GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L19813, doi:10.1029/2006GL026408, 2006

New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks

Amato T. Evan,[1,2] Jason Dunion,[3,4] Jonathan A. Foley,[1] Andrew K. Heidinger,[5] and Christopher S. Velden[6]

Received 3 April 2006; revised 1 August 2006; accepted 30 August 2006; published 10 October 2006.

[1] It is well known that Atlantic tropical cyclone activity varies strongly over time, and that summertime dust transport over the North Atlantic also varies from year to year, but any connection between tropical cyclone activity and atmospheric dust has been limited to a few case studies. Here we report new results that demonstrate a strong relationship between interannual variations in North Atlantic tropical cyclone activity and atmospheric dust cover as measured by satellite, for the years 1982–2005. While we cannot conclusively demonstrate a direct causal relationship, there appears to be robust link between tropical cyclone activity and dust transport over the Tropical Atlantic. **Citation:** 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.

1. Introduction

[2] The recent upswing in Atlantic tropical cyclones (including both hurricanes and tropical storms) affecting North America has raised the awareness of their impact on society and the economy. Currently, there is a debate surrounding the cause of this observed increase in cyclone activity. Several recent studies have explored the relationship between long–term trends in tropical cyclone activity (either in terms of their number or intensity) and environmental factors that may or may not be influenced by global warming [*Emanuel*, 2005a, 2005b; *Landsea*, 2005; *Trenberth*, 2005; *Webster et al.*, 2005]. Other studies, however, have concluded that different environmental factors – not necessarily related to global warming – control trends in cyclone activity [*Goldenberg et al.*, 2001; *Knutson and Tuleya*, 2004].

[3] In this paper, we explore another possible contributor to changing North Atlantic tropical cyclone activity: the role of atmospheric dust. This hypothesis was first suggested by *Dunion and Velden* [2004], who showed that tropical cyclone activity may be influenced by the presence of the Saharan Air Layer, which forms when a warm, well-mixed, dry and dusty layer over West Africa is advected over the low-level moist air of the tropical North Atlantic [*Carlson and Prospero*, 1972]. The Saharan Air Layer rides over the marine boundary layer and can be a significant feature of the atmosphere as it transits over the North Atlantic, often seen as far away as the Caribbean (∼7,000 km west of the Sahara Desert) [*Dunion and Velden*, 2004]. The Saharan Air Layer's longevity is likely enhanced by the persistent temperature inversions that exist at its base and top: daytime thermal heating by dust entrained within the Saharan Air Layer tends to counter nighttime radiative cooling, thus keeping the Saharan Air Layer relatively warm and stable as it traverses the North Atlantic [*Prospero and Carlson*, 1972].

[4] Based on their analysis of several case studies of individual tropical cyclone events, *Dunion and Velden* [2004] suggested that the Saharan Air Layer could inhibit the formation of, or reduce the intensity of, tropical cyclones in the North Atlantic through three primary mechanisms. First, the Saharan Air Layer can introduce dry air into the storm, promoting downdrafts and disrupting the convective organization within the tropical cyclone vortex. Second, the midlevel jet found within the Saharan Air Layer increases the local vertical wind shear, which can decouple the storm's low–level circulation from its supporting mid– and upper–level deep convection. Third, the radiative effects of the dust in the Saharan Air Layer may enhance the preexisting trade wind inversion and act to stabilize the environment, thereby suppressing deep convection.

2. Data and Methods

[5] In our study we examine these hypotheses by putting them into a long-term, climatological context using a new satellite-based atmospheric dust record from the 5–channel Advanced Very High Resolution Radiometer (AVHRR). Our algorithm for dust detection [*Evan et al.*, 2006a] has been developed to improve the distinction between dust and clouds for very optically thick dust storms, which would have previously been classified as cloud under the National Oceanographic and Atmospheric Administration's operational AVHRR cloud mask algorithm. Our algorithm has been assessed by making daily comparisons with data from the Aerosol Robotic Network and by making a climatological comparison with METEOSAT and Total Ozone Mapping Spectrometer data over a portion of the North Atlantic [*Evan et al.*, 2006a, 2006b]. The final half–degree resolu-

[1]Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, University of Wisconsin-Madison, Wisconsin, USA.

