Sensitivity of TOMS aerosol index to boundary layer height: Implications for detection of mineral aerosol sources

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Abstract

The TOMS aerosol index has shown to be a very powerful tool in determining the sources of mineral aerosols. The sensitivity of the TOMS aerosol index to the height of the aerosol layer has been noted previously, but the implications of this sensitivity for deducing sources has not been explicitly considered. Here, we present a methodology and a sensitivity test to show the importance of spatial and temporal variations of the planetary boundary layer height to deducing sources using the TOMS aerosol index. These results suggest that while dry lake bed sources may be large sources of desert dust, conclusions eliminating other types of sources may be premature. Regions on the edges of deserts tend to have lower boundary layer heights than the middle of desert regions, and thus any sources located in these regions are less visible to the TOMS aerosol index.

1.0 Introduction

Identifying the sources of mineral aerosol has been a difficult process, due to the complex natural and anthropogenic processes which are involved in entraining soil particles into

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the atmosphere [e.g. *Okin and Gillette,* 2001]. In situ studies [e.g. *Marticorena and Bergametti,* 1995; *Gillette,* 1998] of the soil particle size distribution and chemical and mineralogical characteristics can provide data about easily erodible soils, but global maps of these characteristics are not available at the resolution required. The *Herman et al.* [1997], *Prospero et al.* [2002], *Ginoux et al*. [2001] and *Goudie and Middleton* [2001] studies marked a large step forward, by showing from the TOMS aerosol index (TOMS AI) and other data that dry lake bed areas (or topographic lows) appear to be the strongest sources.

In *Prospero et al.* [2002] they identify the sources of mineral aerosols as those areas with persistent, high TOMS aerosol index (using a threshold of 0.7, except over North Africa, the Middle East and Central Asia where the threshold is 1.0); while in the *Goudie and Middleton* [2001] study they use mean TOMS AI. However, the TOMS aerosol index (TOMS AI) is well known to have a strong sensitivity to the height of the aerosol layer [*Torres et al.,* 1998, *Prospero et al.,* 2002]. Indeed the *Prospero et al.* [2002] study suggests that there is a strong correlation of the TOMS AI to planetary boundary layer height. However, no one has explored explicitly what the sensitivity to boundary layer height implies for detecting sources using the TOMS AI. In this paper we conduct a sensitivity study including the effects of planetary boundary layer height (PBLH) on the TOMS AI, and look for areas of persistent 'significant' aerosols, similar to *Prospero et al.* [2002] for the region of North Africa. Our sensitivity study consists of calculating a seasonally- and spatially-varying ‘threshold’ that includes the effect of the PBLH, but assumes a constant column of dust and thus a constant dust source.

2.0 TOMS aerosol index sensitivity to PBLH

The uv-absorbing aerosol amount is derived from TOMS measurements using a spectral contrast method in a UV region where the ozone absorption is very small [*Herman et al.* 1997, *Torres et al.,* 1998]. In cloud free conditions, this residue (called the TOMS AI) strongly depends on the amount of absorbing aerosols [*Herman et al.* 1997, *Torres et al.,* 1998]. Here we consider desert dust particles close to the sources and thus, to allow intercomparison, we use the physical properties of the "d3" aerosol type from *Torres et al.* [1998] using the optical properties updated in Synyuk et al. [2003]. The atmospheric radiative transfer is computed with the SBDART code [*Ricchiazzi et al.,* 1998)] that incorporates the LOWTRAN7 band models [*Pierluissi and Peng*, 1985] and the DISORT discrete ordinate method [*Stammes et al.,* 1988]. Our computations reproduce the published results of *Torres et al.* [1998].

