INFLUENCE OF THE SAHARAN AIR LAYER (SAL) ON THE DEVELOPMENT AND INTENSITY OF ATLANTIC HURRICANES

Christopher J. Spells
Hampton University

Abstract

The Saharan Air Layer (SAL) is a layer of warm, dry, dusty air which normally overlays the cooler, more humid surface air of the Atlantic Ocean. Over the Saharan Desert from late spring to early fall, air moving across the desert becomes warm and dry forming a deep, well mixed layer in the troposphere. This layer of air can extend from 1,500-6,000m (1.5-6km) in the atmosphere, be traced as far west as the Gulf of Mexico, and is characterized by mineral dust and strong winds. The SAL has been shown to help increase vertical wind shear and allow for the entrainment of dry air into tropical waves, which aids in weakening tropical disturbances. The dry air aloft forbids the moist air along the oceans surface from rising and condensing to form thunderstorm squalls. Evidence suggests that the SAL was the main culprit for the lack of tropical storm and hurricane development over the Atlantic during the 2006 hurricane season. In an effort to improve hurricane models and predictions, CALIPSO, a polar orbiting satellite which incorporates active LIDAR (Light Detection And Ranging), along with current field missions is enabling scientist to better understand the SAL's structure and interaction with tropical systems.

Introduction

History

Some of the first studies of the SAL were made during the Barbados Oceanic and Meteorological Experiment (BOMEX) of 1969 and by passengers aboard the U.S. Coast Guard vessel Discover in 1970 (Woodworth, 2003). In order to study the SAL, concentrations of dust and radon-222 were measured as this layer of air propagated across the Saharan desert and Atlantic Ocean. Concentrations of radon-222 were initially measured in early SAL studies because radon is released 100 times more often over land than over the ocean. Therefore radon-222, which has a half life of 3.82 days, was used as a tracer for the SAL as the layer moved across Africa and the western Atlantic (*Woodworth,* 2003).

Formation of the SAL

From late spring to early fall, a warm, dry, dusty layer of well mixed air covers expansive portions of North Africa and the North Atlantic Ocean. This layer can often extend up to 500hPa over Africa (*Dunion and Velden,* 2004). The SAL is a result of sensible heating over the central Saharan desert, which leads to the formation of a surface low pressure area which helps create a great deal of low level convergence. The low level convergence assists in lifting mineral dust from the surface into the middle troposphere where dust particles are mixed with dry air. The dry air is a result of dry convection due to sensible heating at the surface, which results in an isentropically, vertically well mixed layer of air from an altitude of approximately 1.5km to 6 km (*Woodworth,* 2003). The potential temperature, or the temperature an unsaturated parcel of dry air would have if brought adiabatically and reversibly from its initial state to a standard pressure, p_o, (1013 hPa), is 315-319 K in this layer of the troposphere.

Figure 1. SAL outbreak over the Atlantic coming off the west coast of Africa on July 20, 2007. Taken by Moderate Resolution Imaging Spectroradiometer (MODIS).

West African dust is primarily composed of quarts (SiO, 49.3%), Aluminum oxide (Al_2O_3, 10.34%), sodium oxide (Na_2O, 4.4%) and variable amounts of titanium oxide (TiO_3), magnesium oxide(MgO), calcium oxide (CaO), and diphosphorous hexaoxide(P_2O_6) (*Michalak,* 2004).

SAL Characteristics

There are three major dynamical elements associated with the SAL; dry air, low level temperature inversion, and increased vertical wind shear in the midlevel easterly jet. In order to have convection in the tropics, there needs to be an abundance of warm moist air. The air associated with the SAL is desiccated, where humidity values are considerably less than the layer below it. This dry air is able to suppress low level convection along the southern and western borders of the SAL. The intrusion of dry air into tropical low pressure systems is one of the most important factors in the suppression of hurricane development and intensity.

