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# Clear Sky Visibility Has Decreased over Land Globally from 1973 to 2007

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the power of combining field-free alignment techniques with ultrafast spectroscopy.


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**Supporting Online Material**
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# Clear Sky Visibility Has Decreased over Land Globally from 1973 to 2007


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**Visibility in the clear sky is reduced by the presence of aerosols, whose types and concentrations have a large impact on the amount of solar radiation that reaches Earth's surface. Here we establish a global climatology of inverse visibilities over land from 1973 to 2007 and interpret it in terms of changes in aerosol optical depth and the consequent impacts on incident solar radiation. The aerosol contribution to "global dimming," first reported in terms of strong decreases in measured incident solar radiation up to the mid-1980s, has monotonically increased over the period analyzed. Since that time, visibility has increased over Europe, consistent with reported European "brightening," but has decreased substantially over south and east Asia, South America, Australia, and Africa, resulting in net global dimming over land.**


Uncertainty about how much the concentration of atmospheric aerosols has increased over the past century and its impact on the global radiation balance have been major obstacles to establishing how observed changes of climate are related to changes in greenhouse gas concentrations. Some long-period observational constraints on aerosols are provided by measurement of solar radiation incident at the surface (*1*) and by estimation of emissions by fossil fuel combustion (*2*). The former can be equally or more greatly affected by changes of cloudiness (*3*), and the latter can be used to estimate changes of limited aerosol types (*2*). Much better estimates of global aerosol impacts can be made over the past decade from both surface and satellite measurements of aerosol optical depth (AOD) (*4*, *5*). For a given vertical profile of aerosols, the meteorological visibility inverse (ViI) is directly proportional to AOD. Thus, we can use these recent measurements of AOD to evaluate the accuracy of ViI in terms of its mean and spatial variability. This evaluation establishes the ViI climatology as a data set that characterizes the spatial and temporal variability of over-land aerosols for the past several decades.

We calculated ViI in $km^{-1}$ from the National Climatic Data Center (NCDC) Global Summary of Day (GSOD) database collected from about 3250 meteorological stations from 1973 to 2007. It is multiplied by a scaling factor of 1.0 km, as inferred from rules described in (*6*). This index is used as an estimate of AOD for a particular aerosol profile, and has other uncertainties described in (*6*). However, its evaluation against other more recent and more direct data sets shows that it estimates AOD with an accuracy comparable to that of the other measures (*6*) and thus can be used to discuss the effects of aerosols on the incidence of solar radiation.

The geographic long-term variation of this AOD measure is determined by aggregating the meteorological station data into continental regions where such data are available, removing time means, and calculating the area-weighted monthly anomaly values for regions where data are available for more than 80% of the stations [see (*6*) for explanation of the gap; see fig. S7 for domains). Aerosols increased on average over all continental regions between 1979 and 2006, with the exception of Europe (Fig. 1). In particular, they increased from 1979 over Australia and south Asia (including India and China), decreased over South America and Africa from 1979 to about 1985, and then increased and were relatively unchanged over north Asia (Siberia).

The large increases of Asian AODs likely were consequences of large increases in industrial activities and are consistent with long-term observations of incident solar radiation and cloud cover in India (*7*) and China (*8*). The European decreases are consistent with numerous past studies based on long-term measurements of aerosols, solar radiation, and clouds (*9*–*11*), which are consistent with changes in emissions of aerosol precursors, $SO_2$ (*12*, *13*), black carbon (*14*), and organic carbon (*14*, *15*).

The variability of measured changes between stations from 1973 to 2007 is summarized in terms of linear trends for the period 1973 to 2007. Figure 2 shows the spatial distribution of the 58% of the stations that have magnitudes of their trends greater than 0.0015 $year^{-1}$—that is, 50% larger than the global area-weight average linear trend of 0.001 $year^{-1}$. This change in AOD is not the same everywhere; AODs substantially declined in Europe after peaking in the 1980s. These changes vary widely from location to location (Fig. 2). Overall, the largest increases of AOD have been in Asia, and these increases have accelerated over the past decade, producing the rapid global increase over this period.

