GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L08815, doi:10.1029/2008GL034072, 2008

Possible linkages between Saharan dust and tropical cyclone rain band invigoration in the eastern Atlantic during NAMMA-06

Gregory S. Jenkins,[1] Aaron S. Pratt,[1] and Andrew Heymsfield[2]

Received 20 March 2008; accepted 2 April 2008; published 30 April 2008.

[1] The Saharan Air Layer (SAL) is a dominant feature that influences the large-scale environment from West Africa to the western tropical North Atlantic. While the SAL can create hostile thermodynamic and kinematic environmental conditions for tropical cyclogenesis, it also provides an infusion of cloud condensation and ice nuclei which can potentially invigorate convection. Here we show that these mechanisms may have been involved with the development of Tropical Storm (TS) Debby and Tropical Depression (TD) 8 (later Hurricane Helene) in 2006. Satellite imagery and rawinsondes indicate SAL outbreaks just prior to the emergence of these disturbances over the extreme Eastern tropical Atlantic Ocean. Here we examine the invigoration of convective bands associated with TS Debby and TD-8 based on satellite and direct aircraft measurement. In-situ aircraft measurements show enhanced cloud water content, cloud and precipitation sized particles, lightning and a 26 ms-1 updraft just south of the SAL with TD-8. **Citation:** Jenkins, G. S., A. S. Pratt, and A. Heymsfield (2008), Possible linkages between Saharan dust and tropical cyclone rain band invigoration in the eastern Atlantic during NAMMA-06, *Geophys. Res. Lett.*, *35*, L08815, doi:10.1029/2008GL034072.

1. Introduction

[2] Aerosols influence surface and tropospheric processes through direct, indirect and semi-direct effects adding uncertainty to understanding anthropogenic climate change [*Takemura et al.*, 2007]. The Sahara Desert and Sahel are the primary sources of aerosols that are transported across the tropical Atlantic. During the Northern Hemisphere (NH) winter season, the direct effects seem more dominant with reduced visibilities from dust in Cape Verde [*Chiapello et al.*, 1995] when compared to the NH summer season. However, the indirect effects may significantly influence precipitation in the Sahelian region [*Prospero and Lamb*, 2003].

[3] During NH summer through autumn seasons, Saharan dust outbreaks are often associated with the Saharan Air Layer (SAL). The SAL is a well-mixed, warm, dusty and dry air mass that moves westward and southwestward from the Sahara Desert out over the eastern Atlantic [*Carlson and Prospero*, 1972; *Dunion and Velden*, 2004]. Relatively cool, moist marine air undercuts the SAL as it moves westward. Typically, the SAL resides between 850–500 hPa in height and is bound by an enhanced trade wind inversion at its base [*Dunion and Velden*, 2004].

[4] Modeling studies suggest that the SAL can be initiated at least some of the time by the 3–5 day African Easterly Waves (AEWs) [*Jones et al.*, 2003]. These AEWs are also the primary source of Atlantic Tropical Cyclones (TCs). The interaction of the SAL with AEWs and their role in tropical cyclone evolution remains an area of active research. In particular there is evidence to support the SAL acting to weaken tropical cyclones but also evidence suggesting that aerosol-cloud microphysical interactions from the SAL can invigorate convective bands in tropical cyclones.

[5] *Dunion and Velden* [2004] found that the SAL negatively impacts TC development through three primary mechanisms: (a) a surge in the mid-level African Easterly Jet (AEJ) increasing vertical shear, (b) the inclusion of dry air, (c) an enhanced trade wind inversion stabilizing the atmosphere. *Wong and Dessler* [2005] noted that the SAL raises the Lifted Condensation Level (LCL) and Level of Free Convection (LFC), making it more difficult for deep convection to develop.

[6] *Evan et al.* [2006] noted an inverse correlation between the coverage of Saharan dust and the amount of TC development in the Atlantic Basin. *Zhang et al.* [2007] using an idealized tropical cyclone show that using high aerosol concentrations (2000 cm^{-3} between 1–5 km), representative of the SAL produced a higher sea level pressure and weaker maximum winds in the tropical cyclone consistent with the studies above.

