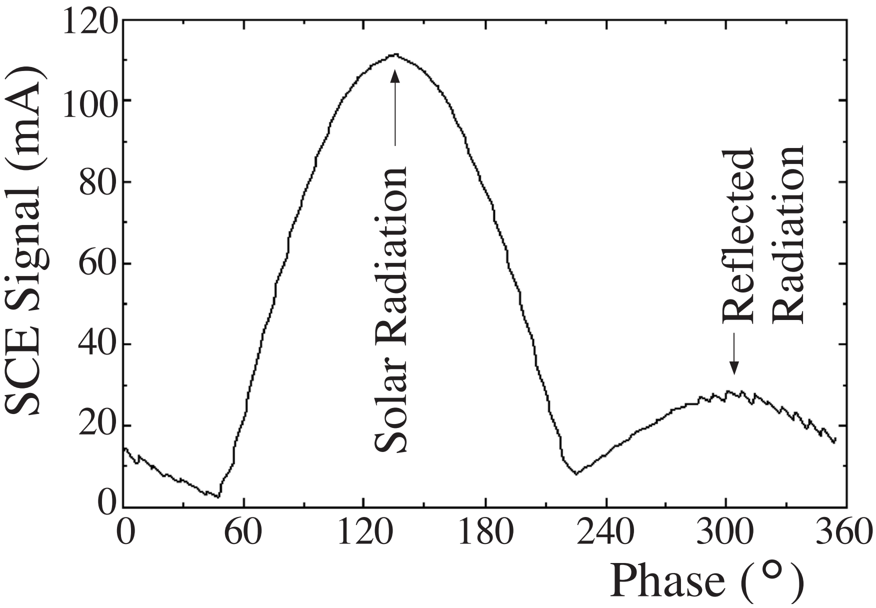


Figure 2. Figure 1 data after the variable is changed from time to satellite spin phase.

However, the exact calculation of albedo requires several mathematical adjustments. The first need is to correct for the effective illuminated area of the solar cell caused by the satellite's spin axis or attitude. The second need is to correct for the sun's ecliptic using spherical coordinates centered on the Earth. Lastly, the need is to take into account the effective area of the Earth's surface that is illuminated at that particular longitude and latitude. A mathematical formula that makes these adjustments is able to correctly calculate albedo and then allows bypasses independent calibrations to account for damage to the solar cells from energy particles outside the Earth's atmosphere.

NUMERICAL SIMULATION

Numerical simulation of albedo validated the result from the solar cell experiment. This numerical simulation began with an image from a Geostationary Operational Environmental Satellite (GOES) satellite obtained in the visible spectrum as shown in Figure 3. The orbit track of the satellite is shown in this figure. The cloud distribution was then simulated in a latitudinal/longitudinal grid as shown in Figure 4.

The albedo seen by the experiment can be represented by

$$A = H[\Sigma(A_{ij}S_{ij}F_{ij}/R_{ij}^3)]/(2\pi) \qquad (1)$$

The parameters A_{ij} and S_{ij} are the reflectivity and area of the elements with latitude j and longitude i, respectively. The parameter H is the altitude of the satellite, and R_{ij} is the distance between the satellite and the grid cell. The parameter F_{ij} is a plane to spherical correction in S_{ij}. Adopting the Earth's surface as a plane, F_{ij} which equals to unity must be considered, but when adopting a spherical model for the Earth's surface, the value of F_{ij} is calculated in terms of area projection.

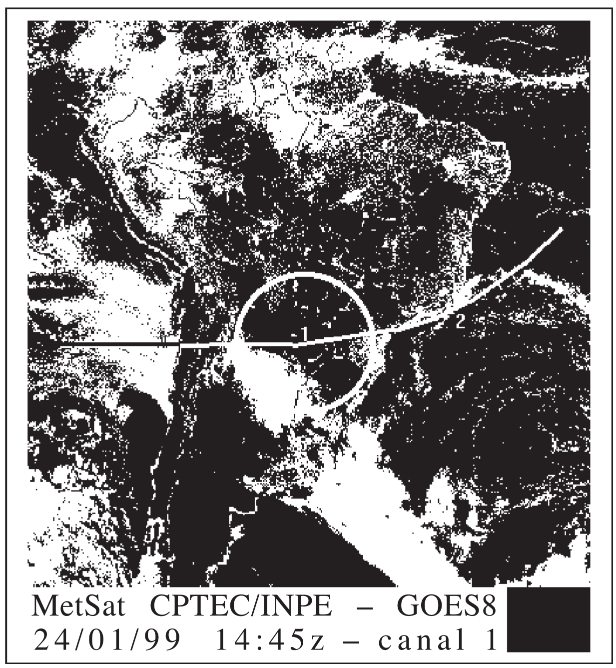


Figure 3. Image of GOES satellite obtained in the visible (VIS) spectrum.