We assume a simple vertical profile with dust in the boundary layer, with a linearly decreasing mixing ratio of mineral aerosol with height and the concentration of zero above the planetary boundary layer height (PBLH). This aerosol distribution is the solution to a Fick's Law type vertical diffusion, assuming there is a constant surface flux with strong mixing and removal from the column at the top of the boundary layer (presumably transport downwind). For this aerosol vertical profile, our calculation using the SBDART code for the dependence of the TOMS AI with the PBLH is displayed in Figure 1 for various aerosol optical thicknesses. Sensitivity tests suggest that parameters which have uncertainties (e.g. vertical aerosol profile, index of refraction or size distribution) do not change the almost linear relationship between PBLH and TOMS AI, although they do change the slope of the relationship. If instead, optical properties from Torres et al. [1998] were used, the intercept shown in Figure 1 would be much lower, suggesting much smaller TOMS AI for dust close to the surface than using the optical depths from Synuk et al. [2003] (not shown). TOMS AI retrievals from satellite also depend on viewing angle and cloud reflectivity—here we exclude days when the reflectivity is higher than 0.2, to exclude cloudy pixels.

3.0 Implications for sources areas

For ease of use and global coverage, we use PBLH derived from the MATCH model using the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP) reanalysis [*Mahowald, et al.,* 1997; *Rasch, et al.,* 1997; *Kalnay et al,* 1996]. We archived daily averaged values, however, and the diurnal cycle in boundary layer heights is very strong, especially in desert areas. The TOMS AI is calculated from satellite observations during the daytime. From a 10-day simulation of the diurnal cycle in the model, we calculate that the best estimate of the daytime boundary layer height from the daily average boundary layer height is (daytime average=(daily average*24-nighttime average*12)/12), where the nighttime average is 200m. The monthly averaged daytime boundary layer heights for January and July are shown in Figure 2 for 1981. The daytime averaged boundary layer heights are very high (greater than 3 km) in some desert regions in the dry season, and much lower elsewhere (500-1000m), even in adjoining regions, as well as in the wet season or winter. The seasonality and height of the boundary layers over arid regions appear to be consistent with our understanding of boundary layer heights and available observations [e.g. *Garratt,* 1992, *Wai, et al.,* 1997].

To highlight regions covered by a 'significant' amount of mineral aerosol, *Prospero et al*. [2002] use a threshold TOMS AI of 0.7 in most of the world, and use 1.0 over North Africa, the Middle East and Central Asia (which we will call a fixed-threshold) and calculate the number of days during each month that this value is exceeded. In order to highlight similar areas, we define a new spatially- and temporally- varying threshold (referred to here as the PBLH-threshold) from Figure 2 as the TOMS AI corresponding to a boundary layer aerosol with an optical depth of 0.5. Clearly, the PBLH-threshold is very different depending on the location and month of the year, as seen in Figure 3 for January and July of 1981, where it varies by a factor 4 seasonally and spatially. Notice that the regions of high PBLH in this analysis correspond to a large extent with the regions identified by Goudie and Middleton [2001] as dominant sources. It is possible that the main reason for the high TOMS AI in these regions is because they are sources, however, this analysis suggests that there is a strong contribution from the high PBLH in these regions. For the Bodele basin, for example, if the source was upwind to the northeast, boundary layers height go from 1.8 to 3.0 km in a short distance—thus dust from these dust sources may not be observable from TOMS AI until they reach the Bodele basin.

The use of time varying thresholds for the TOMS AI is supported by observations available outside the sources regions. During winter, when the "Saharan dust layer" over the North Atlantic is lower, the satellite retrieved TOMS AI is lower for a given optical depth measured at aeronet ground stations than during summer [*Hsu, et al.,* 1999].

