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Vertical and spatial distribution of dust from aircraft and satellite measurements during the GERBILS field campaign

Sundar A. Christopher,[1,2] Ben Johnson,[3] Thomas A. Jones,[2] and Jim Haywood[3]

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[1] The Geostationary Earth Radiation Budget Intercomparisons of Longwave and Shortwave (GERBILS) radiation field experiment was conducted in June 2007 over North Africa to study dust aerosols from aircraft, satellite, and ground measurements. We present results from a case study on June 21, 2007 where coincident measurements from a space borne lidar, aircraft profiles, and multiple satellite instruments from the A-Train are available around 1430 UTC. Backscatter measurements from the space-borne lidar indicate that dust aerosols are present between the surface and altitudes of 4–6 km, which agrees well with aircraft measurements. For low AOD (AOD < 1), the agreement between satellite and aircraft-derived values and amongst the satellite products are within 0.1–0.2. However, most satellite products underestimate AOD when aircraft AOD's are higher (AOD > 1). New satellite sensors coupled with new algorithms are now providing valuable information over desert regions to assess aerosol impacts on climate, air quality and other applications. **Citation:** Christopher, S. A., B. Johnson, T. A. Jones, and J. Haywood (2009), Vertical and spatial distribution of dust from aircraft and satellite measurements during the GERBILS field campaign, *Geophys. Res. Lett.*, *36*, L06806, doi:10.1029/2008GL037033.

1. Introduction

[2] Global dust emissions range from 1000–3000 Mt/yr and Africa contributes more than 50% to this estimate. Dust aerosols affect the radiative balance, visibility, air quality, and serve as a nutrient source for the ocean, and have been linked to tropical cyclone activities in the Atlantic [e.g., *Dunion and Velden*, 2004]. However, further understanding of these processes is needed and is being addressed through a combination of in-situ (aircraft and ground-based), satellite, and modelling studies [*Haywood et al.*, 2008]. A renewed focus on dust aerosol research over North Africa through field experiments and advances in satellite remote sensing has increased our understanding of dust aerosol properties and their effects. Multi-spectral satellite remote sensing techniques, without multi-angle or polarization capabilities, have traditionally experienced difficulties in estimating aerosol concentrations over regions of high surface reflectance (in the visible portion of the electromagnetic spectrum) such as deserts. However, there have been significant advancements in techniques over the last few years that have enabled development of new satellite products over these surfaces. These now allow mapping of aerosols from space, identification of dust sources, quantification of aerosol properties such as dust absorption, and measurement of the vertical distribution of aerosols and clouds. Such tasks are all important for furthering our understanding of how dust aerosols affect climate.

[3] Desert regions are some of the harshest environments for making routine in-situ measurements. However, one of the great successes in aerosol measurements of the last 10–15 years has been the Aerosol Robotic Network (AERONET) program where routine retrievals of aerosol optical depth (AOD) are made at multiple wavelengths at various locations throughout the world, including North Africa [*Holben et al.*, 2001]. Currently, there are several hundred AERONET stations worldwide with more than a dozen located in North Africa. Hourly values of AOD and daily retrievals of aerosol optical properties from the AERONET are routinely made available to the worldwide community for validating satellite retrievals and assessing aerosol-climate impacts.

[4] Since the in-situ measurements cannot cover large spatial areas, space-borne measurements from satellites are increasingly becoming important for mapping the spatial distribution of aerosols, their properties and their impacts on the radiation budget. Traditionally, satellite mapping of aerosols and their properties have been difficult over bright surfaces, such as deserts, due to the limitations of using only multi-spectral visible to infrared (IR) wavelengths. At visible and near-IR wavelengths, it is difficult to separate the aerosol signal from the surface. In the IR, surface emissivity and atmospheric water vapor confound dust retrievals. However, new techniques from multi-angle measurements [*Kahn et al.*, 2005] and other methods that use the ultraviolet part of the electromagnetic spectrum now allow mapping of dust aerosols from space over desert regions [*Hsu et al.*, 2006; *Torres et al.*, 2007]. Aerosol properties such as AOT and single scattering albedo are being retrieved from these sensors. Furthermore, the vertical distribution of aerosols can now be assessed for space-borne lidars [*Winker et al.*, 2007], such as CALIPSO, providing improved capabilities for assessing the impact of dust aerosols on the earth-atmosphere system.

