LIMITS ON DETECTION OF LARGE TOA SHORTWAVE FORCING BY AEROSOLS IN CURRENT SATELLITE RADIATION DATA

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Abstract:

Existing methods for determining aerosol radiative forcing from satellite observations of reflected radiation may lead to an underestimation of the true forcing. The bias is related to the Maximum Likelihood Estimator (MLE) techniques used to identify clear-sky observations in the Earth radiation measurements. The MLE procedure classifies data as clear only if the reflected shortwave radiation falls within a narrow range. In regions of high aerosol loading, for example areas downwind from the Sahara Desert, this procedure can systematically eliminate observations with the highest aerosol forcing from the data set. Model calculations are used to estimate the upper bounds on shortwave aerosol forcing in the ERBE and ScaRaB data sets. These upper bounds are compared to calculations of the forcing expected from daily satellite retrievals of aerosol optical depth. The biases in current estimates of aerosol forcing from TOA radiation data are estimated from this comparison.

1. Global estimates of biases in aerosol shortwave radiative forcing

Several groups have attempted to use observations from ERBE to estimate the regional aerosol radiative forcing associated with biomass burning and with naturally occurring aerosols (Ackerman and Chung, 1992; Christopher et al., 1996; Christopher et al., 1998). The ERBE data have also been used to evaluate GCM estimates of clear-sky albedos over ocean regions (Soden and Ramaswamy, 1998). Some of the differences between the GCM and observations are strongly correlated with independent estimates of aerosol optical depth. There is an urgent need for additional satellite studies to reduce the large uncertainties in current estimates of the climate forcing by anthropogenic aerosols (Charlson et al., 1992; Penner et al., 1994).

Quantitative assessment of aerosol forcing by satellites is complicated by several issues, including incomplete diurnal sampling and misidentification of cloudy scenes as clear. The combination of these errors contributes an uncertainty of approximately 2 W/m^2 in monthly-mean regional clear-sky reflected shortwave fluxes F_{sw} (Harrison et al., 1990). However, the MLE procedure used to identify clear-sky scenes places stringent upper bounds on F_{sw}. These upper limits could exclude regions with high aerosol forcing from the clear-sky sample and thus introduce systematic errors much larger than 2 W/m^2. Over ocean areas affected by dust outbreaks, the systematic errors associated with scene misidentification are estimated to be less than 33 W/m^2, or approximately 10% of the global annual insolation (Ackerman and Chung, 1992). This estimate is based upon an analysis of only one day of satellite data for limited spatial domains (Diekmann and Smith, 1989). In regions with significant biomass burning, the MLE procedure incorrectly classifies most of the clear-sky pixels with smoke contamination as partly cloudy (Christopher et al., 1996).

At present, quantitative estimates of the systematic errors _$F_{sw,a}$ in direct aerosol radiative forcing related to scene misidentification are not available. The errors may be particularly large in tropical regions affected by dust and anthropogenic pollution, in particular the tropical Atlantic and Indian Oceans and South China Sea (Husar et al., 1997). The clear-sky fluxes from the "ERBE-like" versions of Nimbus-7, ScaRaB, and CERES data should be affected by similar systematic errors.

One approach for calculating _$F_{sw,a}$ would be to refine the methodology used to identify clear-sky scenes, perhaps using correlative observations from high-resolution satellite imagers. Differences between the values of F_{sw} using the standard and refined procedures would yield an estimate of _$F_{sw,a}$ This approach suffers from the introduction of a second set of uncertainties associated with the new clear-sky identification scheme.

We calculate _$F_{sw,a}$ for ocean regions from the NOAA Pathfinder aerosol retrievals (Stowe et al., 1997). The Pathfinder product is the only global long-term observational data set for column-integrated aerosol optical depth currently available. For a given scene, we compare the maximum clear-sky shortwave radiance L_{sw} consistent with MLE against a calculation of L_{sw}(_) using the coincident retrieval of _ from Pathfinder:

- If the calculated radiance is larger than the maximum MLE value, the scene has probably been misclassified as cloud contaminated. The shortwave flux F_{sw} corresponding to the maximum MLE clear-sky radiance is computed from the ERBE angular distribution models (Suttles, 1988). The value of F_{sw}(_) corresponding to L_{sw}(_) is computed using the same radiative transfer model. The difference between these fluxes is a lower bound on the instantaneous error _$F_{sw,a}$. The difference between F_{sw}(_) and F_{sw}(_ = 0) is an approximate upper bound on _$F_{sw,a}$.
- If the calculated radiance is lower than the maximum L_{sw} consistent with the MLE method, the instantaneous _$F_{sw,a}$ is set to 0.

In order to derive regional, seasonally averaged maps of _$F_{sw,a}$, a rapid technique for calculating the radiances and fluxes has been developed. Lookup tables for L_{sw} and F_{sw} as functions of sun-satellite geometry, aerosol optical depth, precipitable water, and column ozone amounts have been constructed. The computation of _$F_{sw,a}$ at an individual pixel requires just a table look-up and an evaluation of the Gaussian distributions in the MLE scheme. We then calculate _$F_{sw,a}$ on a pixel-by-pixel basis. Maps of _$F_{sw,a}$ can be constructed by averaging the pixel-level estimates using the ERBE techniques for temporal and spatial averaging (Brooks et al., 1986). Similar calculations could also be run for ScaRaB and CERES.