[7] There is also evidence of Saharan aerosols/cloud microphysics interactions supporting cloud invigoration thereby potentially offsetting negative SAL impacts. Measurements off the coast of Florida during the CRYSTAL-FACE campaign show that there is direct impact of Saharan dust on cloud-microphysics. In particular: (1) Saharan dust significantly increasing ice nuclei (IN) with *DeMott et al.* [2003] reporting the highest measurements of 1 cm^{-3} for particle sizes less than 1 μm. (2) *Sassen et al.* [2003] found that Saharan dust caused glaciation of altocumulus clouds at unusually warm temperatures. (3) *Fridlind et al.* [2004] using observations and model simulations suggest that aerosols from the mid-troposphere are more important for ice particle formation in anvil and cirrus clouds from thunderstorms than aerosols from the boundary layer. Further, *Koren et al.* [2005] suggest that the suppression of warm rain, delayed precipitation and smaller droplets that freeze at higher altitudes can increase latent heat leading to cloud invigoration. Using satellite data they show that in the presence of dust, the cloud top pressure decreases, the cloud fraction increases and the droplet effective radius decreases, which is consistent with convective invigoration. These

---

[1] Howard University Program in Atmospheric Sciences, Washington, DC, USA.

[2] National Center for Atmospheric Research, Boulder, Colorado, USA.

0094-8276/08/2008GL034072$05.00

processes are simulated by *Khain et al.* [2005] and *Van Den Heever et al.* [2006].

[8] During the summer of 2006, the National Aeronautics and Space Administration (NASA) investigated the downstream aspects of the international African Monsoon Multidisciplinary Analyses (AMMA) campaign [*Redelsperger et al.*, 2006] during the August/September 2006 and denoted as NASA-AMMA (NAMMA). This component includes: aircraft and enhanced ground measurements in West Africa and Cape Verde. The NASA DC-8 was equipped with radar, microwave sounding capability, lidar, GPS dropsondes and cloud microphysics sensors. These sensors include the Cloud, Aerosol and Precipitation Spectrometer (CAPS) [*Baumgardner et al.*, 2002], and counterflow virtual impactor (CVI) [*Twohy et al.*, 1997] that measures the condensed water content. These measurements over the Tropical Eastern Atlantic are the first where aircraft have successfully investigated tropical cyclogenesis in close proximity to the African continent.

[9] Here we describe the potential invigoration of rain bands for two developing tropical cyclones (TS Debby and TD-8) from interaction with the SAL as they emerged from the West African coastline using available aircraft, ground and satellite data. In addition to DC-8 measurements, upper air data (Dakar, Senegal, Sal and Praia, Cape Verde) and data from the Tropical Rainfall Measurement Mission (TRMM) [*Kummerow et al. 1998*] are used (precipitation radar (PR) and TRMM Microwave Imager (TMI) 85 GHz polarization corrected temperatures (PCT) [*Mohr and Zipser*, 1996], latent heat rate [*Olson et al.*, 2006], IR and lightning measurements). Aerosol optical thicknesses AOT derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite are used for identifying SAL outbreaks.

2. Results

[10] The vortex associated with TS Debby emerged off the African coast on August 20th at 1200 UTC and was classified as a depression on August 21st at 1800 UTC. This storm reached a maximum intensity of 50 knots and was penetrated by the NASA DC-8 on August 23rd 2006. However, prior to the vortex emerging into a marine environment, intense convective bands (Cloud top temperatures ≅200°K were observed) began to form (Figure 1a). Saharan dust can be seen to the west and north of the convective band in the visible wavelengths at 1330 UTC. MODIS shows high AOT values associated with a dust outbreak that began on August 18th and continued to affect vast areas on August 20th (Figure 1b). Rawinsondes at Dakar, Senegal and Praia, Cape Verde also confirm the influence of a SAL outbreak with both stations showing within the 600–900 hPa layer low relative humidity (20–50%) associated with a SAL temperature inversion during this period (note: the air between surface- 900 hPa had relative humidities of 70–100%).

[11] The tropical disturbance became more organized on August 21st with a TRMM overpass showing cloud temperatures at the vortex center below 210°K at 0122–0124 UTC on August 21st (Figure 1c). An outer band to the northeast of the vortex, which passed over western Senegal also exhibited temperatures below 210°K. The TRMM PR shows the maximum (within the entire vertical scan) radar reflectivies of 40 dBZ over the ocean but the small swath-width of the PR did not cover the convective rain band over land (Figure 1d). The TRMM TMI however, with its larger swath-width did capture the convective band over land. This band is associated with a considerable amount of ice scattering based on PCTs being less than 120°K (Figure 1e). The lower PCTs over land than the vortex in the marine environment, suggest greater convective strength over land. The latent heat release estimated from TMI is greater than 20° C/h over Senegal at 10 km implying a considerable amount of ice formation. Observations of lightning flashes, often an indication of convective strength, was also observed in much higher quantities than over the oceanic convective center; the TRMM Lightning Imaging Sensor (LIS) measured 131 flashes within two minutes in the vicinity of Dakar (in the area of highest latent heat release, low PCT and low cloud top temperatures) between 0122 and 0124 UTC. Based on the afore-mentioned TRMM observations and rawinsonde data, we infer that the SAL influenced cloud-microphysical properties and hence convection associated with the genesis of TS Debby where observations show cold cloud tops, elevated ice concentrations, elevated latent heat release and frequent lightning.

