Long-Term Variability of Airborne Asian Dust observed from TOMS

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Abstract. Recent studies suggest that airborne Asian dust may not only play an important role in the regional radiation budget, but also influence the air quality over North America through long-range transport. In this paper, we use satellite data to investigate the long-term variability of airborne Asian dust as well as the daily variation of the dust aerosol distribution. By combining the TOMS aerosol index with NCEP wind data, our analysis shows a strong correlation between the generation of dust storms in the region and the passage of springtime weather fronts. This is consistent with earlier studies performed by other researchers. According to both the Nimbus-7 and Earth-Probe TOMS data the Takla Makan desert, the Gobi desert, and the arid region of Inner Mongolia are major sources of the eastward-flowing airborne Asian dust. Heavily populated areas in eastern China (e.g., Beijing) are often on the primary path of the dust storms originating in these desert regions. The increasing desertification north of the Beijing region has served to exacerbate problems stemming from these storms. The time series derived from 20 years of TOMS aerosol index data shows the first significant satellite evidence of the atmospheric effect of increasing desertification, indicating that the amount of dust blown eastward has increased strongly during the past few years including the year 2000.

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1. Introduction

The impact of growing air pollution in Asia, and other parts of the world, has gained increasing attention from the scientific community in recent years. Among the many components that contribute to such pollution, airborne mineral dust plays an important role due to its biogeochemical impact on the ecosystem and its radiative-forcing effect on the climate system [Hsu et al., 2000]. In particular, China's capital of Beijing and other large cities are on the primary pathway of dust storm plumes. Satellite views, such as the two shown in Plate 1, illustrate the vast distances over which these dust plumes can extend. The passage of these plumes causes flight delays, pushes grit through windows and doors, and forces people indoors.

Indeed, the problem of "desertification" in China, which is believed to be responsible for the increasing frequency and intensity of the dust storms, has reached an alarming level. A CNN news report indicated that, by the late 1990s, China's deserts were expanding by 2,460 km^2 per year, particularly in the areas of Hebei and Inner Mongolia. Despite its important consequences on daily life, there have been only a few investigations on the behavior of Asian dust [e.g., Prospero et al., 1989, Arimoto et al., 1996, and Zhang et al., 1998] in comparison to numerous studies of Saharan dust [Prospero et al., 1972, Kalu, 1979, Holben et al., 1991, Herman et al., 1997, Chiapello et al., 1999, and Alpert et al., 2000]. In this article, we use aerosol index data from the Total Ozone Mapping Spectrometer (TOMS) [Hsu et al., 1996, Herman et al., 1997, and Torres et al., 1998] to compare the springtime, 2000 seasonally averaged dust loading over East Asia with nearly twenty years of the archived TOMS data (1979-present).