The uncertainties in _$F_{sw,a}$ are related to the accuracy of the radiative transfer model, the retrievals of _, profiles of atmospheric trace gases, and surface boundary conditions. Perhaps the major uncertainty is associated with the aerosol retrievals. The second-generation Pathfinder data set compares favorably with Sun-photometer observations (Stowe et al., 1997). Relative to data from three Sun-photometer sites, the systematic errors are less than 10%, and the random error is approximately __ = 0.04. The Pathfinder group is developing error estimates specifically for dust (L. Stowe, private communication). The effects of these errors have been included in the estimates of _$F_{sw,a}$. The spatial distributions and magnitude of _$F_{sw,a}$ will eventually be compared with calculations based upon aerosol distributions from General Chemical Transport Models (GCTMs). The uncertainties related to the radiative transfer model, trace gases, and surface conditions can be readily quantified with sensitivity experiments.

2. Methodology for calculation of systematic errors in satellite clear-sky albedos related to aerosols

The procedure for evaluating the systematic error _$F_{sw,a}$ in satellite estimates of aerosol direct radiative forcing is based upon comparing measurements of L_{sw} and F_{sw} against model calculations. The calculated shortwave fluxes F_{sw} are organized in look-up tables as functions of solar zenith angle, aerosol optical depth, precipitable water, and column ozone amounts. The shortwave radiances are stored in similar tables, with additional independent variables representing the satellite zenith angle and relative azimuth angle. The angles associated with the sun-satellite geometry are binned with the same angular resolution as used for ERBE (Suttles, 1988).

The radiances and fluxes are calculated using a discrete-ordinates radiative transfer model (Zender et al., 1997) based upon the DISORT code (Stamnes et al., 1988). The model calculations for clear-sky conditions agree well with results from other shortwave codes run at high spectral resolution (Kinne et al., 1998). For a given solar-zenith angle and vertical profile of atmospheric angles) and the hemispheric flux F_{sw}. Thus the look-up tables of L_{sw} and F_{sw} can be generated simultaneously.

For consistency with the NOAA Pathfinder data, we have adopted the aerosol properties used in the second-generation Pathfinder retrieval algorithm (Stowe et al., 1997). All the Pathfinder data have been reprocessed with this algorithm (L. Stowe, private communication). The aerosol is assumed to obey a log-normal size distribution with a modal radius and spread of r_m = 0.1 _m and _ = 2.03 _m, respectively (Stowe et al., 1997). The index of refraction is set to values corresponding to a mixture of sea salt and non-sea-salt sulfate aerosols. We will incorporate error estimates for the retrievals in regions affected by dust and biomass burning as these numbers become available. Like other aerosol retrieval schemes of its class, the errors in _ from the NOAA Pathfinder algorithm can be large when the observed aerosol departs significantly from the properties adopted in the retrieval (Mishchenko and Travis, 1997).

However, the absolute accuracy of the retrieval is not critical for this application. The basic requirements are that the model correctly calculates:

1. The visible radiance L_{vis} used to infer _;
2. The TOA shortwave radiance field L_{sw}; and
3. The TOA shortwave shortwave flux F_{sw}.

The first criterion should be satisfied automatically by adopting the same aerosol model as the retrieval. As a consistency check, we also attempt to quantify and minimize departures of the calculated and observed L_{vis}. The measurements of L_{vis} provided as part of the Pathfinder product. The second and third criteria require an accurate specification of the phase function and spectral scattering properties of the aerosols. Fortunately the aerosol scattering phase function is relatively insensitive to the effective radius (Mishchenko and Travis, 1997) and aerosol type (Koepke and Quenzel, 1979) assumed in the retrieval scheme. The principle difficulty is that the non-absorptive optics used in the Pathfinder retrievals are not appropriate for several important categories of aerosols, in particular dust and soot from biomass burning (e.g., Haywood and Shine, 1995). This could lead to an overestimate of L_{sw}(_), F_{sw}(_), and _$F_{sw,a}$ even when the calculated L_{vis}(_) is identical to the observed L_{vis}. In order to address this issue, we plan to identify regions of UV-absorbing aerosols using the aerosol indices derived from the Nimbus-7 TOMS data (Herman et al., 1997). For those regions, we will calculate the change in _$F_{sw,a}$ when optical properties for dust and soot are substituted in the radiative transfer model. This will require the construction of additional look-up tables for L_{vis}, L_{sw}, and F_{sw} for each set of optics.

The main advantage of this approach is that it will yield estimates for _$F_{sw,a}$ on space and time scales relevant for large-scale climate studies. Future analyses of aerosol direct radiative forcing from satellite observations can use the maps of _$F_{sw,a}$ to quantify systematic errors. New methodologies for scene identification, including the new methods proposed for CERES, could be assessed using these results to see if _$F_{sw,a}$ is reduced. The robustness of the estimates of _$F_{sw,a}$ could also be tested with new aerosol retrievals from the NASA EOS platforms (e.g., MODIS) and CERES data. Differences between the observed and modeled F_{sw} will provide estimates of clear-sky aerosol shortwave forcing over the world's oceans.

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