GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 9, 1475, doi:10.1029/2002GL016762, 2003

Mineral aerosol and cloud interactions

Natalie M. Mahowald[1] and Lisa M. Kiehl[2]

Bren School of Environmental Science and Management and the Institute for Computational Earth System Science,
University of California, Santa Barbara, California, USA

Received 13 December 2002; revised 5 March 2003; accepted 25 March 2003; published 8 May 2003.

[1] Interactions between aerosols and clouds are the subject of considerable scientific research, due to the importance of clouds in controlling climate. Here we consider the relationship between mineral aerosols and cloud properties over North Africa and the North Atlantic using monthly mean observations of mineral aerosols and clouds over 16 years. The results of this study are consistent with mineral aerosols suppressing precipitation in thin low altitude clouds and changing cloud amounts in ice phase clouds. Because we cannot eliminate either spurious correlations, or that the cloud and dust changes are both driven by the same meteorological conditions, we cannot provide definitive conclusions. However, these results suggest complicated and tantalizing feedbacks between mineral aerosols and climate. This question becomes crucial as we note that mineral aerosols from North Africa have increased substantially since the 1960s for reasons which are poorly understood but that may be linked to human activity. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0320 Atmospheric Composition and Structure: Cloud physics and chemistry. **Citation:** Mahowald, N. M., and L. M. Kiehl, Mineral aerosol and cloud interactions, *Geophys. Res. Lett.*, *30*(9), 1475, doi:10.1029/2002GL016762, 2003.

1. Introduction

[2] Cloud interactions with aerosols are hypothesized to be critical to understanding climate change since clouds play such a pivotal role in controlling incoming and outgoing radiation [e.g., *Houghton et al.*, 2001]. Previous studies have suggested from in situ and event-based studies that mineral aerosols interact with liquid clouds by suppressing precipitation [e.g., *Levin and Ganor*, 1996; *Rosenfeld and Nirel*, 1996; *Rosenfeld et al.*, 2001]. In addition, there is some evidence that mineral aerosols can act as effective ice formation nuclei [e.g., *Chen et al.*, 1998; *Pruppacher and Klett*, 1997; *Rosenfeld et al.*, 2001; *Sassen*, 2002; *Zuberi et al.*, 2002]. In this study, we consider whether existing large-scale, long term datasets are consistent with the hypothesis that mineral aerosols interact with both liquid water and ice clouds.

2. Methodology

[3] For our cloud statistics we use the monthly mean cloud amount (fraction of sky covered by clouds) data from the International Satellite Cloud Climatology Project (ISCCP) D2 dataset from 1984 to 1999 [*Rossow and Schiffer*, 1991, 1999]. Uncertainties in this dataset come from the misidentification of clouds and inaccurate retrieval algorithms and are thought to be <10% [*Rossow and Schiffer*, 1991]. Observational data suggests that the ISCCP D2 dataset does not clearly identify thin cirrus clouds, particularly in the morning hours, perhaps because of the presence of low-level clouds beneath the cirrus clouds [e.g., *Stubenrauch et al.*, 1999]. ISCCP data separates clouds by height of the top of the cloud and optical depth into low, medium and high clouds, as well as thin, medium and thick clouds and liquid water or ice clouds. Definitions of thin, medium and thick depend on the retrieved optical thickness of the cloud, while high clouds include all clouds which extend above 440mb, whatever level they entrain at [*Rossow and Schiffer*, 1991, 1999].

[4] Figure 1 shows the annual mean absorbing aerosol index (AI) retrieved from the TOMS (Total Ozone Mapping Spectrometer) instrument [*Torres et al.*, 1998]. The large aerosol plume located over North Africa is mostly due to desert dust, although biomass burning aerosols increase in relative importance closer to the equator [e.g., *Tegen et al.*, 1997]. We use two methods to estimate dusty versus non-dusty months. The first method uses the Barbados in situ surface concentration dataset for the same years [*Prospero and Nees*, 1986; D. Savoie, personal communication, 2001] and in the second method we used an area average of TOMS AI. While the Barbados surface concentration dataset represents mineral aerosols at a point at the western edge of the tropical North Atlantic, model studies (see *Mahowald et al.* [2003] for more details) suggest that the monthly mean mineral aerosol anomalies at Barbados are correlated at a moderate to high level (0.4–0.9) with column amount over a wide region extending from North Africa to the eastern Pacific (Figure 2a). To complement the in situ dataset, we use TOMS absorbing aerosol index for the period 1984 to 1992 since that is when the dataset is most robust [*Torres et al.*, 1998; O. Torres, personal communication, 2001] (see *Cakmur et al.* [2001] for a comparison of TOMS AI and AVHRR optical depths for this region). We derive a regional dust index from the TOMS AI by averaging over the region 40W to 20W and 10 to 30 N. This region is chosen because of the large amounts of desert dust and relatively lower amount of cloud interference and biomass burning aerosols than closer to the equator [*Cakmur et al.*, 2001]. The correlation between the monthly averages in dust at Barbados and in TOMS AI in this region is 0.78 with