Aerosols reduce solar radiation at Earth's surface by upward reflection and absorption. The energy lost in this manner either escapes to space or heats the air. Aerosols can further affect surface radiation by modifying cloud cover and other cloud properties. The long-term trend in over-land ViI AOD that we report is consistent with the long-term variation in incident solar radiation in China, India, and Europe (*7*–*11*). Wild *et al.* (*1*) documented that solar radiation


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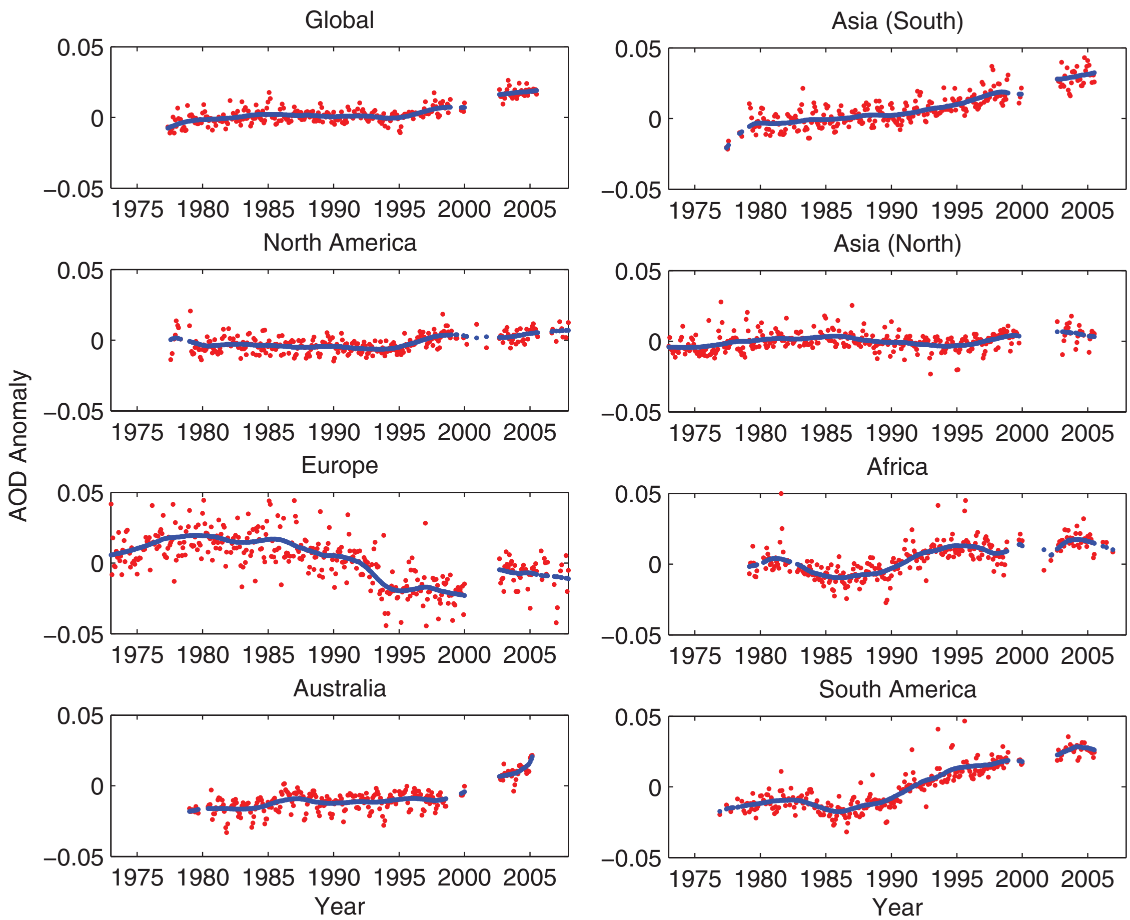


**Fig. 1.** Regional and global averaged monthly AOD anomaly (red dots) over land and their smoothed 5-year averages (blue dots).

