Recent Advances in Satellite Measurements of Aerosol Albedo

L. Franck[1], A. Masterson[2], K. Pistone[1], K. Suski[2]
[1]*Scripps Institution of Oceanography, UCSD, La Jolla, CA*
[2]*Department of Chemistry, UCSD, La Jolla, CA*

ABSTRACT

Error in determining aerosol optical properties, and the effects of anthropogenic aerosols on planetary albedo represent a large source of uncertainty in global climate models. Aerosols directly and indirectly affect planetary albedo in a number of ways: by anisotropically scattering incoming solar radiation, and by altering cloud microphysical properties, differentially affecting their size and lifetime in the troposphere. Remote sensing techniques by satellite-based instruments are used to measure both the spatial distribution and the optical properties of aerosols. This information shows the most potential for quantifying aerosol optical properties and determining the magnitude of the cloud albedo effect. Retrieved raw data must subsequently be adapted into parameters usable by scientists, such as the single scattering albedos, through the use of retrieval algorithms. There are still limitations to these methods and uncertainties in the procured data, but both the instrumentation and the computational techniques are improving. The launch of the Aerosol Polarimetry Sensor as a part of NASA's Glory Mission in December 2008 will enhance measurement capabilities to better determine the influence of aerosols on planetary albedo.

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1. Introduction and Background

1.1 Aerosol Properties and Effects

An aerosol is defined as a solid or liquid suspended in a gas phase. Anthropogenic and natural aerosols, such as SO_2-derived sulfate particles, smoke particles from biomass burning, wind blown mineral dust, bioorganic compounds, and sea salt aerosols demonstrate a strong climatic influence in the troposphere. Aerosols are chemically heterogeneous, have unpredictable spatial distributions, and have atmospheric residence times ranging from seconds to months. As a result, they are the largest source of uncertainty in predicting climate change and in determining the terrestrial radiative balance (Quaas et al. 2008). Incoming shortwave solar radiation is directly scattered and absorbed by atmospheric aerosols, which results in an increase in albedo and a decrease in surface temperature due to a reduction in solar radiation reaching the Earth's surface. However, terrestrial longwave radiation is also absorbed by aerosols, which can then lead to surface warming (Curry and Webster 1999). The range of climatic responses is difficult to quantify and to incorporate into global climate models (IPCC 2007).

In addition to these direct effects, aerosols also have indirect effects on cloud albedo, lifetime, and microphysical properties (Twomey 1977; Albrecht 1989). Aerosols serve as cloud water droplet formation sites called cloud condensation nuclei (CCN). Tropospheric aerosols increase the number of CCN at constant liquid water content (LWC), reducing the cloud droplet effective radius, increasing in the number of droplets per cloud, and increasing the cloud optical thickness (Twomey 1977). Smaller cloud droplets more effectively scatter incident solar radiation, which increases cloud albedo; this is known as the "Twomey effect" or the "first indirect effect" (Haywood and Boucher 2000). The second indirect effect results from cloud microphysical changes, which cause precipitation suppression and increased cloud lifetime (Albrecht 1989; Andreae and Rosenfeld 2008). By increasing the lifetime of clouds, aerosols increase fractional cloud cover leading to an increase in albedo. Atmospheric dimming and subsequent surface cooling can also occur due to increased cloud cover (Curry and Webster 1999). Quantifying these effects via satellite remote sensing has proven difficult; the following review assesses the development of technologies used to measure aerosol albedo from satellites and discusses current advances in the science.