Temperatures in the SAL tend to be warmer than the surrounding tropical air. The SAL absorbs solar (shortwave) radiation during the daytime, due to the mineral dust associated with the layer. Daytime heating of the layer exceeds the longwave cooling of the SAL, thus warming the SAL and reinforcing the temperature inversion at the base of the layer (*Dunion and Velden,* 2004). At approximately 800-900 hPa, or the base of the SAL, the temperature is typically 5-10^{o}C warmer than the Jordan (1958) mean tropical sounding (*Dunion and Velden,* 2004). This temperature inversion is maintained in the tropical central North Atlantic Ocean where the temperature inversion is 1-2^{o}C. Due to mineral dust associated with the SAL absorbing solar radiation, warming of the lower troposphere occurs, which enhances the trade wind inversion that acts to suppress vertical motion through the SAL (*Carlson and Prospero,* 1972).

Wind shear is the change in wind direction and wind velocities at different altitudes in the atmosphere. Increased vertical wind shear is another important characteristic of the SAL because of its effect on hurricane development and intensity. Near the 700 hPa level, at the southern or southwestern edge of the SAL, easterly winds are usually at their maximum. The wind velocities at this level can range from 10- 17 ms^{-1}, and can reach a maximum of 25 ms^{-1}. The wind velocities associated with the SAL are 7-10 ms^{-1} faster than the typical trade winds (*Dunion and Velden,* 2004). The midlevel winds associated with the SAL increase local vertical wind shear by increasing the low to mid level easterly flow. The resulting increase in low to midlevel flow can be detrimental to hurricane development.

The SAL is usually associated with African easterly waves (AEW's) as air masses move westward from the North African coast (*Dunion & Velden,* 2004). African easterly waves are atmospheric troughs, which are normally oriented north to south and characterized by an elongated area of low pressure. AEW's are responsible for spawning many of the tropical storms and hurricanes which form in the North Atlantic between 10^{o}N and 20^{o}N near the west coast of Africa as the waves move from east to west. During the boreal summer months, SAL outbreaks occur every 3-5 days over Central Africa. The SAL maintains characteristics of warm stable air at its base, and dryness and dustiness throughout its vertical profiles as the layer moves as far west as the Caribbean Sea. The SAL can stretch from 4000- 5000km in an east to west wavelength, an area slightly larger than the contiguous United States (*Dunion and Velden,* 2004).

Hurricane Development

Hurricanes unleash some of the most costly and devastating destruction seen on Earth. In this section, hurricane development and maturation will be discussed. For the purpose of this paper, hurricane formation in the North Atlantic, specifically between 10^{o}N and 20^{o}N, will be pinpointed because this area spawns many of the hurricanes which strike the eastern seaboard of the U.S. and this is where the SAL is at its strongest.

Genesis Stage

Hurricanes can be broken down into three stages, the genesis stage, maturation stage, and decaying stage. Hurricane season in the North Atlantic is from the beginning of June to the end of November. However, a majority of hurricane activity occurs from late summer to early fall because this is when sea surface temperatures are warmest. This leads to the first parameter necessary for hurricane development, warm water. In order for hurricane formation to occur, sea surface temperatures need to be at least 26.5^{o}C (80 ^{o}F). This column of water must be at least 50m deep because of the large amount of mixing associated with the low pressure system (see figure 2, number 3). Warm ocean water is the engine for hurricanes because of the large amount of heat energy it provides (*Trenberth,* 2007).