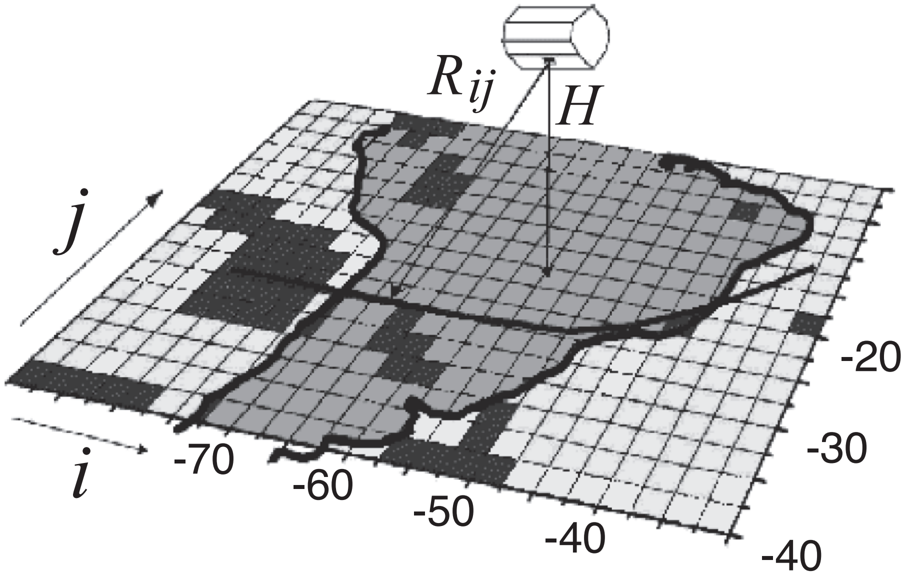


Figure 4. South America map with clouds geometry taken from Figure 3.

The reflectivity values were assumed to be 50% for clouds, 15% for land, and 5% for the ocean. These are, in fact, rough numerical approximations. Although this simulation assumed 15% reflectivity for land, a forest's reflectivity might range between 5 and 20%, depending on the type of trees. The cities have approximately a 15% reflectivity and soil somewhere between 15 and 30%. Figure 5 shows the numerical simulation using equation 1, demonstrating that the albedo measured by the solar cell experiment is in accordance with the momentary weather conditions captured by the GOES image.

The practicality of the solar cells for measuring albedo as compared to conventional methods is also shown by the size of data sets needed to make albedo measurements. Conventional methods using meteorological images from GOES, Landsat, or National Oceanic and Atmospheric Administration satellites would need more than 10 gigabytes of images to do graphic such as Figure 5, but this method to measure global