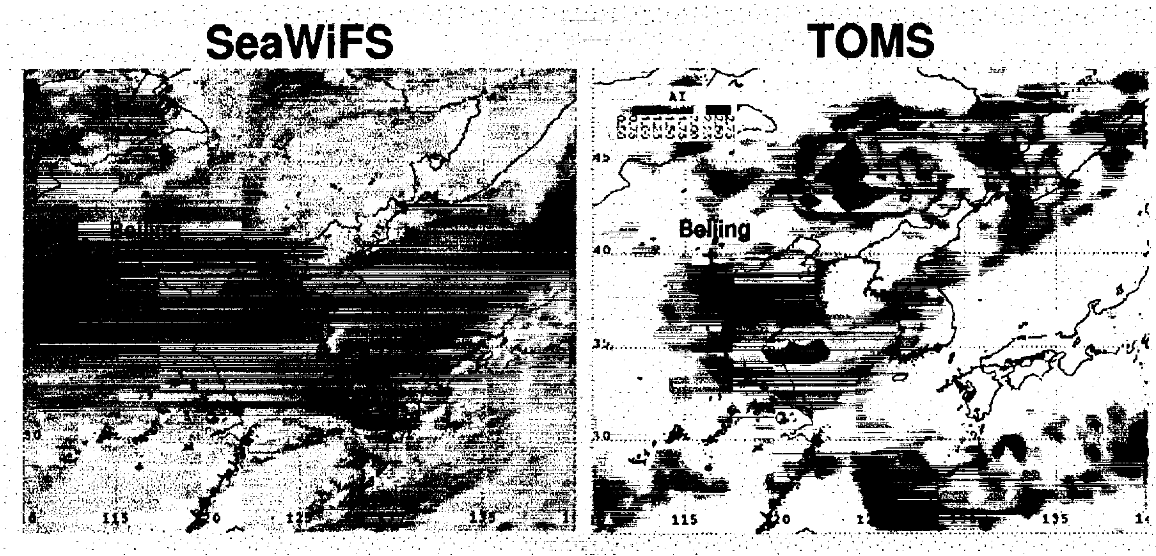


Plate 1. Comparison of two satellite images for a dust event on April 7, 2000. The left image is from SeaWiFS and represents a composite using reflectances from the blue (412 nm), green (555 nm) and red (670 nm) channels after removing Rayleigh scattering and ozone absorption. The right image is the aerosol index from TOMS. The area covered in the two images is 25° N – 50° N and 110° E – 140° E. The dust cloud is clearly seen over eastern China and the Yellow Sea by both satellites. A slight discoloration in the cloud cover can also be seen in the SeaWiFS image for the area of China north of Korea, suggesting the presence of the dust plume above the clouds. This presence is confirmed in the TOMS image, which indicates large aerosol index values over the same region.

2. Evolution of Asian Dust Storms

TOMS aerosol index data, AI, can be used to monitor the evolution of dust storms once dust particles are lifted from their source regions to altitudes above 1 km. The lack of AI sensitivity to aerosols near the ground does not hamper wide-area studies of dust transport, as the AI usually correlates well with ground-based sun photometer optical-depth measurements [Hsu et al., 1999]. The advantage of using AI is that it does not require cloud filtering to detect aerosols, whereas the TOMS aerosol optical depth calculations (sensitive to aerosols all the way to the surface) are meaningful only in cloud-free regions [Torres et al., 1998].