---

[1] Also at National Center for Atmospheric Research, Boulder, Colorado, USA.

[2] Also at Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, California, USA.

0094-8276/03/2002GL016762$05.00

the seasonal cycle and 0.58 with the seasonal cycle removed, indicating a general consistency in defining anomalous dusty periods in the North Atlantic. Model estimates of correlations between the dust index derived from TOMS AI and column desert dust suggest that the dust index is also representative of a large region of desert dust (Figure 2b). The Barbados dataset has the advantage that data is available daily and represents mineral aerosol unambiguously, although it represents small spatial extent. The satellite data covers a larger spatial domain, but includes the impacts of all aerosols as well as interference from clouds and aerosol height. We will show results from the Barbados in situ surface concentration dataset, but the results do not change qualitatively if we showed the results using the regionally averaged TOMS AI instead.

[5] Because both the cloud datasets and the dust loadings contain large seasonal cycles, we remove the climatological monthly mean and consider only the monthly deviation from the mean seasonal cycle, which we call the monthly anomaly (monthly mean – climatological monthly mean), for the correlation analysis. In the correlation analysis, we conduct simple point by point correlations between the time series in cloud amount and 'dustiness' using monthly averaged anomalies.

3. Results

[6] Results of the correlation between the anomalous monthly surface concentrations at Barbados and the anomalous monthly total cloud amount from ISCCP are shown in Figure 3a. Notice that there appears to be a small region of positive correlations between dust and cloud amount centered at 17N at the west coast of North Africa, and negative correlations between −10 and 10 N across North Africa and the Atlantic. Further analysis by cloud type suggests that the positive anomaly in cloud amount is due to a low to moderate correlation (0.2–0.5) with thin low clouds (Figure 3b), while the negative correlation in cloud amount is due to high ice clouds (cirrus and cirrostratus are shown, with a correlation of 0.2–0.3; deep convective clouds show similar but weaker relationships) (Figures 3c and 3d). Notice that in the western edge of the tropical North Atlantic there is a weak dipole structure (a positive and negative adjacent to each other) seen in correlations with cloud amount, especially seen in total cloud amount and high ice clouds (although the negative anomaly is below statistical significance and does not appear clearly in Figures 3c and 3d). This result is consistent with a shift in clouds towards the south during high dust months, perhaps with some increase in cloud amount. It is unclear what may cause this shift in clouds, but is weakly seen in both Barbados and TOMS correlations.

[7] The positive correlation between cloud amount and mineral aerosols at the coast of North Africa in the low altitude liquid water clouds is consistent with the hypothesis that dust acts as a CCN and is acting to suppress precipitation in thin clouds. Because there are already sufficient CCN in the atmosphere, increasing the number of CCN, as occurs during desert dust outbreaks, will decrease the size of each individual cloud droplet, decreasing the chance of precipitation, thereby increasing the length of time a cloud persists and increasing the observed cloud amount. Note that these correlations are unfortunately also consistent with the misidentification of desert dust events as low altitude thin clouds. In addition, dust as represented by Barbados surface concentrations or TOMS AI may underestimate low level dust close to North Africa, and lead to errors in our correlations. As shown in Figure 4a, the region centered around 17N just off the west coast of North Africa has substantial amounts of low liquid clouds, and thus this is the area where we would expect to see the largest signal if mineral aerosols and water clouds were interacting.