[5] In June 2007, the GERBILS campaign was conducted to study dust aerosols in Western North Africa. This campaign investigated the impacts of dust on both the shortwave and longwave portions of the electromagnetic spectrum. Detailed measurements of dust particle size, composition, optical and radiative properties were made by the Facility for Airborne Atmospheric Measurements (FAAM) BAE-146 aircraft on 10 flights. During GERBILS, there were 10 flights primarily between Niamey, Niger and Noukachott, Mauritania. These measurements have been used to help interpret satellite

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[1] Department of Atmospheric Sciences, University of Alabama in Huntsville, Huntsville, Alabama, USA.

[2] Earth System Science Center, University of Alabama in Huntsville, Huntsville, Alabama, USA.

[3] United Kingdom Meteorological Office, Exeter, UK.

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measurements and improve numerical modelling and forecast of dust aerosol fields (see www.metresearch.net/gerbils/ for further details). The goal of this paper is to provide *initial results* from GERBILS including products from multiple satellite sensors and vertical profiles of extinction from the BAE-146 aircraft on June 21, 2007 (∼1440 UTC), a case when near coincidence was achieved between the aircraft and several satellite overpasses.

2. Data

[6] Several satellite data sets and products are used in this study. Only a brief summary of the various satellite algorithms and their limitations are presented. These algorithms report uncertainties in their retrievals by using AERONET as a benchmark. More complete descriptions are provided by references herein. The MODIS operational collection 5 algorithm on Terra and Aqua provides global distribution of aerosols, but not over bright surfaces such as deserts. The reported uncertainty over non bright targets is $\pm 0.05 \pm 0.15\tau$ [*Remer et al.*, 2005]. The MODIS Deep Blue algorithm primarily uses the UV channels to provide aerosol retrievals over deserts and other areas where the operational algorithm cannot and the reported uncertainties are around 25 to 30% [*Hsu et al.*, 2006]. The OMI instrument on the Aura satellite provides aerosol index [*Torres et al.*, 2007] that is then converted to AOD using AOD-AI relationships that is called EAOD. Limited intercomparisons for Saharan desert dust aerosols show that the EAOD's are within 30% of the AERONET values [*Christopher et al.*, 2008]. OMI has two aerosol products, one (OMAERO) that uses a two channel (360 and 380 nm) algorithm [*Torres et al.*, 2007] and the other (OMAERUV) a multi-spectral (19 wavelengths between 330–500 nm) algorithm [*Curier et al.*, 2008]. The reported uncertainties in the OMAERO and the OMAERUV AOT are around 30%. The MISR instrument on Terra utilizes its multi-angle capabilities to provide AOD retrievals over the whole earth without limitations to surface and is becoming the benchmark for aerosol retrievals over bright desert surfaces. Validation studies show that when compared with the AERONET, more than 2/3 of the MISR values are within 20% and 1/3 of the pixels are within 10% of the AOT values type [*Kahn et al.*, 2005]. Note that the Terra satellite has an overpass time roughly three hours prior to the A-Train constellation of satellites that are used in this study. The SEVIRI is a multi spectral instrument on the METOESAT second generation geostationary satellite and provides high temporal resolution measurements. The brightness temperature difference (BTD) between the 11 and 12 μm are typically used to identify dust aerosols [*Brindley*, 2007]. The CALIOP, an active lidar on the CALIPSO satellite, provides vertical profile of backscatter at 532 and 1064 nm both during day and night and samples the vertical distribution of clouds and aerosols over desert regions. Only the level 1 backscatter information is used in this study since the AOD retrievals from CALIOP are currently undergoing refinement and validation.