[12] The second system that we have additional data to support rain band invigoration is TD-8 (Pre-Helene). In this case a strong vortex that originated over Nigeria propagated westward producing a number of mesoscale convective systems, including two significant squall lines. Relative to TS-Debby, the vortex was considerably stronger and, as it approached the coastline, may have been responsible for increasing the dust loading in the atmosphere. This is supported by elevated surface Aerosol Robotic Network (AERONET) AOT values near Dakar beginning on September 10th and low relative humidity at coastal stations (Dakar, Senegal, and Tambacounda Senegal; Nouakchott, Mauritania) and strong mid level winds between 800 and 600 hPa approaching 26 m-s^{-1} (50 knots) from rawinsonde data (not shown).

[13] As the AEW and vortex moved out over the Eastern Atlantic (12.5°N–18°W) during the early morning hours of September 12th, deep convection rapidly developed with the system. This convection was most intense on the western side of the system, as denoted by conventional IR imagery and by lightning data (Figures 2a, and 2c). It is interesting that intense convection developed in such close proximity to the thermodynamically stable atmosphere associated with the SAL (Figure 2b); it suggests the possibility of microphysical processes are compensating for the stability and invigorating the convection of this system. Another factor that would strengthen the disturbance is the strong Mid-level Jet (> 50 knots) that would act as a source of positive vorticity. Satellite imagery throughout the day on September 12th (not shown) indicates that the strongest convection tended to remain on the western semi-circle of the system, near the region of maximum dust loading.

[14] Further suggestions of dust impacting the development of TD 8 can be seen in Figure 3a. The Lidar Atmospheric Sensing Experiment (LASE) instrument aboard the DC-8 revealed the presence of Saharan dust extending from the ocean surface up to nearly 5 km in

