2009

Numerical Simulations of the Impacts of the Saharan Air Layer on Atlantic Tropical Cyclone Development

Donglian Sun

George Mason University

K. M. Lau

NASA, Goddard Space Flight Ctr

Menas Kafatos

Chapman University, kafatos@chapman.edu

Z. Boybeyi

George Mason University

G. Leptoukh

George Mason University

See next page for additional authors

Follow this and additional works at: http://digitalcommons.chapman.edu/scs_articles

Part of the [Atmospheric Sciences Commons](#), [Meteorology Commons](#), and the [Oceanography Commons](#)

Recommended Citation

Sun, D., Lau, W.K.M., Kafatos, M., Boybeyi, Z., Leptoukh, G., Yang, C., Yang, R. (2009) Numerical Simulations of the Impacts of the Saharan Air Layer on Atlantic Tropical Cyclone Development, *Journal of Climate* Vol. 22. pg. 6230-6259. doi: 10.1175/2009JCLI2738.1

This Article is brought to you for free and open access by the Science and Technology Faculty Articles and Research at Chapman University Digital Commons. It has been accepted for inclusion in Mathematics, Physics, and Computer Science Faculty Articles and Research by an authorized administrator of Chapman University Digital Commons. For more information, please contact laughtin@chapman.edu.

Numerical Simulations of the Impacts of the Saharan Air Layer on Atlantic Tropical Cyclone Development

Comments

This article was originally published in *Journal of Climate*, volume 22, in 2009. DOI: [10.1175/2009JCLI2738.1](https://doi.org/10.1175/2009JCLI2738.1)

Copyright

© Copyright 2009 American Meteorological Society (AMS). Permission to use figures, tables, and brief excerpts from this work in scientific and educational works is hereby granted provided that the source is acknowledged. Any use of material in this work that is determined to be “fair use” under Section 107 of the U.S. Copyright Act September 2010 Page 2 or that satisfies the conditions specified in Section 108 of the U.S. Copyright Act (17 USC §108, as revised by P.L. 94-553) does not require the AMS’s permission. Republication, systematic reproduction, posting in electronic form, such as on a web site or in a searchable database, or other uses of this material, except as exempted by the above statement, requires written permission or a license from the AMS. Additional details are provided in the AMS Copyright Policy, available on the AMS Web site located at (<http://www.ametsoc.org/>) or from the AMS at 617-227-2425 or copyrights@ametsoc.org.

Authors

Donglian Sun, K. M. Lau, Menas Kafatos, Z. Boybeyi, G. Leptoukh, C. Yang, and Ruixin Yang

Numerical Simulations of the Impacts of the Saharan Air Layer on Atlantic Tropical Cyclone Development

DONGLIAN SUN,* W. K. M. LAU,⁺ MENAS KAFATOS,[#] ZAFER BOYBEYI,*
GREGORY LEPTOUKH,[@] CHAIWEI YANG,* AND RUIXIN YANG*

** Department of Geography and Geoinformation Science, College of Science, George Mason University, Fairfax, Virginia*

⁺ Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland

[#] Chapman University, Orange, California

[@] NASA Goddard Space Flight Center, Greenbelt, Maryland

(Manuscript received 21 July 2008, in final form 10 July 2009)

ABSTRACT

In this study, the role of the Saharan air layer (SAL) is investigated in the development and intensification of tropical cyclones (TCs) via modifying environmental stability and moisture, using multisensor satellite data, long-term TC track and intensity records, dust data, and numerical simulations with a state-of-the-art Weather Research and Forecasting model (WRF). The long-term relationship between dust and Atlantic TC activity shows that dust aerosols are negatively associated with hurricane activity in the Atlantic basin, especially with the major hurricanes in the western Atlantic region. Numerical simulations with the WRF for specific cases during the NASA African Monsoon Multidisciplinary Analyses (NAMMA) experiment show that, when vertical temperature and humidity profiles from the Atmospheric Infrared Sounder (AIRS) were assimilated into the model, detailed features of the warm and dry SAL, including the entrainment of dry air wrapping around the developing vortex, are well simulated. Active tropical disturbances are found along the southern edge of the SAL. The simulations show an example where the dry and warm air of the SAL intruded into the core of a developing cyclone, suppressing convection and causing a spin down of the vortical circulation. The cyclone eventually weakened.

To separate the contributions from the warm temperature and dry air associated with the SAL, two additional simulations were performed, one assimilating only AIRS temperature information (AIRST) and one assimilating only AIRS humidity information (AIRSH) while keeping all other conditions the same. The AIRST experiments show almost the same simulations as the full AIRS assimilation experiments, whereas the AIRSH is close to the non-AIRS simulation. This is likely due to the thermal structure of the SAL leading to low-level temperature inversion and increased stability and vertical wind shear. These analyses suggest that dry air entrainment and the enhanced vertical wind shear may play the direct roles in leading to the TC suppression. On the other hand, the warm SAL temperature may play the indirect effects by enhancing vertical wind shear; increasing evaporative cooling; and initiating mesoscale downdrafts, which bring dry air from the upper troposphere to the lower levels.

1. Introduction

Dust aerosols generally originate over desert regions such as the Sahara, whereas atmospheric transport allows dust to spread far away from its source regions (Prospero and Carlson 1981; Kaufman et al. 2005). In recent years, the importance of African dust has been increasingly recognized for its potential influences on

weather (such as hurricanes) and climate in many regions of the world (Arimoto 2001; Goudie and Middleton 2002; Kaufman et al. 2002). Radiative forcing (e.g., Carlson and Benjamin 1980; d'Almeida 1987; Li et al. 1996, 2004; Miller and Tegen 1999; Ramanathan et al. 2001; Weaver et al. 2002; Christopher and Jones 2007) is recognized as the most important aspect of African dust. These dust outbreaks are associated with an elevated layer of hot and dry air (e.g., Carlson and Prospero 1972; Prospero and Carlson 1972, 1981). Dry air affects tropical clouds and precipitation directly through the thermal structure and indirectly through dry air entrainment (e.g., Mapes and Zuidema 1996; Yoneyama and Parsons

Corresponding author address: Donglian Sun, Room 252, Research Building I, 4400 University Dr., George Mason University, Fairfax, VA 22030.
E-mail: dsun@gmu.edu

1999; Zhang and Chou 1999; Tompkins 2001). Dry air outbreaks produce substantial effects on convection and precipitation in the tropical Atlantic region (Zhang and Pennington 2004), especially in the Atlantic intertropical convergence zone (ITCZ), and on the formation and intensification of tropical cyclones (Dunion and Velden 2004).

Tropical cyclones in the Atlantic basin often develop from mesoscale convective systems (MCSs) embedded within African easterly waves (AEWs) that develop over West Africa. Previous studies have shown that the Atlantic basin major hurricane (MH) activity is associated with western Sahelian monsoon rainfall and that negative Sahelian rainfall anomalies or Sahel droughts are associated with suppressed Atlantic basin tropical cyclone (TC) activity (Goldenberg and Shapiro 1996). Goldenberg and Shapiro (1996) explained that drought induced stronger vertical wind shear and therefore inhibited TC development.