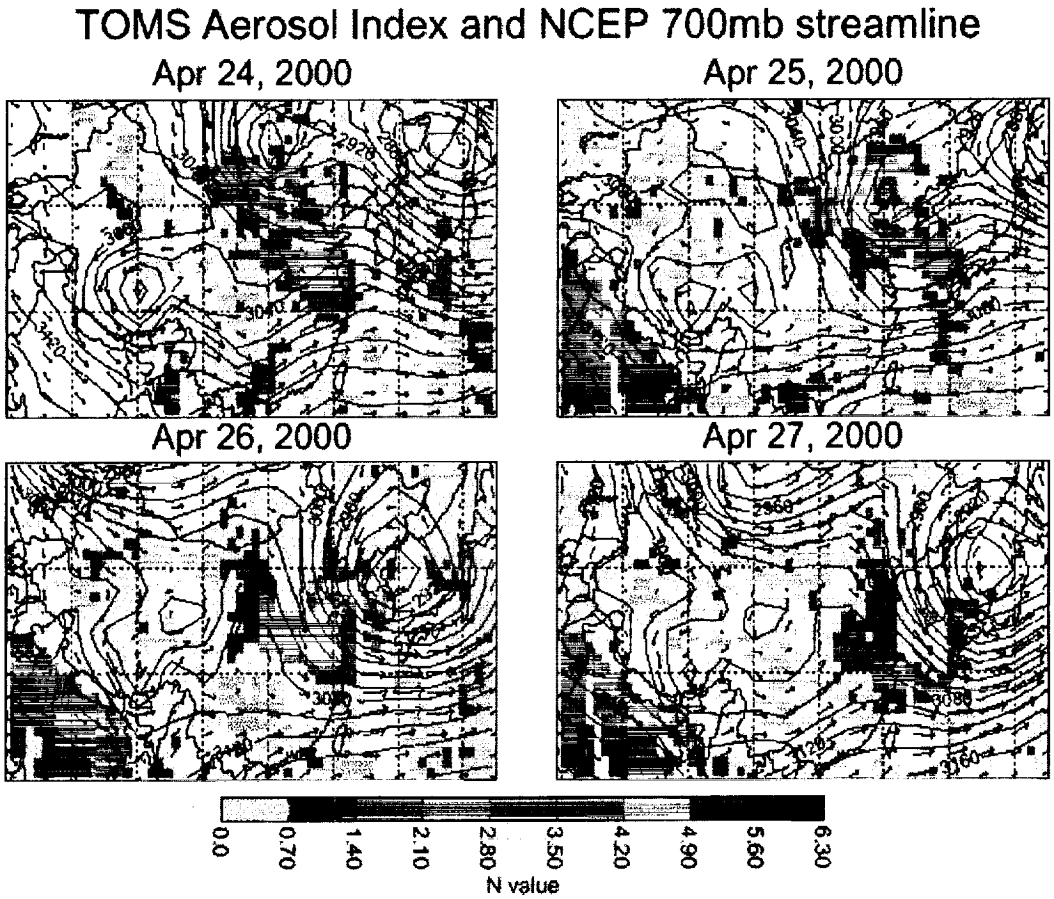


Plate 2. **A four-day composite of the TOMS aerosol index data over East Asia from April 24, 2000 to April 27, 2000. The NCEP wind vector and geopotential height at 700 mb were superimposed on the TOMS data. The dust plume generated by the dust storm on April 24 was transported from the Gobi desert into the Yellow Sea and the East China Sea. The elevated aerosol index over northern India is due to dust aerosols from the Thar Desert.**

Plate 2 shows a four-day time sequence of a dust storm event that occurred on April 24, 2000 over northeastern China. The NCEP wind and geopotential height information at 700 mb were superimposed on the TOMS aerosol index. On this day, a cold air mass moved down from Siberia into Mongolia. Mineral dust was lifted above its source region near the Gobi desert by strong gusty winds associated with this cold front.

Conditions within the Gobi are ideal for producing large amounts of dust. Temperatures vary from an average of -40°F in the winter to 113°F in the summer, with winter being the driest season (less than 3 inches of precipitation) and summer having less than eight inches of rain. While there are strong winds during the entire year, conditions in the springtime are most conducive for transport of dust to the east.

On April 25, TOMS observed the dust plume being transported to northeast China. Steered by an upper level trough centered near Korea, the pressure system moved toward the southeast. In eastern Asia, both the Yellow sea and Korea were covered by heavy dust on April 26. On April 27, TOMS observed the remnant of the dust storm over the East China Sea.

According to the archived TOMS and NCEP data, dust storms in China often occur when there is such a strong high-pressure system in Siberia and a strong low-pressure system over northeast China.

3. Year-to-Year Variations in Occurrences of Dust Storms

An analysis of the 20-year TOMS aerosol index data indicates that the Takla Makan desert, the Gobi desert, and the arid region of Inner Mongolia are the major sources of the airborne Asian dust. There is a strong seasonal variability, with the maximum transport of dust to the east occurring during the spring. In addition to the seasonal variability, there is also a significant amount of variability from year-to-year depending on the amount of rainfall during the preceding summer and on the wind conditions during the spring.

Statistics on the frequency of dust storm occurrences were generated to obtain information on the temporal and spatial distribution of airborne dust particles using

TOMS level-3 aerosol data on a 1° latitude x 1.25° longitude grid. Plate 3 shows the numbers of days in each grid when significant aerosol levels were observed (aerosol index > 1.0 for Earth Probe TOMS) in east Asia during April and May from 1997 to 2000 using Earth Probe TOMS data.