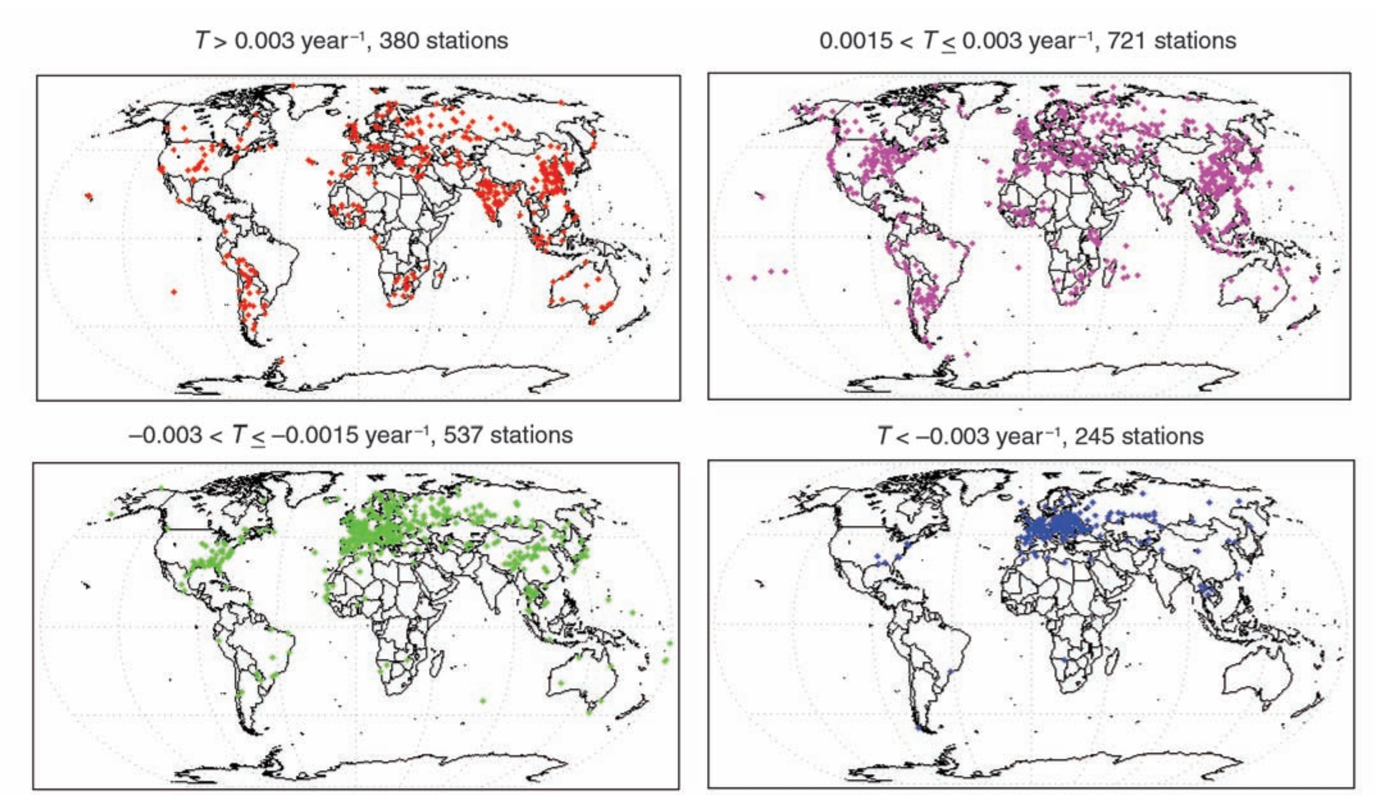


**Fig. 2.** Locations of the ~58% of the 3250 stations where the magnitude of Vil AOD changed (linear trend, $T$) by more than 0.0015 $year^{-1}$ from 1973 to 2007.

increased in Europe after 1990, in agreement with the AOD changes seen in Figs. 1 and 2. However, many more stations have measured visibility and many have longer histories. The use of emissions to infer aerosols introduces considerable uncertainty in the estimation of aerosol impacts on radiation (*16*).