[8] The negative correlation in cloud amount between 10S–10 N across North Africa and the Atlantic is seen in the high clouds (thin cirrus, cirrostratus and deep convective) and occurs in a region of relatively large ice cloud amount (Figure 4b shows cirrus, with similar results for cirrostratus and deep convective clouds) just south of the main desert dust plume. Notice that ideally we would like to use a different record of dustiness for comparison with the region of negative correlation, since the model estimates that both the Barbados in situ record and the TOMS derived dust index are only low to moderately correlated with column dust in this region (Figures 2a and 2b). Unfortunately, no long-term mineral aerosol in situ data exists in this region, and robust satellite retrievals of aerosols are not possible under clouds, thereby reducing our ability to make firm conclusions regarding ice cloud and mineral aerosol interactions. While optical depths are available close to this region, they are available only for a few years and are likely to be dominated by other types of aerosols [*Holben et al.*, 1998]. In addition, there are positive anomalies in the Western North Atlantic between desert dust and ice phase clouds. These appear to be associated with a negative anomaly (not statistically significant in these plots, but seen in Figure 3a) suggesting that there is a shift in the location of ice phase clouds, although there may be a net increase in ice phase clouds.

[9] Ice cloud formation is complicated and may result from either condensation of water vapor directly or by the freezing of liquid cloud droplets. Clay or silicate particles, contained in mineral aerosols, are effective ice nuclei [e.g., *Chen et al.*, 1998; *Pruppacher and Klett*, 1997]. The net effect of the addition of effective ice nuclei on cloud amount is not well understood.

4. Summary

[10] This is the first time that large time and spatial scale correlations between mineral aerosols and cloud properties have been presented. Positive correlations of up to 0.4 between anomalously high dust months and thin low clouds are consistent with mineral aerosols acting as cloud condensation nuclei off the west coast of North Africa during dust events, and suppressing precipitation (similar to *Rosenfeld et al.* [2001]). There are also low negative correlations (−0.2 to −0.3) between high ice clouds (cirrus, stratocirrus and deep convective) and high dust months close to equator in North Africa and the Atlantic. Additionally there are positive anomalies (0.2 to 0.3) in the western equatorial North Atlantic, perhaps associated with more northerly negative anomalies indicating a shift in ice-phase clouds. If mineral aerosols are acting as both cloud condensation nuclei and ice formation nuclei, this suggests very complicated relationships such as those seen here between mineral

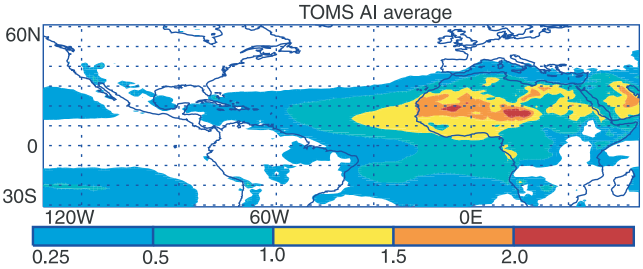
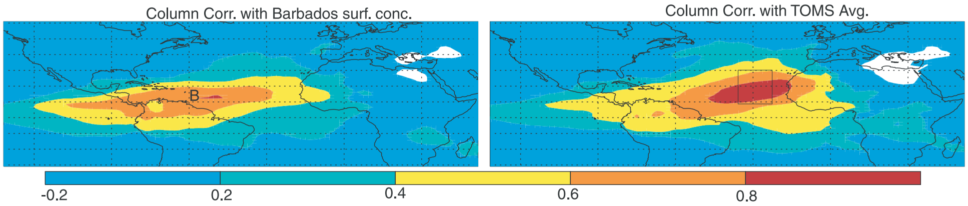

TOMS AI average

Figure 1. Mineral aerosol distribution. TOMS Absorbing Aerosol Index annual mean [*Torres et al.*, 1998], showing the maximum plume over North Africa and the North Atlantic. Note that south of 15N contributions from biomass burning aerosols may be significant.

aerosols and ice phase clouds that should be researched further. Because cloud formation is dominated by large-scale processes, we do not expect higher correlations with mineral aerosols if they are acting as cloud condensation nuclei or ice formation nuclei. Due to the nature of correlations and the datasets used for this study, we cannot make firm conclusions. It is possible that the results here represent spurious correlations, or that the cloud property and dust correlations seen here are both caused by the same meteorological conditions (or by other aerosols such as from biomass burning) but are not causally linked. It is encouraging that the results are seen when we include all months of the year in the analysis, indicating less sensitivity to the large scale changes in meteorology which occur during different seasons.


Column Corr. with Barbados surf. conc.