[2]Now at Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison, Wisconsin, USA.

[3]Hurricane Research Division, AOML/NOAA, Miami, Florida, USA.

[4]Also at Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida, USA.

[5]Office of Research and Applications, NOAA/NESDIS, Camp Springs, Maryland, USA.

[6]Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison, Wisconsin, USA.

0094-8276/06/2006GL026408$05.00

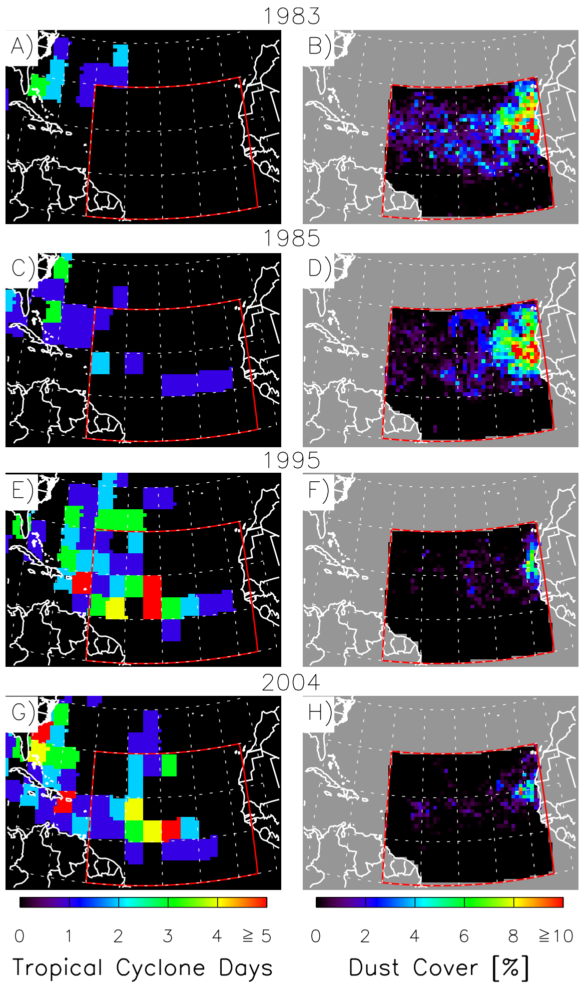

Figure 1. A comparison of variability in Saharan-induced dustiness and North Atlantic tropical cyclone activity for several years. The analyses on the left are of tropical cyclone days at 5–degree grid resolution. The analyses on the right are of dust coverage at 1/2–degree grid resolution. Both images represent average values over the period August 20 through September 30 for their respective year. Figures 1a and 1b are for 1983; Figures 1c and 1d, 1985; Figures 1e and 1f, 1995; Figures 1g and 1h, 2004. The red boxes in the tropical cyclone images represent the area over which we collected data (0–30N and 15–60W) for the tropical cyclone days and dust cover time series shown in Figures 2 and 3. The dust maps represent the percent coverage of optically thick dust plumes and not the percent coverage of all atmospheric dust.

tion dust dataset represents the fractional dust coverage for each grid cell. This is not a measure of the total amount of dust present, but rather the fractional coverage of optically thick dust in a grid cell. (Please see the auxiliary materials[1] for a methods section that further discusses the methodology, merits, and limitations of this dust product.)

