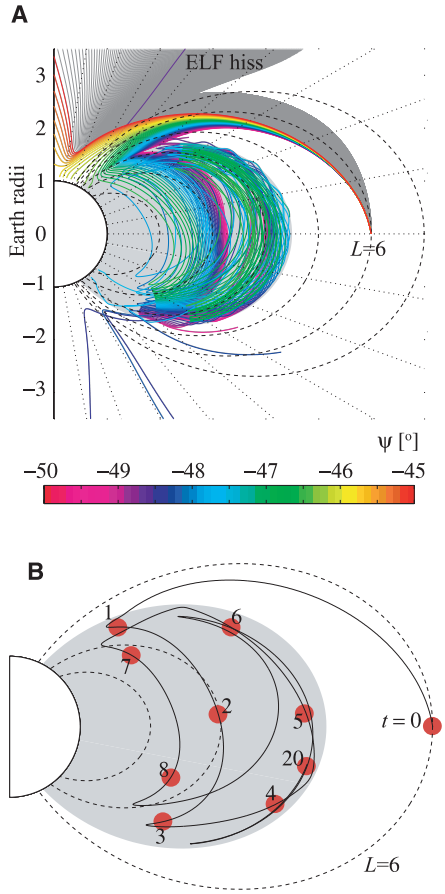

Fig. 4. Ray-tracing model of chorus and hiss. (**A**) Ray paths representing chorus are initiated at the equator, at $L = 6$, $f = 0.21\ f_{ce}$ (~855 Hz), in the range $\psi_0 = -50°$ to 0° (gray ray paths), plotted at every 0.1°, with the key wave normal range $\psi_0 = -50°$ to $-45°$ that enters the plasmasphere shown in color. The corresponding color scale indicates the initial wave normal angle of each ray in degrees. (**B**) A single ray from the group shown in (A) is displayed, with $\psi_0 = -48°$. The red circles indicate group time in seconds, from the time of ray initiation $t = 0$ s. The day-side cold plasma density is modeled according to (*20*), with the plasmapause located at $L = 4.5$, for consistency with the THEMIS observations; and the L-dependent suprathermal flux model was used as in (*7*, *21*) for active conditions. Each ray in (A) and (B) is plotted only while its power is above 1% of its initial value, so that in the case of (B), the ray duration is ~20 s.

the propagation and evolution of discrete chorus elements from their source region outside the plasmasphere into the incoherent noise band that characterizes plasmaspheric hiss, inside the plasmasphere. Understanding the origin of hiss will enable space physicists to calculate spatial maps of hiss characteristics and in turn predict the effect of hiss on the radiation belt electrons that are a known hazard to astronauts and to a variety of technological systems in space (*18*).

References and Notes

1. C. F. Kennel, H. E. Petschek, *J. Geophys. Res.* **71**, 1 (1966).
2. L. R. Lyons, R. M. Thorne, C. F. Kennel, *J. Geophys. Res.* **77**, 3455 (1972).
3. R. W. Abel, R. M. Thorne, *J. Geophys. Res.* **103**, 2385 (1998).
4. L. R. Lyons, R. M. Thorne, *J. Geophys. Res.* **78**, 2142 (1973).
5. R. B. Horne *et al.*, *J. Geophys. Res.* **111**, A03225 (2005).
6. R. M. Thorne, E. J. Smith, R. K. Burton, R. E. Holzer, *J. Geophys. Res.* **78**, 1581 (1973).
7. J. Bortnik, R. M. Thorne, N. P. Meredith, *Nature* **452**, 62 (2008).
8. N. Dunckel, R. A. Helliwell, *J. Geophys. Res.* **74**, 6371 (1969).
9. C. T. Russell, R. E. Holzer, E. J. Smith, *J. Geophys. Res.* **74**, 755 (1969).
10. W. W. L. Taylor, D. A. Gurnett, *J. Geophys. Res.* **73**, 5615 (1968).
11. M. Hayakawa, S. S. Sazhin, *Planet. Space Sci.* **40**, 1325 (1992).
12. R. K. Burton, R. E. Holzer, *J. Geophys. Res.* **79**, 1014 (1974).
13. W. J. Burtis, R. A. Helliwell, *Planet. Space Sci.* **24**, 1007 (1976).
14. S. S. Sazhin, M. Hayakawa, *Planet. Space Sci.* **40**, 681 (1992).
15. O. Santolik, *Nonlinear Process. Geophys.* **15**, 621 (2008).
16. V. Angelopoulos, *Space Sci. Rev.* **141**, 5 (2008).
17. O. Santolik *et al.*, *J. Geophys. Res.* **111**, A10208 (2006).
18. D. N. Baker, *Science* **297**, 1487 (2002).
19. D. Lengyel-Frey *et al.*, *J. Geophys. Res.* **99**, 13325 (1994).
20. D. L. Carpenter, R. R. Anderson, *J. Geophys. Res.* **97**, 1097 (1992).
21. J. Bortnik, R. M. Thorne, N. P. Meredith, *J. Geophys. Res.* **112**, A08204 (2007).