[7] The area of study as shown in Figure 1 is between 35°W–20°E and 0°–30°N although only the coincident information along the CALIPSO and aircraft tracks are discussed for June 21, 2007. The FAAM BAE-146 made measurements of aerosol size, aerosol optical properties, chemical composition, trace gas concentrations and meteorological variables, plus measurements of broadband and spectral shortwave and longwave irradiances (see www.metresearch.net/gerbils for further details). These measurements are similar to those obtained during the Dust And Biomass-burning EXperiment (DABEX), which are fully described by *Haywood et al.* [2008]. In this study, the vertical profile of the aerosol scattering coefficient measured by the aircraft nephelometer is used to assess the altitude of aerosol layers and estimate the total column AOD and the reported uncertainty is around 20% [*Johnson et al.*, 2008]. A complete analysis of the GERBILS data sets including modelling analysis is currently underway by various members of the GERBILS science team.

3. Results and Discussion

[8] On June 21, 2007 the BAE 146 flew from Niamey to Nouakchott while making several profile measurements along the way. Figure 1a shows multiple merged satellite imagery and products during the time of the Aqua overpass and the locations of the aircraft profiles labelled as P1–P8. Note that more than three MODIS overpasses are seamed together to produce these images. Multiple sensors included in this image occur within several minutes of each other (around 1:30 p.m. local time), since they are located on the A-Train constellation of satellites. The Level 1B Aqua MODIS visible reflectance is first plotted with high reflectance cloud features shown in white. Areas of missing data corresponding to the edge of the swaths are indicated by vertical white strips. Over land, AOD retrievals from the MODIS Deep Blue are shown (primarily north of 10°N) and the MODIS Collection 5 retrievals are shown south of this latitude. Note that the MODIS Deep Blue only provides AOD retrievals where MODIS operational retrievals are not performed. The area just off the West Coast of Africa does not contain aerosol retrievals due to sunglint in this region. In Figure 1a, the CALIPSO overpass is shown in grey, running north to south from approximately 30°N, 19°W to 0°, 13°W where it crosses near Dakar on the West Coast of Africa and the aircraft tracks for this day are also shown in yellow lines (Figure 1b). Along this CALIPSO transect, note that there may be regions that visually appear to be thicker dust (around 10°N) that do not have AOD retrievals from MODIS.

[9] Meteorological conditions are also important for the location and transport of the dust aerosols within the atmosphere. To gain some insight on the effects of atmospheric conditions, horizontal wind speed, direction and vertical velocity at 700 hPa from NCEP reanalysis are included with Figure 1b [*Kalnay et al.*, 1996]. Clearly evident are strong southwestward winds extending from 5°W westward into the Atlantic Ocean surrounding a high-pressure system centered near 20°W, 20°N. The center corresponds to a region of sinking air, indicated by the red contours. The easterly winds transport dust from the deserts of Africa into the Atlantic Ocean and finally northward on the western side of the high pressure. Upward vertical motion (blue contours) is maximized northeast of Dakar, near dust source regions. The synoptic-scale upward motion allows for the transport of the dust near the surface upwards into the mid-levels of the atmosphere. The strong surface heating over land drives strong dry convection which leads to the development of