For comparison, we show the number of days that the satellite retrieved TOMS AI are above the fixed-threshold from *Prospero et al*. [2002] in Figure 4 a, c and e for the months of January, July and November, 1981, respectively (similar to *Prospero et al.* [2002] Figure 2). Next we calculate the frequency that the satellite retrieved TOMS AI is above the PBLH-thresholds (shown in Figure 4b, d and f for January, July and November, respectively). Note that if we looked at the percentage of retrieval days with high dust (instead of absolute number of days) we would obtain similar results. An important effect of using the PBLH-threshold, compared with using the fixed-threshold is to change the very strong seasonal cycle seen in previous studies [e.g. Prospero, et al., 2002], to be more consistent with visibility studies of the region [*Mbourou, et al.,* 1997], which show much less dust during the summer. We will not address the biomass burning sources, such as in Africa between about 10N and 15S, nor TOMS AI over ocean regions. Notice that in July, 1981, the frequency of high dust seen in North Africa between 15N and 30N west of 0E is higher than east of 0E, implying that the dust is not advected (e.g. from Bodele basin), but rather appear to be from a local source in this analysis. It is not possible to determine whether this large area of high dust frequency is more consistent with the 'disturbed' sources suggested by *Tegen and Fung* [1995] or *Mahowald et al*. [2002] or a topographic low, as suggested *by Prospero et al.* [2002] since this region includes many seasonal lakes as well as humans and domestic animals.

In Figure 4, we show the frequency of ‘significant’ aerosol events in January (a and b) and November (e and f). These months have the lowest amount of persistent areas, and thus the methodology of *Prospero, et al.* [2003] would use these months to suggest the location of the sources during the whole year. This sensitivity study suggests that in January or November, the removal of the effect of boundary layer height on the TOMS AI increases the area with days with 'significant' aerosol amounts substantially in the western part of the Sahel, on the southern edge of the Sahara. Again, these regions appear to be local sources, not downwind advection from the Bodele basin. The methodology of choosing the month in which the index is generally lowest, and suggesting that the areas with many days above the 'significant' threshold are the most important sources during other times of the year may not be robust. In some areas, there may be low wind speeds as well as low planetary boundary layer heights during the low TOMS AI months, and that may be why there is less mineral aerosols detected by the TOMS AI. Other months may have very different sources [e.g. *Marticorena and Bergametti,* 1996].

4.0 Summary and Conclusions

Prospero et al., [2002] identify regions with persistent 'significant' aerosol amount as the most likely source regions for mineral aerosols using a fixed threshold; while Goudie and Middleton [2001] use mean TOMS AI. These studies have suggested that most of the mineral aerosol comes from dry lake beds in the current climate and not from the large expanses of desert such as the Sahara--an important observation that has assisted many global modelers in improving their mineral aerosol simulations [e.g. *Ginoux et al.,* 2001]. In addition, they argue that the topographic low source areas are not substantially impacted by anthropogenic activities.

But as noted in previous studies [e.g. *Torres et al.,* 1998, *Prospero et al.,* 2002], the TOMS AI is very sensitive to the height of the aerosol layer. We have conducted a simple sensitivity study here, where we use a monthly and spatially varying threshold based on boundary layer height to identify the source regions for one year, 1981. The inclusion of the boundary layer height based thresholds suggest that previous studies may have underestimated the importance of sources on the edges of deserts or other areas where the boundary layer depths are systematically lower than in topographic lows. In addition, these regions may well be impacted by human activities, since they appear to have roads [e.g. http://www.ornl.gov/gist/projects/LandScan/landscan_doc.htm; *Dobson, et al.,* 2000]. Incorporating the PBLH effect on the TOMS AI allows us to have a seasonal cycle that is more consistent with visibility data over North Africa [*Mbuouru, et al.,* 1998].

Identification of the sources of mineral aerosols from satellite retrieved aerosol absorption is inherently a hard problem due to the difficulty of determining whether observed mineral aerosols have been transported or have a local source. Because the TOMS AI is less sensitive to aerosols at a low altitude, this index may not be able to conclusively determine sources. Surface process studies such as *Chomette, et al.* [1999] using satellite retrieved surface properties, or in situ studies such as *Marticorena and Bergametti* [1995], *Gillette* [1988] offer invaluable data about the erodibility of soils. These types of surface oriented studies are required to eliminate or confirm source regions on a global scale. Nevertheless, the TOMS AI represents an excellent long term series of measurements enabling us to better understand the sources, transport, distribution and deposition of mineral aerosols.