[6] We derived a daily measure of North Atlantic dust cover by calculating the average number of dust–covered pixels over the oceanic region west of northern Africa, from 0–30°N and 15–60°W (Figure 1). We then created a "tropical cyclone days" statistic by summing the total number of days any named Atlantic tropical storm was present over the same region used for the collection of dust statistics (Figure 1). Tropical cyclone data were obtained from the National Hurricane Center (NHC) Hurricane Best Track Files (HURDAT), available at http://www.nhc.noaa.gov/pastall.shtml [*Jarvinen et al.*, 1984]. Here, a "named storm" corresponds to a tropical cyclonic system with 1-minute-averaged maximum sustained winds greater than or equal to 34 knots. For each year, we acquired dust and tropical cyclone statistics for August 20–September 30, a period representing one standard deviation of the seasonal tropical cyclone dates, centered on the climatological peak of tropical cyclone activity for 1982–2004, September 9. Just over 50% of all North Atlantic tropical cyclone activity for these years occurs within this 42 day time period. This time period was chosen in order to simplify the study, because if there is a strong relationship between North Atlantic dust cover and tropical cyclone activity, we will have more confidence in the results if this relationship is observed during the peak of the hurricane season, when other seasonal environmental factors are probably less likely to affect tropical cyclone occurrence.

3. Results

[7] Figures 1a–1h show the regions for which dust and tropical cyclone statistics were derived, superimposed over images of monthly–mean dust cover and total tropical cyclone days for years with maximum (1983, 1985) and minimum (1995, 2004) dust activity. Seasonal dust and tropical cyclone maps for all years can be found in the online supplement.

[8] For the 1983 case no tropical cyclone days (Figure 1a) were observed inside of our defined region, and those that are seen in the image are far to the north. In Figure 1b, high mean dust fractions are observed throughout this region, but mainly constrained to latitudes north of 10°N, seemingly to follow the prevalent trade flow. Correspondingly, the other case of maximal dust activity, 1985, shows some tropical cyclone days along the main development region [*Goldenberg and Shapiro*, 1996] and in the western flanks of our region (Figure 1c), but little activity is found in elsewhere in the region. Here, the tropical cyclone days are mostly west of our region and mostly along the eastern US shoreline. For this year, again dust is detected across the whole area of study (Figure 1d), taking a similar latitudinal position as was seen in the 1983 case.

[9] For the 1995 case, there is a large increase in tropical cyclone activity along the main development region of the North Atlantic and across the western Atlantic basin as a whole (Figure 1e). There is also a vast reduction in dustiness as compared to the 1983 and 1985 cases (Figure 1f). The images for 2004 (Figures 1g and 1h) also reflect this condition of little dust and vigorous tropical cyclone activity. Furthermore, in the 1995 and 2004 cases the tropical cyclone days that occur far into the eastern North Atlantic are contained mostly along the more south-

[1]Auxiliary materials are available in the HTML. doi:10.1029/2006GL026408.

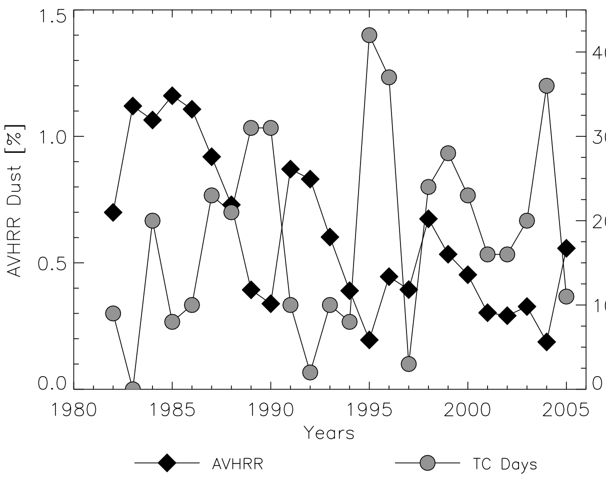

Figure 2. Time series of North Atlantic tropical cyclone days and AVHRR-detected Saharan-induced dust cover for 1982–2005. The black line and diamonds represents the detected dust cover and the gray line and circles represents the tropical cyclone days. Both time series were created by averaging the dust coverage or summing tropical cyclone days over the region of 0–30N and 15–60W for the time period of August 20 through September 30, for each year of the sample. The two time series have a correlation coefficient of −0.53, significant at the 99% level.

ern latitudes (in the main development region), south of the areas where dust activity was recorded.