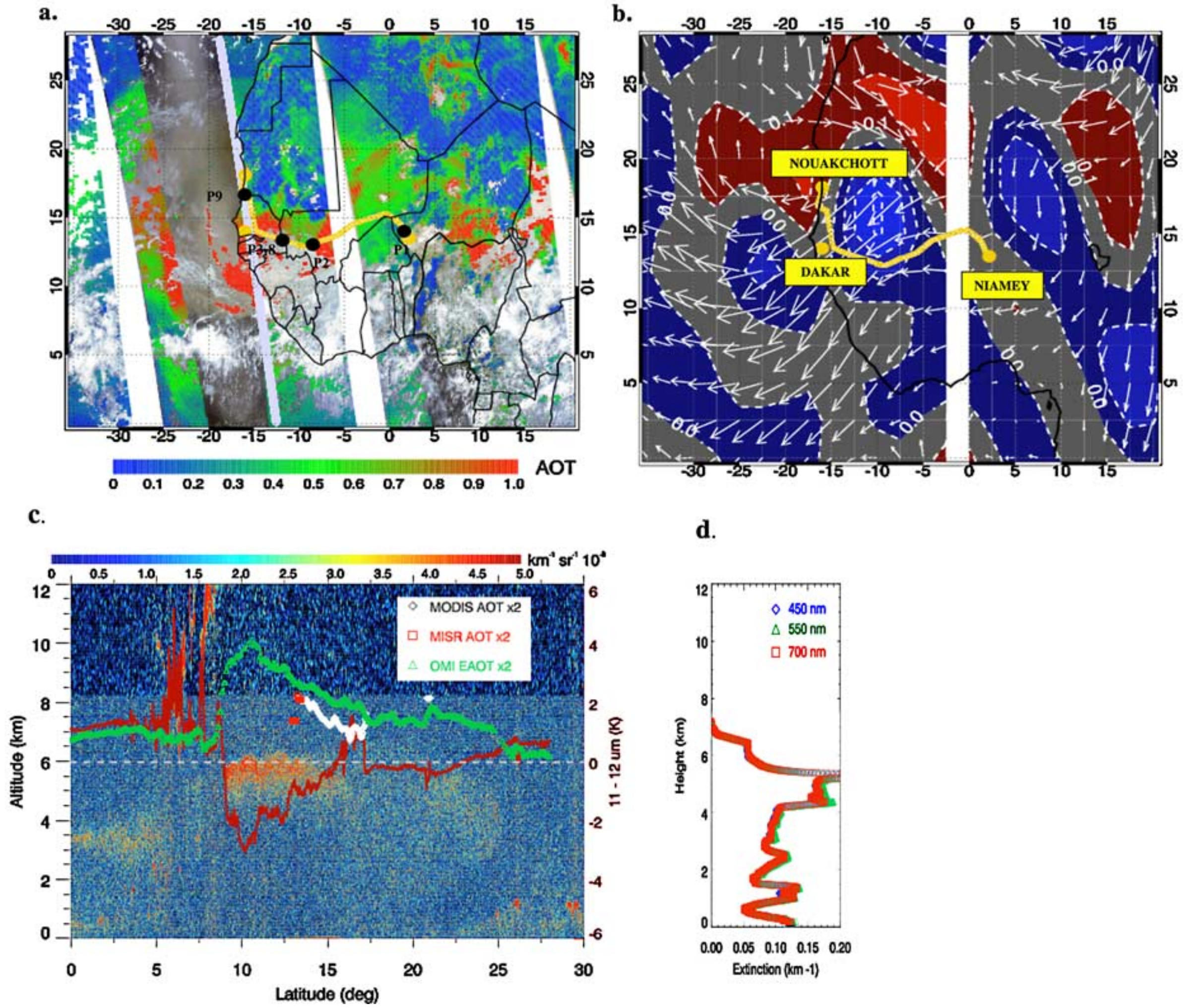

Figure 1. Satellite and aircraft analysis for June 21, 2007, (a) Merged Aqua MODIS, Level 1B visible reflectances show clouds in white, Aqua MODIS Collection 5 AOD over ocean areas and dark targets and Aqua MODIS Deep Blue AOD over high surface reflectance regions. The 500 nm Aerosol retrievals are not available over sunglint regions that are seen just off the cost of West Africa. The CALIPSO track is shown in grey running from North to South passing close to Dakar around 1440 UTC. (b) NCEP 700 hPa wind speeds, directions, and vertical velocities (red is descending and blue is ascending air motion). The aircraft flight track from Niamey to Nouakchott is also shown in yellow. (c) The CALIPSO attenuated backscatter as a function of height is shown for the transect in Figure 1a. Also shown are the corresponding Aqua MODIS AOD in white, MISR AOD from 1105 UTC in red and the estimated AOD (EAOD) from the AI-AOD relationship in green. (All AOD values are multiplied by 2. Scale is on the right side. The SEVIRI 11–12 μm brightness temperature differences are shown in red. (d) BAE 146 vertical profiles of extinction coefficient at 450, 500, and 700 nm from profile P9 (1410 UTC, ~17°N, 16°W).