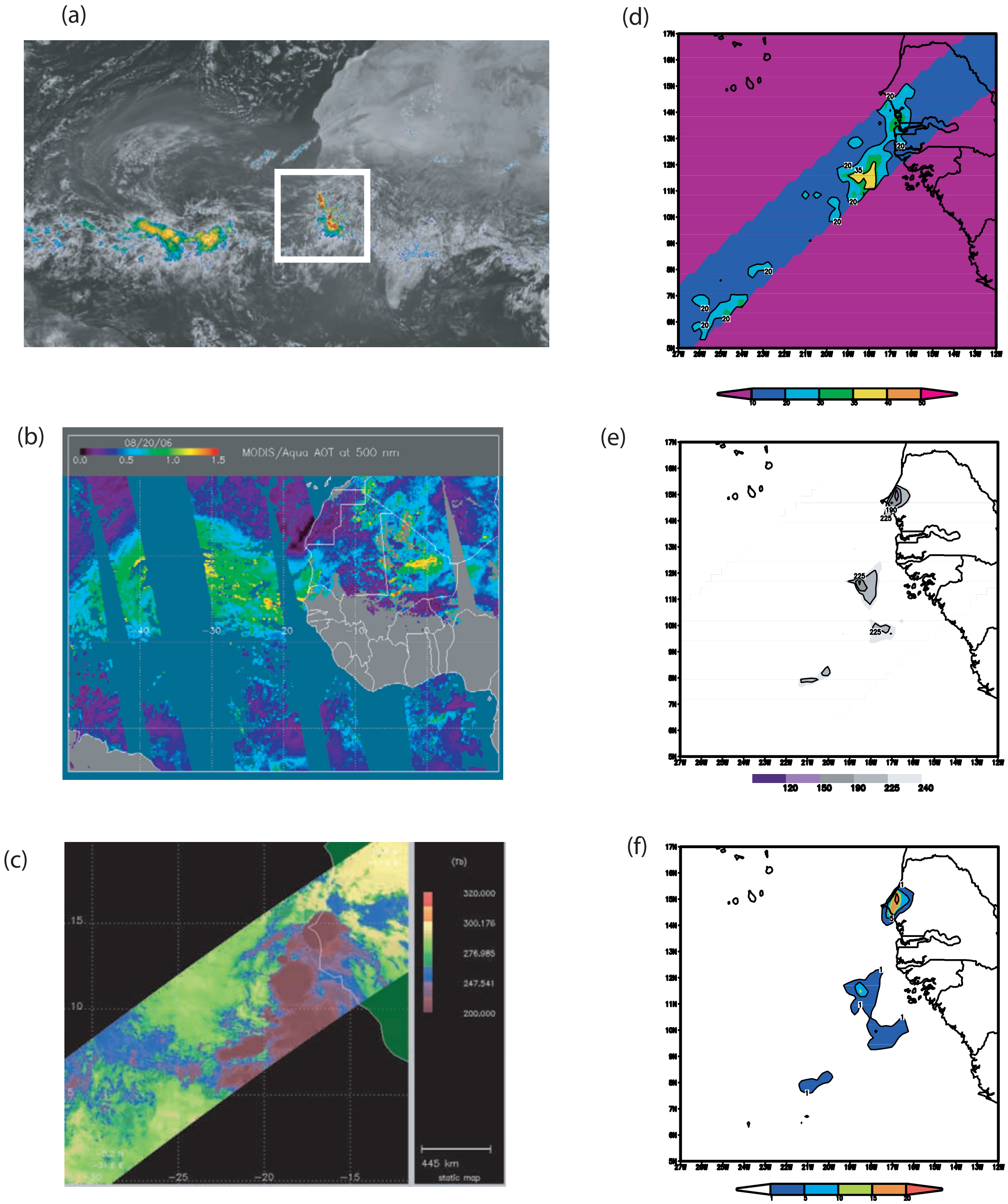

Figure 1. (a, b) Visible with false IR and MODIS Aerosol Optical Thickness at approximately 1330 UTC for August 20, 2006. (c, d) TRMM IR temperatures and PR maximum reflectivity, (e, f) TMI PTC (degree K) and Latent Heat release (Degree C/hr) at 10 km on August 21st 0142 UTC.

altitude, just to the north and west of the system. The depth of SAL is reduced as the DC-8 enters the convection. While most prevalent on the northwestern side of the system, (MODIS) AOT measurements (Figure 2b) show dust wrapping around the western and even southern sides of the circulation. As mentioned above, the convection associated with TD 8 was most intense on the western side of the system with an updraft of approximately 26 m-s^{-1} (50 knots) measured by the DC-8 as it was traversing this convection from west to east (Figure 3b) between 1245–1300 UTC. This