Although rainfall in the Sahel is found to be highly anticorrelated with African dust (Prospero and Lamb 2003), Evan et al. (2006) examined 25 yr of Advanced Very High Resolution Radiometer (AVHRR) aerosol optical depth (AOD) and TC best-track data and found that TC activity in the North Atlantic (NATL) is in fact anticorrelated with African dust outbreaks. Recently, Wu et al. (2006) analyzed the effects of the Saharan air layer (SAL) on TC activity by incorporating the Atmospheric Infrared Sounder (AIRS; on the *Aqua* satellite) measurements into the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5). They found that the SAL may have delayed the formation of Hurricane Isabel and inhibited the development of another tropical disturbance that was following it. Dunion and Velden (2004) have found that the dry SAL can suppress Atlantic tropical cyclone activity by increasing the vertical wind shear and stabilizing the environment at low atmospheric levels. They also suggest that convectively driven downdrafts caused by the SAL dry air can be an important inhibiting factor for TCs. What remains uncertain is the specific role of the SAL in terms of the impact of its midlevel warm temperature and dry air in inhibiting individual AEWs and TCs. Do the environmental stability and moisture play key roles in determining whether disturbances develop or fail to develop into tropical cyclones? Identifying the relative impact of these characteristics of the SAL on a specific TC is a real challenge.

In this study, we will further investigate the impacts of the SAL on the formation and development of TCs in the Atlantic basin by combining long-term analysis, satellite observations, and numerical model simulations.

Data and methodology are described in section 2. Observation analyses and model simulation results are presented in sections 3–6. Section 7 provides summary and discussions.

2. Data used

The data used and their sources are described in the following:

- Moderate Resolution Imaging Spectroradiometer (MODIS) daytime AOD at 550 nm fine mode fraction, and Angstrom exponent from 470 and 660 nm (MOD08-D3), obtained from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Data and Information Services Center (DISC) Giovanni (Acker and Leptoukh 2007).
- AIRS daily vertical temperature and moisture profiles, from the NASA GSFC DISC.
- Tropical cyclone data, obtained from the National Hurricane Center (NHC) best-track hurricane dataset (HURDAT; available online at <http://www.nhc.noaa.gov/pastall.shtml>).
- Dust concentration at the Barbados sampling station (13°10'N, 50°30'W), which provides the most extensive long-term record with aerosol measurements starting from 1965. This is the only available long-term dust record that shows high correlation with the dust outbreaks from North Africa over the North Atlantic Ocean (Prospero and Lamb 2003).
- Aerosol Index (AI) data with $1^\circ \times 1.25^\circ$ resolution from the Ozone Monitoring Instrument (OMI) from the NASA GSFC (available online at http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html).

3. Distributions of Atlantic tropical cyclogenesis locations

The dust AOD is separated from total aerosols based on the methodology proposed by Kaufman et al. (2005). As shown in Fig. 1, TCs are found to develop outside the borders of heavy dusty regions (DR; dust AOD > 0.4), including a southern region over the tropical north Atlantic area (10°–20°N, 80°–15°W), which is also the traditionally defined the main development region (MDR). This may be because the dry SAL associated with heavy dust enhances convection along its southern neighboring region, in the vicinity of the ITCZ (Chen 1985). The MDR is a well-known region for TC formation. There is certainly some enhancement of convection along the southern edge of the SAL, because drier, denser SAL air lifts the moister, less dense tropical air out ahead of it. However, the main reason why TCs are found across the

FIG. 1. The initial locations of tropical cyclones in the Atlantic basin for the period from 1982 to 2006 overlapped with the August–October (ASO) mean dust AOD from the MODIS for the period from 2000 to 2006.

MDR region (south of the SAL) is that this is the main east–west highway for MCSs that are embedded in AEWs moving off the African coast. One could argue that, without the SAL to the north, more TCs might form north of the MDR in the eastern NATL.

In addition to the MDR, tropical cyclones are also found to form over the western North Atlantic Region (WAR; 20° – 35° N, 98° – 50° W), which is to the west of the dusty region and includes the U.S. eastern coast, or western North Atlantic (WNA; 20° – 35° N, 80° – 50° W), and the Gulf of Mexico (GOM; 20° – 30° N, 100° – 80° W). Note that Fig. 1 shows the initial locations of TCs and indicates that a significant number of TCs develop not only in the MDR but also in the WAR.

The DR is more or less like a tongue shape. It should follow the dust corridor (10° – 30° N, 15° – 65° W) as in the SAL conceptual model (Prospero and Carlson 1981), the latitude range should be between 10° – 30° N, and the eastern boundary should be the African coast, whereas the west boundary should depend on how far the dust can be transported to the western Atlantic Ocean by the low–middle-level easterly winds. To recapitulate, within the DR and over the eastern Atlantic, the SAL dry air often passing through this region is unfavorable for TC formation. Moreover, there are several other factors that contribute to the lack of TC activity in this region; this area is fairly far north of the typical tracks of MCSs (embedded in AEWs) that move off the coast, sea surface temperatures (SSTs) in this region are relatively low, and the wind shear is usually high because of the westward extension of the African easterly jet (AEJ) that often flows over this region during the summer. Relatively moist air in the WAR resulting from less dust loading and the effects of the warm ocean current, the Gulf Stream, as well as in the MDR (Sun et al. 2008),

forms the Atlantic warm pool (AWP). The AWP is a large body of warm water ($>28.5^{\circ}\text{C}$), appears during summer and fall (Wang and Lee 2007), and provides favorable conditions for TC formation and intensification; therefore, most TCs are found to form and intensify in the MDR and WAR. It has been found that the size of the AWP might be related to Atlantic hurricane activity (Wang et al. 2006).

4. Long-term relationship between dust and Atlantic TC activity

It has been shown (Carlson and Prospero 1972; Dunion and Velden 2004) that SAL activity tends to peak in the early summer and decrease through the late summer/early fall. Table 1 shows the correlation coefficients between the Barbados dust concentrations with four sets of storm measurements for five TC stages. In Table 1, the total TC days is defined as the total number of days in which a given TC category is found within the region. Duration is the TC days divided by TC number. Accumulated cyclone energy (ACE) is the sum of the square of the maximum wind speed for each 6-h period of all specified TC categories. The ACE reflects the integration of TC number, duration, and intensity during a given hurricane season. TC intensity is defined as the ACE divided by TC days: tropical storm only (TS); hurricane only (HR); weak hurricane (WHR; categories 1 and 2); major hurricane (MHR; categories 3, 4, and 5); and all, including TS and HR (ALL). Lau and Kim (2006) found that the Barbados dust data from June–September (JJAS) are better correlated with TC activity. The period 1980–2004 was used to avoid the trend in Barbados dust observations, because during this period the dust amount has no significant increasing or decreasing trend.