an extremely deep dust-laden boundary layer extending to altitudes of greater than 6 km [e.g., *Marsham et al.*, 2008].

[10] Figure 1c shows the CALIPSO backscatter as a function of height for the latitudinal transect (shown by the grey-line in Figure 1a). The altitude scale in km is shown on the left. Overlaid on this image, for the CALIPSO transect, are Aqua MODIS AOD in white circles, Terra MISR AOD in red squares, and the estimated AOD (EAOD) from the OMI AI and MISR AOD relationship as green diamonds. The AOD scale is shown on the right and the values have been multiplied by 2. Also shown is the SEVIRI 11–12 μm BTD along the CALIPSO transect. This negative temperature difference is used to separate dust from clouds in geostationary SEVIRI imagery [*Brindley*, 2007]. In Figure 1c, the high CALIPSO backscatter shown in red indicates a broad area of dust between 10–15°N. This corresponds well with the negative BTD between 10–15°N. This dust plume is strongest between altitudes of 4–6 km (although it is not confined exclusively to that altitude range), which is confirmed by the corresponding vertical distribution of aerosol extinction (at 13.34°N) derived from the BAE-146 nephelometer measurements (Figure 1d). The EAOD derived from the OMI and MISR (shown in green) also shows high AOD's over this area between 10–15°N. The MODIS, MISR, and EAOD's are all consistent between 12–15°N when all three retrievals are available. Between 10–12°N only EAOT values are available whereas the MODIS and MISR have no retrievals. Note that the MISR overpass occurs 3 hours prior to the A-Train

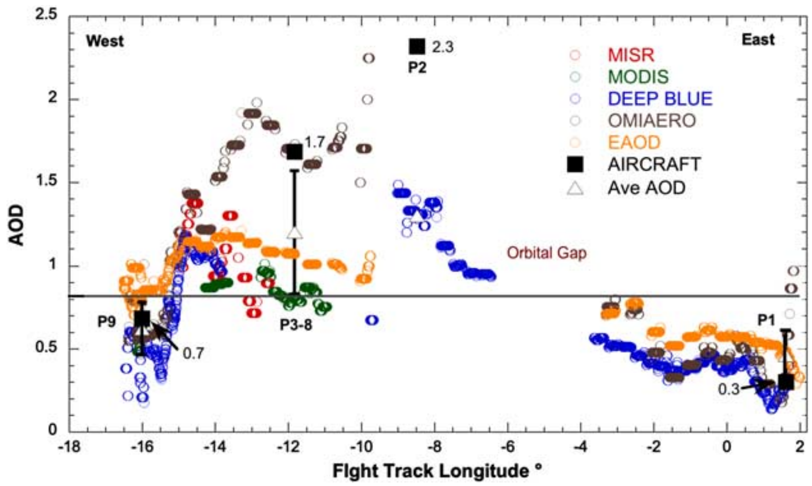

Figure 2. AOD from various satellite products along the aircraft flight path for June 21, 2007 the mean AOD corresponding to the flight profile and the standard deviation among the satellite AOD's are also shown. MODIS 11 – 12 mm data are also plotted, with negative values indicating regions of greatest dust concentrations. Shown in black squares are the AOD values retrieved from the profiles made by the BAE-146.