Column Corr. with TOMS Avg.

Figure 2. ‘Representativeness’ of dust indices. Correlation between model estimates of monthly anomalies (monthly mean – climatological monthly mean) of column amount and Barbados surface concentrations (a) and a satellite derived dust index (column amount between 10N and 30N, 40W and 20W) (b). The location of Barbados (B) and the averaging region (box) are shown on each plot.

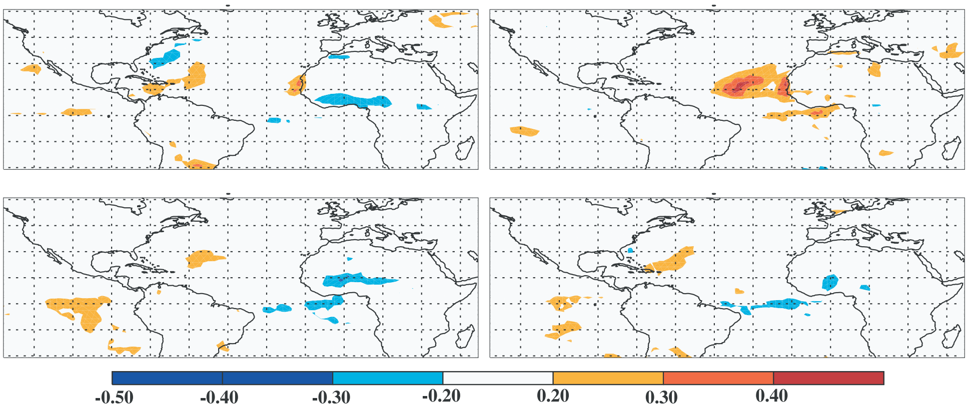
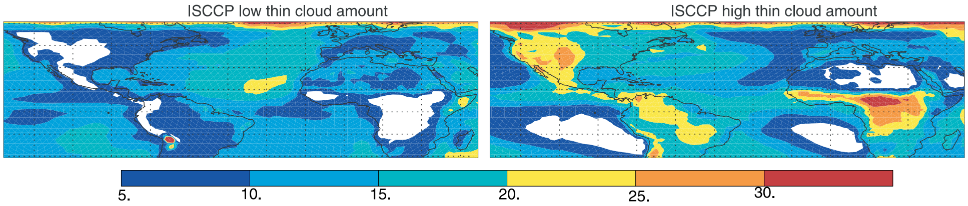


Figure 3. Mineral aerosol and cloud Interactions. Correlation between monthly anomalies (monthly mean - climatology monthly mean) of surface desert dust at Barbados and total Cloud Amount from ISCCP for all clouds (a), low thin clouds (b) and high thin (cirrus) ice clouds (c) and high cirrostratus clouds (d). Assuming independent variables and normal distributions, correlations are significant at the 95% level at 0.2.


ISCCP low thin cloud amount

ISCCP high thin cloud amount

Figure 4. Cloud distributions. Annual mean ISCCP retrieved cloud amount for low thin clouds (a) and thin high (cirrus) clouds (b).

[11] While the large-scale, long-term results presented here can only be tentative in their conclusions, in combination with available process based studies [e.g., *Levin and Ganor*, 1996; *Rosenfeld and Nirel*, 1996; *Chen et al.*, 1998; *Pruppacher and Klett*, 1997; *Rosenfeld et al.*, 2001; *Sassen*, 2002; *Zuberi et al.*, 2002], they suggest that interactions between mineral aerosols and clouds may be climatically significant and should be further studied. The suppression of precipitation in low clouds close to the source areas also suggests that mineral aerosols may play a role in intensifying droughts such as observed over the Sahel since the 1960s [*Rosenfeld et al.*, 2001]. Potential feedbacks between mineral aerosols and clouds are especially important in the context of the observed 2–4-fold increase in mineral aerosols in the North Atlantic since the 1960s, which occurred for reasons which are poorly understood but may be related to human activities [*Prospero and Nees*, 1986; *Tegen et al.*, 1996; *Mahowald et al.*, 2002a].

[12] **Acknowledgments.** We would like to acknowledge the assistance of Pete Petersen and John del Corral. ISCCP and TOMS AI data was provided by NASA, and the Barbados data was provided courtesy of Dennis Savoie and Joe Prospero at University of Miami. This work was funded by NASA-IDS and NASA-NIP. Portions of this work come from L. Kiehl's Master's Thesis at UCSB.