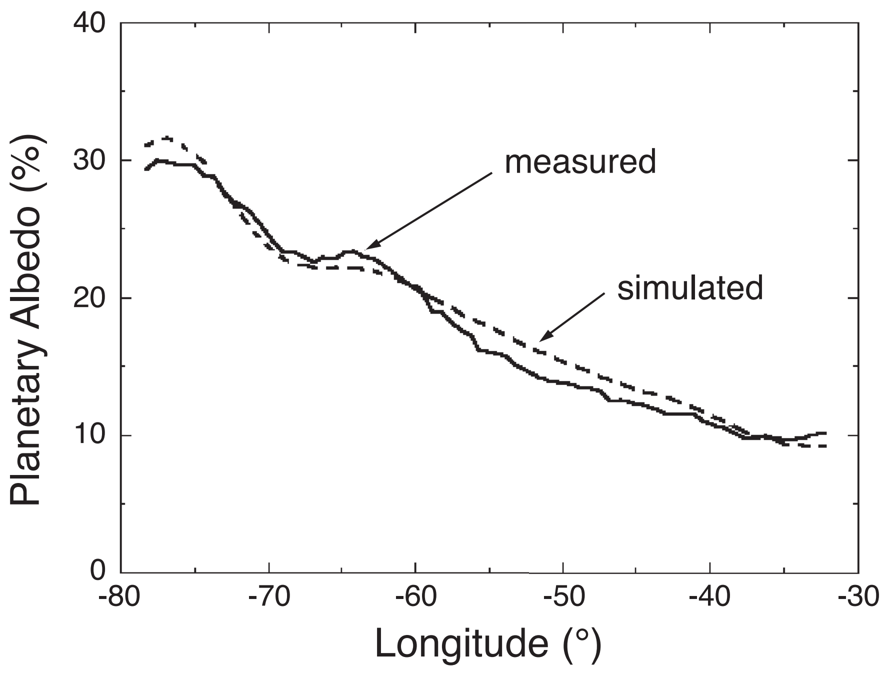


Figure 5. Planetary albedo measured by the experiment and simulated using equation 1 and map data of Figure 4.

albedo only requires 15 megabytes of data. To do the same task when analyzed with Origin software makes near real-time calculations feasible.

EXPERIMENTAL RESULTS

The solar cell experiment data that permit to extract South American albedo values began in November 1998, the date of SCD2 satellite launching (Veissid and Pereira, 2000). Three Brazilian cities are depicted here: Recife (8°S, 35°W); São Paulo (24°S, 47°W); and Manaus (3°S, 60°W). These cities have different climates. Recife has good weather nearly year round. São Paulo, in contrast, is famous for weather instability, with temperatures governed by cold fronts that come suddenly from the south. Finally, Manaus is located in the Amazon forest and has a climate that is governed by the season. Figure 6 shows the planetary albedo obtained in these cities during 1999 and 2000. The values were taken in the latitude and longitude ranges given above within a resolution of ±5°.

Based on the data shown in Figure 6, it is possible to extract four parameters of albedo as a function of time: (1) the maximum value of albedo for each month (Figure 7); (2) the minimum value of albedo for each month (Figure 8); (3) the mean value of albedo for each month (Figure 9); and (4) the standard deviation from the mean shown as weather variability for each month (Figure 10). A rigorous analysis of these curves allows one to obtain knowledge about global change.

ANALYSIS

An analysis of the Origin-generated graphs reveals the following.

Recife

The minimum albedo is stable at approximately 8% in Recife city during the full year, the mean value ranges approximately 14%, and the maximum ranges approximately 20% for both 1999 and 2000. An interesting finding in the maximum and minimum albedo readings (Figure 7, 8) is that there is a perturbation in the months of February, November, and December. These are summer months in the southern hemisphere, when more solar energy causes the strong convective forces in the atmosphere that creates these perturbations. This effect is demonstrated in the variability chart (Figure 10), when the summer months show significantly higher values than the typical 3% variability. However, the month of January does not show this perturbation despite its also being a summer month. Why similar instability does not occur in January 1999 and 2000 is not yet known. Data analysis of the albedo in future years can confirm (or not) this behavior. Overall, the curves in the figures related to the city of Recife do indicate that it has very good weather nearly throughout the year.