TABLE 1. Correlations of Barbados dust concentration during JJAS with four sets of storm measurements: total TC frequency, duration, ACE, and intensity. The number in the parenthesis shows the case number for each category. Note that the sum of WHR and MHR may not be equal to the total HR number, because some MHR may develop from WHR.

Barbados dust (JJAS 1980–2004)	MDR (10°–20°N, 80°–15°W)	WAR (20°–35°N, 98°–50°W)
TC frequency		
TS	0.1812 (62)	–0.1412 (203)
HR	–0.4617 (138)*	–0.2796 (326)
WHR	–0.4617 (119)*	–0.2298 (185)
MHR	–0.1750 (19)	–0.3610 (141)
ALL	–0.3060 (200)	–0.1593 (529)
TC duration		
TS	–0.0414	–0.1156
HR	–0.6206*	–0.1130
WHR	–0.6292*	0.0087
MHR	–0.4437*	–0.5028*
ALL	–0.5275*	–0.2876
ACE		
TS	0.0923	–0.1736
HR	–0.4837*	–0.3522
WHR	–0.5194*	–0.1654
MHR	–0.4961*	–0.4999*
ALL	–0.4486*	–0.3440
TC intensity		
TS	–0.1045	0.0892
HR	–0.5280*	–0.3762
WHR	–0.6017*	–0.0564
MHR	–0.4946*	–0.3662
ALL	–0.4401*	–0.4127*

* Correlations exceeding the 95% confidence level.

The negative relationship between dust and hurricanes is stronger than those between dust and tropical storms. Over the MDR, dust affects all the measurements of hurricanes, including the number of occurrence, duration, intensity, and hence their integration (ACE). Similarly, the negative correlation between dust and the duration of major hurricane stages is stronger than those between dust and the duration of other (tropical storm and weak hurricane) stages. One hypothesis might be that SAL associated with dust can suppress deep convection (Wong and Dessler 2005) and hence inhibit TC intensification, playing a role in preventing TCs from becoming more intense (Karyampudi and Carlson 1988; Kamineni et al. 2006). We will further investigate this issue from the case studies.

5. The SAL from satellite sounding observations

Because dust aerosols absorb solar radiation in the atmosphere, those aerosols can heat the atmosphere in the dust layer because of their absorbing characteristics (Ramanathan et al. 2001; Dunion and Velden 2004; Sun

et al. 2008). This increase in heating is in addition to the hot air that originates from the desert upstream. As shown by Wu et al. (2006), the dry and warm air associated with the SAL can be identified from the AIRS observations. The AIRS vertical temperature profile data show that air temperature in the low–middle atmosphere (e.g., 850 hPa) is 1–4 K higher in the heavy dust area (dust AOD > 0.4) than in the low-dust regions (MDR and WAR; Fig. 2a). The presence of warm SAL air associated with dust aerosols that frequently move through the DR may explain some of the relatively warmer temperatures that are noted here, because the air in SAL air masses is quite warm compared to the background environment, especially in the eastern NATL. Because of its origins from the hot Sahara, the SAL is always warmer than the surrounding marine air, especially in an area like the DR that is so close to the Sahara (less time for longwave cooling to occur). Regardless of whether dust induces radiative forcing, one would expect the DR to be warmer than the MDR and WAR because of the presence of warm SAL outbreaks that move through this area on a regular basis. Meanwhile, dry air in the low–middle atmosphere, with relative humidity (RH) at 700 hPa or RH₇₀₀ less than 50%, coincides with the large dust AOD (>0.4) region, whereas moist air (RH₇₀₀ > 50%) exist over the MDR and WNA (Fig. 2b), where most TCs form and develop.

The meridional and zonal cross sections of RH show that dry air with RH less than 40% exists in the lower troposphere over the DR (Fig. 3). Moist air with RH greater than 60% is found in the low–middle troposphere (1000–500 hPa) along the southern (MDR; Fig. 3a) and western (WNA) regions (Fig. 3b).

The stability K index (KI) can be represented as

$$KI = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700}), \quad (1)$$

where T is air temperature and T_d is dewpoint used to express humidity. The K index can be used as an indicator of potential convection. It increases with decreasing static stability between 850 and 500 hPa, increasing moisture at 850 hPa, and decreasing temperature–dewpoint difference or increasing relative humidity at 700 hPa.

According to the K index theory, the dry air layer in the low–middle-level atmosphere over the dusty region will reduce the potential convection, and therefore inhibits TC formation. While along its southern (MDR) and western (WAR) regions, the increasing moisture at 850 hPa and high relative humidity at 700 hPa (RH₇₀₀) enhances convection, which is beneficial for TC development. Hoyos et al. (2006) showed that the 850-hPa specific humidity over 5°–25°N, 90°W–20°E (MDR and partial WAR) may be linked to the number of intense

FIG. 2. The JJAS (a) averaged air temperature (K) at 850 hPa and (b) SST ($^{\circ}$ F) in 2005 as obtained from the AIRS daytime vertical temperature profiles.

(category 4 and 5) hurricanes. Wu (2007) indicated that the 850-hPa humidity averaged over 10° – 20° N, 30° – 80° W, which is similar to the MDR, is correlated with the mean peak hurricane intensity.

Following this observational analysis, modeling experiments are performed to further explain and understand the influences of dust aerosols on Atlantic hurricane activity.

FIG. 3. (a) Meridional cross section of RH (%) as averaged along 40°–20°W (a), and (b) zonal cross section of RH (%) as averaged along 25°–35°N from the AIRS profile data during the JJAS period in 2006.

6. Model simulated SAL impacts on specific Atlantic TC case

a. TC case selection

An ideal case for simulating the SAL impacts on TC activity is a specific TC that formed and developed

at the same time as dust outbreaks. The AI from the OMI measurements can help distinguish absorbing aerosols, such as dust and smoke, from scattering type aerosols, such as sulfates. Positive AI values are associated with absorbing aerosols. Chiapello et al. (1999, 2005) showed that AI values were highly correlated

with dust measurements made at ground level at sites in the tropical North Atlantic and with AOD measured in dusty regions of North Africa, whereas smoke usually originates from Southern Africa, so the OMI AI images can be used to identify the dust outbreaks from North Africa.

The OMI AI images show that, during the period from 28 August to 9 September 2006, there were two SAL outbreaks: one that originated from Africa on 28 August and the other that emerged from the coast of Africa late on 4 September. Meanwhile, Hurricane Florence was found to form and develop from an AEW that was found initially to the south of these large SAL outbreaks. Figure 4 shows the dust outbreak process during the formation and development period of this storm (4–9 September). On 4 September 2006, dust aerosols spread to the central Atlantic and Caribbean from their source region of western Africa, with wave-like structures oriented in the northeast–southwest direction, and reached west to 60°W and south to 10°N. On 5 September 2006, there was another dust outbreak beginning to emerge from the western African coast. From 6 to 7 September, the northern branch of dust became weak and disappeared, whereas the southern branch spread southwesterly up to 10°N, 40°W. It then became weaker on 8 and 9 September 2006.