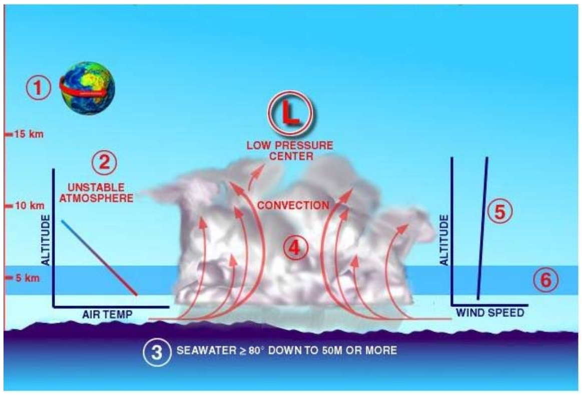

Figure 2. Schematic of developing hurricane

A low pressure system forming no farther south than 5 ^{o}N is also necessary for hurricane development. Low pressure systems can not be too close to the equator due to the Coriolis Effect. The Coriolis Effect deflects air parcels to the right in the Northern Hemisphere. Without the Coriolis Effect, the low pressure system can not deepen or be sustained. The Coriolis Effect is greatest at the poles, and decreases near the equator because this is where the surface of the Earth is parallel to the axis of rotation (figure 2, number1). The Coriolis force is a term in the Rossby equation, given by:

$R_o = U / Lf$, where
U= characteristic velocity
L= length scale
f= Coriolis force

The Rossby number is a dimensionless number which describes fluid flow. The larger the Rossby number the greater effect the Coriolis force has on that air parcel. The Coriolis force is given by:

$f = 2\Omega\sin\theta^{o}U$, where
Ω = the angular velocity of Earth,
θ^{o} = latitude in degrees,
U = the velocity of an air mass.

Although hurricanes have large Rossby numbers, they do feel some of the Coriolis force because these systems stay on the earth's surface for a long period of time. This is one reason why hurricanes tend to deflect to the northeast as they approach the U.S. east coast.

Low vertical wind shear values are a necessity for developing tropical systems. (figure 2, number 5). Typically, these shear values must be less than 10 ms^{-1}. Winds blowing at different directions and speeds can tear developing and mature tropical systems apart. Changes in weather patterns can create upper level winds blowing in different directions than low level winds. Also, during El Nino years, westerly winds increase at high altitudes, which results in fewer tropical disturbances.

A moist unstable atmosphere is important for hurricane formation (see figure 1 number 2). Low humidity's are unfavorable to hurricane development given that dry air is destructive to convective clouds originating in the boundary layer, as they rise through the mid-troposphere. Also a large portion of mass convergence occurs above the boundary layer (figure 2, number 6), and dry air at this level results in less total moisture for convergence, and therefore less latent heat.

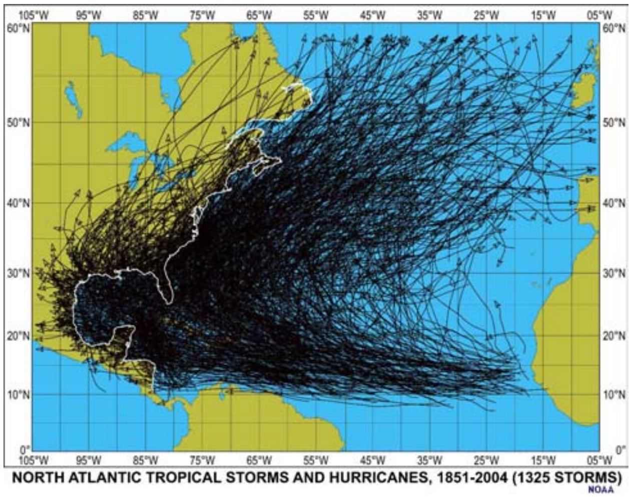

Figure 3. Composite of all tropical storm and hurricane tracks from 1851-2004. Notice how most the tracks start between 10N and 20N.

Maturation Stage

Many of the tropical disturbances that batter the east coast of the United States form off of the coast of West Africa between 10^{o}N and 20^{o}N. One of the most notable hurricanes to have formed in this area is Hurricane Andrew in 1992, which devastated South Florida. Notice that in figure 3, a majority of storms are spawned between 10^{o}N and 20^{o}N. A maturing tropical disturbance will first indicate cyclonic flow. As the low pressure system becomes well organized, air pressure begins to fall around the storm. The development of cyclonic (counter-clockwise in the Northern Hemisphere) circulation develops (*Trenberth,* 2007 see figure 4).

