Remote sensing of tropospheric aerosols from space: from AVHRR to Glory APS

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Abstract

Analysis of the long-term Global Aerosol Climatology Project dataset reveals a likely decrease of the global optical thickness of tropospheric aerosols by as much as 0.03 during the period 1991–2005. This recent trend mirrors the concurrent global increase in solar radiation fluxes at Earth's surface and may have contributed to recent changes in surface climate. Existing satellite instruments cannot be used to determine unequivocally whether the recent trend is due to long-term global changes in the natural or anthropogenic aerosols. It is thus imperative to provide uninterrupted multidecadal monitoring of aerosols from space with dedicated instruments like the Glory Aerosol Polarimetry Sensor in order to detect long-term anthropogenic trends potentially having a strong impact on climate.

Recent observations of downward solar radiation fluxes at Earth's surface have shown a recovery from the previous decline known as global "dimming" with the "brightening" beginning around 1990. The increasing amount of sunlight at the surface profoundly affects climate and may represent diminished effects of certain counter-balances of the greenhouse warming, thereby making it more evident during the past decade.

It has been suggested that tropospheric aerosols have contributed significantly to the switch from solar dimming to brightening via both direct and indirect aerosol effects. It has further been argued that the solar radiation trend mirrors the estimated recent trend in primary anthropogenic emissions of SO_2 and black carbon, which contribute significantly to the global aerosol optical thickness (AOT). Therefore, it is important to provide a direct and independent assessment of the actual global long-term behavior of the AOT. We accomplish this by using the longest uninterrupted record of global satellite estimates of the column AOT over the oceans, the Global Aerosol Climatology Project (GACP) record (http://gacp.giss.nasa.gov). The latter is derived from the International Satellite Cloud Climatology Project (ISCCP) DX radiance dataset composed of calibrated and sampled Advanced Very High Resolution Radiometer (AVHRR) radiances.

The solid black curve in Fig. 1 depicts the global monthly average of the column AOT for the period August 1981 – June 2005. The two major maxima are caused by the stratospheric aerosols generated by the El Chichon (March 1982) and Mt Pinatubo (June 1991) eruptions, also captured in the Stratospheric Aerosol and Gas Experiment (SAGE) stratospheric AOT record. The quasi-periodic oscillations in the black curve are the result of short-time aerosol variability.

The red line traces the overall behavior of the column AOT during the eruption-free period from January 1986 to June 1991. It shows only a hint of a statistically significant tendency and indicates that the average column AOT value just before the Mt Pinatubo eruption was close to 0.142. After the eruption, the GACP curve is a superposition of the complex volcanic and tropospheric AOT temporal variations. However, the green line reveals a clear long-term decreasing tendency in the tropospheric AOT. Indeed, even if we assume that the stratospheric AOT just before the eruption was as large as 0.007 and that by June 2005 the stratospheric AOT became essentially zero (*cf.* the blue curve), still the resulting decrease in the tropospheric AOT during the 14-year period comes out to be 0.03. This trend is significant at the 99% confidence level.

Figure 2 shows the difference between the GACP AOT averaged over the periods 2002–2005 and

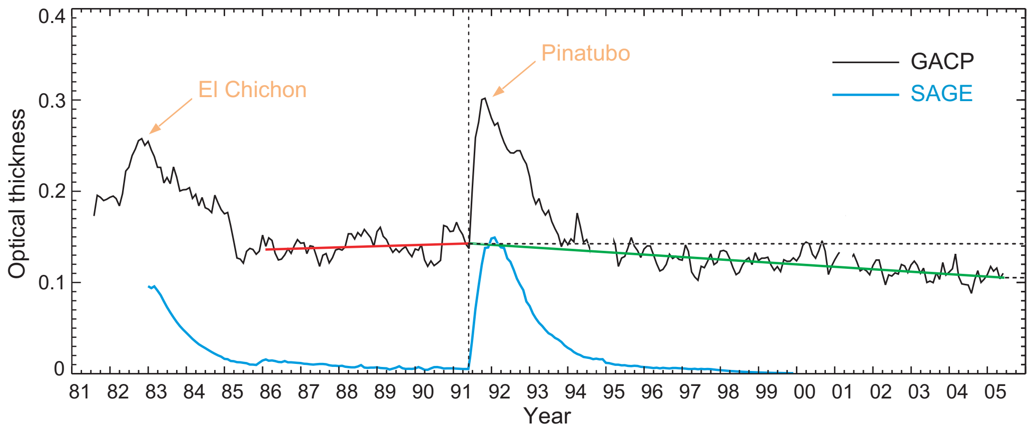

Fig. 1. GACP record of the globally averaged column AOT over the oceans and SAGE record of the globally averaged stratospheric AOT.