Florence developed from an AEW in the tropical Atlantic Ocean on 3 September 2006. When it first encountered the dry SAL, its development slowed down. Because of unfavorable conditions, the system failed to organize initially; as a result, the storm grew to an unusually large size (Beven 2006). It continued its motion to the west-northwest while tracking around the southern periphery of a deep SAL to its north. Though deep convection was restricted from the core and remained strong near the outer periphery of the SAL, the overall organization continued to steadily increase and intensified into Tropical Storm Florence on 5 September. After several days, Florence encountered an area of lesser wind shear (near 27.10°N, 65.20°W) and intensified into a hurricane on 10 September. Because Florence formed and developed almost at the same time with the dust and SAL outbreaks, interactions between this TC and the SAL may be operative, so we choose this Florence case to perform numerical experiments with a state-of-the-art Weather Research and Forecasting model (WRF).

b. WRF simulations

1) WITH AIRS DATA ASSIMILATION

To understand the SAL impacts on the formation and development of TCs in the Atlantic basin, we performed

data assimilation and numerical simulation experiments for the Hurricane Florence with an Advanced Research WRF (ARW-WRF, version 3.0; Dudhia 2004; Skamarock et al. 2005) and its three-dimensional variational data assimilation (3DVAR) system (Barker et al. 2004). Numerical experiments with the assimilation of AIRS vertical temperature and humidity profiles and surface skin temperature data are performed for the Hurricane Florence case from 4 to 9 September 2006 covering its formation and development stages. The integration period of 120 h includes the formation and development of Hurricane Florence and the evolution of a tropical disturbance to the east. A single domain is used with (x, y) dimensions of 652×290 and horizontal grid interval ($\Delta x, \Delta y$) of 14 km covering an area from 4° to 38°N and –94° to –6°W. There are 28 vertical levels with higher resolution in the planetary boundary layer (PBL). The outputs from the Global Forecast System (GFS; 1° grid interval) from the National Centers for Environmental Prediction (NCEP) are used to provide the initial and boundary conditions. No bogus vortex is included in the initial conditions. The Noah land surface model (LSM), which includes four soil layers, is coupled with the atmospheric model. Model physics options include the Kain–Fritsch cumulus parameterization (Kain and Fritsch 1990, 1993), the Medium-Range Forecast (MRF) PBL scheme (Hong and Pan 1996), the RRTM (Rapid Radiative Transfer Model) longwave radiation scheme (Mlawer et al. 1997), the Goddard shortwave (Chou and Suarez 1994), and microphysics based on Lin et al. (1983), in which six classes of hydrometeors are included: water vapor, cloud water, rain, cloud ice, snow, and graupel.

In the control experiment, the AIRS vertical profiles are used as the observations over the Atlantic Ocean region that is largely devoid of conventional data. The AIRS level 3 version 5 (V5) daily temperature and humidity profile data for 4 September 2006 are assimilated into the WRF through the 3DVAR scheme. The AIRS is capable of measuring the atmospheric temperature in the troposphere with radiosonde accuracies of 1 K over 1-km-thick layers under both clear and partial cloudy conditions, whereas the accuracy of the derived moisture profiles exceeds that obtained by radiosondes. The AIRS V5 data are used, because significant improvements in the AIRS V5 data include the ability to generate accurate case-by-case, level-by-level error estimates for the atmospheric temperature and humidity profiles. These error estimates are used for quality control of the retrieved products. Based on the error estimate thresholds, each profile is assigned a characteristic pressure, down to which the profile is characterized as good for use for data assimilation purposes. Only the highest-quality data with a quality control (QC) flag of 0,

FIG. 4. OMI AI images show western African dust outbreaks from 4 to 9 Sep 2006.

indicating that data products individually meet our accuracy requirements and may be used for data assimilation, are assimilated.

The thermodynamic effect of the SAL is simulated through the assimilation of the AIRS temperature and humidity profiles. For comparison, a second experiment is performed with all other conditions the same but without the assimilation of the AIRS data. For the second case, information on the SAL is included only through the initial and lateral conditions from the GFS analysis.

As shown in Fig. 5, with the assimilation of AIRS vertical temperature and humidity profile, the warm (temperature at 850 hPa (T_{850}) warmer than 19°C; in orange and red) and dry (with relative humidity at 700 hPa (RH_{700}) lower than 50%) SAL, which originated from the hot western Africa and always associated with the easterly or northeasterly winds, can be identified. After the 36-h simulations valid at 1200 UTC 5 September 2006, there were three tropical disturbances, including Tropical Depression Florence and another two tropical disturbances located to the west and the east of Florence, formed from AEWs, which were positioned south of a large SAL outbreak (Fig. 5a), in the vicinity of the ITCZ (Chen 1985). As the ITCZ migrates north from the equator during the Northern Hemi-

sphere's summer season, it acquires increasing vorticity. Additionally, the strong solar heating over the Sahara desert in summer increases the baroclinicity and strengthens the AEJ, enhancing barotropic instability south of the AEJ. Both processes are favorable to make the formation of tropical cyclones within this zone more possible. After the 60-h forecast valid at 1200 UTC 6 September 2006, the tropical disturbance at the west side of Florence merged with Florence, whereas the tropical disturbance at the east side of Florence developed slightly and formed a weak, closed low pressure center (1012 hPa; Fig. 5b). At the same time, consistent with the southward movement of an African dust outbreak (Fig. 4), warm and dry SAL air approached this tropical disturbance; when the warm and dry air intruded into this tropical disturbance to the east of Florence at 1200 UTC 7 September 2006 after the 84-h simulations (Fig. 6a), it soon began to weaken and finally disappeared at the time of 0000 UTC 8 September 2006, after the 96-h forecast, and therefore failed to develop into a named tropical cyclone (Fig. 6b).

2) CONTRASTING THE WRF SIMULATIONS WITH AND WITHOUT AIRS DATA ASSIMILATION

For the WRF simulations without AIRS data assimilation, compared to the same time with AIRS data assimilation (Fig. 6), Fig. 7 shows that the warm and dry

FIG. 5. SLP (black contours), surface (10 m) wind barbs, 850-hPa temperature (shaded), and 700-hPa RH (white contours) from the WRF simulations with assimilation of AIRS data for (a) 36-h forecast valid at 1200 UTC 5 Sep 2006 and (b) 60-h forecast valid at 1200 UTC 6 Sep 2006.

SAL extended less to the west; there was still a tropical disturbance developing to the east of Florence after the 84-h simulations valid at 1200 UTC 7 September 2006 (Fig. 7a). Even after the 96-h simulation valid at 0000 UTC 9 September 2006, there was still a weak tropical disturbance to the east of Florence (Fig. 7b), whereas this tropical disturbance disappeared for simulations with AIRS data assimilation (Fig. 6a). However, with the weakening of dust outbreaks on 9 September 2006, the area of the warm air of the SAL shrank. Tropical Depression Florence developed into a tropical storm with a clear warm core (Fig. 7b) as it recurved to the northwest and separated far away from the suppressing influence of the southward-moving SAL; the moist environment around Florence acts like a “pouch” that moves along the AEWs and protects the developing

storm from the dry and warm SAL that would inhibit the storm’s development. Later, Florence intensified into a hurricane.