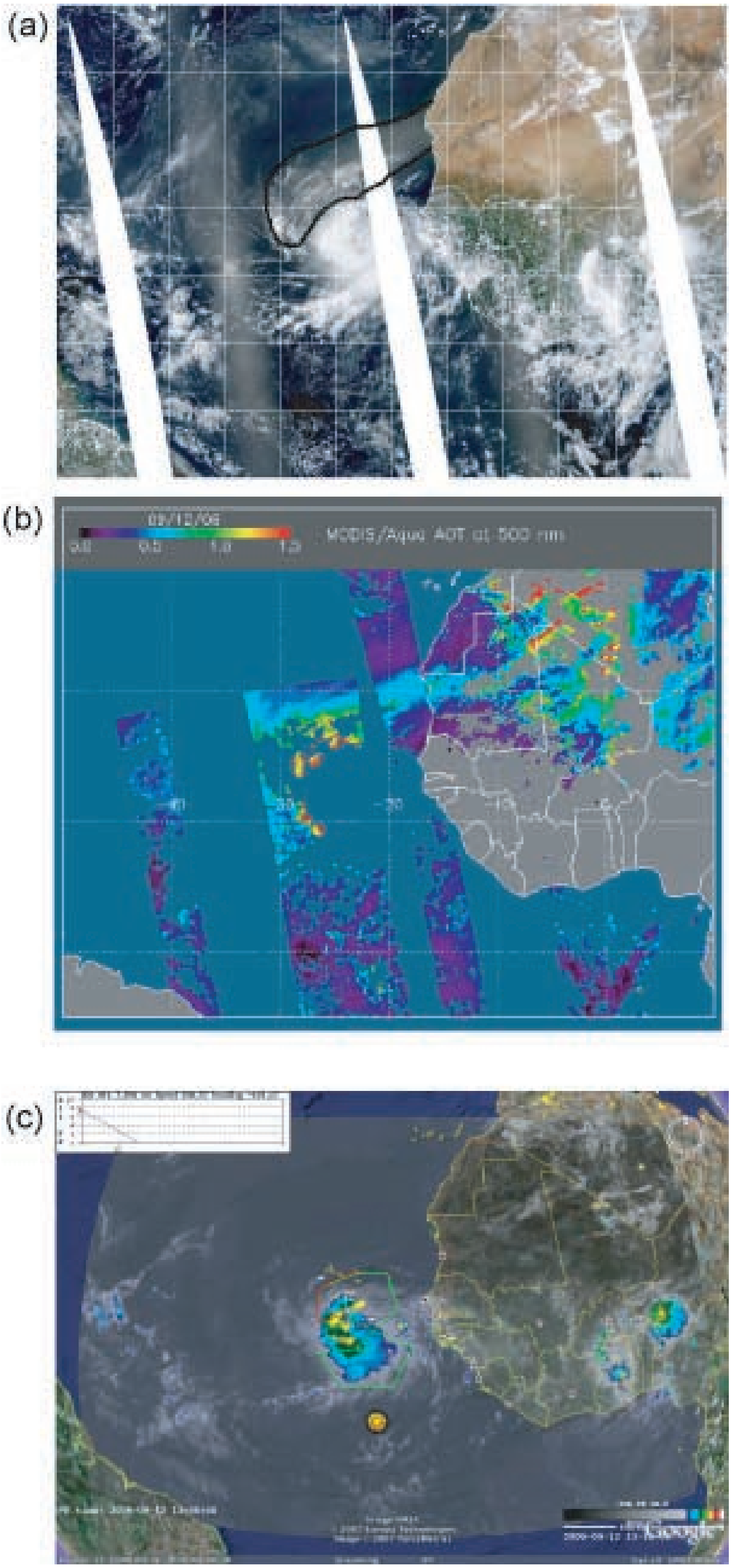

Figure 2. (a) 1330 UTC MODIS imagery of TD 8, (b) 1330 UTC MODIS AOT, (c) 1345 UTC MeteoSat IR imagery with flight track (red) and lightning strikes.