Acknowledgements:

The TOMS AI data used in this paper was kindly made available by the NASA/GSFC TOMS Ozone Processing Team (OPT). We would like to acknowledge the support of NASA through the NIP and IDS programs, and NSF through the Biocomplexity project. This paper benefited from conversations with Omar Torres, Paul Ginoux, Greg Okin, Johann Fedema, Masaru Yoshioka and Chao Luo. We appreciate the substantial computer assistance provided by John del Corral.

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Figure Captions:

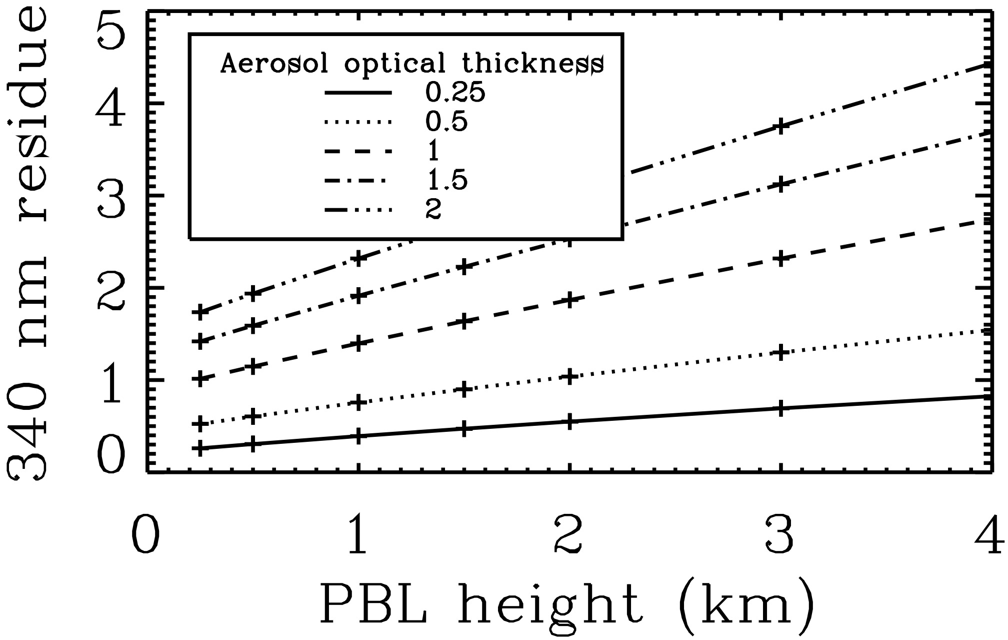
Figure 1: Dependence of the TOMS AI at 340nm, defined as the 340 nm residue, as a function of the PBLH, for various aerosol optical thicknesses at 380 nm. The aerosol mixing ratio decreases linearly with height and reaches zero at the top of the PBL. The

aerosol size distribution follows a lognormal distribution (r_0=0.50μm, σ=2.2) and the refractive index comes from *Sinyuk et al.* [2003]. Other conditions are solar zenith angle 40˚, nadir view for the satellite, surface reflectivity 0.05, summer mid-latitude atmospheric profile.

Figure 2: Monthly averaged daytime boundary layer heights for January (a) and July (b), 1981, from the MATCH model, in km.

Figure 3: TOMS AI thresholds (refered to as PBLH-thresholds in text), assuming an optical thickness of 0.5 in Figure 1, and the boundary layer heights in Figure 2 for January (a) and July (b), 1981.

Figure 4: Number of days of 'significant' dust events for using a constant threshold of 1.0 for January (a), July (c) and November (e) and using time and spatially varying thresholds from Figure 3 for January (b), July (d) and November (f) for 1981 (similar to Figure 2 from *Prospero et al.* [2002]).