1987–1990. As expected, this map reveals increased aerosol loads in Asia and reduced pollution in Europe. Another interesting trend is the significant reduction in the amount of dust aerosols coming from the Sahara desert.

Admittedly, AVHRR is not an instrument designed for accurate aerosol retrievals from space. Among the remaining uncertainties is radiance calibration which, if inaccurate, can result in spurious aerosol tendencies. Similarly, significant systematic changes in the aerosol single-scattering albedo or ocean reflectance can be misinterpreted in terms of AOT variations. However, the successful validation of GACP retrievals using precise sun-photometer data taken from 1983 through 2004 indicates that the ISCCP radiance calibration is likely to be reliable. This conclusion is reinforced by the close correspondence of the calculated and observed TOA solar fluxes. Furthermore, the GACP AOT record appears to be self-consistent, with no drastic intra-satellite variations, and is consistent with the SAGE

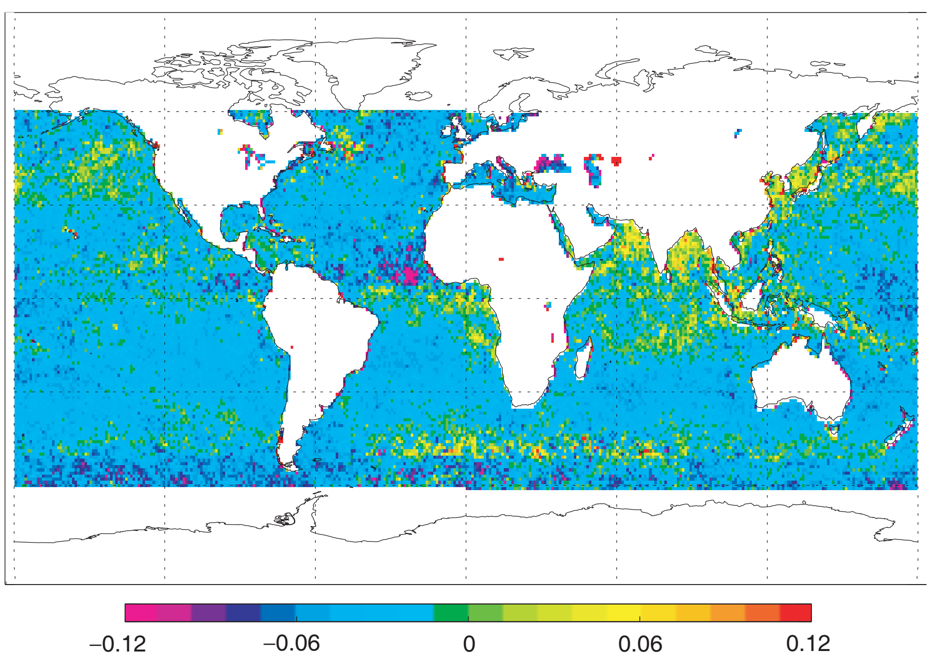

Fig. 2. Aerosol optical thickness difference between the early 2000s and late 1980s.

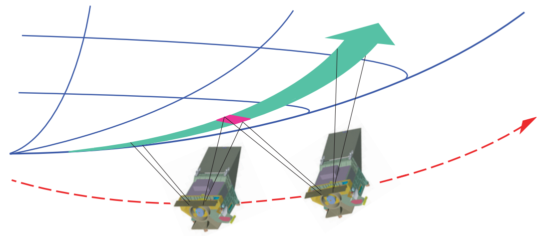

Fig. 3. Along-track multi-angle APS measurements via 360º scanning from the sun-synchronous polar-orbiting Glory spacecraft.

record.

The unique advantage of the AVHRR dataset over the datasets collected with more advanced recent satellite instruments is its duration, which makes possible reliable detection of statistically significant tendencies like the substantial decrease of the tropospheric AOT between 1991 and 2005. With all the uncertainties, the global tropospheric AOT decrease over the 14-year period is estimated to be at least 0.02. This change is consistent with long-term atmospheric transmission records collected in the Former Soviet Union.

Our results suggest that the recent downward trend in the tropospheric AOT may have contributed to the concurrent upward trend in the surface solar fluxes. Neither AVHRR nor other existing satellite instruments can be used to determine unequivocally whether the recent AOT trend is due to long-term global changes in the natural or anthropogenic aerosols. This discrimination would be facilitated by an instrument like the Aerosol Polarimetry Sensor (APS) scheduled for launch in December 2008 as part of the NASA Glory Mission (http://glory.giss.nasa.gov).

