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Note

Aerosol retrievals from channel-1 and -2 AVHRR radiances: Long-term trends updated and revisited

Michael I. Mishchenko [a,*], Li Liu [b], Igor V. Geogdzhayev [b], Jing Li [a], Barbara E. Carlson [a], Andrew A. Lacis [a], Brian Cairns [a], Larry D. Travis [a]

[a] NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA
[b] Columbia University, 2880 Broadway, New York, NY 10025, USA

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ABSTRACT

The nominal Global Aerosol Climatology Project (GACP) record of aerosol optical thickness (AOT) and Ångström exponent (AE) over the oceans is extended by 6 months to cover the period from August 1981 through December 2005. The most recent 4-year segment reveals no significant short-term tendencies in globally and hemispherically averaged AOTs and AEs. This finding is consistent with contemporaneous MODIS and MISR results and the accumulating evidence of a gradual transition from global brightening to global dimming. We also analyze the retrieval implications of allowing the imaginary part of the aerosols refractive index Im(m) to change over the duration of the GACP record. Our sensitivity study shows that increasing Im(m) from 0.003 during the 4-year pre-Pinatubo period up to 0.007 during the most recent 4-year segment of GACP data eliminates the previously identified long-term decreasing AOT trend. Should this long-term trend in Im(m) be real then it would cause the global absorption AOT over the oceans to more than double and the global single-scattering albedo to decrease from ~0.95 to ~0.88. Such changes could make tropospheric aerosols significant contributors to the recent surface temperature increase.

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1. Introduction

Despite their limited information content, Advanced Very High Resolution Radiometer (AVHRR) radiance data have been used extensively to retrieve long-term records of the total column aerosol optical thickness (AOT) and Ångström exponent (AE) over the oceans [1–23]. The main rational for using the less-than-ideal AVHRR data is their availability since the late 1970s coupled with the growing recognition of the profound and potentially varying effects of aerosols on climate [24–30]. Furthermore, the AVHRR dataset is a good proving ground for studying limitations imposed by the physics of electromagnetic scattering and radiative transfer on radiance-only aerosol retrievals.

Among several intriguing results derived from channel-1 and -2 AVHRR radiances have been the downward trend in the globally and hemispherically averaged AOTs over the oceans between the late 1980s and early 2000s [19,21] as well as several regional AOT trends [20]. The global/hemispherical AOT trend appears to be consistent with the contemporaneous switch from global dimming to global brightening [31–39] as well as with the expected effect of global warming on aerosol number concentrations [40,41]. The regional trends are qualitatively consistent with the results of extensive ground-based observations [17,42–45] and recent emission-inventory assessments [46–50]. Yet one should recognize the inherent significant limitations of the AVHRR dataset, viz.,

- the absence of polarimetric measurements (cf. Refs. [51–59]);
- the absence of multi-angular observations (cf. Refs. [51–60]);

* Corresponding author. Tel.: +1 212 678 5590; fax: +1 212 678 5552.
E-mail address: michael.i.mishchenko@nasa.gov (M.I. Mishchenko).

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- the availability of only two spectral channels with relatively close central wavelengths ($\lambda_1 \approx 650$ nm and $\lambda_2 \approx 850$ nm); and
- the absence of on-board radiance calibration.

As a consequence, the AVHRR radiances can be used to retrieve at most two aerosol parameters (usually AOT and a crude size characteristic such as AE), while all the other aerosol as well as surface parameters must be assigned globally and temporally fixed values. It is not, therefore, inconceivable that at least part of the downward trend in the globally and hemispherically averaged AOTs is an artifact of a subtle vicarious calibration trend or, more likely, of a long-term trend in one or more of the aerosol (and/or surface) parameters that are assumed to remain constant in the retrieval algorithm.

An aerosol parameter that could, in principle, undergo a significant long-term change is the single-scattering albedo (SSA). Indeed, it is estimated that regional emissions of nonabsorbing sulfate aerosols have been decreasing [46–50], while emissions of absorbing soot and soot-containing aerosols have been increasing [48,61,62] over the past few decades. A likely consequence of these estimated changes could have been a decreasing trend in SSA.