São Paulo

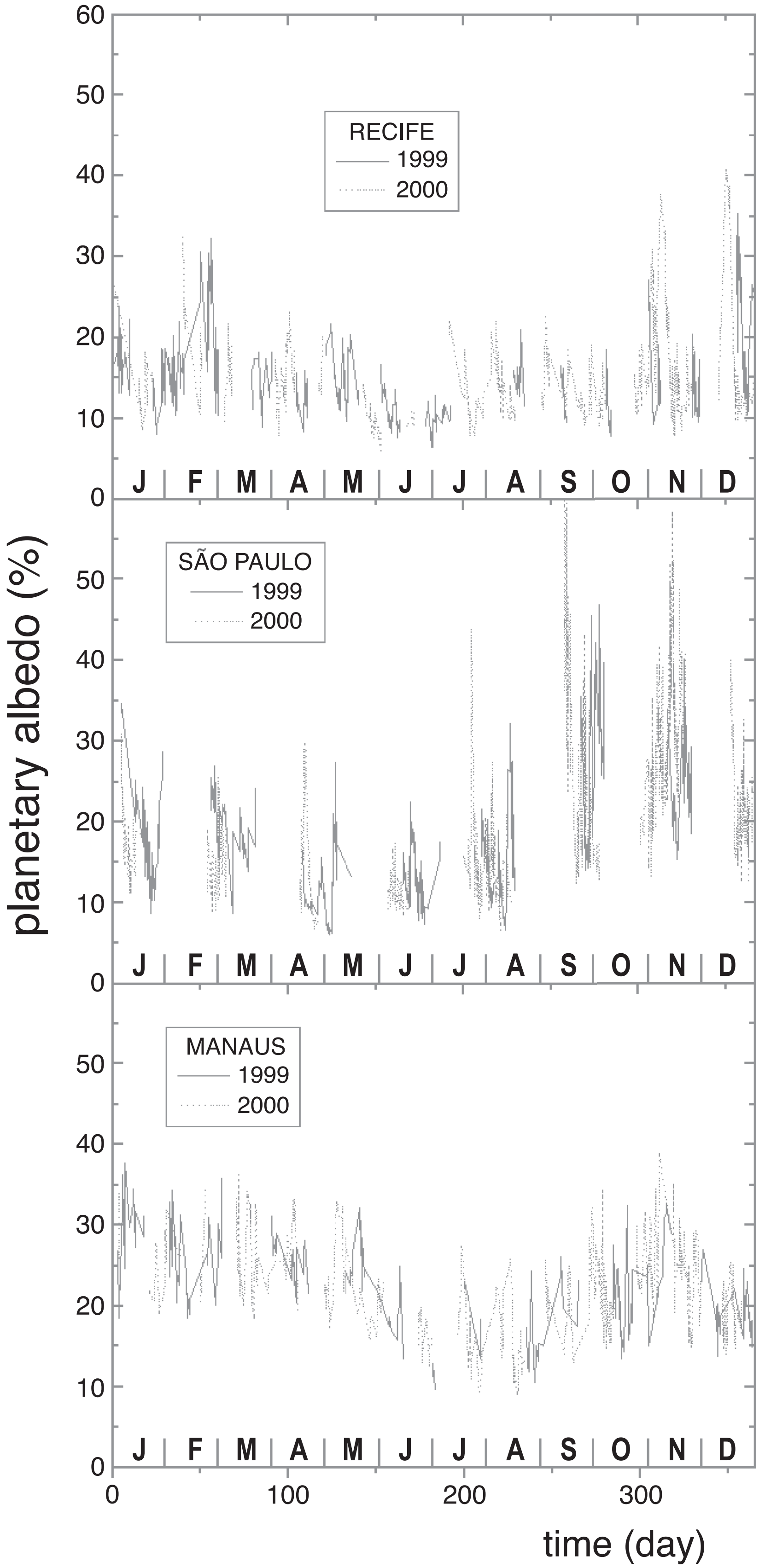
The region of São Paulo shows the highest albedo. Figure 7 clearly depicts the unstable climate of this city. To exemplify, the months of April and August 1999 and April, June, July, August, and November 2000 had the maximum albedo value very different from that of the successive month. This vacillation gives a handsaw aspect to the curve in Figure 10. Figure 8 shows a minimum albedo of approximately 9%. However, in May and August 1999 and April and August 2000, this minimum is around 6%, an observation that detects the thermal inversion that periodically plagues this city, because such thermal inversions are known to be exacerbated by pollution. These albedo studies over the long term hold promise of providing objective gauges of climate effects in this regard.

Manaus

The maximum albedo value for the city of Manaus is closely related to seasonal fluctuations in the Amazon forest. During the winter (June, July, August, and September), there are few clouds, and the maximum albedo is low, as shown in Figure 7. Additionally, the curve of minimum albedo (Figure 8) also shows a lower value during the winter months, presumably for the same reason. This is explained by Paul and Shukla's (1994) demonstration that evapotranspiration and air humidity is lower during winter months. Consequently, during winter months, the air reflectivity caused by persistent humidity is diminished.

Figure 10 shows a very stable variability curve, never higher than 6%. This can be explained by the Amazon forest being a very good climate regulator. Although this process is not well explained, it reinforces the value of monitoring albedo. Such monitoring will demonstrate adverse global changes, such as damage to the climate-regulating ability of the rain forest.

Figure 6. Regional albedo measured during 1999 and 2000.