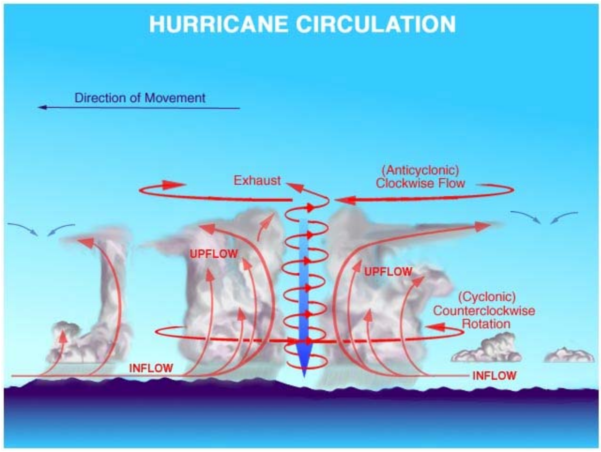

Figure 4. Mature hurricane structure

As the surface pressure continues to fall, water vapor condenses and releases latent heat. Latent heat is the energy released or absorbed during the phase change of a substance, in this case water vapor. In response to the heating of the atmosphere, the surrounding air becomes less dense and begins to rise (*Trenberth,* 2007). As warm air rises, it expands, and cools initiating more condensation and the release of more latent heat. Consequently, buoyancy is further increased, allowing more air to rise (see figure 4).

As mass transport of energy from the surface continues, the temperature at the center of the storm increases, which lowers surface pressure even more. Due to this lower surface pressure, there is more rapid inflow of air at the surface (*Trenberth,* 2007). As a result, there is more heat and more thunderstorms, stronger winds, and if located far enough from the equator, the Coriolis force will induce counterclockwise flow.

In response to latent heat, the air pressure at the top of the storm rises. Due to the higher air pressure aloft, air diverges around the top of the eye of the tropical disturbance. The diverging air aloft prevents the air converging at the surface from piling up around the center of the storm. If the converging air at the surface were allowed to pile up around the center, the storm would eventually weaken, or be destroyed.

Mechanisms Which Inhibit Hurricane Formation and Intensity

There are three mechanisms associated with the SAL which could possibly inhibit the formation, or reduce the intensity of Atlantic hurricanes. The first mechanism is the introduction of dry air into the storm, promoting downdrafts and disrupting the convective organization within the tropical cyclone vortex (*Evan et al.,* 2006). The southern and western boundary of the SAL is characterized by strong temperature, moisture, and dust concentration gradients. As stated previously, hurricanes need moist warm air, specifically in the mid troposphere, in order to form convective clouds. However, the SAL contains dry air in the middle troposphere, which acts to erode these clouds, sapping all of the moisture as clouds rise through the middle troposphere.

The SAL contains 50% less moisture than the warm moist layer below it. This lack of moisture makes it difficult for convection to occur, especially above the boundary layer. The SAL is also characterized by sinking motion due to negative vorticity advection associated with the 700 hPa ridge (*Karyampudi & Carlson,* 1988). The downdrafts which persist within the layer squashes a majority of the convection taking place from the surface to the middle troposphere. The dissipation of deep convection in the interior of a storm interacting with the SAL greatly affects hurricane forecasting models because they tend to overestimate the storms intensity (*Wong and Dessler,* 2005).

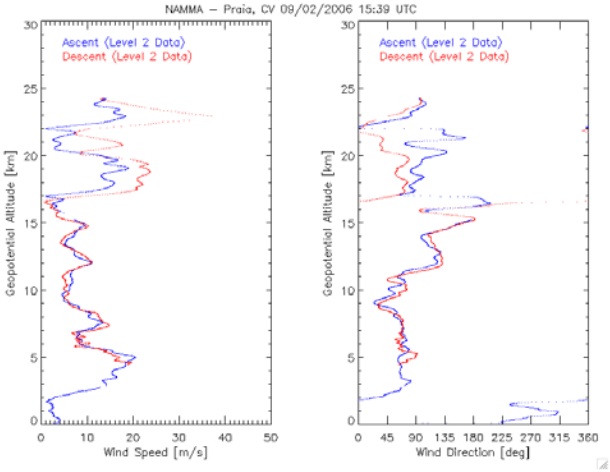

Figure 5. Vertical wind profile taken on Sept. 2, 2006 showing wind speed and direction during the NAMMA project. Notice the wind speed increase around the 5km geo. altitude.