1.2 Aerosol Optical and Physical Parameters

One must accurately determine spatial and temporal estimates of aerosol optical parameters and must also reconcile the large numerical inconsistencies between different satellite and land-based measurements in order to construct an accurate model of Earth's radiative budget. Consistent measurements of the Ångstrom exponent, the asymmetry g factor, the aerosol optical depth (AOD), and the single scattering albedo (SSA) ω are critical in evaluating the direct climatic influence of tropospheric aerosols (Liu et al. 2008). The Angstrom exponent relates the wavelength dependence of optical depth and the asymmetry parameter g, and is an integrated ratio of the angular distribution of scattered radiation. AOD quantifies the amount of incoming solar radiation scattered or absorbed by atmospheric aerosols. Single scattering albedo (SSA) ω, the ratio of scattering optical depth to total optical depth, is the most important parameter in determining the magnitude of aerosol radiative forcing (Seinfeld and Pandis 1998). Incoming solar radiation is scattered in all directions; the efficiency of scattering is dependent upon the incident wavelength and the size and type of the aerosol droplets (Charleson et al. 1992; Quaas et al. 2008). Aerosol SSA varies globally, therefore radiative balance models usually employ SSA as a derived quantity from total AOD measurements, which are intrinsically subject to their own radiometric error. Errors in these measurements are usually large due to spatial variability and error in determination of aerosol properties (Ayash et al. 2008). The usage of different model parameters such as AOD measurements from ground-based and satellite-based sources is a large source of error because measurements are made at different times and are frequently site specific. Modeling the indirect effects of aerosols on albedo also presents a challenge; models are limited in their ability to characterize the effects of heterogeneous aerosol properties on clouds already demonstrating a wide range of microphysical and physical properties (Ayash et al. 2008). Increasing the number of the measured wavelength bands in optical property measurements, and determining the angular distribution of scattered radiation will prove critical in detailing the primary interaction of aerosols with incident radiation.

1.3 Climatic Effects of Aerosols

Qualitatively we understand the impact of human behavior on the climate system, but recent research aims to quantify the effects of anthropogenic aerosols, i.e. those present because of human activity, such as aerosols produced from burning fossil fuels. Aerosol direct radiative forcing (DRF) is defined as the perturbation of the radiative flux caused solely by anthropogenic aerosols (Bellouin et al. 2005). Aerosol type, size distribution, and column density in the atmosphere are still sources of uncertainty when interpreting atmospheric satellite data. The indirect interaction of aerosols with clouds and their influence on the liquid water path (LWP) --the vertical integral of the liquid-water mixing ratio-- inside clouds is an inherently complicated effect to quantify (Quaas et al. 2008). Anthropogenic aerosols tend to be smaller in diameter yet are increasingly more numerous than those occurring naturally; a shift of this type fundamentally alters the behavior of the cloud and precipitation system. The increased number of particles produces a decrease in the droplet effective radius for a cloud of constant water content. Precipitation suppression can extend the lifetime of clouds and increase the fraction of cloud cover. The Twomey effect describes an increase in the amount of reflected incident solar radiation corresponding to increases in anthropogenic aerosol concentration in the atmosphere. These shifts not only affect aerosol albedo characteristics, but also alter weather patterns around the globe (Curry and Webster 1999). Understanding these parameters and effects is necessary for incorporating aerosols into predictive climate models, and to understanding future weather patterns.

2. Satellite Measurements of Aerosol Albedo

Most early satellite measurements of aerosol albedo were made on instruments originally designed for other purposes. These satellites include the Advanced Very High Resolution Radar (AVHRR) and Meteostat. More recent satellites include instruments specifically designed for albedo observation quantification with emphasis on aerosol and cloud variables. One of the primary satellite tools used in current aerosol observation is MODIS (MODerate resolution Imaging Spectroradiometer). During the lifetime of this instrument alone, great improvements have been made in the accuracy of the calculations. There are two MODIS instruments currently in orbit aboard the NASA satellites Terra and Aqua. The Terra satellite was launched on December 18, 1999, and Aqua on May 4, 2002. The two satellites orbit in opposite north-south directions to view the entire terrestrial surface every 1 to 2 days from an altitude of 700km –Terra orbiting across the equator north-to-south in the morning, with Aqua (included in the A-Train) passing south-to-north in the afternoon. MODIS utilizes 36 different μm channels, corresponding to different wavelengths and resolutions, to collect data over the spectral range from 0.41 to 15 μm. For the specific purpose of aerosol observation, the 0.47 to 2.13 μm bands (seven of the 36 channels) are used, with specific emphasis on the 0.47, 0.66, and 2.12 μm channels (Remer 2005). This is a much broader spectral range than previous satellite sensors. MODIS also has three spatial resolutions: two channels at 250 m, five channels at 500m, and the remaining 29 channels at 1 km (0.66 μm has 250 m resolution, while the 0.47 and 2.12 μm bands have 500 m resolution). These improved parameters as compared to previous satellites have allowed MODIS to collect a higher accuracy on the actual value of optical depth (τ) for different wavelengths. MODIS makes use of algorithms to derive both the aerosol optical thickness (AOT), which determines the absorptivity of the atmosphere to light. Algorithms also estimate aerosol loading, size distributions, which are used for determining additional optical parameters.