Aerosol optical thickness
0.25
0.5
1
1.5
2
340 nm residue
0
1
2
3
4
5
0
1
2
3
4
PBL height (km)

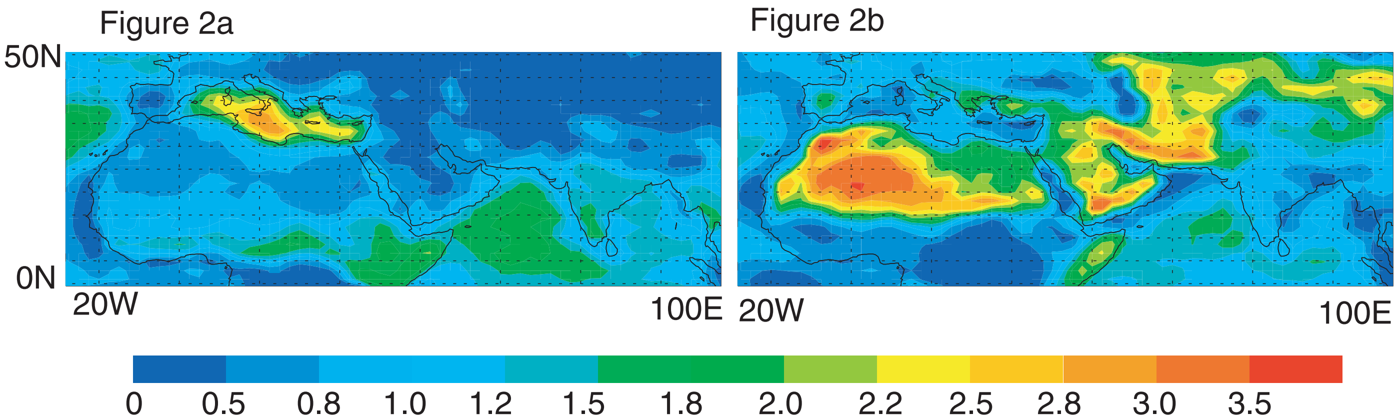
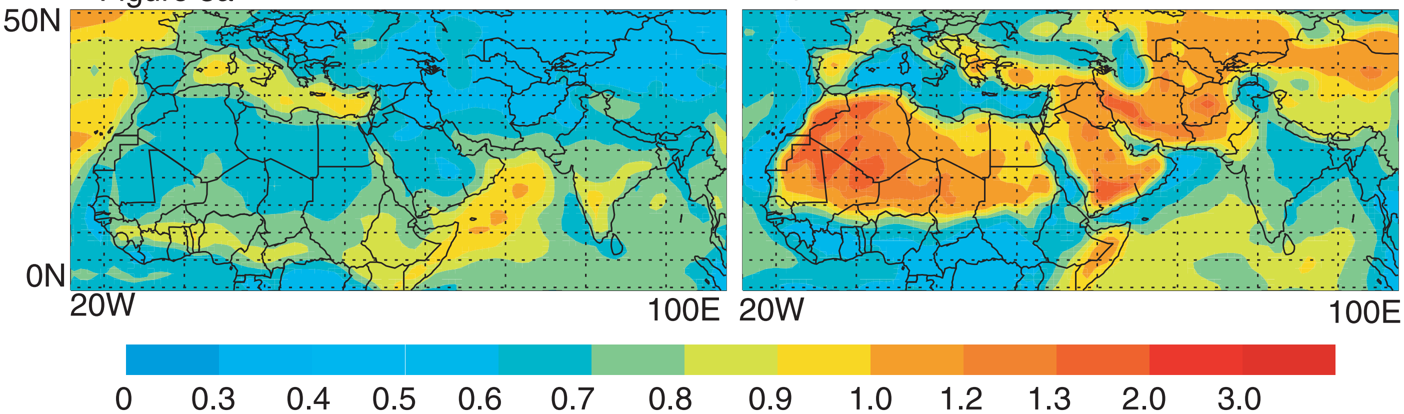


Figure 2a
Figure 2b
50N
0N
20W
100E
20W
100E
0
0.5
0.8
1.0
1.2
1.5
1.8
2.0
2.2
2.5
2.8
3.0
3.5