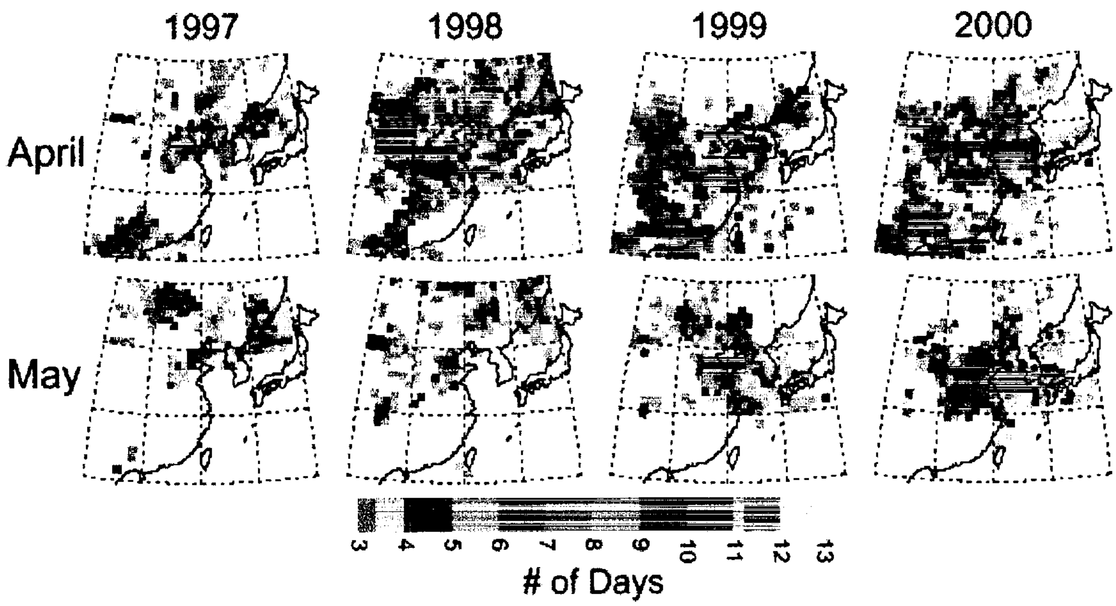


Plate 3. The monthly frequency of occurrence of areas covered by dust in East Asia during springtime (i.e., April and May) from 1997 to 2000 as observed by Earth Probe TOMS.

Multiple types of aerosols are often observed in China during springtime. According to the AVHRR fire count measurements; there are extensive biomass burning activities in Southeast Asia during early springtime along with the severe dust storms discussed above. These smoke and dust aerosols usually are transported to the east by prevailing winds into the Pacific. As shown in Plate 3, there is a large year-to-year variability in dust aerosols lifted away from the source regions. Also, it is obvious that the occurrence of springtime dust storms is more intense during 2000 than in the previous three years.

The implied trend seen in Plate 3 is confirmed by looking at the 20-year history of TOMS aerosol index measurements. Figure 1 (top) shows the springtime averaged TOMS aerosol index over a region near eastern China and the Yellow Sea (32° N - 40° N and 112° E – 130° E) during March, April, and May from 1979 to 2000. The data from