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The Role of Aerosols in the Evolution of Tropical North Atlantic Ocean Temperature Anomalies

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Observations and models show that northern tropical Atlantic surface temperatures are sensitive to regional changes in stratospheric volcanic and tropospheric mineral aerosols. However, it is unknown whether the temporal variability of these aerosols is a key factor in the evolution of ocean temperature anomalies. We used a simple physical model, incorporating 26 years of satellite data, to estimate the temperature response of the ocean mixed layer to changes in aerosol loadings. Our results suggest that the mixed layer's response to regional variability in aerosols accounts for 69% of the recent upward trend, and 67% of the detrended and 5-year low pass–filtered variance, in northern tropical Atlantic Ocean temperatures.

Since 1980, tropical North Atlantic Ocean temperatures have been rising at a rate of nearly 0.25°C per decade (*1*). Studies have attributed this increase, explicitly and implicitly, to global warming (*2*, *3*), mean Northern Hemisphere temperature variations (*4*), changes in the thermohaline circulation (*5*, *6*), or some combination of these factors (*7*). However, many of these studies fail to provide either a mechanism for or direct evidence of how these variables control tropical North Atlantic Ocean temperatures. At the same time, models (*8*) and observations (*1*, *9*) demonstrate that local changes in aerosol cover should have a non-negligible impact on Atlantic Ocean temperature via the scattering of sunlight and reduction in surface solar insolation.

The tropical North Atlantic is unique among tropical ocean basins because of its oftentimes extensive and heavy aerosol cover (*10*), a consequence of being downwind of West Africa, the world's largest dust source (*11*). Annual North African dust emission and deposition to the North Atlantic have been estimated to be 240 to 1600 Tg and 140 to 259 Tg, respectively (*12*), with the peak in West African dust production occurring during the boreal summer months (*13*). A smoothed time series of northern tropical Atlantic dust cover (Fig. 1) shows a maximum and minimum in dust activity that occurred in 1985 and 2005, respectively, and a downward trend in dust optical depth over the record. It has been shown that during both the summer (*14*) and winter seasons (*15*) these year-to-year changes

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in dust cover are related to variations in previous-year Sahelian precipitation. Additionally, wintertime dust production is strongly related to the strength of the North Atlantic Oscillation (*16*) and, to a lesser extent, the El Niño–Southern Oscillation (*15*).

Evan *et al.* (*9*) used satellite retrievals of aerosol optical thickness (AOT) from the Advanced Very High Resolution Radiometer (*17*) as the input to a shortwave radiative transfer model that estimated the change in surface solar radiation and the associated instantaneous cooling of sea surface temperatures (SSTs) by dust. Here, we update those methods by also estimating the longwave surface forcing by dust, including the radiative impact of stratospheric aerosols in our analysis (*18*), and using a stochastic ocean temperature model with a variable mixed layer depth (*19*), to calculate the response of local SSTs to radiative forcing by dust and volcanic aerosols (*20*). We force our model with satellite observations of aerosols over the 1982–2007 period to estimate how the temperature of the ocean mixed layer responds to month-to-month changes in tropospheric mineral dust and stratospheric volcanic aerosols (*21*).