Figure 3a

Figure 3b



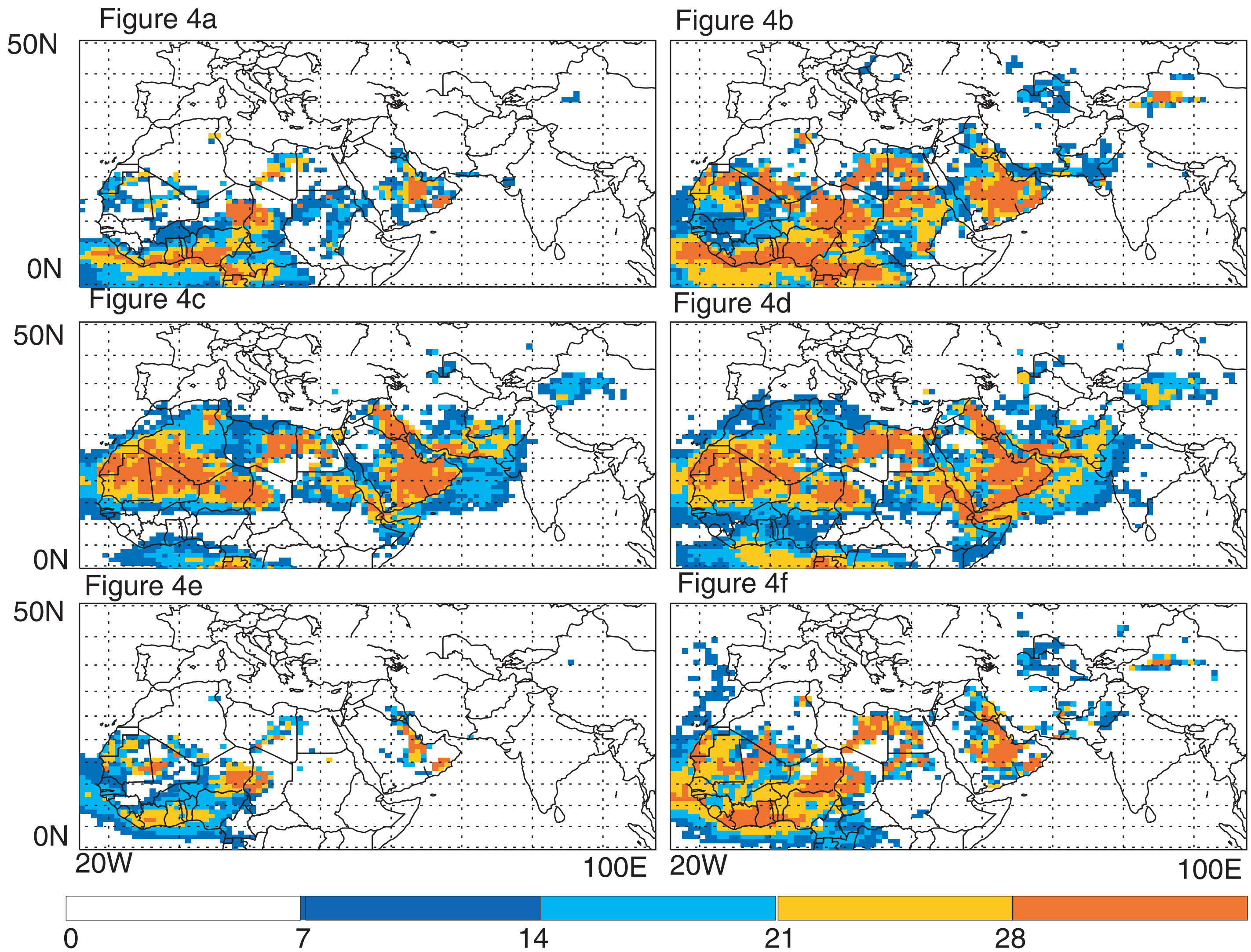


Figure 4a
Figure 4b
Figure 4c
Figure 4d
Figure 4e
Figure 4f
50N
0N
20W
100E
0
7
14
21
28