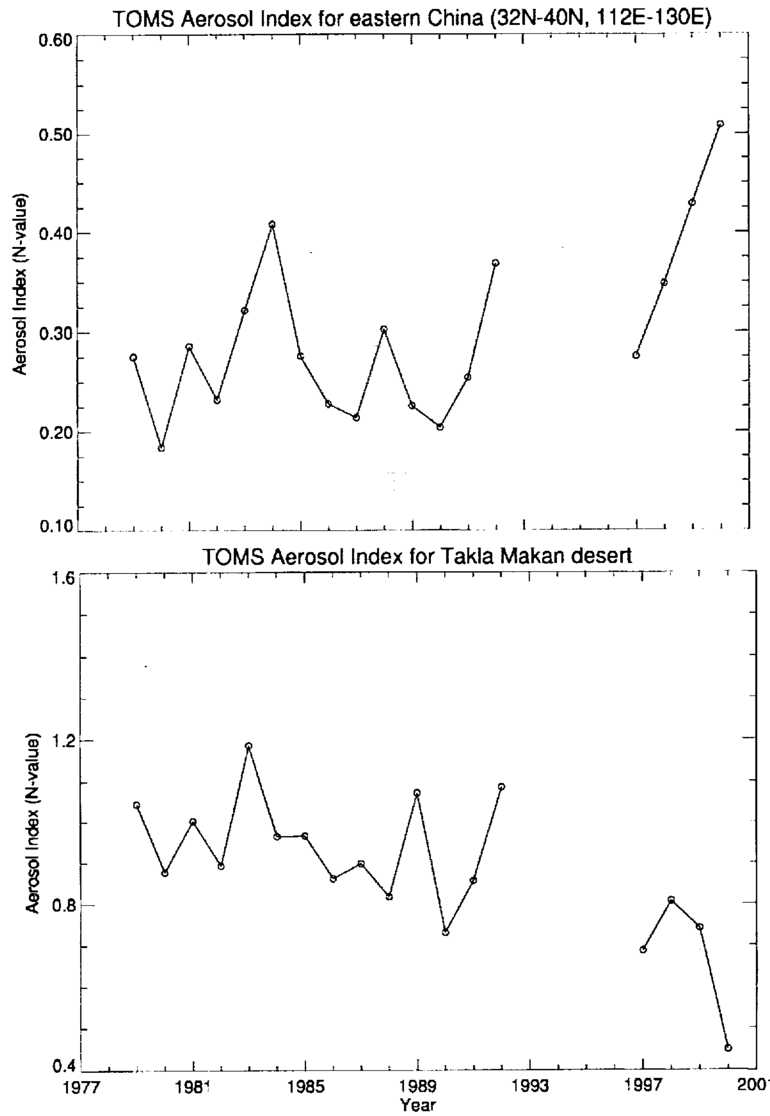


Figure 1. The time series of the springtime (Mar.-May) averaged aerosol index over a box between 32°N - 40°N, 112°E – 130°E (top) and over Takla Makan desert between 36°N – 42°N, 80°W-92°W (bottom) from the year 1979 to 2000 using Nimbus 7 TOMS and Earth Probe TOMS measurements. Because different wavelengths were used, the NIMUS-7/TOMS AI values are adjusted to match the sensitivity of those from EP-TOMS for a given aerosol amount [Hsu et al., 1999].

Numbus-7 TOMS (1979-1992) was combined with those from Earth Probe TOMS (1997-2000) after adjusting for the wavelength difference used in the aerosol index calculations [Hsu et al., 1999] for each TOMS instrument. Cloudy pixels were screened out in our analyses. The upward trend during the past few years is larger than previous variability. The dust loading is particularly high during the last two years (1999 and 2000) of the time series. In contrast, a time series of aerosol index over a region near the Takla Makan desert (36°N – 42°N and 80°W - 92°W) shows a downward trend, especially during the past two years (as shown in the bottom of Figure 1). The airborne dust amount detected by TOMS over this area was generally lower in the late 1990's compared to that in the 1980's. It indicates that the increase in the amount of mineral dust aerosols seen in the continental outflow is most likely due to the increasing contribution from the Gobi desert and the arid region of Inner Mongolia, suggesting a change in the sources of airborne dust in Asia.

4. Discussion

East Asia is one of the more complex regions in the world in terms of the physical and optical properties of aerosols emitted into the air. Air masses from the north often merge with air masses from the south near the coastal provinces of Shandong and Jiangsu, and near the Yellow Sea and the East China Sea before they continue to travel eastward to the Pacific. The result is long-range transport of dust with changing particle properties depending on the distance from the source of dust.

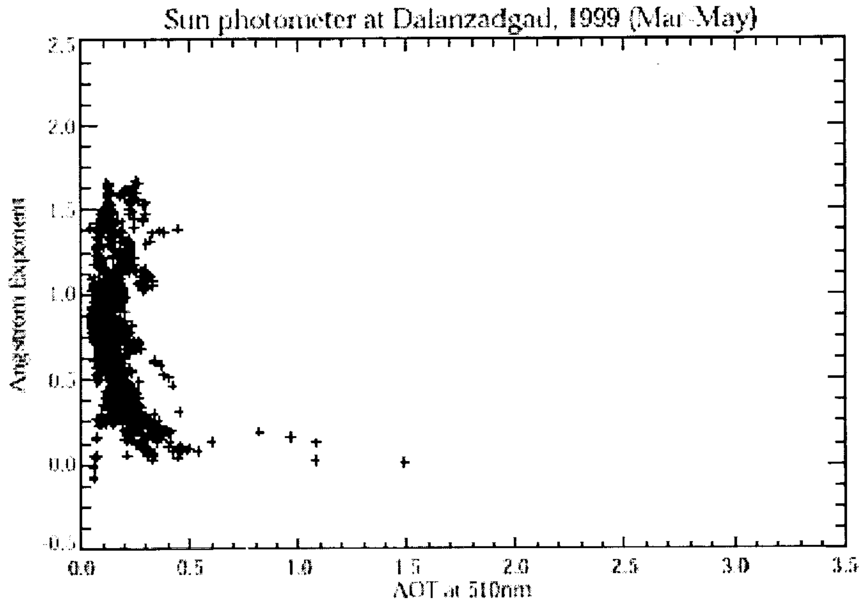
Figure 2 shows the contrast in the observed particle size from AERONET sun photometer data taken at a site near the desert dust source (Figure 2a, Dalanzadgad, Mongolia; 43.58° N, 104.42° E) and at another site downwind from the source (Figure 2b

Chinhae, Korea; 35.16° N, 128.65° E). In both 2a and 2b, the particle size, in terms of the Angstrom exponent, is plotted as a function of aerosol optical depth. The measurements at both of these two sites were taken during the March – May, 1999 period. Data from cloudy days have been screened out [Holben et al., 1998]. A difference in the derived Angstrom exponent pattern between the two sites can be seen.

