Aerosol invigoration and restructuring of Atlantic convective clouds

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[1] Clouds and precipitation play crucial roles in the Earth's energy balance, global atmospheric circulation and the availability of fresh water. Aerosols may modify cloud properties and precipitation formation by modifying the concentration and size of cloud droplets, and consequently the strength of cloud convection, and height of glaciation levels thus affecting precipitation patterns. Here we evaluate the aerosol effect on clouds, using large statistics of daily satellite data over the North Atlantic Ocean. We found a strong correlation between the presence of aerosols and the structural properties of convective clouds. These correlations suggest systematic invigoration of convective clouds by pollution, desert dust and biomass burning aerosols. On average increase in the aerosol concentration from a baseline to the average values is associated with a 0.05 ± 0.01 increase in the cloud fraction and a 40 ± 5mb decrease in the cloud top pressure. **Citation:** Koren, I., Y. J. Kaufman, D. Rosenfeld, L. A. Remer, and Y. Rudich (2005), Aerosol invigoration and restructuring of Atlantic convective clouds, *Geophys. Res. Lett.*, *32*, L14828, doi:10.1029/2005GL023187.

1. Introduction

[2] Based on a few case studies, it has been suggested [*Andreae et al.*, 2004; *Williams et al.*, 2002] that the suppression of warm rain by aerosol causes most of the condensates to ascend, freeze and release the latent heat of freezing before precipitating. Delayed precipitation leads to more persistent updrafts and to more vigorous clouds before the precipitation-induced downdrafts take over. In addition, smaller droplets freeze at higher altitudes and at lower temperatures [*Rosenfeld and Woodley*, 2000]; therefore more latent heat is released higher in the atmosphere. The magnitude and robustness of these aerosol effects have not yet been investigated in a variety of meteorological conditions.

[3] Here we report strong correlations between aerosol loading and convective cloud properties. We see the correlations in all scales, from droplet scale to the extent and shape of the entire cloud. We show using large statistics that an increase in aerosol concentration correlates with changes in the cover, height and anvil portion of convective clouds. We show these correlations occur repeatedly in three latitude belts of the Atlantic Ocean each with its own unique cloud dynamics and aerosol type.

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2. Analysis

[4] We use three months (June-August 2002) of MODIS (MODerate resolution Imaging Spectroradiometer) [*Salomonson et al.*, 1989] Level 3 data from the Terra satellite over the northern Atlantic Ocean from 60°N to the Equator (covering ~4 billion km2). The satellite products include cloud fraction, optical thickness and droplet effective radius, each further partitioned by thermodynamic phase (ice/water), cloud top pressure and temperature [*King et al.*, 2003; *Platnick et al.*, 2003] and also by aerosol optical depth (AOD) at 550 nm [*Tanré et al.*, 1997; *Kaufman et al.*, 1997; *Remer et al.*, 2005]. MODIS measures daily cloud and aerosol reflection of sunlight with resolution of 0.25–1 km. The daily data are averaged into a 1-degree grid (MODIS algorithms, Level 3, available at http://modis-atmos.gsfc.nasa.gov/DAILY/atbd.html), that includes information on clouds and the surrounding aerosols (unless the grid box is completely overcast). We also used NCEP (National Center for Environmental Prediction) reanalysis [*Kalnay et al.*, 1996] and MODIS precipitable water vapor as a measure of the meteorology.

[5] In this study we focus on correlations between aerosols and the properties of deep convective and high cloud fields. Clouds were classified based on their top pressure, thermodynamic phase and cloud spatial homogeneity. Convective clouds are identified based on the variation in cloud top pressure among adjacent grid boxes and based on the optical depth of ice and water. The cloud classification algorithm was tuned on manually classified clouds followed by manual verification process of randomly selected cases. During the northern hemisphere summer, the average cloud fraction in the studied area is ~0.6, of which 75% are classified as deep convective and high clouds and 25% as marine stratocumulus and shallow cumulus (analyzed in a different study [*Kaufman et al.*, 2005]).