The second mechanism that can influence hurricanes is the midlevel jet found within the Saharan Air Layer. The midlevel jet increases, the local vertical wind shear, which can decouple the storm’s low-level circulation from its supporting mid and upper-level deep convection (*Evan et al.,* 2006). The midlevel easterly jet is a result of the thermal wind balance between the warm, dry air in the SAL, and the cooler, moist tropical air to the south (*Woodworth,* 2003). As previously stated, the midlevel easterly jet can have wind velocities which are 7-10 ms^{-1} faster than typical trade wind velocities. The increase in wind velocities, especially at 3-5 km, cause the lower level circulation to race ahead of the upper level circulation, decoupling the storms vortex, thus disrupting the heat engine organization of the hurricane (*Dunion and Velden,* 2004). Figure 5 shows a vertical wind profile from September 2, 2006 during the NASA African Monsoon Multidisciplinary Analyses (NAMMA). Dropsondes were released from a DC-8 aircraft to take this data. Figure 6, is the corresponding CALIPSO plot which shows the SAL out break between 13.9^{o}N and 21.9^{o}N latitude (left side of image).

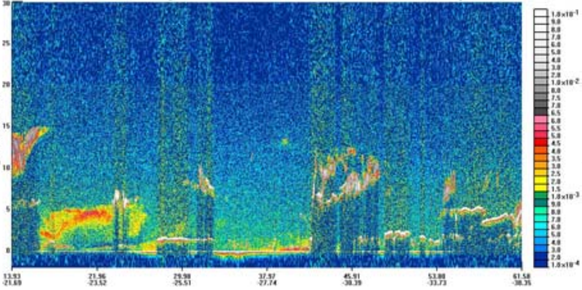

Figure 6. September 2, 2006 CALIPSO plot showing a SAL outbreak between 13.9N and 21.9N latitude (lower left side of image).

The third mechanism associated with the SAL is that 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 (*Evan et al.,* 2006). Hurricanes need a moist unstable environment with massive amounts of convection in order to develop and intensify. The mineral dust associated with the SAL absorbs shortwave radiation which warms that particular layer of air. Due to diabatic heating, temperatures actually increase with altitude; this represents the inversion in the middle troposphere. Temperatures typically decrease with altitude in the troposphere, and as stated earlier, hurricanes also need temperatures to decrease with altitude. This temperature inversion in the middle troposphere again suppresses any convection in the lower altitudes. However, there is some dispute in the science community over the role SAL dust actually plays in hurricane development.

Some believe that the dust particles of the SAL can act as cloud condensation nuclei (CCN), or surfaces in which vapor can coalesce and form clouds, which would eventually lead to rain and thunderstorms. Much of the precipitation which occurs in the tropics is a result of small cloud droplets coalescing on small particles, where the droplets grow large enough to eventually fall as precipitation. However, dust particles in the SAL tend to impact microscopic growth of cloud droplets and alter the proportions of super cooled water and ice that develop within clouds (*Halverson,* 2007). This in turn impacts how heat energy is released in ascending turrets. Since phase changes of water, such as vapor condensing to liquid releases varying amounts of latent heat.