The ViI AOD over land is a complementary constraint to satellite-derived AOD (*4*, *5*) that is most readily obtained over oceans. The latter includes volcanic and high-level dust contributions that are necessarily excluded by the ViI approach. The AOD estimated from the Advanced Very High Resolution Radiometer (AVHRR) instrument (*17*–*19*) for the period 1991 to 2005, averaged globally over the oceans, indicates a change comparable in magnitude but opposite in sign to that indicated by Fig. 1. Changes seen in regional analyses of these data (*18*, *19*), however, appear to be entirely consistent with those found here, showing decreases in Europe and increases in industrializing Asia. In particular, the strongest decreases (greater than 0.003 $year^{-1}$) indicated in Fig. 2 are over a belt north of the Mediterranean extending into Asia, matching the analyses over the Mediterranean, Black, and Caspian seas (*19*), and the strongest increases (greater than 0.003 $year^{-1}$) are in near-coast industrializing Asia, thereby matching these analyses (*19*). Thus, it would appear that estimates of change over these regions for the period since 1991 might be improved by combining the ViI and AVHRR estimates.

Although increases in the concentrations of many types of aerosols may have contributed to the AOD increase, by far the largest documented changes in aerosols and their precursors are those from the increased use of fossil fuels, in particular $SO_2$. If so, the changes reported here appear to be inconsistent with the conclusions of the Intergovernmental Panel on Climate Change (IPCC) [(*20*), chapter 2, p. 160], which cited studies concluding that global emissions of sulfate aerosol decreased by 10 to 20 Tg $year^{-1}$ from 1980 to 2000. Those estimates may not have adequately accounted for the 20 Tg $year^{-1}$ increase of sulfate emission over Asia during that period (*21*). Increases in biomass burning of tropical forest and agriculture (*22*, *23*) may also have contributed to increases in AOD. The decrease of AOD in Europe is a consequence of near-constant fossil fuel use coupled with a large decrease in sulfur content as required by air quality regulations.

Current descriptions of AOD as provided by satellite data (*6*) have been used as a major constraint on the aerosol radiative forcing used as part of the IPCC modeling of climate change (*4*, *5*). However, the objective of simulating the 20th-century climate as a means of validating the models has been limited by an absence of observational information on the time history of AOD, a shortcoming that is remedied by the data set described here.

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# Recent Changes in Phytoplankton Communities Associated with Rapid Regional Climate Change Along the Western Antarctic Peninsula


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The climate of the western shelf of the Antarctic Peninsula (WAP) is undergoing a transition from a cold-dry polar-type climate to a warm-humid sub-Antarctic–type climate. Using three decades of satellite and field data, we document that ocean biological productivity, inferred from chlorophyll a concentration (Chl a), has significantly changed along the WAP shelf. Summertime surface Chl a (summer integrated Chl a ~63% of annually integrated Chl a) declined by 12% along the WAP over the past 30 years, with the largest decreases equatorward of 63°S and with substantial increases in Chl a occurring farther south. The latitudinal variation in Chl a trends reflects shifting patterns of ice cover, cloud formation, and windiness affecting water-column mixing. Regional changes in phytoplankton coincide with observed changes in krill (*Euphausia superba*) and penguin populations.


Over the past several decades, the marine ecosystem along the western continental shelf of the Antarctic Peninsula (WAP) (62° to 69°S, 59° to 78°W, ~1000 by 200 km) has undergone rapid physical climate change (*1*). Compared with conditions in 1979 at the beginning of satellite data coverage, seasonal sea ice during 2004 arrived 54 ± 9 (1 SE) days later in autumn and departed 31 ± 10 days earlier in spring (*2*). Winter air temperatures, measured between 62.2°S, 57.0°W and 65.3°S, 64.3°W, warmed at up to 4.8 times the global average rate during the past half-century (*3*–*5*). This warming is the most rapid of the past 500 years and stands in contrast to a marked cooling between 2700 and 100 years before the present (*5*–*7*). As the once-perennial sea ice and glaciers retreat (*6*, *8*), maritime conditions are expanding southward to displace the continental, polar system of the southern WAP (*9*).

As a result, populations of sea ice–dependent species of lower and higher trophic levels are being demographically displaced poleward and are being replaced by ice-avoiding species (e.g.,


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