Figures 8–10, show the comparisons of 850-hPa relative humidity (RH_{850} ; shaded, the white color shows dry area with RH_{850} less than 60%), temperature (red contours), and geopotential height (black contours) and wind barbs for 60-, 84-, and 96-h forecasts. The simulated dry (shown as white) and warm air ($T_{850} > 19^{\circ}\text{C}$) of the SAL was always associated with easterly or northeasterly winds. The simulated warm and dry air extended farther to the west in the experiments with AIRS data assimilation than in those without assimilation. Tropical Storm Florence (with warm core) and another tropical disturbance developed at the south of the SAL and ahead of a trough with Saharan dry air to the north.

FIG. 6. SLP (black contours), surface (10 m) wind bars, 850-hPa temperature (shaded), and 700-hPa RH (white contours) from the WRF simulations with assimilation of AIRS data for (a) 84-h forecast valid at 1200 UTC 7 Sep 2006 and (b) 96-h forecast valid at 0000 UTC 8 Sep 2006.

The upward motion ahead of the trough is beneficial to the TC development. At the 60-h forecast valid at 1200 UTC 6 September 2006 (Fig. 8), for simulations with AIRS data assimilation, the warm air ($T_{850} > 19^{\circ}\text{C}$) spread ahead of the dry air tongue and intruded into the tropical disturbance at the eastern side of Florence (Fig. 8a); for simulations without AIRS data assimilation, the tropical disturbance at the east side of Florence already formed a warm core and the warm air did not

intrude into the core. At the time of the 84-h simulations valid at 1200 UTC 7 September, this tropical disturbance already became weakened. With the farther southward approach of one SAL outbreak, in the experiment with AIRS data assimilation, the simulated warm air further intruded into this tropical disturbance, it then became weakened and disorganized (Fig. 9), and it later disappeared and failed to develop into a named tropical cyclone (Fig. 10a); in the experiment without AIRS data

FIG. 7. SLP (black contours), surface (10 m) wind barbs, 850-hPa temperature (shaded), and 700-hPa RH (white contours) from the WRF simulations without assimilation of AIRS data for (a) 84-h forecast valid at 1200 UTC 7 Sep 2006 and (b) 96-h forecast valid at 0000 UTC 8 Sep 2006.

assimilation, the dry air did not intrude into this tropical disturbance, and it survived until the 96-h simulations (Fig. 10b). The control experiment with AIRS data assimilations show that, when warm and dry SAL intrude into a tropical disturbance, it causes the tropical disturbance to weaken and fail to develop into a named tropical cyclone. These numerical experiments further confirm that the effect of the SAL is to suppress the development of TCs, which is consistent with the ob-

servations shown by Dunion and Velden (2004). In the following sections, we will give more detailed analysis and explanations.

Figure 11 compares the vertical cross section of temperature and relative humidity differences between WRF 60-h simulations with (AIRS) and without AIRS (No-AIRS) data assimilations. Because absorbing aerosols, such as dust, can increase temperatures in certain portions of the atmosphere because of their absorbing

FIG. 8. 850-hPa height (black contours), wind barbs, temperature (red lines), and RH (shaded) from the WRF simulations (a) with and (b) without assimilation of AIRS data, for 60-h forecast valid at 1200 UTC 6 Sep 2006.

characteristics (Ramanathan et al. 2001), the temperature difference between AIRS and No-AIRS simulations (Fig. 11a) reveals warming in the middle troposphere (850–500 hPa) but cooling near the surface and upper atmosphere in the east of 60°W, whereas humidity differences between AIRS and No-AIRS simulations (Fig. 11b) suggest significant drying in the middle troposphere (850–500 hPa) to the east of 65°W for simulations with AIRS data assimilation. This is the typical characteristics of the SAL (Dunion and Marron 2008) and agrees with intra-annual analysis (Sun et al. 2008). The cross section of 20°N is selected, because, as shown in Fig. 8, warm and dry air (SAL) at the middle atmosphere spread along 20°N and between 55° and 45°W, right to the north quadrant of tropical storm Florence, where the maximum wind speed and pre-

cipitation usually happen, so the SAL effects may be more evident there.

c. SAL effects on downdrafts

As indicated in many previous studies (Leary and Houze 1979; Brown 1979), evaporative and melting cooling could induce mesoscale downdrafts beneath anvil regions. Evaporative and melting cooling can create negative buoyancy and initiate mesoscale downdrafts. Zhu and Zhang (2006) found that the cooling effects of cloud water and rainwater evaporation is the same or even larger than that of melting of snow, ice, and graupel in retarding the development of hurricanes. Does the warm SAL have any effects to increase evaporative and melting cooling and downdrafts and therefore inhibit hurricane development?

FIG. 9. 850-hPa height (black contours), wind barbs, temperature (red lines), and RH (shaded) from the WRF simulations (a) with and (b) without assimilation of AIRS data, for 84-h forecast valid at 1200 UTC 7 Sep 2006.

Figure 12 shows east–west cross sections of potential temperature (θ , shaded) and u – w wind vectors and difference fields between WRF simulations with and without AIRS data assimilation though the hurricane center at the 72-h simulation. Warm cores can be clearly identified from both of the No-AIRS and AIRS simulations, whereas the warm core is larger and the potential temperature around the TC center from the AIRS simulation is warmer than those from the No-AIRS simulation. The downdraft and the resulting cold pool at low levels (below 800 hPa) at the western side of the storm center from the AIRS simulation are stronger than those from the No-AIRS simulation (Fig. 12c). As shown in Figs. 12c,d, corresponding to the increased downward motion from the AIRS simulation, potential temperature be-

comes warmer and humidity decreases in the middle to upper atmosphere (800–200 hPa). This is because air that sinks will warm adiabatically, whereas downdrafts will transport dry air from the upper troposphere downward.

Because downdrafts transport cold air from the upper troposphere downward to the low levels (below 800 hPa) and produce some cold pools (i.e., lower potential temperature area) near the surface, Fig. 13 shows clearly that the θ at 900 hPa (θ_{900}) at the western side of the storm center are much lower from the AIRS simulation, forming a surface cold pool with dry air, as compared to those from the No-AIRS simulations. Meanwhile, the dry air tongue at the middle atmosphere, as indicated by low relative humidity at 700 hPa, can also be found at the

FIG. 10. 850-hPa height (black contours), wind barbs, temperature (red lines), and RH (shaded) from the WRF simulations (a) with and (b) without assimilation of AIRS data, for 96-h forecast valid at 0000 UTC 8 Sep 2006.

western side of the storm center from the AIRS simulation (Fig. 13b). The modeled TC intensity is therefore found to be weaker with the minimum center pressure of 997 hPa from the AIRS simulation, as compared to 994 hPa from the No-AIRS simulation.

d. Comparisons with simulations assimilating temperature or humidity information separately

From the previously described simulations, we can see that, for SAL outbreaks, warm temperature and dry air were always associated with each other. To isolate their specific roles, we performed two additional simulations, one assimilating only AIRS temperature profile (AIRST) and one assimilating only AIRS humidity profile (AIRSH), and kept all other conditions the same as simulations without AIRS (No-AIRS) and assim-

ilating both AIRS temperature and humidity profiles (AIRS).