We will not discuss specifically the actuality of this trend and whether it can be inferred reliably from existing in situ and/or remote-sensing data (cf. Ref. [63]). However, averaging Aerosol Robotic Network (AERONET; [64,65]) retrievals of SSA from eight quasi-oceanic locations shown in Fig. 1 does reveal a noticeable downward trend (Fig. 2). Given the potentially strong (yet poorly quantified) effect of absorbing aerosols on climate [61,66,67], a global SSA trend like the one shown in Fig. 2 can be expected to have profound consequences.

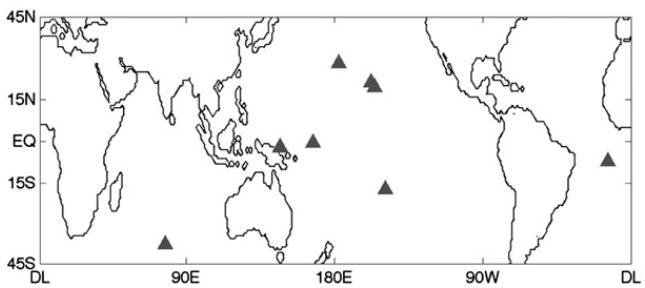

Fig. 1. Eight quasi-oceanic AERONET stations.

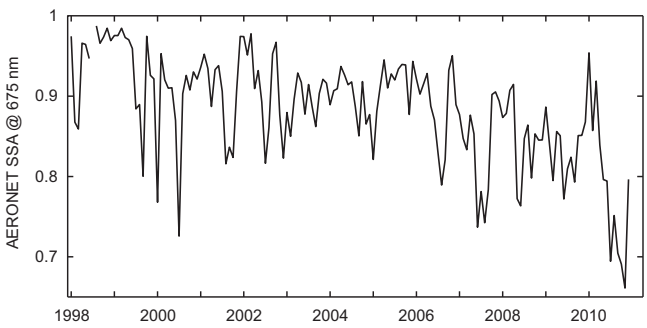

Fig. 2. Average aerosol single-scattering albedo at 675 nm based on data from eight AERONET stations depicted in Fig. 1.

In the framework of a two-channel retrieval algorithm [1,3,5,12], the AVHRR dataset cannot be used to retrieve the aerosol complex refractive index in addition to AOT and AE. Instead, the refractive index has to be fixed at an *a priori* value. For example, the nominal Global Aerosol Climatology Project (GACP) algorithm is based on the value $m=1.5+0.003i$, where $i=(-1)^{1/2}$ [5]. This implies that potential long-term compositional changes of aerosols and the resulting SSA trends cannot be retrieved explicitly. Yet, given the climatological importance of absorbing aerosols, it would be quite instructive to analyze whether "unfreezing" the imaginary part of the refractive index $\mathrm{Im}(m)$ in the retrieval could have a significant effect on the GACP AOT product.

The objective of this Note is twofold. First, we extend the nominal GACP record of globally and hemispherically averaged AOTs and AEs through December 2005 and discuss the implications of the most recent 4-year segment.

Second, we analyze potential consequences of allowing aerosol absorption to change during the period of AVHRR observations. Given the limited nature of the AVHRR radiance dataset, one can think of several indirect ways to perform this analysis. The simple approach adopted for this Note is to consider the downward trend in the globally and hemispherically averaged AOTs over the oceans as an artifact and determine what long-term change in $\mathrm{Im}(m)$ would be required to eliminate this trend.