[10] As the dust observations are a good proxy for the Saharan Air Layer, we suggest that the contrast between the presence of dust and the lack of tropical cyclone activity for the 1983 and 1985 cases, and the appearance of cyclone days where dust is lacking in the 1995 and 2004 cases suggests an inverse correlation between dust and tropical cyclone activity that is consistent with the hypothesis of *Dunion and Velden* [2004]. It is possible that the intense activity of the Saharan Air Layer for the 1983 and 1985 cases indicates the presence of an environment less conducive to deep convection and tropical cyclogenesis, whereas the lack of Saharan Air Layer activity in the 1995 and 2004 cases demonstrates the opposite.

[11] Figure 2 shows the time series of annual tropical cyclone days and dust coverage averaged over our entire study region for August 20–September 30 for the years 1982–2005. Dust activity during the 1980s was more intense than during any other period in the record. A 5 to 8–year oscillating behavior is also seen in the dust record, superimposed over a downward trend in dustiness. The early 1980s are characterized by a relatively suppressed period of cyclone activity, with the minimum of tropical cyclone days occurring in 1983. This is followed by several years of increased activity and then another period of decreased activity from 1991–1994. The maximum in tropical cyclone activity is observed in 1995 and followed by a sharp drop during 1997, a strong El Niño year generally associated with reduced tropical storm activity due to the accompanied increase in vertical wind shear across the Atlantic Basin [*Gray*, 1984; *Goldenberg and Shapiro*, 1996; *Landsea et al.*, 1999]. Throughout this paper we are using a July–September averaged Niño 3.4 index to describe ENSO related atmospheric conditions that may be relevant to our analysis. A strong Niño (Niña) event is defined as a three month running mean Niño 3.4 value that is at least 1 degree Celsius above (below) the climatological mean for 1971–2000 (data provided by the Climate Prediction Center, http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). The last 8 years of the record show more consistent, and elevated, tropical cyclone activity, corresponding to some of the trends shown by *Goldenberg et al.* [2001]. A correlation coefficient of −0.53 is observed between the two series, significant at 99% (all significance values are based on the 2–tailed t–score for the correlation coefficient). Furthermore, the correlation between the two time series after their respective trends are removed is only slightly reduced to −0.49 (significant at 98%).

[12] Figure 3 is the standardized (subtracting the mean and dividing by the standard deviation of the respective time series) version of the two data sets and their associated linear trends, with the dust series on an inverse scale. Here, the long–term relationship between observed dustiness and tropical cyclones, and the departure from this covariance during the 1997 El Niño, is clearer. Strong El Niño events also occurred in 1982 and 1987. However, neither of these years clearly show a reduction in tropical cyclone activity. Additionally, we looked at the two strong Niña events that occur in our time series, 1988 and 1998. For both of those years we do see that the tropical cyclone numbers are larger than what we may expect solely based on the dust data. This could be due to the reduction in vertical wind shear across the basin generally associated with Niña events.

[13] The dust and cyclone days observations in 1994 are both nearly one standard deviation below the mean. The lack of a negative correlation for this year could be reflective of a gap in the AVHRR data record of more than 15 days in late September 1994. If we remove the 1994 data points, the correlation between the two time series increases to −0.58 (significant at greater than 99.5%). If we remove