As shown in Fig. 14a, temperature at midlevel (i.e., T_{700}) area averaged over the $1000 \text{ km} \times 1000 \text{ km}$ of the storm center from the AIRS simulation is warmer than that from the No-AIRS simulation before the 84-h mark. As expected, for temperature fields, the temperature-only assimilation (AIRST) is close to the full AIRS simulations (AIRS), whereas the humidity-only assimilation (AIRSH) is close to the No-AIRS simulation. However, for the humidity fields, it is not the AIRS humidity assimilation (AIRSH) but the temperature-only assimilation (AIRST) that is the closest to the full AIRS assimilation experiment. The relative humidity values at 700 hPa (RH_{700}) averaged over the TC center show significant drying in the AIRS and AIRST experiments until

FIG. 11. Cross section (20°N) of (a) temperature and (b) RH differences between WRF simulations with and without AIRS data assimilation, for 60-h forecast valid at 1200 UTC 6 Sep 2006.

the 72-h integrations. Our results indicate that the warm temperature may lead to the dry air, because the thermal structure of the SAL with warm air aloft and cool marine air beneath is critical in determining the dynamics of the developing cyclone. Such a structure will lead to increased stability, reduce the upward transport of moisture

from the marine boundary layer, and hence cause the dry air. The resulted decrease in the moisture exchange or latent heat flux between atmosphere and ocean will also impede the development of the cyclone (Kafatos et al. 2006). On the other hand, from the discussion in section 6c, the warm SAL temperature may increase precipitation

FIG. 12. Cross sections (20°N) of $(u, 100 \times w)$ vectors and potential temperature from the WRF simulations (a) with and (b) without AIRS assimilation; (c) $(u, 100 \times w)$ difference vectors and potential temperature difference; and (d) relative humidity difference (shaded) and vertical velocity ($100 \times w$) difference (contour) between WRF simulations with and without AIRS data assimilation for 72-h forecast valid at 0600 UTC 7 Sep 2006.

evaporation and therefore induce evaporative cooling (Figs. 12, 13) and downdrafts (Figs. 12, 13), which bring dry air from the upper atmosphere to lower levels. The water vapor mixing ratio indicates that even the low-middle-level air from the AIRSH simulation is not as dry as that from the AIRST simulation. Dunion and Marron (2008) suggest that SAL is often very dry at midlevels. If this dry air is entrained into the TC circulation, it leads to enhanced downdrafts driven by evaporating precipitation. Our results suggest that the dry air may be induced by the SAL warm temperature, which may increase evaporative cooling and enhance downdrafts transporting dry air from the upper atmosphere downward.

The vertical wind shear, as calculated as the wind speed difference between 200 and 850 hPa ($|V|_{200} - |V|_{850}$; averaged over the area of $1000 \text{ km} \times 1000 \text{ km}$ around the storm center), shows increases for the AIRS

and AIRST experiments during the entire 120-h integrations (Fig. 15); this may be because warmer temperatures at the middle atmosphere over the heavy dusty region (Fig. 2) from the WRF simulations, with the full AIRS or AIRS temperature assimilations, increased the meridional temperature gradient. A stronger meridional temperature contrast across the tropical Atlantic associated with the SAL warm temperature enhances the baroclinicity, the easterly thermal winds, and therefore the midtropospheric easterly jet. The associated enhanced wind shear is unfavorable for hurricane development (Dunion and Velden 2004; Emanuel et al. 2004). However, our simulated hurricane intensity seems more coincident with the variations of K index, an indicator of potential convection, which shows a decrease, indicating a more convective stable condition from the AIRS and AIRST experiments before the 72-h

FIG. 13. Horizontal spatial distributions of potential temperature at 900 hPa (shaded), RH at 700 hPa (red contour), and surface wind barbs from the WRF simulations (a) without and (b) with AIRS assimilation for 72-h forecast valid at 0600 UTC 7 Sep 2006.

integrations (Fig. 16b). Meanwhile, it is found that changes in the K index are consistent with the humidity fields (Fig. 15b). Dunion and Velden (2004) suggest that SAL is comparatively warm, leading to an inversion at the interface between the maritime boundary layer and the SAL. The associated enhanced vertical stability hinders

convective developments, which could weaken TCs. However, our results indicate that the enhanced stability or reduced instability, as indicated by the K index here, is mainly linked to dry air. The correlations between K index and humidity (RH_{700}) are all above 0.95 and significant at 0.01 levels, whereas the correlations

FIG. 14. The time series of 700-hPa (a) T_{700} and (b) RH_{700} averaged within 1000 km of the TC center for four WRF experiments: No-AIRS, AIRS, AIRST, and AIRSH.

between the K index and temperature (T_{700}) are either insignificant or much smaller (-0.62).

Figure 16 compares storm intensity forecasts in terms of the minimum sea level pressure (SLP; Fig. 16a) and maximum wind speed (Fig. 16b) along the Florence track from the observations (NHC best-track data), WRF simulations with (AIRS) and without AIRS (No-AIRS) data assimilations, and two additional sensitive experiments (AIRST and AIRSH). The minimum SLP and maximum wind speed from the control experiments with the AIRS or the AIRST experiments show a simulated weaker storm than the No-AIRS or the AIRSH experiments. The simulated intensity from the AIRS and AIRST experiments are very close to the observations from the NHC best-track data for the 72-h forecast. This means that the memory for model initialization with AIRS data assimilations is about three days. However, with the assimilation of full AIRS or AIRS temperature information, when surrounded by warm and dry SAL air, Florence can still intensify. As shown in Figs. 8–10, the moist environment around Florence acts like a “marsupial” that protects Hurricane Florence from the dry and warm SAL that would inhibit the storm’s development. However, our results in Figs. 12–14

FIG. 15. The time series of (a) vertical wind shear and (b) KI averaged within 1000 km of the TC center for four WRF experiments: No-AIRS, AIRS, AIRST, and AIRSH.

show a warmer, drier, and higher wind shear; lower K index; shallower central pressure; and weaker wind for the AIRS or AIRST simulations, reflecting the weaker Florence in the AIRS or AIRST simulations than in the No-AIRS or AIRSH experiments. This means that, without the impacts of the SAL air, Florence could further intensify. These experiments suggest that the SAL’s impacts are indeed negative. The model simulated negative effects of warm SAL air to the development of a tropical cyclone/hurricane further confirm the long-term climate data analysis described in section 4.