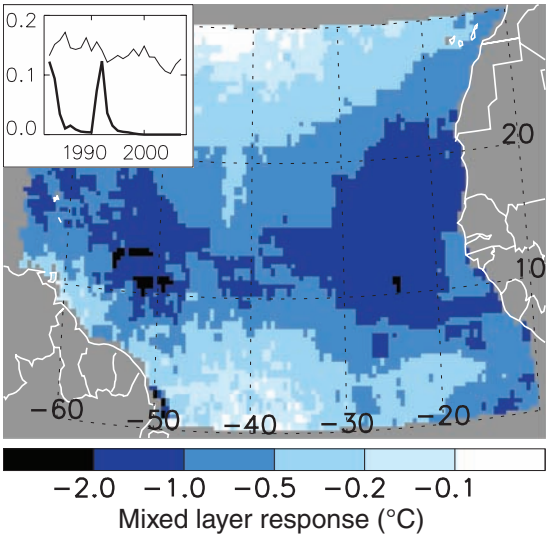

Fig. 1. Map of the mixed layer response to the presence of dust and volcanic aerosols and time series of aerosol optical depth. Estimations of mixed layer temperature response to surface radiative forcing by mineral dust and stratospheric volcanic aerosols are averaged over the 1982–2007 period and have a spatial resolution of 0.5°. The inset plot is a time series of annual mean monthly dust optical depth (thin black line) and stratospheric aerosol optical depth (thick black line), both averaged over the northern tropical Atlantic (0° to 30°N, 15° to 65°W).

From the model output, the spatial pattern of the mixed layer response to aerosol surface forcing (Fig. 1) is strongly indicative of the distribution of dust (fig. S1) and cloud cover (fig. S5), and of ocean mixed layer depth (fig. S6) (*20*). Aerosols exert their strongest influence on ocean temperatures along the coast of West Africa and extending westward between roughly 10° and 20°N; across the tropical North Atlantic, climatological cooling of the ocean mixed layer by aerosols ranges from –0.1° to –2.0°C (Fig. 1).

An annual time series of the mixed layer temperature response to local changes in dust and stratospheric aerosols, averaged over the tropical North Atlantic (0° to 30°N and 15° to 65°W), shows that mean cooling can range from –1.1° to –0.4°C, with the maximum and minimum in the magnitude of cooling occurring in 1983 and

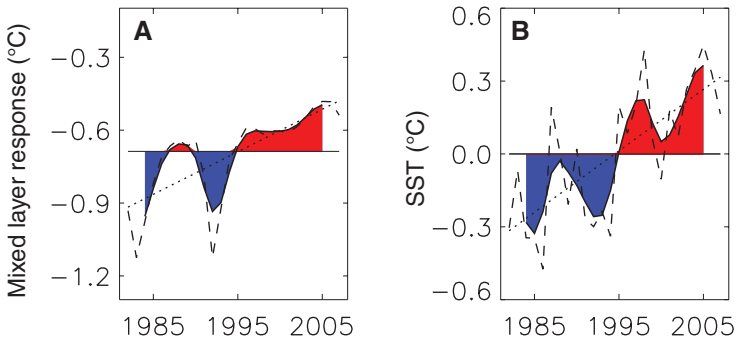

Fig. 2. Time series of mixed layer response to dust and stratospheric aerosol forcing (**A**) and observed SST anomalies (**B**). Data for both are averaged over the tropical North Atlantic (0° to 30°N, 15° to 65°W). In each panel the dashed line represents the annual mean values, the thin solid line is the climatological mean, the dotted line is the linear least-squares trend, and the thick black line is the annual mean time series processed with a 1-4-6-4-1 filter. The red and blue regions correspond to periods that are above and below the climatological mean, respectively.