3. Satellite Data Algorithms

3.1 The MODIS Algorithm

In order to convert the raw data collected by satellites into a form usable by scientists, an algorithm must be invoked. Different types of raw data will require different processing algorithms. With advances in satellite and data collection technology come advances in algorithmic calculation as well, to perhaps an even greater degree.

In the case of MODIS, different algorithms must be applied over land and ocean, but in both cases the raw radiances and reflectance are first corrected for water vapor, ozone, and carbon dioxide. The MODIS satellite radiometer utilizes in particular the three channels mentioned previously: two in the visible range (0.47 and 0.66 μm) and one in the near-infrared (2.12 μm). This data is then organized into 10km boxes of 400 pixels (20×20) each. Each pixel can then be classified as cloudy, snow/ice, or water; the ocean algorithm requires that all 400 pixels be classified as water (Remer 2005). The land algorithm is the easier of the two: the pixels are all masked, and the brightest 50% and darkest 20% are discarded to eliminate residual cloud contamination or cloud shadows. If at least 12 pixels remain then the mean measured reflectance is calculated from the surface reflectances at 0.47 and 0.66 μm. Dust is distinguished from non-dust and, using a continental model lookup table (LUT), optical depth τ, flux, and other parameters are output (Remer 2005). The process for the ocean algorithm begins in much the same way; however, extra care must be taken not to mistakenly classify aerosols as clouds, or vice versa. A spatial variability test, combined with infrared and near-infrared cloud tests can classify the pixels as cloudy or not, and assign corresponding quality control flags. Ground-based aerosol measurements provide a measure for data validation. The accuracy varies with wavelength and location, but on a global basis the data averaged around 65% cloud determination accuracy (61% for 0.47 μm, 68% for 0.55μm, and 71% for 0.66 μm) for land data, with similar numbers for the ocean, though the percent relative error is consistently slightly larger over land, and bright surfaces (Remer 2005).

3.2 Quality Control and Algorithmic Advances

Within the lifetime of MODIS, the accuracy of the calculations has seen vast improvement. As more data has been received from the Terra and Aqua satellites, it has become possible to validate the data with land-based measurements, particularly the measurements from ground-based Sun photometers from the Aerosol Robotic Network (AERONET). Over the past eight years,

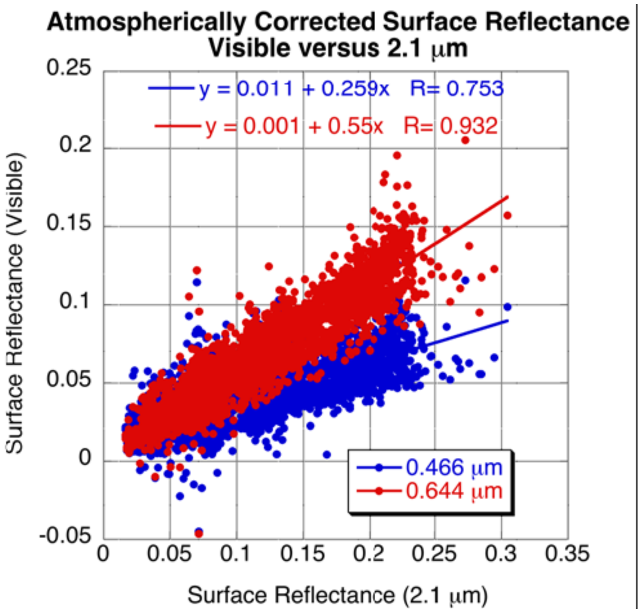

Figure 1: Relationship of Visible (0.466 µm and 0.644 µm) surface reflectance to satellite measured SWIR surface reflectance at 2.1 µm, as determined from MODIS/AERONET co-locations.
Figure from Levy et al. (2007).

the algorithm has been improved with cloud masking and pixel selection (Levy et al. 2007). In short, many generalizations and assumptions used in the original algorithms were later found to have been too broad, and much in this area has since been improved. Specifically, empirical surface reflectance relationships, with much greater accuracy than was previously available, have replaced generalized assumptions, gleaned from four years of MODIS/AERONET data.