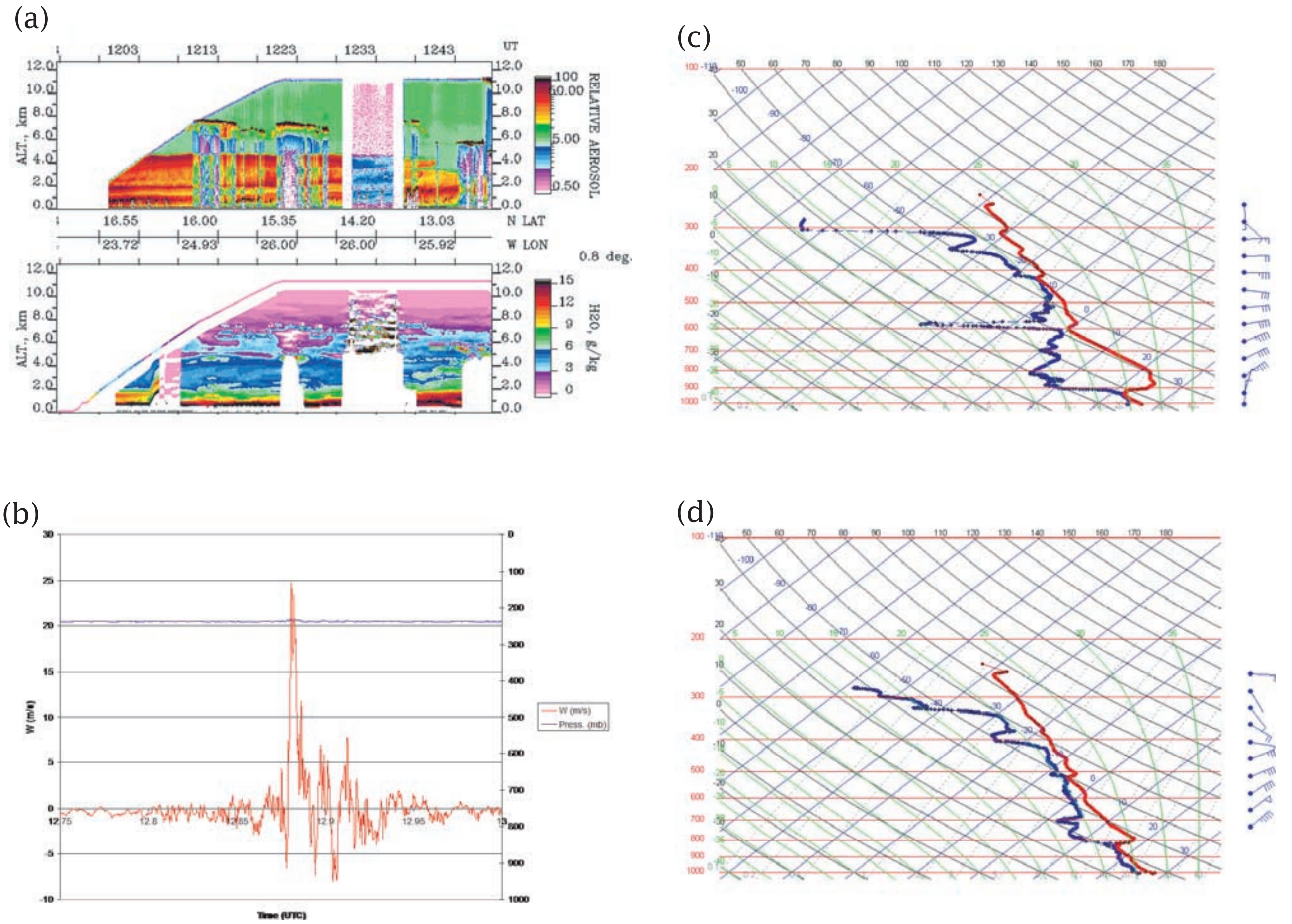

Figure 3. (a) 1200–1248 UTC LASE imagery of aerosol scattering and water vapor mixing ratio, (b) vertical updraft speed in m/s and altitude in mb from 1245–1300 UTC, (c) dropsonde temperature and dew point profile for 1220 UTC, and (d) 1242 UTC.

updraft is the strongest ever encountered by the DC-8 or other research aircraft [*Black and Hallett*, 1999] investigating tropical cyclones. GPS dropsondes released from the DC-8 at 1220 UTC and 1242 UTC (Figures 3c–3d) reveal a strong temperature inversion and sharp drop-off in dew point just above the marine boundary layer associated with the SAL. The strong mid-level jet associated with the SAL can also be seen in the wind profile from these two dropsondes. Based on the GPS dropsonde at 1242 UTC, we would expect an entrainment of dust particle at altitudes greater than 825 hPa level where the base of the inversion is found.

[15] Figure 4 shows aerosol, cloud and precipitation particle number concentrations (normalized by bin width) measured by CAPS from 1245–1400 UTC on September 12. Temperatures (not shown) ranged between −40°C and −50°C from approximately 1245–1400 when the aircraft flew through the convective band, hence the cloud and precipitation-sized particles are frozen at the 11 km flight level. In particular, there is a sharp spike in all particle concentrations just before 1300 UTC as the DC-8 crossed the strong line of convection with lightning and strong vertical velocity. The increase in the largest (>4200 μm) particles around this time period indicates that entrained Saharan dust enhanced this convective band to the point where relatively large particles were able to form and remain suspended due to the strong updraft. Cloud invigoration is also evident from the amount of condensate as measured by CVI at 11 km that has been transported vertically as measured by cloud water content (CWC). CWC values are approximately 1.8 g-m^{-3} in association with the strong updraft before the loss of data (Figure 4b). We also note that a significant proportion of the sub-micron particle concentration increase might be due to shattering of larger ice crystals upon the inlet probe of CAPS, and the CVI can become saturated under certain conditions (CWC > 1.5 g-m^{-3}) which probably led to a loss of data after encountering the strong updraft just before 1300 UTC.

3. Conclusion

[16] In this paper we have shown measurements that support the hypothesis that Saharan dust may have led to invigoration of rain bands associated with tropical cyclogenesis. The results are based on satellite observations/rawinsondes associated with TS Debby and aircraft measurements of TD 8 during the 2006 NAMMA field campaign. The evidence includes: observed SAL outbreaks and associated dust particles inferred from aircraft lidar and