[6] We performed the analysis of the convective clouds separately for three regions characterized by different synoptic conditions: 0–15°N, including the ITCZ (Intertropical Convergence Zone), where the prevailing wind is easterly and carries mainly dust aerosol from the Sahara to the tropics of America; 16N–45N (sub tropical zone), where most of the deep convection develops in the southerlies along the Americas, transporting aerosols from the tropics to the mid-latitudes; and 46N–60N, where the system is dominated by the westerly wind that brings pollution aerosol from North America to Europe (mid-latitudes). In the tropical and mid-latitude zones the average flow is zonal (east-west) and the convective clouds are distributed

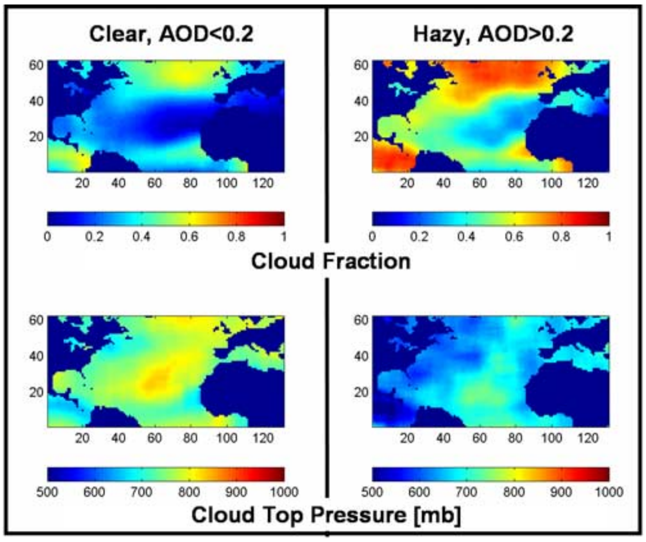

Figure 1. Difference between clear (aerosol optical depth - AOD < 0.2) and aerosol-laden conditions (AOD > 0.2) in convective and high clouds properties over the Atlantic Ocean during June–August 2002. The upper row shows the cloud fraction, and the bottom row shows the cloud top pressure in mb. The left column is for the clean conditions and the right column for the hazy conditions. The lower cloud top pressures suggest stronger convection.

uniformly between the continents. However in the subtropical zone, the flow is meridional (southerlies) and the deep convective clouds are concentrated more on the west part of the Atlantic.

[7] The most striking relationships between aerosol and convective cloud in all three zones are the increase in cloud top height and coverage with increasing aerosol loading seen in Figure 1. Here, the data are sorted into clear and hazy conditions and then averaged. The hazy conditions exhibit higher cloud fraction and lower cloud top pressure throughout the entire study area.

[8] In Figure 2 we show the variation of the cloud properties as a function of the AOD using ~40,000 samples divided into 10 AOD bins of ~4,000 samples each. For all three regions, despite their different dynamic conditions and different aerosol properties, there is a consistent and monotonic increase in cloud fraction with the AOD from average cloud fraction of 0.30 for AOD ~0.05 to 0.7 for AOD ~0.5. This is accompanied by a decrease in the cloud top pressure by 200 mb in the two northern zones and by 50 mb in the ITCZ.