2. Extension of the nominal GACP dataset

The nominal GACP aerosol product, documented in Refs. [5,10,20] and available at http://gacp.giss.nasa.gov, is derived from the International Satellite Cloud Climatology Project (ISCCP) DX radiance dataset composed of calibrated and sampled channel-1 and -2 AVHRR radiances [68]. It is based on data from the following sun-synchronous polar-orbiting platforms: NOAA-7 (August 1981–January 1985), NOAA-9 (February 1985–October 1988), NOAA-11 (November 1988–September 1994), NOAA-14 (February 1995–June 2001), and NOAA-16 (October 2001–December 2005). The GACP retrieval algorithm yields AOT (reported at $\lambda=550$ nm) and constrained AE for each cloud-free ISCCP pixel by minimizing the differences between the pairs of measured and modeled AVHRR radiances. The AE is defined as

$$\mathrm{AE} = -\left.\frac{d[\ln C_{\mathrm{ext}}(\lambda)]}{d(\ln\lambda)}\right|_{\lambda=\lambda_1}, \tag{1}$$

where C_{ext} is the ensemble-averaged extinction cross section per particle. GACP retrievals are limited to areas over large water bodies such as oceans, seas, and lakes, in which case the surface reflectance is typically low and can be parameterized with acceptable accuracy.

With only two units of radiance data per pixel available, the GACP retrieval algorithm cannot yield aerosol parameters other than AOT and AE and thus must rely on a number of *a priori* assumptions. It is assumed, in particular, that aerosol particles are homogeneous

spheres with a wavelength-independent refractive index $m=1.5+0.003i$ and obey the following power-law size distribution [5]:

$$n(r)=\begin{cases} C, & r\le r_1, \\ C\left(\frac{r}{r_1}\right)^{-\alpha}, & r_1<r\le r_2, \\ 0, & r>r_2, \end{cases} \tag{2}$$

where $r_1=0.1\ \mu m$, $r_2=10\ \mu m$, and $\alpha\in[2.5,\ 5]$. The constant C is determined by satisfying the normalization condition

$$\int_0^\infty dr n(r)=1 \tag{3}$$

Thus the two directly retrieved aerosol characteristics are AOT and α, the latter defining the respective AE.