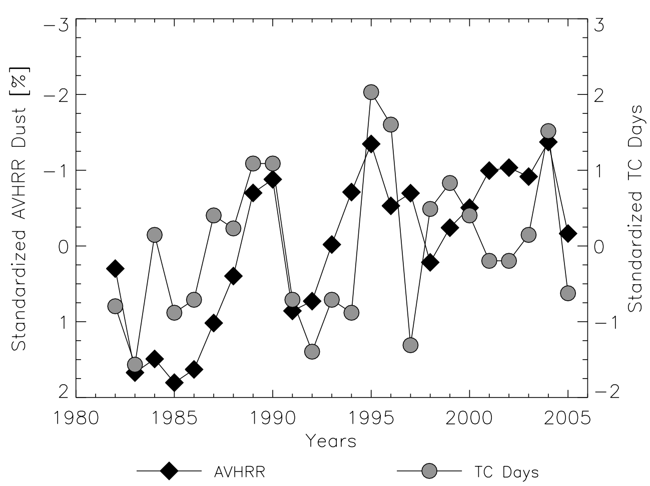

Figure 3. Standardized (subtracting the mean of and dividing by the standard deviation of the respective time series) total tropical cyclone days (gray line and circles) and average dust cover (black line and diamonds) time series, with the dust series on an inverse scale. Otherwise, description of the data is the same as for Figure 2.

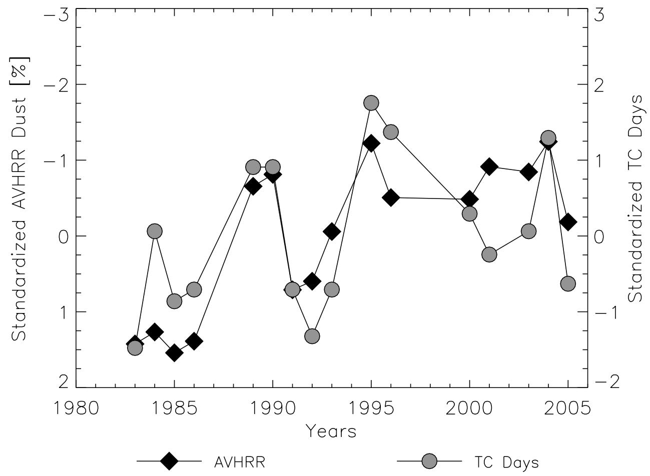

Figure 4. Same description as Figure 3 except that data points from three positive phase (1982, 1987 and 1997), and two negative phase (1998 and 1999) ENSO events, and a year with missing satellite data (1984) are removed. The correlation coefficient between the two time series is 0.71, significant at the 99.9% level.

the Niño years of 1982, 1987, and 1997 this correlation improves to −0.70, and if we also remove the Niña years of 1988 and 1998 the correlation goes to −0.71 (both of which are significant at greater than 99.5%), which can be seen in Figure 4. Additionally, partial correlation analysis of the dust and cyclone days data holding the Niño 3.4 index constant gives a correlation coefficient of −0.60 (also significant at greater than 99.5%).

[14] Sea surface temperature is important in shaping the interannual variability of North Atlantic tropical cyclones [*Goldenberg et al.*, 2001; *Landsea et al.*, 1999]. To account for the role of the ocean's temperature we created two time series of mean August and September sea surface temperature averaged over 0–30N and 15–60W using the Hadley ISST [*Rayner et al.*, 2003] and Reynolds OISST [*Reynolds et al.*, 2002] data sets (Hadley ISST data courtesy of UK Met office Hadley Centre, NOAA OISST data provided by NOAA/OAR/ESRL PSD, http://www.cdc.noaa.gov/). The partial correlation of dust and tropical cyclone days holding the Hadley and then OISST time series constant is −0.37 and −0.51, significant at 92.2% and 98.8%, respectively. However, over the last 25 years regional tropical cyclone activity and sea surface temperature exhibit an upward trend, while dust activity shows a downward one. The partial correlation coefficients of the de-trended time series are both −0.50, significant at 98.5%. Implying that Saharan dust activity can account for variance in the tropical cyclone record that cannot be attributed to ocean temperature. Furthermore, both sea surface temperature records utilize AVHRR data, so it is possible that the presence of dust aerosols over the North Atlantic negatively bias the retrieved ocean temperature [*Rayner et al.*, 2003], resulting in artificially low partial correlation coefficients.