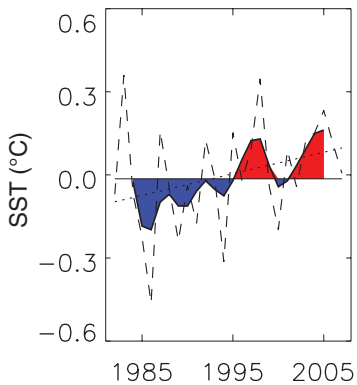

Fig. 3. Anomaly time series of observed SST (Fig. 2B) minus the aerosol forced component (Fig. 2A). Description is otherwise the same as for Fig. 2.

Table 1. Sensitivities in estimating aerosol forcing of tropical North Atlantic Ocean temperatures. The first row gives the mean SST forcing by dust and stratospheric aerosols estimated by (from left to right) the standard model without any modifications, increasing and decreasing cloud cover by 5%, decreasing and increasing AOT by 0.1, deepening and shoaling the mixed layer depth (MLD) by 5 m, and using an upper and lower limit on the so-called feedback parameter (λ) in the stochastic temperature model (*20*). The remaining rows report the percent of the variance in the detrended and smoothed SST time series that is due to stratospheric aerosols, the percent reduction in the SST trend when effects from stratospheric aerosols are removed, and the SST trend when effects from stratospheric aerosols are removed (the residual SST); the values in parentheses take into account both dust and stratospheric aerosols. All values are from time series averaged over the northern tropical Atlantic (0° to 30°N and 15° to 65°W). Note that the trend in observed SST over this region is 0.25°C per decade (Fig. 2B).

	Standard case	Clouds (+5%)	Clouds (–5%)	AOT (–0.1)	AOT (+0.1)	MLD (+5 m)	MLD (–5 m)	λ (upper)	λ (lower)
Mean forcing (°C)	–0.70	–0.62	–0.78	–0.31	–1.31	–0.56	–0.95	–0.62	–0.79
Reduction in variance (%)	55 (67)	56 (66)	52 (66)	54 (64)	56 (68)	56 (65)	43 (60)	56 (66)	52 (67)
Reduction in SST trend (%)	46 (69)	41 (61)	52 (77)	48 (69)	44 (64)	37 (56)	61 (93)	42 (63)	52 (77)
Residual SST trend (°C/decade)	0.14* (0.08)	0.15* (0.10)	0.12* (0.06)	0.13* (0.08)	0.14* (0.09)	0.16* (0.11*)	0.10 (0.02)	0.14* (0.09)	0.12* (0.06)

*Trends statistically significant at the 95% level (*23*).

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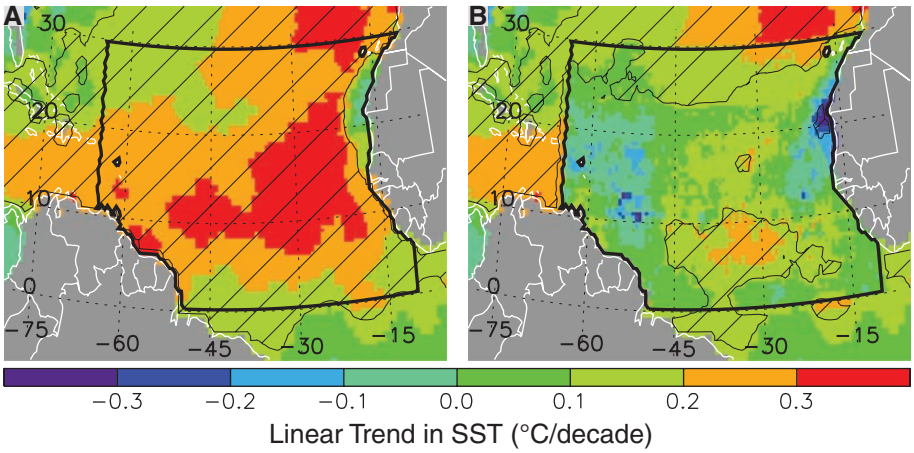