[9] Profiles of the relationship between cloud properties and aerosol are shown for the sub tropical region in Figure 3. The data are sorted into 6 subgroups of AOD with equal number of samples. Then each subgroup is sorted by the cloud top pressure and plotted with an inverted vertical scale so that the lowest pressures corresponding to the tallest clouds appear at the top. The lowest cloud top pressures (tallest clouds) are shifted towards lower values (taller clouds) for higher aerosol concentrations indicating enhancement of cloud convection (Figure 3a). Figure 3b shows a monotonic growth in cloud fraction profiles with the AOD. Figures 3e and 3f confirm Twomey's analysis [*Twomey*, 1977; *Rosenfeld and Lensky*, 1998], showing a reduction of the droplet's effective radius for higher aerosol concentrations in any given pressure level (Figure 3f), and corresponding increase in the water cloud optical depth (COD – Figure 3e). Note that averaging cloud properties at a one degree scale combines pressure levels of ice and water resulting in a non-zero ice portion for averaged pressures above freezing level. Figure 3c shows the ice fraction vs. the total cloud fraction per pressure level indicating delay in freezing for polluted clouds [*Rosenfeld and Woodley*, 2000]. While the cloud water optical depth increases with AOD (Figure 3e) the cloud ice optical depth decreases, hence the total cloud optical depth, apart from the most clean clouds, stays constant (Figure 3d). The delayed freezing, the systematic increase in cloud fraction for all pressure levels (water and ice), and the lower pressures reached by the polluted clouds, all indicate that polluted clouds have stronger convection with higher towers, occupying larger area and developing more extensive ice anvils.

[10] To what extent are the observed correlations between aerosols and cloud properties due to the aerosols? Clouds and aerosols are both affected by variations in meteorological conditions, e.g. conversion zones can concentrate aerosol and water vapor, while generating unstable meteorological conditions that promote cloud formation. We also cannot completely rule out any residual contamination of the satellite retrievals of aerosols and clouds.

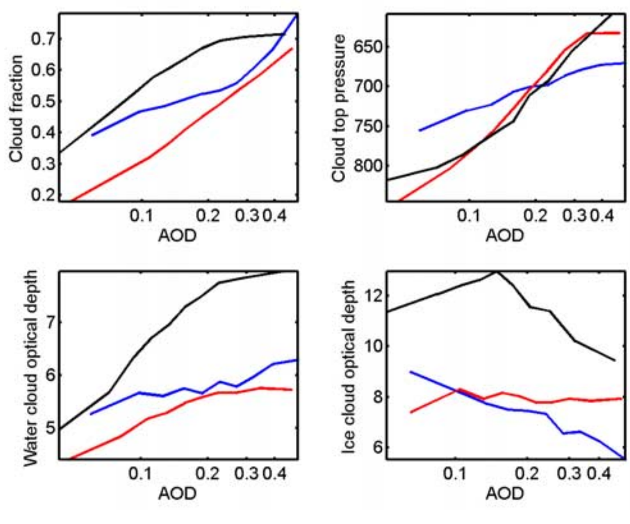

Figure 2. Cloud properties as a function of AOD for the three regions in the Atlantic Ocean: Blue – tropics (ITCZ), red – subtropics (STC), black – mid-latitudes (MLC). For each zone the data are sorted as a function of the AOD and averaged into 10 sequential subgroups. The upper left plot shows the cloud fraction as function of the AOD (in logarithmic scale). The upper right plot shows the cloud top pressure vs. AOD. The left and right plots on the lower row show the water COD and the ice COD as function of AOD respectively. The water optical depth increases with AOD but the ice COD decreases or remains constant, suggesting formation of more anvils that increase the ice cloud fraction but decrease the average COD.