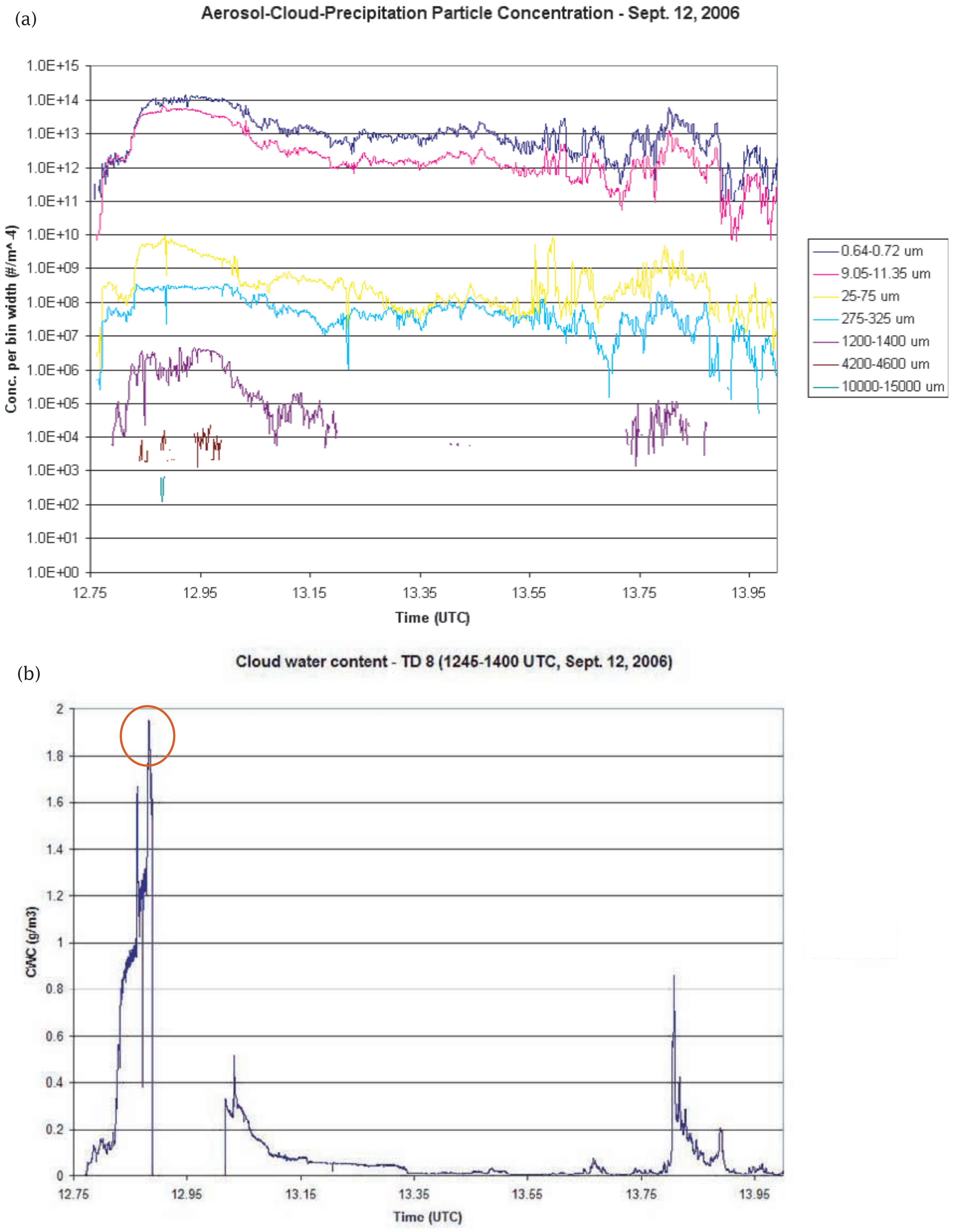

Figure 4. (a) Particle concentrations normalized by bin width as measured by CAPS from 1250–1400 UTC, (b) Cloud Water content (CWC) from 12:30–14:00 UTC on Sept. 12, 2006.

MODIS AOT values, strong vertical updrafts during TD-8 of 26 ms^{-1} (50 knots), large precipitation sized particles and high cloud water content, lightning, significant ice concentrations in the upper parts of the system - as measured by aircraft and satellite.

[17] There are still many questions about both systems with regard to internal processes, which cannot be fully addressed due to incomplete measurements. A primary question surrounds the role of Saharan dust serving as IN, which would lead to stronger convection as suggested by *DeMott et al.* [2003]. Although IN concentrations were not directly measured during NAMMA flights, we believe that they were indeed enhanced because of the close proximity to the Sahara. Modeling studies will be required to constrain the limited NAMMA measurements. The results presented here suggest that the SAL and potential aerosol-cloud micro-

physics impacts on convection cannot be neglected and could be a key factor in the intensity of convection associated with TC genesis in the extreme Tropical Eastern Atlantic.

[18] **Acknowledgments.** This work was supported through NASA grant # NNX06AC78G. We thank the NAMMA team for providing satellite images and useful discussions.

References

Baumgardner, D., H. Jonsson, W. Dawson, and R. Newton (2002), The cloud, aerosol and precipitation spectrometer (CAPS): A new instrument for cloud investigations, *Atmos. Res.*, *59–60*, 251–264.