In all simulations, the vertical wind shear generally decreases with time and corresponds to the slow intensification of the tropical cyclone during this period. Meanwhile, with the decrease of the K index and the increase of the vertical wind shear from the AIRS and AIRST experiments, the simulated storm intensities also became weaker and closer to the observations. Because the K index is highly correlated with the RH_{700} , the dry air is directly linked to the reduced parcel instability or potential convection. Hence, dry

FIG. 16. The time series of (a) minimum SLP at storm center and (b) maximum 10-m wind speed from the observation (NHC best track), and four WRF experiments: No-AIRS, AIRS, AIRST, and AIRSH.

air entrainment and enhanced vertical wind shear are likely more direct and crucial players in the suppression of the TC development. On the other hand, the dry air and the increased vertical wind shear from the AIRS and AIRST simulations may result from the SAL warm temperature, which may be the root cause or fundamental factor. This is why the AIRST experiment has almost the same performance as the full AIRS data assimilation. The thermal structure of the SAL may play the indirect effects in the suppression of the TC intensification, whereas the dry air and enhanced vertical wind shear are more likely the direct players.

7. Summary and discussion

In this study, multisensor satellite data have been used to analyze the characteristics of African dust aerosols and the midlevel dry air. The long-term relationship between dust and Atlantic TC activity show that dust aerosols are negatively associated with hurricane activ-

ity in the Atlantic basin. The numerical simulations with the WRF to the specific cases during the NASA African Monsoon Multidisciplinary Analyses (NAMMA) experiment period show that, with the assimilation of AIRS vertical temperature and humidity information, the warm and dry SAL, which is always associated with the easterly or northeasterly winds, can be identified. Tropical disturbances formed from AEWs are found to develop to the south of the SAL, in the vicinity of the ITCZ. When the warm and dry air of the SAL intruded into the tropical disturbance, it caused the storm to weaken and fail to develop into a named tropical cyclone, whereas Tropical Depression Florence developed into a named tropical storm and later a hurricane as it separated far away from the suppressing influence of the southward-moving SAL.

Because warm and dry air are always associated together, to separate the contributions from these two factors (temperature and humidity), we performed two additional simulations, one assimilating only temperature information (AIRST) and one assimilating only humidity information (AIRSH), keeping all other conditions the same. It is found that the AIRST experiments show almost the same simulations as the full AIRS assimilation experiments, whereas the AIRSH is close to the No-AIRS simulation. This is because the thermal structure of the SAL (warm above, cold below) increases parcel stability; hence, it inhibits the moisture exchange between atmosphere and ocean and reduces the upward flux of moisture into the core of the developing TC. Once the AIRS SAL thermal structure is assimilated, the model takes care of the dynamics of drying processes, because the assimilation of the SAL thermal structure may increase the evaporation of precipitation and downdrafts, which transport dry air from the upper troposphere to lower levels. On the contrary, without such a thermal structure, the evaporative cooling and downdrafts from the No-AIRS and AIRSH simulations are much weaker than those from the AIRS or the AIRST experiments.

There are significant differences in vertical shear of horizontal wind between the AIRS and No-AIRS simulations during the whole 120-h simulation period. Our analyses suggest that the SAL warm temperature may be the indirect but root cause or fundamental factor, whereas the dry air is a direct factor in leading to the TC suppression by increasing parcel stability in the vicinity of the developing storm.

Because no satellite wind data were assimilated, the midlevel easterly jet might only result from the enhanced baroclinicity and easterly thermal winds associated with the SAL warm temperature though the assimilation of the AIRS data and therefore may not be

adequately represented in the model. Another limitation is that the AIRS data (even with cloud-clearing techniques) cannot consistently retrieve temperature and moisture information under overcast cloudy conditions. This may be especially true under the central dense overcast (CDO) condition, which occurs when TC wind speeds reach the 45–55-kt range before the formation of an eye. The dry air associated with the SAL is probably closer to the storm than the AIRS can depict; therefore, the model probably does not have the dry air as close to the center as it should be. These uncertainties could be more closely examined at some point in the future.

Acknowledgments. This work was supported by NASA Grants NNX06AF30G and NNG06GB54G. The numerical simulations with the WRF were performed at the UCAR's supercomputers under NSF Grant NSF0543330. We thank Alok Sahoo for his helps to process the MODIS data. We thank Dr. Joe Prospero for providing the Barbados dust observation data and helpful comments. We are grateful to the editor Dr. Anthony D. Del Genio for his precious time and selfless contributions to the community and for his serious efforts to keep and improve the quality of this journal. We appreciate the reviewers for their detailed and constructive comments on our manuscript.

REFERENCES

- Acker, J., and G. Leptoukh, 2007: Online analysis enhances use of NASA earth science data. *Eos, Trans. Amer. Geophys. Union*, **88**, 14, doi:10.1029/2007EO020003.
- Arimoto, R., 2001: Eolian dust and climate: Relationships to sources, tropospheric chemistry, transport and deposition. *Earth Sci. Rev.*, **54**, 29–42.
- Barker, D. M., W. Huang, Y.-R. Guo, A. J. Bourgeois, and Q. N. Xiao, 2004: A three-dimensional variational data assimilation system for MM5: Implementation and initial results. *Mon. Wea. Rev.*, **132**, 897–914.
- Beven, J., 2006: Tropical Cyclone Report Hurricane Florence (AL062006) 3–12 September 2006. National Hurricane Center Document TCR-AL062006, 12 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL062006_Florence.pdf.]
- Brown, J. M., 1979: Mesoscale unsaturated downdraft driven by rainfall evaporation: A numerical study. *J. Atmos. Sci.*, **36**, 313–338.
- Carlson, T. N., and J. M. Prospero, 1972: The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic. *J. Appl. Meteor.*, **11**, 283–297.
- , and S. G. Benjamin, 1980: Radiative heating rates for Saharan dust. *J. Atmos. Sci.*, **37**, 193–213.
- Chen, Y.-L., 1985: Tropical squall lines over the eastern Atlantic during GATE. *Mon. Wea. Rev.*, **113**, 2015–2022.
- Chiapello, I., J. M. Prospero, J. R. Herman, and N. C. Hsu, 1999: Detection of mineral dust over the North Atlantic Ocean and Africa with the Nimbus 7 TOMS. *J. Geophys. Res.*, **104**, 9277–9291.
- , C. Moulin, and J. M. Prospero, 2005: Understanding the long-term variability of African dust transport across the Atlantic as recorded in both Barbados surface concentrations and large-scale Total Ozone Mapping Spectrometer (TOMS) optical thickness. *J. Geophys. Res.*, **110**, D18S10, doi:10.1029/2004JD005132.
- Chou, M.-D., and M. J. Suarez, 1994: An efficient thermal infrared radiation parameterization for use in general circulation models. NASA Tech. Memo. 104606, Vol. 3, 85 pp.
- Christopher, S. A., and T. Jones, 2007: Satellite-based assessment of cloud-free net radiative effect of dust aerosols over the Atlantic Ocean. *Geophys. Res. Lett.*, **34**, L02810, doi:10.1029/2006GL027783.
- d'Almeida, G. A., 1987: On the variability of desert aerosol radiative characteristics. *J. Geophys. Res.*, **92**, 3017–3026.
- Dudhia, J., 2004: The weather research and forecast model version 2.0: Physics update. *MM5/WRF User's Workshop*, Boulder, CO, NCAR, 4 pp.
- Dunion, J. P., and C. S. Velden, 2004: The impact of the Saharan air layer on Atlantic tropical cyclone activity. *Bull. Amer. Meteor. Soc.*, **85**, 353–365.
- , and C. S. Marron, 2008: A reexamination of the Jordan mean tropical sounding based on awareness of the Saharan air layer: Results from 2002. *J. Climate*, **21**, 5242–5253.
- Emanuel, K., C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental control of tropical cyclone intensity. *J. Atmos. Sci.*, **61**, 843–858.
- 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.
- 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. Climate*, **9**, 1169–1187.
- Goudie, A. S., and N. J. Middleton, 2002: Saharan dust storms: Nature and consequences. *Earth Sci. Rev.*, **56**, 179–204.
- Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.*, **124**, 2322–2339.
- Hoyos, C. D., P. A. Agudelo, P. J. Webster, and J. A. Curry, 2006: Deconvolution of the factors contributing to the increase in global hurricane intensity. *Science*, **312**, 94–97.
- Kafatos, M., D. Sun, R. Gautam, Z. Boybeyi, R. Yang, and G. Cervone, 2006: The role of warm Gulf waters in the intensification of Hurricane Katrina. *Geophys. Res. Lett.*, **33**, L17802, doi:10.1029/2006GL026623.
- Kain, J. S., and J. M. Fritsch, 1990: A one-dimensional entraining/detraining plume model and its application in convective parameterization. *J. Atmos. Sci.*, **47**, 2784–2802.
- , and —, 1993: Convective parameterization for mesoscale models: The Kain–Fritsch scheme. *The Representation of Cumulus Convection in Numerical Models*, Meteor. Monogr., No. 46, Amer. Meteor. Soc., 165–170.
- Kamineni, R., T. N. Krishnamurti, S. Pattnaik, E. V. Browell, S. Ismail, and R. A. Ferrare, 2006: Impact of CAMEX-4 data sets for hurricane forecasts using a global model. *J. Atmos. Sci.*, **63**, 151–174.
- Karyampudi, V. M., and T. N. Carlson, 1988: Analysis and numerical simulations of the Saharan air layer and its effect on easterly wave disturbances. *J. Atmos. Sci.*, **45**, 3102–3136.
- Kaufman, Y. J., D. Tanré, and O. Boucher, 2002: A satellite view of aerosols in the climate system. *Nature*, **419**, 215–223.
- , I. Koren, L. A. Remer, D. Tanré, P. Ginoux, and S. Fan, 2005: Dust transport and deposition observed from the

- Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean. *J. Geophys. Res.*, **110**, D10S12, doi:10.1029/2003JD004436.
- Lau, W. K. M., and K.-M. Kim, 2006: How nature foiled the 2006 hurricane forecasts. *Eos, Trans. Amer. Geophys. Union*, **88**, 105–107.
- Leary, C. A., and R. A. Houze Jr., 1979: Melting and evaporation of hydrometeors in precipitation from anvil clouds of deep tropical convection. *J. Atmos. Sci.*, **36**, 669–679.
- Li, F., A. M. Vogelmann, and V. Ramanathan, 2004: Saharan dust aerosol radiative forcing measured from space. *J. Climate*, **17**, 2558–2571.
- Li, X., H. Maring, D. Savoie, K. Voss, and J. M. Prospero, 1996: Dominance of mineral dust in aerosol light-scattering in the North Atlantic trade winds. *Nature*, **380**, 416–419.
- Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor.*, **22**, 1065–1092.
- Mapes, B. E., and P. Zuidema, 1996: Radiative and dynamical consequences of dry tongues in the tropical troposphere. *J. Atmos. Sci.*, **53**, 620–638.
- Miller, R. L., and I. Tegen, 1999: Radiative forcing of a tropical direct circulation by soil dust aerosols. *J. Atmos. Sci.*, **56**, 2403–2433.
- Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102** (D14), 16 663–16 682.
- 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**, 5255–5265.
- , and —, 1981: Saharan air outbreaks over the tropical North Atlantic. *Pure Appl. Geophys.*, **119**, 677–691.
- , and P. J. Lamb, 2003: African droughts and dust transport to the Caribbean: Climate change implications. *Science*, **302**, 1024–1027, doi:10.1126/science.1089915.
- Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld, 2001: Aerosols, climate, and the hydrological cycle. *Science*, **294**, 2119–2124.
- Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF version 2. NCAR Tech. Note NCAR/TN-468+STR, 88 pp.
- Sun, D. L., K. M. Lau, and M. Kafatos, 2008: Contrasting the 2007 and 2005 hurricane seasons: Evidence of possible impacts of Saharan dry air and dust on tropical cyclone activity in the Atlantic basin. *Geophys. Res. Lett.*, **35**, L15405, doi:10.1029/2008GL034529.
- Tompkins, A. M., 2001: Organization of tropical convection in low vertical wind shears: The role of water vapor. *J. Atmos. Sci.*, **58**, 529–545.
- Wang, C. Z., and S. K. Lee, 2007: Atlantic warm pool, Caribbean low-level jet, and their potential impact on Atlantic hurricanes. *Geophys. Res. Lett.*, **34**, L02703, doi:10.1029/2006GL028579.
- , D. B. Enfield, S. K. Lee, and C. W. Landsea, 2006: Influences of the Atlantic warm pool on western hemisphere summer rainfall and Atlantic hurricanes. *J. Climate*, **19**, 3011–3028.
- Weaver, C. J., P. Ginoux, N. C. Hsu, M.-D. Chou, and J. Joiner, 2002: Radiative forcing of Saharan dust: GOCART model simulations compared with ERBE data. *J. Atmos. Sci.*, **59**, 736–747.
- 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.
- Wu, L., 2007: Impact of Saharan air layer on hurricane peak intensity. *Geophys. Res. Lett.*, **34**, L09802, doi:10.1029/2007GL029564.
- , S. A. Braun, J. J. Ou, and X. Hao, 2006: Simulating the formation of Hurricane Isabel (2003) with AIRS data. *Geophys. Res. Lett.*, **33**, L04804, doi:10.1029/2005GL024665.
- Yoneyama, K., and D. B. Parsons, 1999: A proposed mechanism for the intrusion of dry air into the tropical western Pacific region. *J. Atmos. Sci.*, **56**, 1524–1546.
- Zhang, C., and M.-D. Chou, 1999: Variability of water vapor, infrared radiative cooling, and atmospheric instability for deep convection in the equatorial western Pacific. *J. Atmos. Sci.*, **56**, 711–723.
- , and J. Pennington, 2004: African dry air outbreaks. *J. Geophys. Res.*, **109**, D20108, doi:10.1029/2003JD003978.
- Zhu, T., and D.-L. Zhang, 2006: Numerical simulation of Hurricane Bonnie (1998). Part II: Sensitivity to cloud microphysical processes. *J. Atmos. Sci.*, **63**, 109–126.