Fig. 4. Map of linear trends in observed SST (**A**) and the residual SST (**B**). Trends are calculated from the annual mean time series at each 0.5° grid cell over the 1982–2007 period. Hatched areas represent regions with linear trends that are statistically significant at the 95% level (*23*). The area enclosed by thick black lines (i.e., the oceanic regions of 0° to 30°N and 15° to 65°W) represents the region over which mean time series are calculated (Figs. 2 and 3), and in (B) is the area where the aerosol direct effect and its impact on ocean temperatures have been estimated.

2005, respectively (Fig. 2A). Cooling in 1992 was slightly less than that in 1983, both reflecting increases in stratospheric aerosols after volcanic eruptions of El Chichón and Mount Pinatubo, respectively (Fig. 1). The anomalously weak cooling of 2005 is caused by the minimum in dust cover observed for that year (Fig. 1). A 5-year smoothed (using a 1-4-6-4-1 filter) version of the annual mean time series highlights the two similar periods of anomalous cooling and the anomalous warming at the end of the record (Fig. 2A). A trend based on the linear least-squares fit of the annual time series gives a weakening in the magnitude of aerosol cooling of 0.18°C per decade (Fig. 2A).

To contrast our estimation of the ocean mixed layer response to changes in aerosol loadings with observed SSTs, we plotted the time series of the northern tropical Atlantic SST anomaly using the Hadley Centre HadSST data set (*22*) (Fig. 2B). Over the past 26 years, the range of SST anomalies is 1.0°C, from –0.5°C in 1986 to 0.5°C in 2005, with a linear trend of 0.25°C per decade, significant at the 99.9% level (*23*). The 5-year smoothed SST series shows periods of anomalous cooling and warming that are separated at 1995, a point thought to represent the transition from negative to positive phase of the Atlantic Multidecadal Oscillation (*6*).

The smoothed versions of the modeled mixed layer temperature response to aerosols (Fig. 2A) and the observed SST anomalies (Fig. 2B) are very similar; both show local minimums in the early 1980s and early 1990s, in addition to a maximum in temperature in 2005. The plot of the temperature response to aerosols also exhibits a transition from generally negative to positive anomalies around 1995 but does not exhibit the local maximum around 1997, and the maximum in 2005 is about 0.1°C cooler than is that from the Hadley Centre SST observations.

To better determine the extent to which aerosols have contributed to the evolution of this tropical North Atlantic temperature anomaly, we subtracted our monthly estimates of the oceanic cooling by dust and stratospheric aerosols from the observed tropical North Atlantic SST and plotted the anomaly of the residual (Fig. 3). This is our estimation of variability in northern tropical Atlantic SST that is not directly driven by local changes in aerosols, which we term the residual SST. The trend in the residual SST time series is 0.08°C per decade (Table 1 and Fig. 3), weaker than the trend in observed SST by 0.17°C per decade (Fig. 2B) and not statistically significant (*23*). These calculations suggest that 69% of the recent upward trend in northern tropical Atlantic SST is due to changes in aerosols. Separating by aerosol type, 46% of the trend in SST here is driven by changes in stratospheric volcanic aerosols, and 23% of the trend is driven by changes in tropospheric mineral aerosols (Table 1). The 5-year smoothed residual SST exhibits a less pronounced transition than is seen in the observations from anomalously cool to warm temperatures in 1995 (Fig. 2B). In the residual SST, the anomalous warming of 2005 has a magnitude that is roughly half of what is seen in the observations, consistent with previous studies suggesting that changes in surface solar insolation played a role in the warming during those summer months (*9*, *24*).