overpass and therefore such differences are possible due to several reasons including meteorology and algorithm inconsistencies. There also appears to be no MODIS AOD retrievals between 10 – 12°N and a visual inspection of Figure 1a indicates that this is possibly due to highly reflective dust in some pixels being mis-diagnosed as clouds. Optically thick aerosol plumes could be classified as clouds or rejected from the AOD retrieval process as this is a limitation of some satellite algorithms [e.g., *Brennan et al.*, 2005]. Figure 2 compares various satellite products from a region centred along and approximately 50 km^2 around the flight path of the BAE-146 on June 21, 2007, as indicated by the yellow line in Figure 1b from Niamey to Noukachott. Note that all satellite values are from approximately 1440 UTC except those from MISR that are about 3 hours prior to the A-Train overpass. Also indicated on Figure 2 in black squares are the four AOD estimates derived from aircraft profiles. These values are all reported for a wavelength of around 550 nm. The aircraft started measurements just east of 0° longitude at around 1000 UTC and ended in Nouakchott around 1450 UTC. The missing data around 5°W is largely due to gaps in orbital swaths (refer to Figure 1a). The trends in AOD among all the products are remarkably similar along the flight track. However, the magnitudes differ at several points along the flight track. Note that such intercomparisons between aircraft and satellite data sets are extremely challenging since the satellite provides snapshots in space and time over large 2-D footprints (10 – 30 km^2) whereas aircraft AODs from profile ascents/descents are essentially 1-D averages over a horizontal track of about 100 km. Nevertheless, at the start of the flight, for profile P1 (1.6°E), the aircraft AOD's is 0.3 and the mean and standard deviation among the various satellite products is 0.46 ± 0.15 that is within the retrieval uncertainties. For profiles P2 (8.5°W) and P3 – P8 (11.9°W) the aircraft AOD values are 2.32 and 1.67 respectively. Only the OMAERUV captures these high values and the other satellite products are lower by about 0.5. This is possibly due to the high reflectivity pixels that are possibly being classified as clouds and/or are screened out of the retrieval process. Near P2, we examined the MODIS 11 – 12 um differences (BTD) for the flight track along with the 412, 490 and 670 nm reflectances (not shown). The values indicate negative BTD consistent with dust aerosol signatures and high 670 nm reflectances indicative of optically thick aerosols. Finally for profile P9, where the aircraft AOD was 0.685, the mean and standard deviation among satellite products are 0.62 ± 0.17.

4. Summary and Conclusions

[11] Until recently, quantitative aerosol information from satellites was scarce over North Africa, especially over the highly reflective Sahara desert. Although the MISR instrument on Terra has been providing reliable aerosol retrievals over deserts, the swath width of the MISR is too narrow to provide daily coverage. Newly launched satellite instruments (e.g., OMI and CALIPSO) coupled with improvements in satellite algorithms are now beginning to provide much needed information over the deserts. Aerosol properties such as AOD are now available over desert regions from multiple sensors. Several efforts are underway to assess the accuracy of these satellite retrievals. We used multiple satellite sensors and aircraft measurements to assess some of the current capabilities. Spatial distributions are now routinely available from MODIS, MISR, and OMI and vertical distributions of dust can also be obtained from CALIPSO. Aircraft measurements from field campaigns, such as the GERBILS experiment, provide valuable information that will help refine such satellite algorithms. Results from these case studies indicate that the satellite and aircraft derived dust aerosol heights are consistent. There are differences between aircraft and satellite AOD owing to the very different spatial and temporal sampling of aircraft and satellite retrievals. There are also differences among satellite products, but these are to be expected since these products are relatively new and are undergoing refinement. For AOD < 1 there appears to be consistency among satellite products and aircraft estimates and are well within the uncertainty estimates. However, for AOD > 1 (as derived from the aircraft) most satellite algorithms have lower AOD's than the aircraft, possibly due to

aerosol-cloud identification issues that requires further investigation. Finally, we note that this research only represents a single case study day, which is a limitation, but complete analysis of the GERBILS satellite, ground, and aircraft data sets are underway and promise to further our understanding of dust aerosols.