References

Cakmur, R. V., R. L. Miller, and I. Tegen, A comparison of seasonal and interannual variability of soil dust aerosols over the Atlantic Ocean as inferred by the TOMS AI and AVHRR AOT retrievals, *J. Geophys. Res.*, *106*(D16), 18,287–18,303, 2001.

Chen, Y., S. Kreidenweis, L. McInnes, D. C. Rogers, and P. J. DeMott, Single particle analyses of ice nucleating aerosols in the upper troposphere and lower stratosphere, *Geophys. Res. Lett.*, *25*(9), 1391–1394, 1998.

Holben, B. N., et al., AERONET—A federated instrument network and data archive for aerosol characterization, *Remote. Sens. Environ.*, *66*(1), 1–16, 1998.

Houghton, J., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (Eds.), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, 881 pp., Cambridge Univ. Press, New York, 2001.

Levin, Z., and E. Ganor, The effects of desert particles on cloud and rain formation in the eastern Mediterranean, in *The Impact of Desert Dust Across the Mediterranean*, edited by S. Guerzoni and R. Chester, pp. 77–86, Kluwer Acad., Norwell, Mass., 1996.

Mahowald, N., C. Zender, C. Luo, J. del Corral, D. Savoie, and O. Torres, Understanding the 30-year Barbados desert dust record, *J. Geophys. Res.*, *107*(D21), 4561, doi:10.1029/2002JD002097, 2002a.

Mahowald, N. M., C. Luo, J. del Corral, and C. Zender, Interannual variability in atmospheric mineral aerosols from a 22-year model simulation and observation data, *J. Geophys. Res.*, doi:10.1029/2002JD002821, in press, 2003

Prospero, J. M., and R. T. Nees, Impact of the North African drought and El Niño on mineral dust in the Barbados trade winds, *Nature*, *320*, 735–738, 1986.

Pruppacher, H., and J. Klett, *Microphysics of Clouds and Precipitation*, Kluwer Acad., Norwell, Mass., 1997.

Rosenfeld, D., and R. Nirel, Seeding effectiveness—The interaction of desert dust and the southern margins of rain cloud systems in Isreal, *J. Appl. Meteorol.*, *35*, 1502–1509, 1996.

Rosenfeld, D., Y. Rudich, and R. Lahav, Desert dust suppressing precipitation: A possible desertification feedback loop, *Proc. Natl. Acad. Sci. U. S. A.*, *98*, 5975–5980, 2001.

Rossow, W., and R. Schiffer, ISCCP cloud data products, *Bull. Am. Meteorol. Soc.*, *72*, 2–20, 1991.

Rossow, W., and R. Schiffer, Advances in understanding clouds from ISCCP, *Bull. Am. Meteorol. Soc.*, *80*, 2261–2287, 1999.

Sassen, K., Indirect climate forcing over the western US from Asian dust storms, *Geophys. Res. Lett.*, *29*(10), 1465, doi:10.1029/2001GL014051, 2002.

Stubenrauch, C. J., W. B. Rossow, F. Cheruy, A. Chedin, and N. A. Scott, Clouds as seen by satellite sounders (3I) and imagers (ISCCP), part I: Evaluation of cloud parameters, *J. Clim.*, *12*(8), 2189–2213, 1999.

Tegen, I., A. A. Lacis, and I. Fung, The influence on climate forcing of mineral aerosols from disturbed soils, *Nature*, *380*, 419–422, 1996.

Tegen, I., P. Hollrig, M. Chin, I. Fung, D. Jacob, and J. Penner, Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results, *J. Geophys. Res.*, *102*(D20), 23,895–23,915, 1997.

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*(D14), 17,099–17,110, 1998.

Zuberi, B., A. K. Bertram, C. A. Cassa, L. T. Molina, and M. J. Molina, Heterogeneous nucleation of ice in $(NH_4)_2SO_4$-H_2O particles with mineral dust immersions, *Geophys. Res. Lett.*, *29*(10), 1504, doi:10.1029/2001GL014289, 2002.

L. M. Kiehl and N. M. Mahowald, Bren School of Environmental Science and Management and the Institute for Computational Earth System Science, University of California, Santa Barbara, CA 93106, USA. (natalie@bren.ucsb.edu)