One of the main challenges to accuracy has been in the lookup tables, specifically how the values therein were calculated, and how they were used. In the previous LUTs (those known as C004 or earlier), the values were calculated using the SPD[1] radiative transfer code, as is standard in the remote sensing community (Levy et al. 2007). However, it later was proved that under some geometries neglecting polarization would result in significant inaccuracies in the top of atmosphere reflectance, which would then propagate exponentially through to the calculation of the optical depth and other parameters. To address this issue, the newer version of the code, as described in Levy et al. (2007), allows for toggling polarized and non-polarized models, giving approximately 1% accuracy.

The principal difficulty in obtaining satellite measurements of aerosols, however, remains separating the observed reflectance into surface and atmospheric contributions, and then further separating out the aerosol contribution. This process is substantially easier over the open ocean, where the surface reflectance can be well-approximated by zero for wavelengths ≥0.66 µm. On land, however, the surface reflectance can vary substantially with different surfaces, and is often far from zero. Previously, the algorithm utilized the fact that the visible surface reflectance of vegetated and dark soiled surfaces exhibits a correlation with the surface reflectance at 2.12 µm (Levy et al. 2007). In the C004 algorithm, the 0.47 and 0.66 µm values (within the visible range) were taken to be 25% and 50%, respectively, of the reflectance at 2.12 µm (near-infrared). However, when compared to the AERONET photometer data, the results agreed ~60-65%, but with a positive offset of 0.1—this version of the algorithm tended to overestimate τ. This issue was partially improved upon by increasing the ratios for 0.47 and 0.66 µm versus 2.12 µm to 0.33 and 0.65, respectively. The values over the coastline and regions near the coast saw significant improvements in values of τ; however, this modification resulted in an overcorrection in the surface reflectance of areas far from the shore likely an effect of calculations having given τ to be negative (Levy et al. 2007). Processing MODIS data is difficult because a single set of visible-to-infrared ratios cannot be applied over all surfaces. It has been shown that this ratio is also a function of scattering geometry, particularly the scattering angle (Levy et al. 2007), which further complicates the algorithm, though this characteristic will not be discussed as it is beyond the scope of this review.

Plotting the correlation (from locations with simultaneous MODIS and AERONET data available) between visible and 2.12 µm surface reflectances, it is evident that there is a much stronger relationship between the 0.66 and 2.12 µm reflectances, than between the 0.47 and 2.12 µm reflectances. Additionally, when the 0.644 µm reflectance is plotted against the 0.466 µm reflectance, this relation is seen to have a correlation that is stronger than the 0.47/2.12

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[1] Non-polarized, as compared with the VPD or vector (polarized) version of the code; however, the vector version of the code is not well understood

relationship, but weaker than 0.66/2.12 ratio. Thus, instead of calculating the visible versus 2.12 μm relationship for both 0.47 and 0.66 μm, for increased accuracy, the new algorithm should first estimate the 0.66 μm reflectance from the 2.12 μm data, then find 0.47 from 0.66 μm. This new algorithm results in differences of less than 1% (Levy et al. 2007).

There have been equally substantial improvements made with respect to quantifying the atmospheric effects of the aerosol. For accuracy, one limitation that must still be imposed is the need to only consider data points of low τ, or about 10,000 of the original 15,000 points. Levy et al. (2007) indicated that previous studies used some version of the Continental aerosol model, which, while it results in reasonably accurate simulations around 0.55 μm, offers no such accuracy for $\tau_{2.12}$ μm, even only considering small τ. Either a fine- or a coarse-dominated aerosol model must be assumed, which results in a range of $\tau_{2.12}$ from 0.03 to 0.16, which could lead to errors if the wrong size is chosen. Other errors arise in models because they assume that all aerosols are spherically shaped, while in reality aerosols take on a variety of shapes. For instance sea salt, a dominant natural aerosol, is cubic. These uncertainties have complicated the measurements of aerosols, but current research aims at resolving many of the limitations.

3.2 Recent Algorithms

Sim et al. (2008) developed a new satellite-based measurement algorithm that determines spatial distribution of atmospheric aerosols and calculates surface reflectance. The algorithm was created based on known aerosol characteristics in the atmosphere. Atmospheric reflectance was simply determined by subtracting surface reflectance from the total measured reflectance (Sim et al. 2008). To use the algorithm effectively, one needs data from both Landsat TM and MODIS. These data and algorithm are useful in providing a regional view, or coarse resolution simulation, of atmospheric aerosols and pollution. The authors suggest that their methods are most applicable to remote regions where no other data are available. This study continues to broaden the coverage ability of satellite data.