The key measurement requirements for the retrieval of aerosol and cloud properties from photopolarimetric data are high (i.e., fine) accuracy, a broad spectral range, and observations from multiple angles, including a method for reliable and stable calibration of the measurements. The APS measurement approach to ensure high accuracy in polarimetric observations employs Wollaston prisms to make simultaneous measurements of orthogonal intensity components from the same scene. The broad spectral range of APS is provided by dichroic beam splitters and interference filters that define nine spectral channels centered at the wavelengths $\lambda = 410$, 443, 555, 670, 865, 910, 1370, 1610 and 2200 nm. The critical ability to view a scene from multiple angles is provided by scanning the APS IFOV along the spacecraft ground track (Fig. 3) with a rotation rate of 40.7 revolutions per minute with angular samples acquired every 8 ± 0.4 mrad, thereby yielding ~250 scattering angles per scene. The scanner assembly also allows a set of calibrators to be viewed on the side of the scan rotation opposite to the Earth. The APS on-board references provide comprehensive tracking of polarimetric calibration throughout each orbit, while radiometric stability is tracked monthly to ensure that the aerosol and cloud retrieval products are stable over the period of the mission.

Since APS shares many design features with its aircraft predecessor, the Research Scanning Polarimeter (RSP), the latter can be expected to provide a close model of the future APS performance. Examples of the fidelity of the AOT, size distribution, and absorption estimated from the APS type of remote-sensing measurement during seven different flights are shown in Fig. 4. In panel (a) we see that the spectral AOT values retrieved from polarimetric measurements agree well with those measured by ground-based sunphotometers over an AOT range from 0.05 to more than 1. The absence of spectrally-dependent biases in these retrievals also demonstrates the reliability of the size distribution estimate for both small and large modes of a bimodal aerosol distribution. Comparisons have also been made between in situ and retrieved size distributions and have also been found to agree extremely well (difference in aerosol effective radius of less than 0.04 μm).

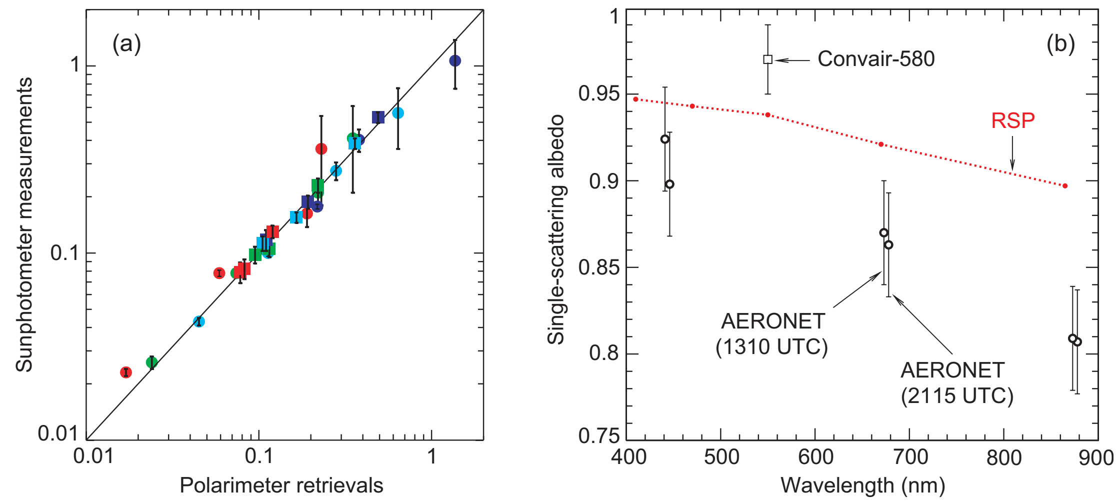

Fig. 4. (a) Optical thickness comparison. Sunphotometer measurements at 410/443, 500, 673, and 865 nm shown as blue, turquoise, green, and red symbols, respectively, are compared with RSP retrievals for the same wavelength. The circular symbols are for retrievals over land while the square symbols are for retrievals over ocean. Error bars are only shown for the sunphotometer measurements. (b) Single-scattering albedos as a function of wavelength. The red dotted line shows the best-estimate values retrieved from RSP data. Also included are estimates from data collected during Convair-580 flight 1874 and from the AERONET data.

The aerosol single-scattering albedo (SSA) can also be estimated from polarimetric measurements because of the differing sensitivities of polarized and unpolarized reflectances to aerosol absorption. In Fig. 4(b), the SSA derived from polarimetry is compared with *in situ* and ground-based sky radiance estimates. The discrepancy between these estimates may be related to the loss of particles in the sampling system for *in situ* measurements, humidification of the *in situ* extinction (but not the absorption) coefficients, and uncertainties in the SSA retrieval from sky radiances that may be caused by horizontal variability in the aerosol burden. Nonetheless the polarimetric estimate of SSA is consistent with the other measurements given their inherent uncertainties. Overall, Fig. 4(b) illustrates the complexity of retrieving SSA from both *in situ* and remote-sensing measurements and suggests that the validation of SSA retrievals from APS data will be a challenging task.

Acknowledgments

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