To quantify the overall importance of changes in aerosols to the evolution of the SST time series, in addition to the percent reduction in the trend, we also report the percent variance attributable to aerosol variability in the detrended, 5-year smoothed ocean temperature time series. This is defined as 1 – [(detrended residual low-frequency variance)/(detrended observed low-frequency variance)] × 100% (*20*). In the case of Fig. 3, the variance in the smoothed and detrended residual time series is 33% of that for the detrended measured SST series, which suggests that 67% of the detrended low-frequency variability in northern tropical Atlantic temperatures is driven by local variations in aerosol loadings (Table 1). Separating by aerosol type, 55% of the smoothed detrended temperature variance is due to changes in volcanic stratospheric aerosols, and 12% of the variance is due to changes in tropospheric mineral aerosols (Table 1). When we repeated this analysis for only the boreal summer months (July to September), we found that 75% of the variance in observed SST (after detrending and smoothing) can be attributed to changes in aerosol loadings, and the 0.23°C per decade trend in summertime SST—which is statistically significant at the 99% level (*23*)—is nearly an order of magnitude stronger than the 0.03°C per decade residual summertime trend, which is not statistically significant (*20*).

A map of the linear trends in observed annual mean SST for the 1982–2007 period shows that recent warming is not uniform across the tropical Atlantic basin (Fig. 4A). Although the trends in SST are statistically significant throughout the area we are interested in, the warming is most pronounced between 10° and 20°N and east of 60°W, with values here exceeding 0.3°C per decade. This pattern of northern tropical Atlantic SST trends (Fig. 4A) is similar to that of annual mean dust loadings (fig. S1) and the climatological mixed layer temperature response to surface aerosol forcing (Fig. 1). Linear trends in the residual SST, also based on annual means for the 1982–2007 period, are weaker and more uniform across our region of interest. For example, the warming in the region of 10° to 20°N and east of 60°W is neither strongly positive nor statistically significant. North of roughly 25°N there are statistically significant upward trends in the residual SST, which seem to be a continuation of the warming pattern north of 30°N.

Because there are uncertainties associated with our methodology for estimating the impact of aerosol loadings on ocean temperature, we also ran our model with modifications to parameters to which the output is sensitive (Table 1). This includes increasing and decreasing cloud cover by 5%, deepening and shoaling the mixed layer depth by 5 m, increasing and decreasing AOT by 0.1, and applying an upper and lower limit to the so-called feedback parameter (*20*). Although the results from the sensitivity study show that our estimation of the magnitude of aerosol cooling of ocean temperatures is sensitive to our model parameters (mean cooling values range from –1.31° to –0.31°C), estimations of the detrended and smoothed SST variance attributed to aerosols are more robust (values range from 60 to 68%), as are estimations of the percent reduction in the residual SST trend (values from 56 to 93%) and the magnitude of the residual SST trends (0.02° to 0.11°C per decade). Additionally, for each case in the sensitivity study except increasing the mixed layer depth, none

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of the residual SST trends are statistically significant at the 95% level (*23*). Note that our analysis does not show that aerosols explain year-to-year changes in SST, but that their effect is realized when considering variability on longer time scales because year-to-year changes in tropical Atlantic SST are more strongly modulated by wind-induced latent heat fluxes (*24*, *25*).

The present analysis is an estimate of the direct effect of dust radiative forcing on the upper-ocean heat budget. Our analysis does not exclude other sources of variability in the northern tropical Atlantic (*24*), nor does it account for reductions in atmospheric water vapor (*20*, *26*) or possible increases in cloudiness (*20*, *27*) associated with dust outbreaks. Nor does it include dynamical feedbacks from an atmospheric response to aerosol forcing and associated SST changes, including changes in the latent and sensible heat fluxes (*28*–*30*). Therefore, further analysis of coupled and dynamical feedbacks to aerosol forcing of tropical ocean temperatures is warranted.