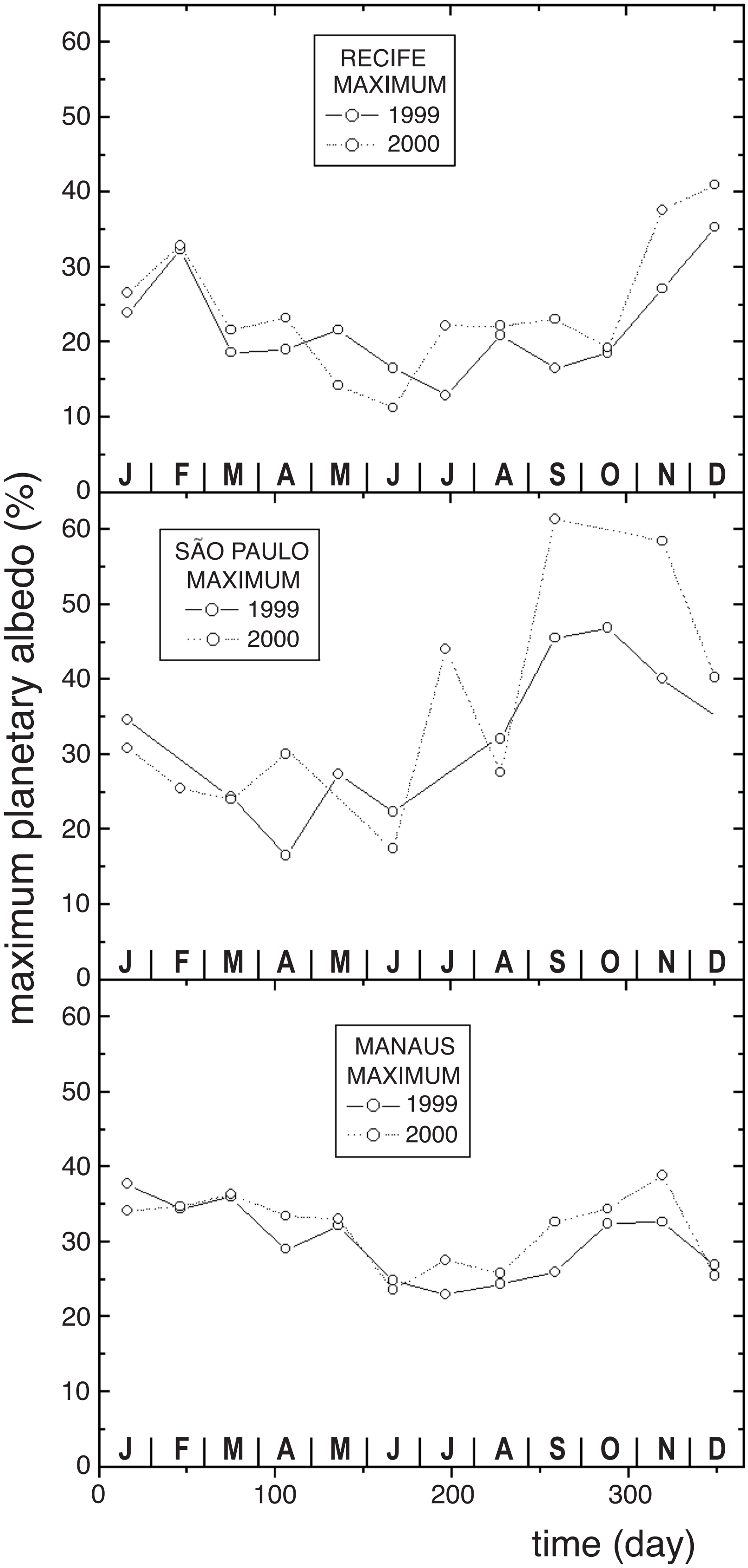
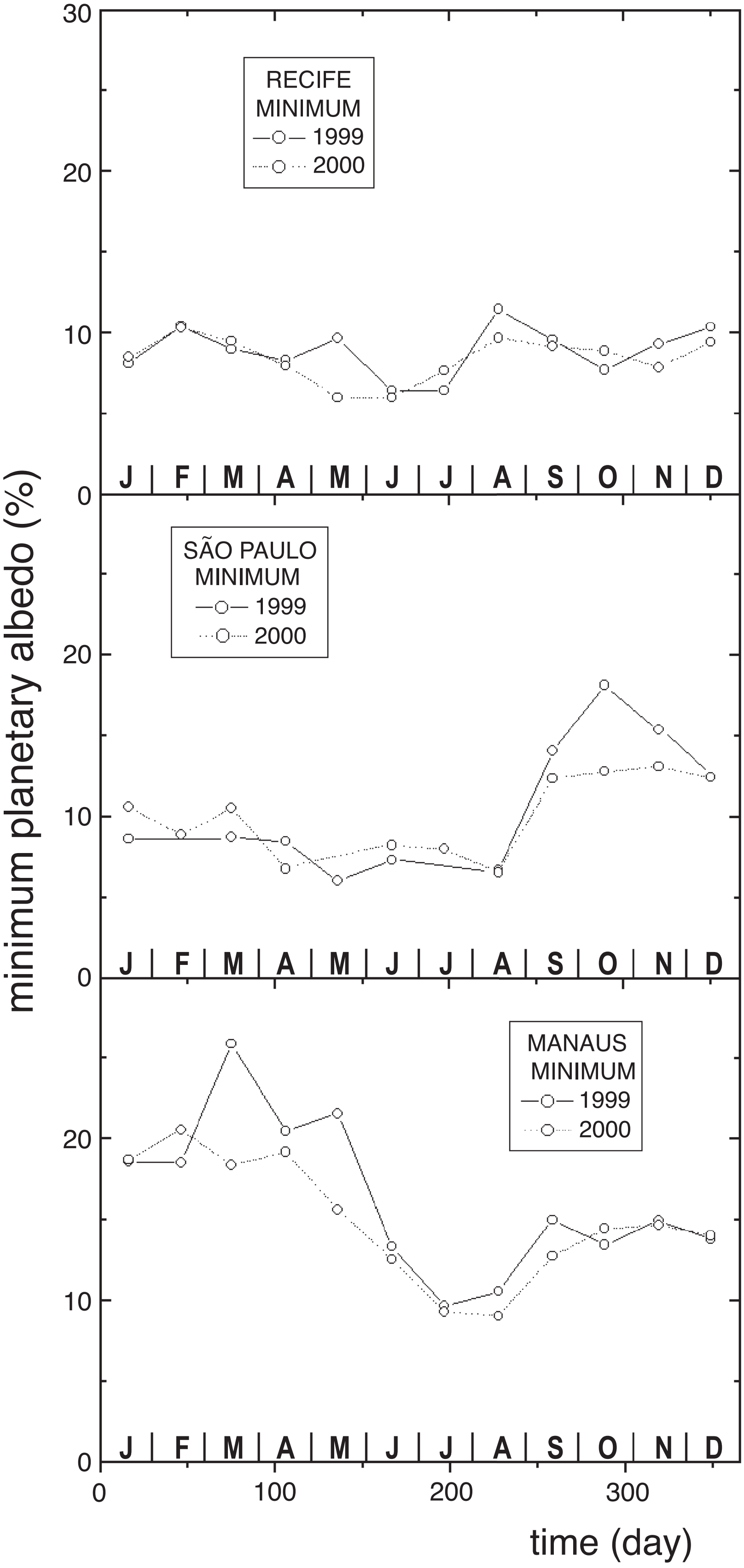