The SAL has been blamed for the production of fewer North Atlantic hurricanes during the 2006 season. The number of tropical storms and hurricanes produced in 2006 (9 named storms) paled in comparison to the historical hurricane season of 2005 (in which there were 28 named storms). The forecast for the 2006 hurricane called for above average activity (the average is 10 storms per year). During July, August, and September of 2005, nine tropical storms and hurricanes formed over the western Atlantic and Caribbean, as well as the Gulf of Mexico, and five hurricanes made landfall. For the 2006 North Atlantic season, no hurricanes were found over this area. Forecasts for the 2006 hurricane season called for above average hurricane activity because sea surface temperatures (SST) were above normal, vertical wind shear was low, and sea level pressure was reduced (*Lau and Kim,* 2007). However, the summer of 2006 produced an active SAL season, maybe due to the lack of rain received in the Sahel, or sub-Saharan Desert.

Due to the intense, optically thick SAL outbreaks of 2006, SST are said to have been about 1.2^{o}C cooler than the year before (*Lau and Kim,* 2007). However, one would think that there would be some kind of lag time between SAL outbreaks and SST decreases, especially considering the specific heat of water. Nevertheless, there is strong evidence which indicates that intense SAL outbreaks increased wind shear and enhanced the trade wind temperature inversion through satellite and aircraft measurements.

Instrumentation

The SAL has been studied to a great extent off of the West African coast over the last 30 to 35 years. However, there is large gap of missing information over the Atlantic Ocean, because until recently there were no instruments which continually monitored the SAL. In this section instruments currently used to monitor the SAL will be discussed.

Launched in April 2006, CALIPSO is a collaborative satellite mission between NASA and the French space agency CNES.

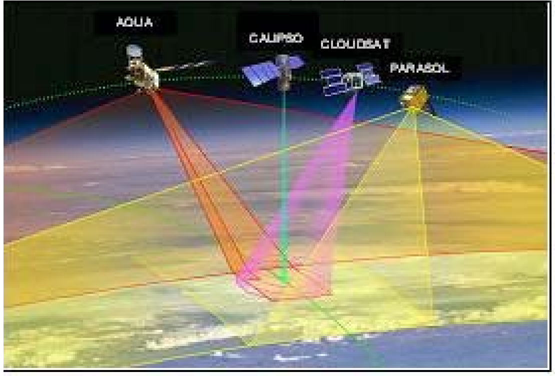

Figure 7 CALIPSO in the A-train

CALIPSO utilizes an active lidar (Light Detection and Ranging) with three channels, 1064 nm and 532 nm wavelengths, along with a depolarization channel at 532nm. The depolarization channel characterizes dry aerosols from moist aerosols. CALIPSO carries its own laser light source, and provides elastic backscatter measurements in the aforementioned channels for atmospheric aerosols, clouds, and gases. CALIPSO is part of the "A-Train" constellation of Earth Observing Satellites, and is providing vertically resolved measurements of aerosols which will help scientist improve climate models and forecasts.

The CALIPSO payload includes three nadir viewing instruments, the Imaging Infrared Radiometer (IIR), Wide Field Camera (WFC), and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). A diode pumped Nd:YAG laser produces linearly polarized pulses of light at 1064nm and 532nm. Each laser produces 110 mJ of energy at each of the two wavelengths, at a pulse repetition of 20.2Hz (McCormick et al, 2003). A beam diameter of 70 meters is produced at the Earth's surface.

CALIPSO is a polar orbiting satellite meaning that it travels around the earth at 705km above the surface. The vertically resolved aerosol data CALIPSO is providing allows researchers to get an idea of where the SAL dust and dry air is located vertically. Until recently, satellites monitoring the SAL mostly produced horizontally resolved data. With CALIPSO, researchers may get a better idea of how the SAL's altitude may rise or fall while propagating across the Atlantic Ocean.

Another satellite that allows researchers to study the SAL is the Geostationary Operational Environmental Satellites (GOES) Satellites, specifically GOES-12. Unlike CALIPSO, which is polar orbiting, GOES Satellites are geostationary, meaning that they orbit the equatorial plane of the Earth at the same speed as the Earth's rotation (appear to be stationary from Earth). GOES-12 covers the Atlantic Ocean, the coast of Africa, and most of the continental U.S., but only gives data horizontally. Since GOES has problems detecting the SAL with visible and infrared (IR) sensors at certain levels as it travels across the Atlantic Ocean (unlike CALIPSO which can detect the level of the SAL across the ocean), multi-spectral IR split image satellite imagery was developed to continuously track the SAL across the Atlantic (Dunion et al., 2004).