Over the past 30 years, temperatures in other tropical ocean basins have been rising steadily, but at a slower rate than in the Atlantic (*31*). At the same time, projections of surface temperature increases under a doubled carbon dioxide climate suggest that the Atlantic should be warming at a rate slower than the other observations (*32*). We suggest that this apparent disconnect between observations and models may be due to the influence of Atlantic dust cover. Our results imply that because dust plays a role in modulating tropical North Atlantic temperature, projections of these temperatures under various global warming scenarios by general circulation models should account for long-term changes in dust loadings. This is especially critical because studies have estimated a reduction in Atlantic dust cover of 40 to 60% under a doubled carbon dioxide climate (*33*), which, on the basis of model runs with an equivalent reduction of the mean dust forcing, could result in an additional 0.3° to 0.4°C warming of the northern tropical Atlantic.

References and Notes

1. G. R. Foltz, M. J. McPhaden, *Geophys. Res. Lett.* **35**, L20706 (2008).
2. T. P. Barnett *et al.*, *Science* **309**, 284 (2005); published online 2 June 2005 (10.1126/science.1112418).
3. B. D. Santer *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 13905 (2006).
4. M. E. Mann, K. A. Emanuel, *Eos* **87**, 233 (2006).
5. T. L. Delworth, M. E. Mann, *Clim. Dyn.* **16**, 661 (2000).
6. S. B. Goldenberg, C. W. Landsea, A. M. Mestas-Nuñez, W. M. Gray, *Science* **293**, 474 (2001).
7. K. E. Trenberth, D. J. Shea, *Geophys. Res. Lett.* **33**, L12704 (2006).
8. M. Yoshioka *et al.*, *J. Clim.* **20**, 1445 (2007).
9. A. T. Evan *et al.*, *Geochem. Geophys. Geosyst.* **9**, Q05V04 (2008).
10. R. B. Husar, J. M. Prospero, L. L. Stowe, *J. Geophys. Res.* **102**, 16889 (1997).
11. A. S. Goudie, N. J. Middleton, *Earth Sci. Rev.* **56**, 179 (2001).
12. S. Engelstaedter, I. Tegen, R. Washington, *Earth Sci. Rev.* **79**, 73 (2006).
13. S. Engelstaedter, R. Washington, *Geophys. Res. Lett.* **34**, L15805 (2007).
14. J. M. Prospero, P. J. Lamb, *Science* **302**, 1024 (2003).
15. A. T. Evan, A. K. Heidinger, P. Knippertz, *J. Geophys. Res.* **111**, D12210 (2006).
16. C. Moulin, C. E. Lambert, F. Dulac, U. Dayan, *Nature* **387**, 691 (1997).
17. L. L. Stowe, A. M. Ignatov, R. R. Singh, *J. Geophys. Res.* **102**, 16923 (1997).
18. M. Sato, J. E. Hansen, M. P. Mccormick, J. B. Pollack, *J. Geophys. Res.* **98**, 22987 (1993).
19. C. Deser, M. A. Alexander, M. S. Timlin, *J. Clim.* **16**, 57 (2003).
20. See supporting material on *Science* Online.
21. PATMOS-x data are available at http://cimss.ssec.wisc.edu/patmosx.
22. N. A. Rayner *et al.*, *J. Geophys. Res.* **108**, 4407 (2003).
23. All reported significance levels are based on the two-tailed *t* score for the correlation coefficients.
24. G. R. Foltz, M. J. McPhaden, *Geophys. Res. Lett.* **33**, L19703 (2006).
25. G. R. Foltz, M. J. McPhaden, *J. Clim.* **21**, 5048 (2008).
26. J. P. Dunion, C. S. Marron, *J. Clim.* **21**, 5242 (2008).
27. Y. J. Kaufman, I. Koren, L. A. Remer, D. Rosenfeld, Y. Rudich, *Proc. Natl. Acad. Sci. U.S.A.* **102**, 11207 (2005).
28. P. Chang, R. Saravanan, L. Ji, G. C. Hegerl, *J. Clim.* **13**, 2195 (2000).
29. G. R. Foltz, M. J. McPhaden, *J. Clim.* **19**, 6122 (2006).
30. S. Wong, A. E. Dessler, N. M. Mahowald, P. R. Colarco, A. da Silva, *Geophys. Res. Lett.* **35**, L07812 (2008).
31. G. J. Holland, P. J. Webster, *Philos. Trans. R. Soc. London Ser. A* **365**, 2695 (2007).
32. G. A. Vecchi, B. J. Soden, *Nature* **450**, 1066 (2007).
33. N. M. Mahowald, C. Luo, *Geophys. Res. Lett.* **30**, 1903 (2003).