Figure 7. Monthly maximum values of regional albedo taken from Figure 6.

Figure 8. Monthly minimum values of regional albedo taken from Figure 6.



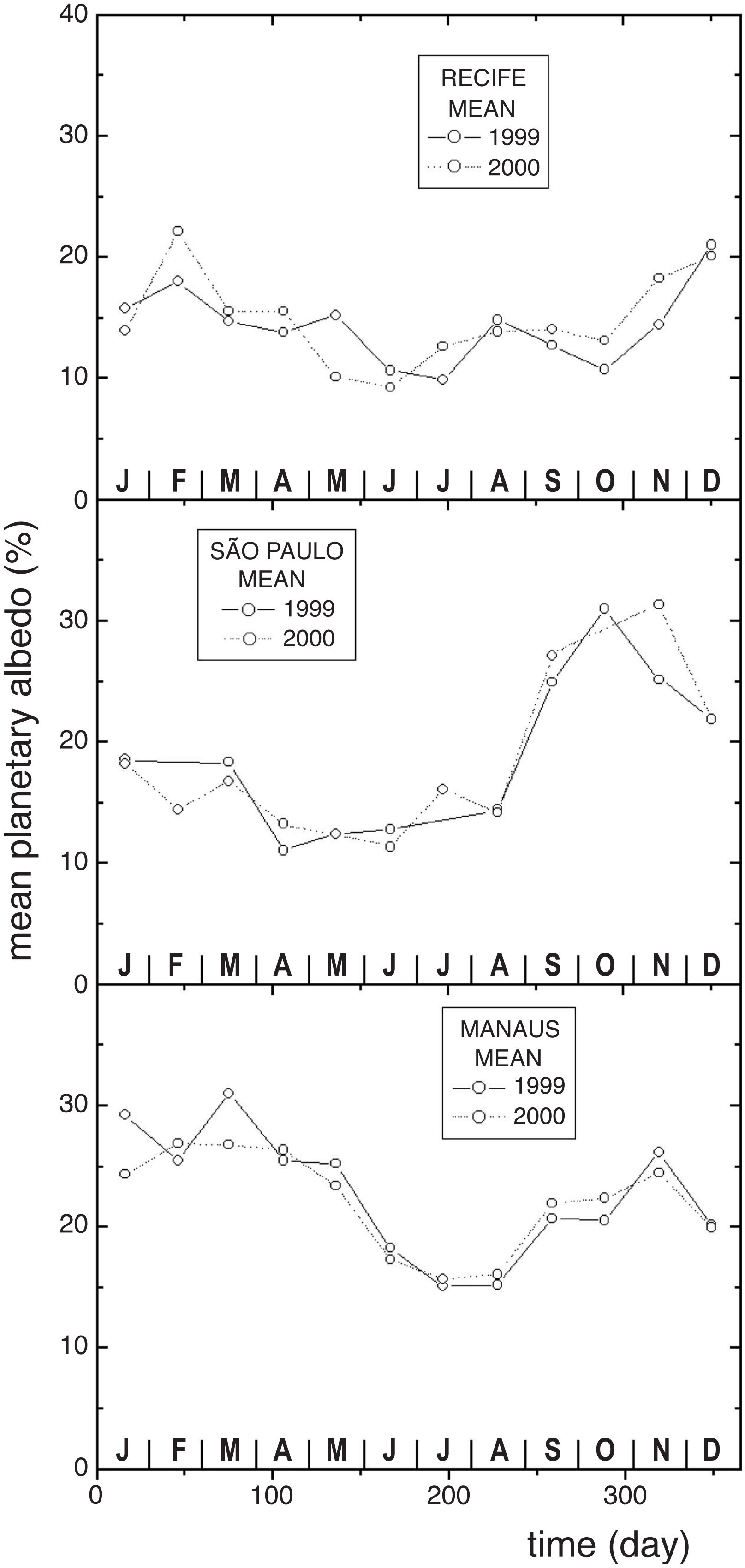
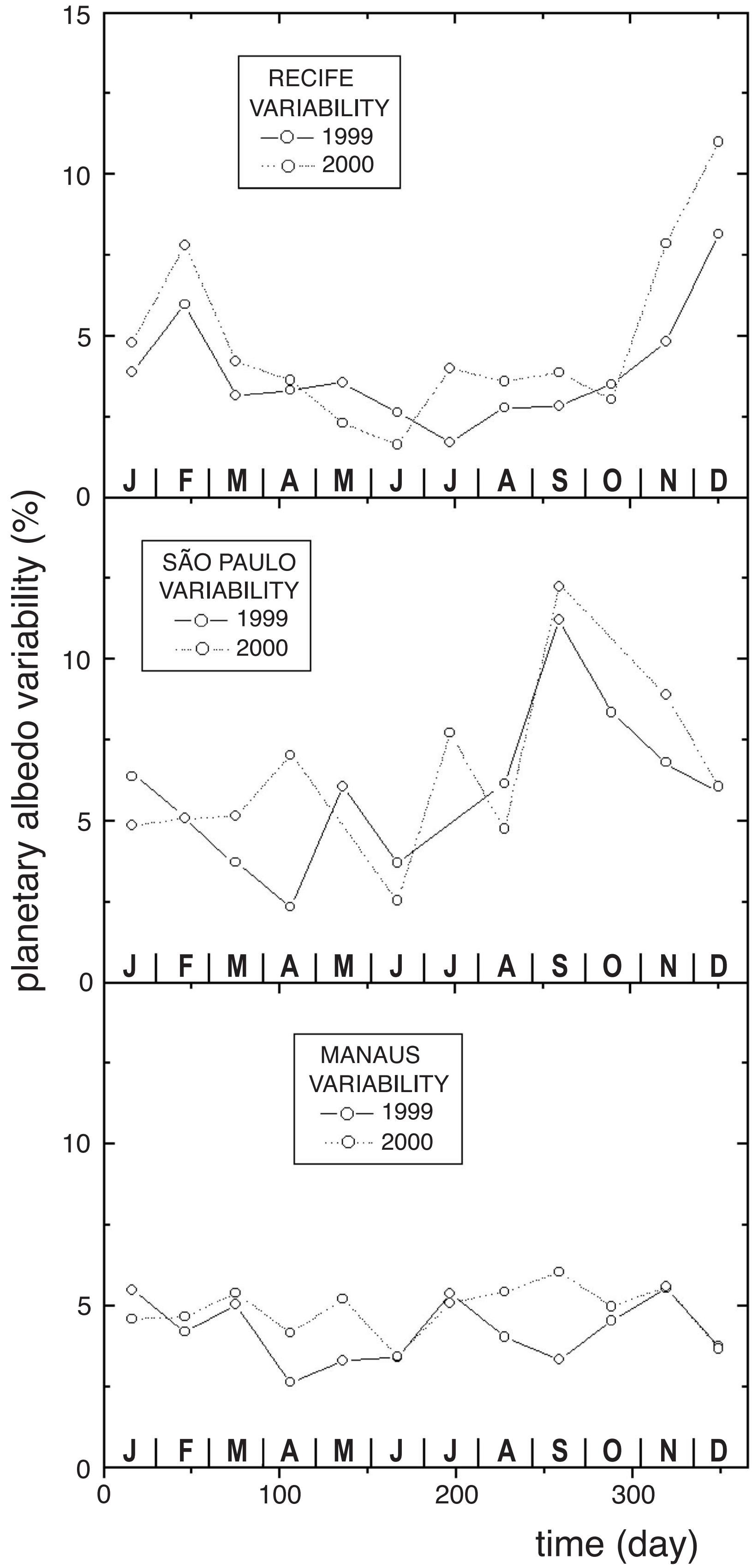