4. Improvements in Satellite Measurements

4.1 Expanded Coverage

Although the satellites used to measure aerosol albedo have not changed since they were launched (Terra in 1999, Aqua in 2002), new methods have made raw data more usable and technological advances have aided in refining the data. Both technologies and methods are most effective when used together and with the most recent algorithms. Recent advances have allowed for remote access, more complete coverage of the globe, and improvement of algorithms by ground-truthing with in-situ measurements.

Satellites have been used to study aerosol DRF. However, older satellite measurements were confined to the oceans and were limited in their abilities to differentiate between aerosol types. Bellouin et al. (2005) combine satellite-based measurements of aerosols and surface wind speeds to estimate clear-sky direct radiative forcing for the year 2002 over both land and oceans. The results indicate that modern forcing by aerosols is actually stronger than suggested by numerical models. The fraction of submicron aerosols has been successfully retrieved by MODIS over the oceans (Bellouin et al. 2005). This broader view allows for more complete understanding of atmospheric aerosol distribution, and finally allows for studies over land. Different types of aerosols behave differently, so being able to categorize aerosols remotely is an advantage when characterizing the total effect of aerosols.

4.2 Active Satellites

There have been major advancements in satellite measurements of clouds and aerosols in the last few years. NASA and CNES developed two new instruments, CloudSat and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation), which were launched simultaneously on April 28, 2006 to study cloud and aerosol effects on weather, climate and air quality (Stephens 2008). These satellites were designed to compliment each other and are both part of the A-Train. The CALIPSO satellite houses a visible Wide Field Camera, a passive Infrared Imaging Radiometer (IIR), and active lidar (CALIOP). CALIOP can produce vertical and geographical profiles of clouds and aerosols and can measure particle size and cirrus cloud emissivity by using two-wavelengths of polarization-sensitive LIDAR (Trepte 2008). CALIPSO data provides new information about cloud properties that will aid in quantifying the indirect aerosol effects. For instance, CALIPSO can detect clouds that were previously undetected like Polar Stratospheric Clouds and upper tropospheric subvisible clouds. CloudSat measures precipitation, cloud profiles and liquid and ice water content using Cloud Profiling Radar (CPR). The CPR actively measures cloud scattering ability by sending radar out toward the cloud and measuring the scatter as a function of distance (Stephens 2008). The CPR data is then combined with MODIS radar measurements from Aqua and LIDAR data from CALIPSO to provide a full description of cloud properties. Both CloudSat and CALIPSO can provide estimates of atmospheric warming and albedo changes resulting from cloud and aerosol properties.

4.3 New Technology

New technology has emerged to observe aerosol and cloud microphysical interactions. Similar to more familiar autonomous underwater vehicles, autonomous unmanned aerial vehicles (UAV) have been developed to explore the atmosphere. Roberts et al. (2008) used UAV measurements to closely examine aerosol-cloud indirect effects, and found a link between aerosol cloud condensation nuclei (CCN) and maximum cloud droplet concentrations. This idea was familiar (the Twomey Effect), but was found by the authors to be much more sensitive than previously thought. The studies involved simultaneous measurements below, in, and above individual clouds to determine aerosol-cloud-albedo interactions on a much smaller scale than is possible with satellites. The authors also develop a relationship between cloud albedo and aerosol concentration. Their measurements yielded an aerosol-cloud effect of 1-2.9±0.7 W/m^2. For comparison, an increase of 1 W/m^2 due to CO_2 emissions would result in several degrees of atmospheric warming in the next century (IPCC 2007). Studies using UAVs can resolve aerosol-cloud-albedo interactions at a much higher resolution than satellites, and the results of such studies can be used to improve future satellite algorithms. They provide a way of downscaling coarse satellite data and resolving more local interactions and effects. The UAV technology is useful alone, but most significant when paired with satellite data to illuminate fine scale behavior.