[15] This analysis was repeated using the Accumulated Cyclone Energy (ACE) Index for our region of study and time period (August 20–September 30) over the years of 1982–2004. The ACE index is a wind energy index derived from the Hurricane Best Track Files [*Jarvinen et al.*, 1984], and is defined as the sum of the squares of the maximum sustained surface wind speed (knots) measured every six hours for all named systems while they are at least tropical storm strength (ACE data courtesy Chris Landsea). The ACE time series is also well correlated with our dust cover index, having a correlation coefficient of 0.59 (significant at 99.5%) and a partial correlation coefficient of 0.69 when holding the Niño 3.4 index constant (significant at 99.9%), possibly reflecting the effects of the Saharan Air Layer on cyclone intensity as well as genesis, as suggested by *Dunion and Velden* [2004].

4. Concluding Remarks

[16] Although Figures 2 and 3 show that mean dust coverage and tropical cyclone activity are strongly (inversely) correlated over the tropical North Atlantic, this does not provide conclusive evidence that the dust itself is directly controlling tropical cyclone activity. It has been suggested that a link exists between Sahel precipitation and North Atlantic hurricanes. Here, increases in Sahel precipitation are thought to cause increases in North Atlantic hurricane activity through enhancement of African easterly waves, and reductions in Sahel precipitation and North Atlantic hurricane activity have been tied together through the associated changes in wind shear across the Atlantic basin [*Gray*, 1990; *Landsea and Gray*, 1992]. Therefore, it is possible that if precipitation changes in the Sahel alter West African dust outbreaks, then this variability in rainfall may be the cause of our observed correlations. However, it has been shown that, at least for the summertime months, interannual changes in dustiness over the North Atlantic are related to changes in Sahel precipitation from the previous year and are not strongly correlated with same−year Sahel precipitation events [*Moulin and Chiapello*, 2004].

[17] Additionally, to what extent dust source regions in the Sahel or the Sahara contribute to the overall dust activity seen over the North Atlantic is still debated. For instance, it has recently been shown that fluctuations in the low level jet that sits over the Bodélé Depression (a dry lake bed dust source region in the Sahara) may cause of much of the observed variability in wintertime West African dust activity (at least for the years of maximum and minimum dustiness) [*Washington and Todd*, 2005]. Furthermore, it is unknown which environmental (or possibly anthropogenic) factors are critical in determining the atmospheric dust loading during the peak hurricane season months. Therefore, we propose that new investigation is needed regarding the relative importance of West African dust source regions and the factors that determine their activity, particularly during the North Atlantic hurricane season.

[18] We again suggest that because dust is a good tracer for the Saharan Air Layer, these observed correlations may result from the effect of the Saharan Air Layer acting as a control on cyclone activity in the Tropical Atlantic, consistent with the hypotheses of *Dunion and Velden* [2004]. It is worth noting that the variability in the dust time series may not only reflect variations of the presence of the Saharan Air Layer, but it may also reflect changes in dust loadings within the Saharan Air Layer itself, which could also have important meteorological implications.

[19] While no direct causality has been established here, our analysis suggests the variability in dust (and variability in the presence of the Saharan Air Layer) is strongly linked to changes in North Atlantic tropical cyclone activity. Whether there is a direct or indirect link remains elusive, but at the very least a strong argument is made for new field observations and modeling experiments designed to further explain and understand the observed relationships between the Saharan Air Layer, African dust, and tropical cyclone activity over the North Atlantic.

[20] **Acknowledgments.** The authors would like to thank M. Kulie, N. Mahowald, and G. Narisma for their comments on the manuscript. We are also grateful to the anonymous reviewers for their helpful comments and to Chris Landsea for supplying us with ACE index data. Funding for this research was provided by the NOAA/NESDIS Polar Program and the NOAA/NESDIS/ORA AVHRR Reprocessing Program. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

References

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.

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*(3), 353–365.

Emanuel, K. (2005a), Meteorology—Emanuel replies, *Nature*, *438*(7071), E13.