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Figs. S1 to S8
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UV Absorption Cross Sections of ClOOCl Are Consistent with Ozone Degradation Models

Hsueh-Ying Chen,[1]* Chien-Yu Lien,[1]* Wei-Yen Lin,[1,2] Yuan T. Lee,[1,2] Jim J. Lin[1,3]†

Recently, discrepancies in laboratory measurements of chlorine peroxide (ClOOCl) absorption cross sections have cast doubt on the validity of current photochemical models for stratospheric ozone degradation. Whereas previous ClOOCl absorption measurements all suffered from uncertainties due to absorption by impurities, we demonstrate here a method that uses mass-selected detection to circumvent such interference. The cross sections of ClOOCl were determined at two critical wavelengths (351 and 308 nanometers). Our results are sufficient to resolve the controversial issue originating from the ClOOCl laboratory cross sections and suggest that the highest laboratory estimates for atmospheric photolysis rates of ClOOCl, which best explain the field measurements via current chemical models, are reasonable.

After the discovery of the Antarctic ozone hole (*1*), scientists directed great effort toward studying the underlying chemical and photochemical processes. Until recently, the consensus was that the chemical processes that are responsible for the formation of the ozone hole were reasonably well understood (*2*). However, laboratory data on the ultraviolet absorption spectrum of chlorine peroxide (ClOOCl) published in 2007 by Pope *et al.* (*3*) cast doubt (*4*–*6*) on that understanding. The absorption cross sections measured by Pope *et al.* (*3*) at wavelengths longer than 300 nm ($\lambda > 300$ nm) are much smaller than previously accepted values (*7*). If these recent data are correct, the atmospheric photolysis rates of ClOOCl are much smaller than originally thought, and it would be impossible to produce enough Cl atoms to explain the observed ozone loss via any known chemical mechanisms. Moreover, atmospheric measurements of constituents such as ClO/ClOOCl could not be reconciled with the Pope *et al.* data (*3*), which raises questions (*4*–*6*) about the validity of either the laboratory measurements or model calculations, thus heightening the need for new laboratory studies to either confirm or refute those findings.

Among the major factors controlling ozone loss in the polar stratospheric vortices is the kinetics of the ClOOCl catalytic cycle, in which the photolysis rate of ClOOCl plays a key role (*2*, *5*, *8*). The ultraviolet absorption spectrum of ClOOCl shows a relatively strong and broad feature with a peak at ~245 nm and a long tail extending to 300 nm and longer wavelengths (*3*, *8*–*11*). Because ozone strongly absorbs and therefore depletes sunlight of $\lambda < 300$ nm, it is the

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Editor's Summary

Dust in the Wind

The temperature of North Atlantic surface waters has a major effect on climate in a variety of ways, not least because its heat content helps to control hurricane formation and strength. The North Atlantic surface has warmed considerably in recent decades, a trend generally associated with global or regional air temperature increases, or with changes in ocean circulation. **Evan *et al.*** (p. 778, published online 26 March) use nearly 30 years of satellite data to examine another source of ocean temperature variability, the radiative effects of atmospheric aerosols. Low frequency changes in local tropical North Atlantic surface temperatures seem mostly to be caused by variability in mineral and stratospheric aerosol abundances. Thus, to provide more accurate projections of these temperatures, general circulation models will need to account for long-term changes in dust loadings.

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