Black, R. A., and J. Hallett (1999), Electrification of the hurricane, *J. Atmos. Sci.*, *56*, 2004–2028.

Carlson, T. N., and J. M. Prospero (1972), The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic, *J. Appl. Meteorol.*, *11*, 283–297.

Chiapello, I., G. Bergametti, L. Gomes, B. Chatenet, and F. Dulac (1995), An additional low layer transport of Sahelian and Saharan dust over the north-eastern tropical Atlantic, *Geophys. Res. Lett.*, *22*, 3191–3195.

DeMott, P. J., K. Sassen, M. R. Poellot, D. Baumgardner, D. C. Rogers, S. D. Brooks, A. J. Prenni, and S. M. Kreidenweis (2003), African dust aerosols as atmospheric ice nuclei, *Geophys. Res. Lett.*, *30*(14), 1732,doi:10.1029/2003GL017410.

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, doi:10.1175/BAMS-85-3-353.

Evan, A. T., J. Dunion, J. A. Foley, A. K. Heidinger, and C. S. Velden (2006), New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks, *Geophys. Res. Lett.*, *33*, L19813,doi:10.1029/2006GL026408.

Fridlind, A. M., et al. (2004), Evidence for the predominance of mid-tropospheric Aerosols as subtropical anvil cloud nuclei, *Science*, *304*, 718–721.

Jones, C., N. Mahowald, and C. Lou (2003), The role of easterly waves on African desert dust transport, *J. Clim.*, *16*, 3628–3716.

Khain, A. P., D. Rosenfeld, and A. Pokrovsky (2005), Aerosol impact on the dynamics and microphysics of convective clouds, *Q.J.R. Meteorol. Soc.*, *131*, 2639–2663.

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.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson (1998), The Tropical Rainfall Measuring Mission (TRMM) sensor package, *J. Atmos. Oceanic Technol.*, *15*, 809–817.

Mohr, K. I., and E. J. Zipser (1996), Defining mesoscale convective systems by the 85-GHz ice scattering signatures, *Bull. Am. Meteorol. Soc.*, *77*, 1179–1188.

Olson, W. S., et al. (2006), Precipitation and latent heat distributions from satellite passive microwave radiometry. part I: Improved method and uncertainties, *J. Appl. Meteorol. Climatol.*, *45*, 702–720.

Prospero, J. M., and P. J. Lamb (2003), African droughts and dust transport to the Caribbean: Climate change implications, *Science*, *302*, 1024–1026.

Redelsperger, J.-L., et al. (2006), African monsoon multidisciplinary analysis: An international research project and field campaign, *Bull. Am. Meteorol. Soc.*, *87*, 1739–1746.

Sassen, K., P. J. DeMott, J. M. Prospero, and M. R. Poellot (2003), Saharan dust storms and indirect aerosol effects on clouds: CRYSTAL-FACE results, *Geophys. Res. Lett.*, *30*(12), 1633,doi:10.1029/2003GL017371.

Takemura, T., Y. J. Kaufman, L. A. Remer, and T. Nakajima (2007), Two competing pathways of aerosol effects on cloud and precipitation formation, *Geophys. Res. Lett.*, *34*, L04802,doi:10.1029/2006GL028349.

Twohy, C. H., and A. J. Schanot (1997), Measurements of condensed water content in liquid and ice clouds using an airborne counterflow virtual impactor, *J. Atmos. Oceanic Technol.*, *14*, 197–202.

Wong, S., and A. E. Dessler (2005), Suppression of deep convection over the tropical North Atlantic by the Saharan air layer, *Geophys. Res. Lett.*, *32*, L09808,doi:10.1029/2004GL022295.

Van Den Heever, S. C., et al. (2006), Impacts of nucleating aerosol on Florida storms. part I: Mesoscale simulations, *J. Atmos. Sci.*, *63*, 1752–1775.

Zhang, H., G. M. McFarquhar, S. M. Saleeby, and W. R. Cotton (2007), Impacts of Saharan dust as CCN on the evolution of an idealized tropical cyclone, *Geophys. Res. Lett.*, *34*, L14812,doi:10.1029/2007GL029876.

A. Heymsfield, National Center for Atmospheric Research, Boulder, CO 80307, USA. (heyms1@ucar.edu)

G. S. Jenkins and A. S. Pratt, Howard University Program in Atmospheric Sciences, Washington, DC 20059, USA. (gjenkins@howard.edu; a_pratt@howard.edu)