Geostationary satellites are strategically located around the earth's equator to provide full coverage of all weather events happening on Earth. These satellites are located 35,800km above the earth's equator and contain 5 channels, 1 visible and 4 IR, as well as a radiometer. CALIPSO together with GOES, along with other instruments such as AQUA, have allowed researchers to get a better understanding of the SAL's characteristics and interaction with hurricane activity.

Summary

While there is a sufficient amount of data which indicates that the SAL does impact hurricane development and intensification negatively, researches still don't completely understand which aspect of the layer impacts tropical systems the most. While some believe the dusty layer of air is directly responsible for limiting hurricane formation and development, there are other scientists that believe the dry air associated with the SAL impacts hurricane formation the most. While dust is the main tracer of the SAL, it is important to remember that the SAL is not only characterized by dust, but also by extremely dry air, increased temperatures in the middle troposphere, and increased midlevel winds.

There are a few research projects which have recently been completed that are allowing researchers to get a better understanding about the SAL and its interactions with hurricanes. One project, particularly, the NASA African Monsoon Multidisciplinary Analyses (NAMMA), took place in August and September of 2006 in the Cape Verde Islands, approximately 350 miles west of Senegal, which is on the west coast of Africa. Data was taken via a NASA DC-8 which used dropsondes to gather data, along with other instruments onboard and by ground instruments. The goal of the project was to study the SAL and compare the ground based data with air based data, as well as satellite data. During the project, other science agencies from Europe aided in gathering data.

It will take cooperation, which is evident through the NAMMA project, to better understand the SAL. If hurricane models are able to improve their forecasts because researchers can better predict SAL outbreaks and better understand their effects on hurricane intensity, destruction of precious materials can be avoided and lives could be saved.

References

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

Dunion, J.P. and C.S. Velden (2004), The impact of the Saharan air layer on Atlantic tropical cyclone activity, *Bull. Of Amer. Meteor. Soc.,* March 2004, **Vol. 85**, 353-365

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

Halverson, J.B., 2007: Hunting Hurricanes: NASA Seeks Answers in African Dust, *Weatherwise* (Magazine), May/June 2007, 46-51

Karyampudi, V.M., and T.N. Carlson, 1988: Analysis and numerical simulations of the Saharan air layer and its effects on easterly wave disturbances. *J. Atmos. Sci.*, **45**, 3102-3136

Lau, W.K.M., andJ.-M. Kim (2007), How nature foiled the 2006 hurricane forecasts, *Eos Trans. AGU*, **88**(9), 105-107

McCormick, M.P., Pelon, Jacques, Winker, D.M, "The CALIPSO mission: Spaceborne lidar for observation of aerosols and clouds," *Proceedings of SPIE* **Vol. 4893**

Michalak, Arthur E., Properties and influences of the Saharan air layer on tropical cyclogenesis, Department of Physics, Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder

Trenberth, K.E., 2007: Warmer oceans, stronger hurricanes: *Scientific American*, July 2007, 45-51

Wong, S., and A.E. Dessler (2005), Suppression of deep convections over the tropical North Atlantic by the Saharan Air Layer, *Geophys. Res. Lett.*, 32, L09808, doi:10.1029/2006GL026408

Woodworth, P.A., 2003, The Saharan Air Layer: Its characteristics and Interactions with mid-level easterly flow, Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

Acknowledgments

Chris Velden and Tim Olander, UW-Madison, CIMSS

Jason Dunion, NOAA Hurricane Research Division, NAMMA Mission

Dr. John Anderson and Dr. Bill Smith, Hampton University, APS

Ladi Rezac, Sydney Paul, Taumi Daniels &
Jasper Lewis, Hampton University

NOAA-CREST

Virginia Space Grant Consortium