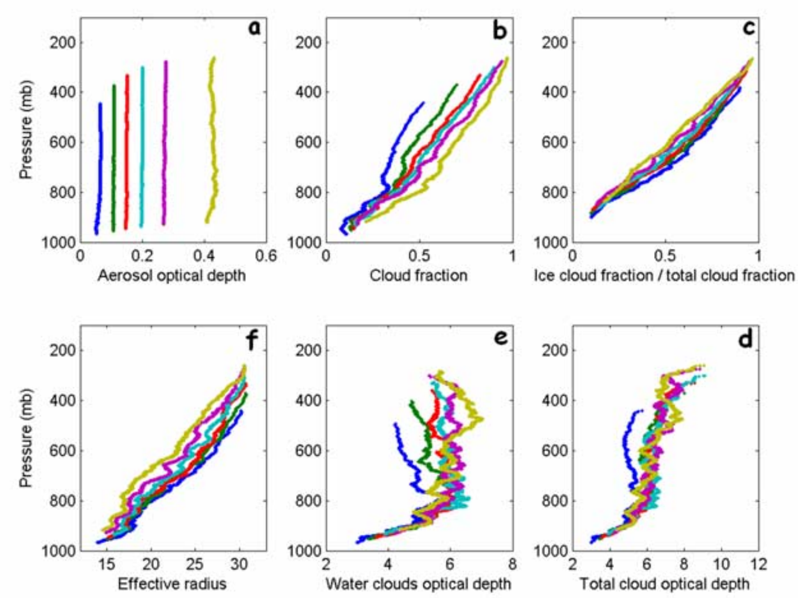

Figure 3. Cloud properties as a function of cloud top pressure for the sub-tropical clouds. Top left – the average AOD of the 6 subgroups vs. the pressure. Top middle, the cloud fraction for the 6 AOD levels. Top right, the ice cloud fraction over the total cloud fraction – indicating the transition to ice with height. Lower left, effective droplet radius vs. cloud top pressure. Lower middle, water optical depth and lower right, total cloud optical depth. Note - in all of the plots the higher the AOD, the higher is the cloud top height (lower pressure).

[11] To address these issues and to try to decouple the meteorology from the aerosol effect through microphysics we use NCEP meteorological data. We found that the single most significant NCEP parameter that correlates with MODIS convective clouds is the vertical wind velocity. The correlation between the vertical winds at 500mb to the cloud top pressure and cloud fraction is larger than 0.90 for all three zones, however the correlation between the vertical winds and AOD is 0.6 for the ITCZ and negative −0.7 for the other regions suggesting different associations between meteorology and aerosols in these regions, despite the identical associations between aerosol and convective clouds in all regions. By restricting the data to several narrow ranges of vertical winds, we can reduce the variation in the meteorological effects and concentrate on variations in the cloud field that are attributed to the aerosol effect.

[12] Further, we divided the data to nine vertical velocity (at 500mb) ranges and calculated the correlations of the cloud properties with AOD. As expected, for each zone, the correlations of the cloud properties with all other NCEP meteorological parameters (winds, pressure levels, potential temperatures, SST etc) were reduced dramatically, while the correlations with the aerosol remained strong (see Table 1). This suggests that the meteorological effects are less dominant for a narrow range of values of the vertical wind and a larger part of the effects can be attributed to microphysical processes affected by the aerosols.

[13] To reduce possible artifacts in the satellite retrievals that might influence our results we took the following steps. First, we restricted the data to AOD less than 0.5 [*Brennan et al.*, 2005]. This eliminates the possibility that heavy aerosol is mistakenly classified as a cloud. Second, we checked the relationship between MODIS-derived precipitable water vapor [*Gao and Kaufman*, 2003] and the convective cloud fraction. If convergence is accumulating aerosol in convective regions, then it may also accumulate

Table 1. Decoupling the Aerosols From the Vertical Winds[a]