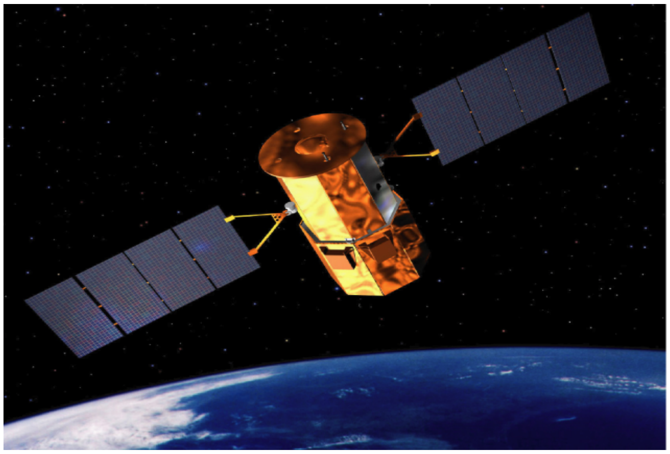

Fig. 3: NASA Glory Satellite to be launched in December 2008. Onboard instruments will include the Total Irradiance Monitor (TIM) and Aerosol Polarimetry Sensor (APS).

The technology associated with aerosol measurements is still largely associated with satellite-based measurements. The satellite methods have not changed significantly since MODIS was launched; however the associated data processing has improved. Algorithms like those produced by Sim et al. (2008) have improved the ability of scientists to process aerosol data collected by satellites. Part of how algorithms are refined is from studies such as Roberts et al. (2008) that provide in-situ data for comparison. Although these data are often local and very small scale, they allow the global satellite information to be calculated more finely, and remove some of the estimations and assumptions used in the original algorithms.

4.4 Aerosol Polarimetry Sensor and the Glory Mission

The December 2008 launch of the Aerosol Polarimetry Sensor (APS) as a part of the NASA Glory mission aims to measure many aerosol optical characteristics in order to improve radiative budget calculations, and global climate model simulations (Mishchenko et al. 2007). Launched on the Glory satellite as a part of the NASA A-Train satellite system, APS will represent the next generation of remote-sensing instruments designed for climate studies. APS aims to simultaneously measure aerosol optical depth, particle size distributions, refractive indices and single scattering albedo, for each size mode in aerosol particle distributions. Built by Raytheon as a part of the U.S Climate Change Science Program, the APS will have a broad spectral range, with nine channels measuring from 0.41 μm-2.2 μm and a multiangle measurement system that is capable of polarimetric accuracy down to 0.2%. Simultaneous orthogonal measurements allows for APS to observe anisotropic radiation resulting from aerosol scattering; the localization of these simultaneous measurements will allow for more accurate determination of the particle size dependence of the single scattering albedo, total cloud optical thickness, and the asymmetry factor. This enhanced accuracy will also improve the measurement of aerosol optical properties from surfaces difficult to measure such as sand and ice (Mishchenko et al. 2007). The upcoming Glory Mission launch of APS will provide new and relevant information, refining our understanding of aerosol albedo.

5. Conclusion

Natural and anthropogenic aerosols are compositionally heterogeneous and show wide variances in global distribution. Aerosol albedo is the largest source of uncertainty in predicting global climate, so it is necessary to refine and improve methods to produce precise estimates.

While earlier satellite measurements like MODIS measured aerosol type and distribution, advances in aerosol optical property algorithms have improved the interpretation of the existing satellite data. The launch of the APS in December 2008 will improve models of aerosol effects on albedo by simultaneously measuring their total optical depth, global abundance, size distribution, and single scattering albedo. Multiangle measurements will improve accuracy by allowing for correction of anisotropic scattering, and a broad spectral range and synergistic measurements with airborne and ground-based instruments will help determine the global distribution of the single scattering albedo of multicomponent aerosol systems. Instrumentation and calculation techniques of detecting aerosol distribution and type from satellites is still a developing science with limitations and data uncertainties, however it is constantly improving. Ground-truthing with in situ measurements like AERONET allows refinement of algorithms, and a steady increase in new technology is constantly improving instrumentation and methods. In particular, the APS launch will offer new insights. Current methods and calculations still incorporate a large range of variability relative to the sensitivity required for global climate models, but a combination of refined algorithms, improved technology, and new methods are decreasing the margin of error. Accurate measurements of aerosol parameters are necessary to calculate albedo, which is crucial in making future predictions.

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