The measurements over Dalanzadgad show a wide range of Angstrom exponent (0.85±0.85), indicating the presence of both coarse and fine particles in the background over this site. However, as the dust cloud moves over the site (indicated by measurements with optical depths larger than 0.5), the Angstrom exponent decreases to close to zero, which is consistent with the presence of large dust particles.

A number of different patterns can be seen from the measurements over Chinhae. First, the Angstrom exponents for the background aerosols over this site (1.0-1.5) indicate that they are composed of smaller particles than those over Dalanzadgad. Second, the high aerosol events over this site are due to a combination of factors, including sulfate and dust, indicating a more complex situation than Dalanzadgad. Finally, measurements of the Chinhae dust event indicate a slightly larger Angstrom exponent than over Dalanzadgad, suggesting a smaller particle size.

Due to prevailing weather patterns, dust plumes in this region generally are transported to the south and east. Since Dalanzadgad is on the northern fringe of this area, the optical depths measured there are usually lower than those measured at Chinhae, which is directly in the path of the plumes.



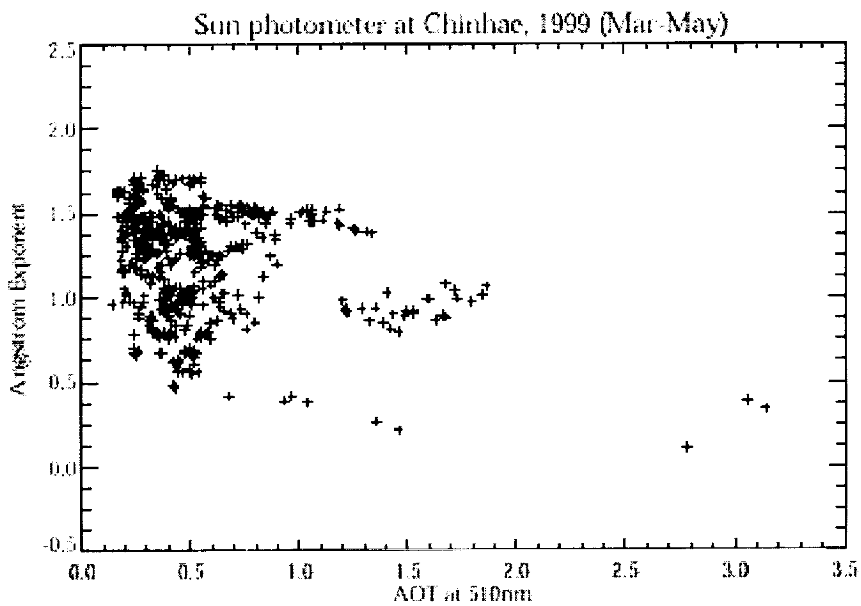


Figure 2. The relationship of aerosol optical thickness and Angstrom exponent measured by AERONET sun photometers at (a) Dalanzadgad, Mongolia (43.58° N, 104.42° E), and (b) Chinhae, Korea (35.16° N, 128.65° E). The former site is close to the source of desert dust, while the later site is downwind from the source and is often under the influence of the China desert dust during the springtime.

The large amount of dust over heavily populated areas in eastern China has become a major ecological problem which will get worse if desertification continues (see Figure 1). While the composition of the dust itself may be benign for health, inhalation of small particles (~0.1 micron or smaller) over extended periods of time can lead to respiratory problems. Where surface dust plumes are extremely heavy, such as those in the 0° to 10°N region of Africa during the winter-spring months (January to April), people are driven indoors for significant periods. While this is not yet the case in eastern China, increasing drought and changing weather patterns in the Gobi region could lead to more frequent and more intense dust episodes.

Summary

Both ground and satellite observations of dust indicate that the amount over eastern China has increased during the past few years. The cause of the increase appears to be the increasing desertification occurring in China's deserts (e.g., the Gobi, 43°N,105°E, and Takla Maken deserts, 40°N 80°E). Dust from the Gobi blowing eastward over eastern China, Korea, and Japan has been observed by TOMS since 1979 and, more recently, from SeaWiFS. The problem now manifests itself in the effect on densely populated areas such as that the one around Beijing.