Figure 9. Monthly mean values of regional albedo taken from Figure 6.

Figure 10. Monthly values of regional albedo variability taken from Figure 6.



These data obtained in this work can be shown also in the form of images on the map of South America. This different way to present data can be seen in the web site of the author. In this site, there are two-dimensional graphs that map images of the albedo values as a function of latitude and longitude, where the contour lines in the images are calculated using Origin software.

CONCLUSION

Neither the advanced data analysis and graphing software from Origin nor the solar cells used in these experiments are new. Origin software has been used by a wide range of research scientists in many fields. Solar cells are the mechanisms of various radiometers used for measuring visible radiation. Instead, what is new is the algorithm used for interpreting data. Although other methods must rely on expensive sensor calibrations to account for damage from the energetic particles outside of the Earth, these albedo measurements are self-calibrated through the algorithm. In fact, the quotient between both peaks of Figure 2 eliminates effects of solar cell degradation and temperature variation during the signal measuring and during the life of the satellite.

The parameters of albedo graphed for Recife, São Paulo, and Manaus show that with the 2-yr span of these experiments, these solar cell studies provide insights that can help us gauge change caused by deforestation, pollution, and other man-made or natural (volcano) effects on the planet.

REFERENCES CITED

Paul, A. D., and J. Shukla, 1994, Albedo as a modulator of climate response to tropical deforestation: Journal of Geophysical Research, v. 99, no. D10, p. 20,863–20,866.

Rauschenbach, H. S., 1980, Solar cell array design handbook: New York, Van Nostrand Reinhold Comp, 549 p.

Veissid, N., P. Nubile, and A. F. Beloto, 1997, Results of the solar cell experiment of the first Brazilian satellite: Solar Energy Materials and Solar Cells, v. 46, no. 1, p. 1–16.

Veissid, N., and E. B. Pereira, 2000, Estimativa do albedo planetário empregando dados do experimento célula solar do satélite Brasileiro SCD2: Brazilian Journal of Geophysics, v. 18, no. 1, p. 25–38.