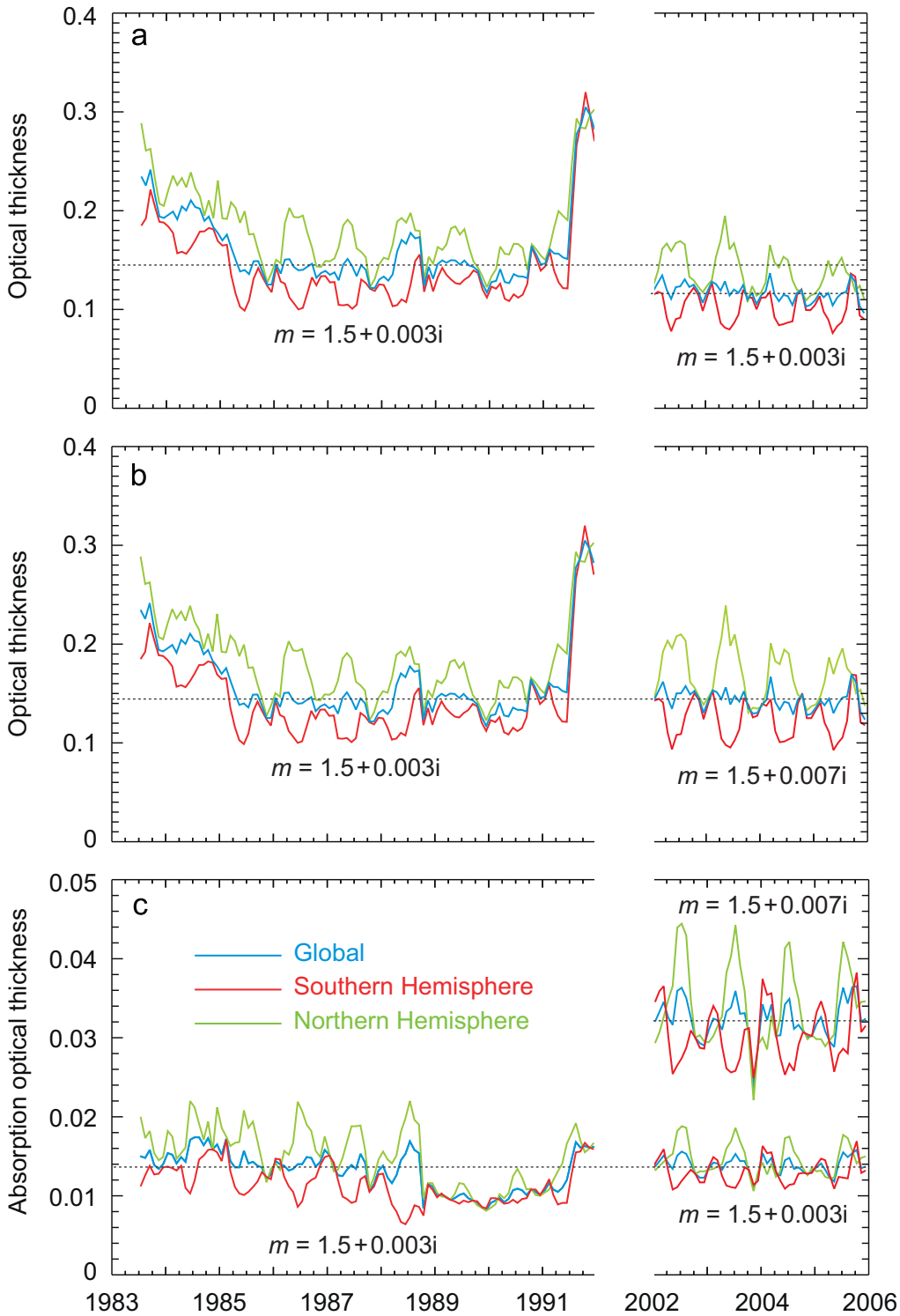

Fig. 3. (a) Monthly global and hemispheric AOT averages over the oceans at 550 nm retrieved assuming a constant refractive index of $1.5+0.003i$. (b) As in panel (a), but assuming a refractive index of $1.5+0.007i$ for the NOAA-16 segment. (c) As in panel (b), but for the absorption AOT. For comparison, absorption AOT averages retrieved for the refractive index $1.5+0.003i$ are also shown.