Average Vertical Wind	−0.41	−0.18	−0.11	−0.06	−0.02	0.01	0.04	0.08	0.17
ITCZ - AOD vs. CTP	−0.49	−0.57	−0.46	−0.59	−0.71	−0.55	−0.54	−0.50	−0.64
Sub Tropics - AOD vs. CTP	−0.60	−0.82	−0.82	−0.83	−0.84	−0.81	−0.83	−0.80	−0.82
Mid latitude - AOD vs. CTP	−0.53	−0.80	−0.82	−0.85	−0.84	−0.87	−0.86	−0.88	−0.82
ITCZ - AOD vs. CFR	0.65	0.71	0.72	0.76	0.82	0.80	0.76	0.81	0.80
Sub Tropics - AOD vs. CFR	0.71	0.81	0.87	0.85	0.89	0.90	0.87	0.86	0.85
Mid latitude - AOD vs. CFR	0.44	0.63	0.57	0.67	0.61	0.71	0.79	0.78	0.84
ITCZ - VW vs. CTP	0.12	0.21	0.13	0.06	0.00	−0.02	−0.10	0.03	−0.14
Sub Tropics - VW vs. CTP	−0.37	0.16	−0.12	−0.09	−0.18	−0.11	0.14	−0.04	−0.14
Mid latitude - VW vs. CTP	−0.36	0.08	−0.27	−0.10	−0.13	−0.04	0.09	−0.05	−0.17

[a]In the upper line is the averaged vertical wind for each bin. The upper block lists the correlations between the aerosol optical depth and cloud top height (CTP). The second block lists, the correlations between the aerosol optical depth and cloud fraction (CFR) and in the third block – a measure to the effectiveness of the decoupling - the correlations between the vertical wind (VW) and the cloud top pressure. Note that apart from few exceptions the correlation in the third block are significantly lower and sometimes appear with the opposite sign compared to the upper blocks.

water vapor. However, we found no significant correlation with the water vapor. Third, the MODIS cloud mask used in the aerosol retrieval [*Martins et al.*, 2002] automatically rejects the first layer of non-cloudy pixels surrounding a cloud. This reduces the probability for cloud contamination and also reduces the contribution of highly humidified aerosols.

3. Discussion

[14] Strong correlations between the aerosol optical depth and convective cloud properties are observed in three different latitude zones governed by different meteorology and affected by different types of aerosols. When clouds develop in the presence of high aerosol loading, the cloud fraction increases and the cloud top pressure decreases. For any given pressure level as a function of the aerosol loading: the droplet effective radius decreases, the cloud fraction increases, the optical thickness increases for water and decreases (or stays constant) for ice. Moreover, for each pressure level, polluted clouds have smaller ice portion.

[15] Similar trends are observed when the main meteorological component – vertical wind, was decoupled by restricting the data to several specific vertical velocity ranges. For a change from clean - baseline aerosol AOD of 0.06 [*Kaufman et al.*, 2001], to average aerosol loading of 0.21 the estimated aerosol effect on the decoupled dataset, is an increase of 5% ± 1% in cloud fraction and a decrease of 40 ± 5 mb in cloud top pressure.

[16] Though it is difficult to fully decouple meteorological influences, we are suggesting that a substantial portion of the observed changes in the convective cloud properties is due to a sequence of feedbacks that begin with changes in the droplet size and concentration caused by aerosol.

[17] A possible scenario is: More aerosols contain more CCN that create more numerous and smaller cloud droplets (Figure 3 - smaller effective radius for any given pressure level). Droplet growth by collision and coalescence is less efficient for the smaller cloud droplets further delaying the formation of large droplets and therefore causing a delay or suppression of downdrafts and warm rain. The resulting overall updrafts may be stronger due to the release of the condensation latent heat without balancing it with the downdrafts due to large droplets. Stronger updrafts will create taller clouds (Figures 2 and 3 - higher water clouds with larger optical depth and larger water cloud fraction). Moreover, smaller droplets that are uplifted by stronger winds will freeze at higher altitudes releasing the freezing latent heat in colder places (Figures 3b and 3c), further increasing the convection.

[18] The measured cloud optical depth associated with ice in convective clouds is composed of two components: the optically thick cloud towers at the center of convective cells, and the optically thinner anvils that form around the towers. The anvils become thinner away from the towers with substantially smaller COD. Invigoration of the convection results in strengthening the tower mainly on the vertical scale (taller towers) and more area covered by anvils. Therefore, the observed ice fraction will be larger but the averaged ice optical depth, which will be composed of a greater portion of anvils, will be smaller (as seen in Figure 3b – more cloud fraction in the low pressure levels and Figure 2 for ice optical depth).