Emanuel, K. (2005b), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*(7051), 686–688.

Evan, A. T., A. K. Heidinger, and M. J. Pavolonis (2006a), Development of a new over-water advanced very high resolution radiometer dust detection algorithm, *Int. J. Remote Sens.*, *27*(18), 3903–3929.

Evan, A. T., A. K. Heidinger, and P. Knippertz (2006b), Analysis of winter dust activity off the coast of West Africa using a new 24-year over-water advanced very high resolution radiometer satellite dust climatology, *J. Geophys. Res.*, *111*(D12), D12210, doi:10.1029/2005JD006336.

Goldenberg, S. B., and L. J. Shapiro (1996), Physical mechanisms for the association of El Niño and west African rainfall with Atlantic major hurricane activity, *J. Clim.*, *9*(6), 1169–1187.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nunez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: Causes and implications, *Science*, *293*(5529), 474–479.

Gray, W. M. (1984), Atlantic seasonal hurricane frequency: 1. El-Niño and 30-Mb quasi-biennial oscillation influences, *Mon. Weather Rev.*, *112*(9), 1649–1668.

Gray, W. M. (1990), Strong association between West African rainfall and United-States landfall of intense hurricanes, *Science*, *249*(4974), 1251–1256.

Jarvinen, B. R., C. J. Neumann, and M. A. Davis (1984), A tropical cyclone data tape for the North Atlantic Basin, 1886–1983: Contents, limitations, and uses, *NOAA Tech. Memo. NWS NHC 22*, 21 pp., Coral Gables, Fla.

Knutson, T. R., and R. E. Tuleya (2004), Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization, *J. Clim.*, *17*(18), 3477–3495.

Landsea, C. W. (2005), Meteorology—Hurricanes and global warming, *Nature*, *438*(7071), E11–E13.

Landsea, C. W., and W. M. Gray (1992), The strong association between western Sahelian monsoon rainfall and intense Atlantic hurricanes, *J. Clim.*, *5*(5), 435–453.

Landsea, C. W., R. A. Pielke, A. Mestas-Nunez, and J. A. Knaff (1999), Atlantic basin hurricanes: Indices of climatic changes, *Clim. Change*, *42*(1), 89–129.

Moulin, C., and I. Chiapello (2004), Evidence of the control of summer atmospheric transport of African dust over the Atlantic by Sahel sources from TOMS satellites (1979–2000), *Geophys. Res. Lett.*, *31*(2), L02107, doi:10.1029/2003GL018931.

Prospero, J. M., and T. N. Carlson (1972), Vertical and areal distribution of Saharan dust over the western equatorial North Atlantic Ocean, *J. Geophys. Res.*, *77*(27), 5255–5265.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Q. Wang (2002), An improved in situ and satellite SST analysis for climate, *J. Clim.*, *15*(13), 1609–1625.

Trenberth, K. (2005), Uncertainty in hurricanes and global warming, *Science*, *308*(5729), 1753–1754.

Washington, R., and M. C. Todd (2005), Atmospheric controls on mineral dust emission from the Bodele Depression, Chad: The role of the low level jet, *Geophys. Res. Lett.*, *32*(17), L17701, doi:10.1029/2005GL023597.

Webster, P. J., G. J. Holland, J. A. Curry, and H. R. Chang (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, *309*(5742), 1844–1846.

J. Dunion, Hurricane Research Division, 4301 Rickenbacker Causeway, Miami, FL 33149, USA. (jason.dunion@noaa.gov)

A. T. Evan, A. K. Heidinger, and C. S. Velden, Cooperative Institute for Meteorological Satellite Studies, 1215 W Dayton Street, Madison, WI 53706, USA. (atevan@wisc.edu; andrew.heidinger@ssec.wisc.edu; chris.velden@ssec.wisc.edu)

J. Foley, Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, University of Wisconsin-Madison, 1710 University Avenue, Madison, WI 53726, USA. (jfoley@wisc.edu)