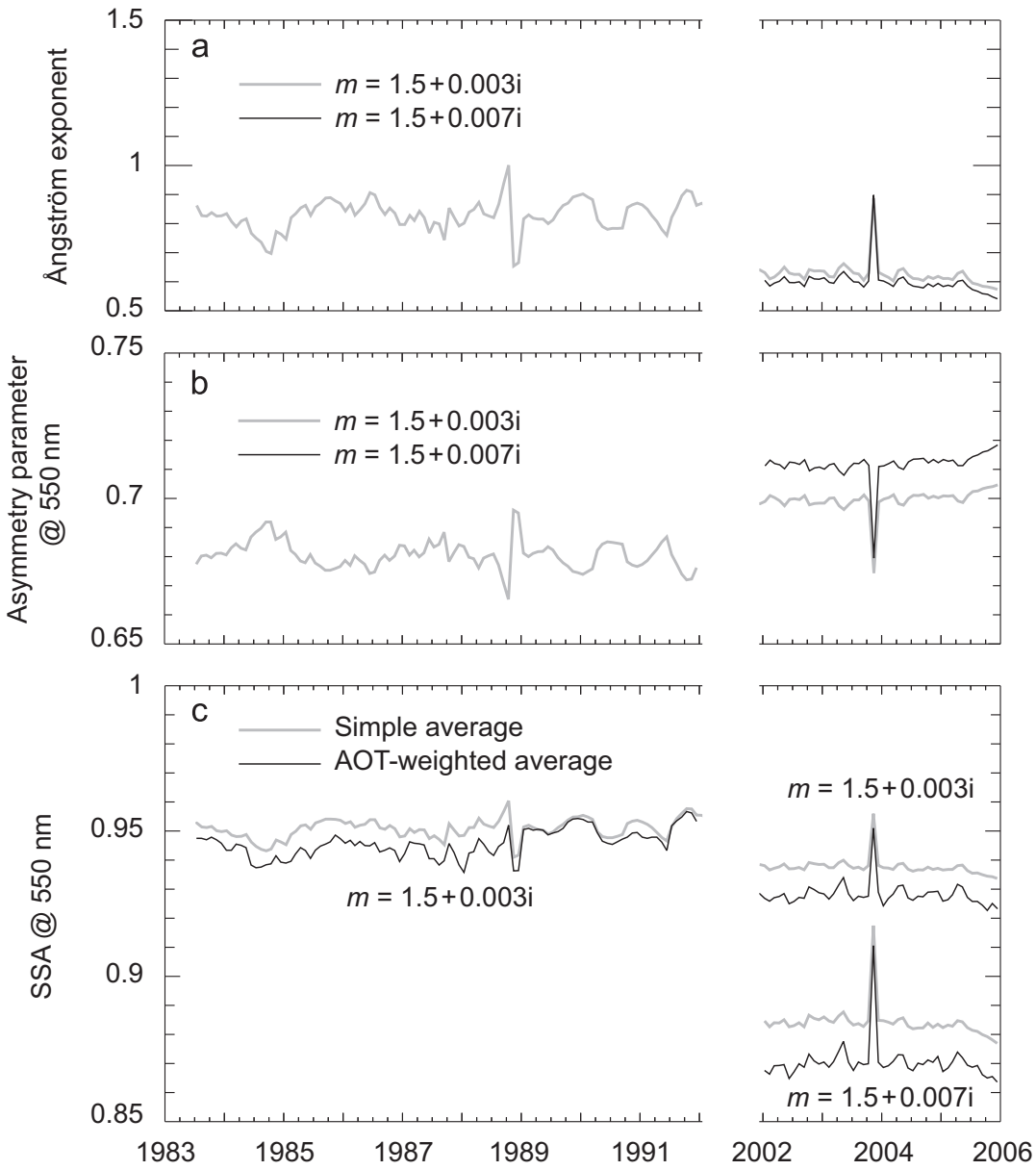

Fig. 4. (a) Monthly global AE averages over the oceans retrieved assuming refractive indices $1.5+0.003i$ and $1.5+0.007i$. (b) As in panel (a), but for the globally averaged asymmetry parameter at 550 nm. (c) Simple and AOT-weighted monthly global averages of SSA at 550 nm derived for two values of the aerosol refractive index.

The retrieval look-up table is created using a radiative transfer model that incorporates the reflectance of the rough ocean surface via the modified Kirchhoff approximation [69] assuming a globally uniform wind speed value of 7 m/s and the effect of water vapor, oxygen, and CO_2 absorption via the *k*-distribution technique [70]. The radiance contributions of the upwelling radiation from within the ocean body and of the white caps are modeled as additive fixed Lambertian terms. Single-scattering properties of aerosols are computed with the Lorenz–Mie code described in Ref. [71].

The bracketing temporal segments of the global and hemispheric monthly averages of AOT derived from the standard GACP product are shown in Fig. 3(a). It is seen that relative to the pre-Pinatubo period June 1987–May 1991, the most recent global AOTs reveal a $\sim$0.03 decrease identified previously in Refs. [19,20]. Fig. 3(c) shows that the corresponding averages of the absorption AOT (defined as the product $(1-\mathrm{SSA})\times\mathrm{AOT}$) remained largely the same. According to the gray curves in Fig. 4(a), the globally averaged AE had undergone a relatively small decrease implying an increase in the average particle size. The latter is the cause of a slight increase in the globally averaged asymmetry parameter (see Fig. 4(b)) as well as small decreases in the simple and AOT-weighted global averages of SSA (Fig. 4(c)) (the AOT-weighted average is defined as $\langle \mathrm{SSA}\times\mathrm{AOT}\rangle/\langle \mathrm{AOT}\rangle$, where the angular brackets denote monthly global averages).