The causes of these dust storms are directly related to the weather patterns in the season preceding their occurrence, as well as the weather pattern just days before the onset. The seasonal pattern leading to increased amounts of dust is consistent with hot dry weather in the region, with just enough rain during the summer months to cause a considerable amount of fine dust to accumulate. When the local springtime weather pattern is appropriate, strong gusty winds loft the dust eastward, with fine particles able cover long distances, occasionally carrying all the way to the west coast of North America. While the plumes are observed at altitudes up to about 10 km, most of the dust is concentrated at lower altitudes, with substantial amounts at ground level. The ground level plumes are the cause of considerable concern due to their effect on economic activity and for their possible effect on health.

References

Alpert, P., J. Herman, Y. J. Kaufman and I. Carmona, Response of the Climatic Temperature to Dust Forcing, inferred from TOMS Aerosol Index and the NASA Assimilation Model, Atmos. Res. 53, 3-14, 2000.

Arimoto, R., R.A. Duce, D.L. Savoie, J.M. Prospero, R. Talbot, J.D. Cullen, U. Tomza, N.F. Lewis, and B.J. Ray, Relationships among aerosol constituents from Asia and the North Pacific during PEM-West A, *J. Geophys. Res., 101,* 2011-2024, 1996.

Chiapello, I., J.R.Herman, C. Hsu, J. Prospero, NIMBUS-7/TOMS detection of mineral dust over the north Africa and the eastern north Atlantic Ocean, J. Geophys. Res. 104, 9277-9291, 1999.

Herman, J.R., P.K. Bhartia, O.Torres, C. Hsu, C. Seftor, E. Celarier Global Distribution of UV-Absorbing Aerosols From Nimbus-7/TOMS Data, J.Geophys. Res., 102, 16,911-16,922, 1997.

Holben, B. N., et al., AERONET- a federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, **66**, 1-16, 1998.

Holben, B. N., T. F. Eck, and R. S. Fraser, Temporal and spatial variability of aerosol optical depth in the Sahel region in relation to vegetation remote sensing, *Int. J. Remote Sensing*, **12**, 1147-1163, 1991.

Hsu, N. C., J. R. Herman, P. K. Bhartia, C. J. Seftor, O. Torres, A. M. Thompson, J. F. Gleason, T. F. Eck, and B. N. Holben, Detection of biomass burning smoke from TOMS measurements, *Geophy. Res. Lett.*, 23, 745-748, 1996.

Hsu, N. C., J. R. Herman, O. Torres, B. N. Holben, D. Tanre, T. F. Eck, A. Smirnov, B. Chatenet, and F. Lavenu, Comparisons of the TOMS aerosol index with sun-photometer aerosol optical thickness: results and applications, *J. Geophys. Res.*, 104, 6269-6279, 1999.

Hsu, N. C., Herman, J.R., and C. Weaver, Determination of Radiative Forcing of Saharan Dust Using Combined TOMS and ERBE Data, J. Geophys. Res., 105, 20649-20662, 2000.

Kalu, A. E., The African dust plume: its characteristics and propagation across west Africa in winter, in *Saharan Dust: Mobilization, Transport, Deposition*, edited by C. Morales, John Wiley, New York, 1979.

Prospero, J.M. and T.N.Carlson, Vertical and areal distribution of Saharan dust over the western equatorial north Atlantic Ocean, *J. Geophys. Res.*, 27, 5255-5265, 1972.

Prospero, J.M., M. Uematsu, and D.L. Savoie, Mineral aerosol transport to the Pacific Ocean, in *Chemical Oceanography, vol. 10*, edited by J.P. Riley, R. Chester, and R.A. Duce, pp. 219-250, Academic, San Diego, Calif., 1989.

Torres, O., P. K. Bhartia, J. R. Herman, Z. Ahmad, and J. Gleason, Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation. Theoretical basis, *J. Geophys. Res.*, 103, 17099-17110, 1998.

Zhang, X. Y., R. Arimoto, G. H. Zhu, T. Chen, and G. Y. Zhang, Concentration, size-distribution and deposition of mineral aerosol over Chinese desert regions, *Tellus* 50B, 317-330, 1998.

Figure Captions

Plate 1.Comparison of the TOMS aerosol index data with the SeaWiFS true color image between 25° N – 50° N and 110° E – 140° E for April 7, 2000. The SeaWiFS image is made using reflectance from blue (412 nm), green (555 nm), and red (670 nm) channels, after removing Rayleigh scattering and ozone absorption effect.

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