[19] Changes in the initial droplet size and distribution may induce changes at larger scales. The effects can propagate to the dynamics of the clouds and to the overall structure and size of the clouds. These differences may have a major impact on the Earth's hydrological cycle and energy budget.

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References

Andreae, M. O., D. Rosenfeld, P. Artaxo, A. A. Costa, G. P. Frank, K. M. Longo, and M. A. F. Silva-Dias (2004), Smoking rain clouds over the Amazon, *Science*, *303*, 1337–1342.

Brennan, J. I., Y. J. Kaufman, I. Koren, and R.-R. Li (2005), Aerosol-cloud interaction—Misclassification of MODIS clouds in heavy aerosol, *IEEE Trans. Geosci. Remote Sens.*, *43*(4), 911–915.

Gao, B.-C., and Y. J. Kaufman (2003), Water vapor retrievals using MODIS Near-IR channels, *J. Geophys. Res.*, *108*(D13), 4389, doi:10.1029/2002JD003023.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Kaufman, Y. J., D. Tanré, H. R. Gordon, T. Nakajima, J. Lenoble, R. Frouin, H. Grassl, B. M. Herman, M. D. King, and P. M. Teillet (1997), Passive remote sensing of tropospheric aerosol and atmospheric correction for the aerosol effect, *J. Geophys. Res.*, *102*, 16,815–16,830.

Kaufman, Y. J., A. Smirnov, B. N. Holben, and O. Dubovik (2001), Baseline maritime aerosol methodology to derive the optical thickness and scattering properties, *Geophys. Res. Lett.*, *28*, 3251–3254.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Rosenfeld, and Y. Rudich (2005), The effect of smoke, dust and pollution aerosol on shallow cloud development over the Atlantic Ocean, Proc. Natl. Acad. Sci., in press.

King, M. D., et al. (2003), Cloud and aerosol properties, precipitable water, and profiles of temperature and humidity from MODIS, *IEEE Trans. Geosci. Remote Sens.*, *41*, 442–458.

Martins, J. V., D. Tanré, L. A. Remer, Y. J. Kaufman, S. Mattoo, and R. Levy (2002), MODIS cloud screening for remote sensing of aerosol over oceans using spatial variability, *Geophys. Res. Lett.*, *29*(12), 8009, doi:10.1029/2001GL013252.

Platnick, S., et al. (2003), The MODIS cloud products: Algorithms and examples from Terra, *IEEE Trans. Geosci. Remote Sens.*, *41*, 459–473.

Remer, L. A., et al. (2005), The MODIS aerosol algorithm, products and validation, *J. Atmos. Sci.*, *62*(4), 947–973.

Rosenfeld, D., and I. M. Lensky (1998), Satellite based insights into precipitation formation processes in continental and maritime convective clouds, *Bull. Am. Meteorol. Soc.*, *79*, 2457–2476.

Rosenfeld, D., and W. L. Woodley (2000), Deep convective clouds with sustained supercooled liquid water down to −37.5°C, *Nature*, *405*, 440–442.

Salomonson, V. V., W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow (1989), MODIS: Advanced facility instrument for studies of the Earth as a system, *IEEE Trans. Geosci. Remote Sens.*, *27*, 145–153.

Tanré, D., Y. J. Kaufman, M. Herman, and S. Mattoo (1997), Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances, *J. Geophys. Res.*, *102*, 16,971–16,988.

Twomey, S. (1977), The influence of pollution on the shortwave albedo of clouds, *J. Atmos. Sci.*, *34*, 1149–1152.

Williams, E. D., et al. (2002), Contrasting convective regimes over the Amazon: Implications for cloud electrification, *J. Geophys. Res.*, *107*(D20), 8082, doi:10.1029/2001JD000380.

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