3. Modified long-term trends

Let us now analyze what could happen if we were to "unfreeze" the imaginary refractive index of tropospheric aerosols during the period of AVHRR observations. It is

reasonable to assume that if the temporal variability of Im(m) is real then it is nearly continuous, thereby requiring the creation of a large number of look-up tables corresponding to different values of Im(m) and applying them to consecutive segments of AVHRR data. To simplify the problem, we will consider only the pre-Pinatubo AOTs retrieved during the period June 1987–May 1991 and the AOTs retrieved during the period January 2002–December 2005. We assume that the imaginary refractive index Im(m) remained constant during either period, but its respective values are now allowed to be different. Specifically, we use the nominal GACP value Im(m_1)=0.003 for the first period and determine Im(m_2) from the requirement that the global and hemispheric AOT averages during the second period equal those during the first period while assuming that Re(m_2)=Re(m_1)=1.5.

A trial-and-error search has shown that using the imaginary refractive index Im(m_2)=0.007 in the GACP retrieval algorithm during the NOAA-16 segment of AVHRR data does eliminate the downward trend in the globally and hemispherically averaged AOTs (Fig. 3(b)). Needless to say, increasing the imaginary refractive index by more than a factor of two can be expected to have a significant effect on the resulting absorption AOT and SSA. Indeed, Figs. 3(c) and 4(c) show that the globally and hemispherically averaged absorption AOTs during the NOAA-16 segment more than double relative to the pre-Pinatubo period, while the simple and AOT-weighted SSA averages drop from ~0.95 and ~0.94 to ~0.885 and ~0.87, respectively.

The effects of increasing Im(m_2) from 0.003 to 0.007 on the retrieved AE and inferred asymmetry parameter are much weaker. Indeed, the globally averaged AE hardly changes (Fig. 4(a)), while the globally averaged asymmetry parameter increases by about 0.012 (Fig. 4(b)).

Note that although the data in Figs. 3 and 4 are shown for only two fixed values of the imaginary refractive index, the results for intermediate values can be estimated by simple linear interpolation.

4. Discussion and conclusions

The scope of our sensitivity analysis in the preceding section is necessarily constrained by the limited information content and relatively low accuracy of the AVHRR radiance dataset. One can argue, for example, that other aerosol and surface parameters could also have changed over the duration of the GACP record. Furthermore, allowing the imaginary refractive index to increase while not taking into account the resulting effect of complex morphology of mineral, soot, and soot-containing aerosols on the aerosol phase function (e.g., Refs. [14,72–77]) can hardly be viewed as a self-consistent approach. These factors illustrate vividly the immense complexity of the aerosol remote-sensing problem and reinforce the need for orbital instruments providing the requisite capability to *retrieve* rather than *assume* all relevant parameters of the atmosphere–surface system [51,53,69,78].

Despite the inherent deficiencies of our analysis and the impossibility to overcome its limitations in an objective and self-consistent way, its outcome is instructive and illustrates that it is quite easy to misinterpret a long-term change in the chemical composition of tropospheric aerosols in terms of a significant artificial AOT trend. As we have stated before, it is not a goal of this study to scrutinize the plausibility of a chemical-composition trend that could result in an increase of the imaginary refractive index from ~0.003 to ~0.007. It is obvious, however, that if such a change were to happen, it would have a strong warming effect on the lower atmosphere potentially contributing to the recently observed surface temperature rise [79]. We feel, therefore, that it is important for the atmospheric community to recognize the importance of accurate global retrievals of SSA from satellite observations. It is essential to parallel recent assessments of the existing AOT retrieval capability from space [80–84] by a critical analysis of the existing SSA retrieval capability. It is quite possible that the inability to distinguish between AOT and SSA trends is typical of retrieval algorithms based on radiance observations alone. Should this be the case, satellite instruments providing high-accuracy polarimetric as well as radiance data (e.g., Ref. [53]) must be flown in order to provide the requisite retrieval capability.

As far as the nominal GACP record is concerned, it is interesting to note that the most recent 4-year segment of the AOT and AE averages reveals no significant short-term tendencies. While this period may be too short for drawing far-reaching conclusions, the very lack of noticeable tendencies is consistent with contemporaneous MODIS and MISR results [82] as well as with the accumulating evidence of a gradual transition from global brightening to global dimming [37,38].

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