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References

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*, 911–915.

Brindley, H. E. (2007), Estimating the top of atmosphere longwave radiative forcing due to Saharan dust from satellite observations over a West African site, *Atmos. Sci. Lett.*, *8*, 74–79.

Christopher, S. A., P. Gupta, J. Haywood, and G. Greed (2008), Aerosol optical thicknesses over North Africa: 1. Development of a product for model validation using Ozone Monitoring Instrument, Multiangle Imaging Spectroradiometer, and Aerosol Robotic Network, *J. Geophys. Res.*, *113*, D00C04, doi:10.1029/2007JD009446.

Curier, R. L., J. P. Veefkind, R. Braak, B. Veihelmann, O. Torres, and G. de Leeuw (2008), Retrieval of aerosol optical properties from OMI radiances using a multiwavelength algorithm: Application to western Europe, *J. Geophys. Res.*, *113*, D17S90, doi:10.1029/2007JD008738.

Dunion, J. P., and C. S. Velden (2004), The impact of the Saharan air layer on Atlantic tropical cyclone activity, *Bull. Am. Meteorol. Soc.*, *85*, 353–365.

Haywood, J. M., et al. (2008), Overview of the Dust and Biomass-burning Experiment and African Monsoon Multidisciplinary Analysis Special Observing Period-0, *J. Geophys. Res.*, *113*, D00C17, doi:10.1029/2008JD010077.

Holben, B. N., et al. (2001), An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET, *J. Geophys. Res.*, *106*, 12,067–12,097.

Hsu, N. C., S.-C. Tsay, M. D. King, and J. R. Herman (2006), Deep blue retrievals of Asian aerosol properties during ACE-Asia, *IEEE Trans. Geosci. Remote Sens.*, *44*, 3180–3195, doi:10.1109/TGRS.2006.879540.

Johnson, B. T., B. Heese, S. A. McFarlane, P. Chazette, A. Jones, and N. Bellouin (2008), Vertical distribution and radiative effects of mineral dust and biomass burning aerosol over West Africa during DABEX, *J. Geophys. Res.*, *113*, D00C12, doi:10.1029/2008JD009848.

Kahn, R. A., B. J. Gaitley, J. V. Martonchik, D. J. Diner, K. A. Crean, and B. Holben (2005), Multiangle Imaging Spectroradiometer (MISR) global aerosol optical depth validation based on 2 years of coincident Aerosol Robotic Network (AERONET) observations, *J. Geophys. Res.*, *110*, D10S04, doi:10.1029/2004JD004706.

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

Marsham, J. H., D. J. Parker, C. M. Grams, C. M. Taylor, and J. M. Haywood (2008), Uplift of Saharan dust south of the intertropical discontinuity, *J. Geophys. Res.*, *113*, D21102, doi:10.1029/2008JD009844.

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

Torres, O., A. Tanskanen, B. Veihelmann, C. Ahn, R. Braak, P. K. Bhartia, P. Veefkind, and P. Levelt (2007), Aerosols and surface UV products from Ozone Monitoring Instrument observations: An overview, *J. Geophys. Res.*, *112*, D24S47, doi:10.1029/2007JD008809.

Winker, D. M., W. H. Hunt, and M. J. McGill (2007), Initial performance assessment of CALIOP, *Geophys. Res. Lett.*, *34*, L19803, doi:10.1029/2007GL030135.

S. A. Christopher, Department of Atmospheric Sciences, University of Alabama in Huntsville, 320 Sparkman Drive, Huntsville, AL 35806-1912, USA. (sundar@nsstc.uah.edu)

J. Haywood and B. Johnson, United Kingdom Meteorological Office, FitzRoy Road, Exeter EX1 3PB, UK.

T. A. Jones, Earth System Science Center, University of Alabama in Huntsville, 320 Sparkman Drive, Huntsville, AL 35806-1912, USA.