Popular Summary

Improving our understanding of Atlantic tropical cyclones through knowledge of the Saharan Air Layer: Hope or hype?

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The existence of the Saharan air layer (SAL), a layer of warm, dry, dusty air that frequently moves westward off of the Saharan desert of Africa and over the tropical Atlantic Ocean, has long been appreciated. As air moves over the desert, it is strongly heated from below, producing a very hot air mass at low levels. Because there is no moisture source over the Sahara, the rise in temperature causes a sharp drop in relative humidity, thus drying the air. In addition, the warm air produces a very strong jet of easterly flow in the middle troposphere called the African easterly jet that is thought to play a critical role in hurricane formation. In recent years, there has been an increased focus on the impact that the SAL has on the formation and evolution of hurricanes in the Atlantic. However, the nature of its impact remains unclear, with some researchers arguing that the SAL amplifies hurricane development and with others arguing that it inhibits it. The argument for positively influencing hurricane development is based upon the fact that the African easterly jet produces the waves that eventually form hurricanes and that it leads to rising motion south of the jet that favors the development of deep thunderstorm clouds. The potential negative impacts of the SAL include 1) low-level vertical wind shear associated with the African easterly jet; 2) warm SAL air aloft, which increases thermodynamic stability and suppresses cloud development; and 3) dry air, which produces cold downdrafts in precipitating regions, thereby removing energy needed for storm development. As part of this recent focus on the SAL and hurricanes (which motivated a 2006 NASA field experiment), there has been little emphasis on the SAL's potential positive influences and almost complete emphasis on its possible negative influences, almost to the point of claims that the SAL is the major suppressing influence on hurricanes in the Atlantic.

Multiple NASA satellite data sets (TRMM, MODIS, and AIRS/AMSU) and National Centers for Environmental Prediction global analyses are used to characterize the SAL's properties and evolution in relation to developing hurricanes. The results show that storms generally form on the southern side of the jet, where favorable background rotation is high. The jet often helps to form the northern side of the storms and rarely moves over their inner cores, so jet-induced vertical wind shear does not appear to be a negative influence on developing storms. Warm SAL air is confined to regions north of the jet and generally does not impact the tropical cyclone precipitation south of the jet. Of the three proposed negative influences, dry air appears to be the key influence; however, the presence of dry SAL air is not a good indicator of whether a storm will weaken since many examples of intensifying storms surrounded by such dry air can be found. In addition, a global view of relative humidity shows moisture distributions in other ocean basins that are almost identical to the Atlantic. The dry zones correspond to regions of descending air on the eastern and equatorward sides of semi-permanent oceanic high pressure systems. Thus, the dry air over the Atlantic appears to be primarily a product of the large-scale flow, but with enhanced drying at low levels associated with the Sahara. As a result, we conclude that the SAL is not a major negative influence on hurricanes. It is just one of many possible influences and can be both positive and negative.

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Capsule Summary

NASA satellite data and NCEP global analyses raise questions about the extent to which the Saharan Air Layer is a negative influence on tropical cyclogenesis and evolution in the Atlantic.

Abstract

The existence of the Saharan air layer (SAL), a layer of warm, dry, dusty air frequently present over the tropical Atlantic Ocean, has long been appreciated. The nature of its impact on hurricanes remains unclear, with some researchers arguing that the SAL amplifies hurricane development and with others arguing that it inhibits it. The potential negative impacts of the SAL include 1) low-level vertical wind shear associated with the African easterly jet; 2) warm air aloft, which increases thermodynamic stability; and 3) dry air, which produces cold downdrafts. Multiple NASA satellite data sets and National Centers for Environmental Prediction global analyses are used to characterize the SAL's properties and evolution in relation to developing hurricanes. The results show that storms generally form on the southern side of the jet, where the background cyclonic vorticity is high. The jet often helps to form the northern side of the storms and rarely moves over their inner cores, so jet-induced vertical wind shear does not appear to be a negative influence on developing storms. Warm SAL air is confined to regions north of the jet and generally does not impact the tropical cyclone precipitation south of the jet. Dry air appears to be the key mechanism for SAL influence, but the presence of dry SAL air is not a good indicator of whether a storm will weaken since many examples of intensifying storms surrounded by such dry air can be found. A global view of relative humidity shows moisture distributions in other ocean basins that are almost identical to the Atlantic. The dry zones correspond to regions of descending air on the eastern and equatorward sides of semi-permanent high pressure systems. Thus, the dry air over the Atlantic appears to be primarily a product of the large-scale flow, but with enhanced drying below 700 hPa associated with the Sahara.

1. Introduction

The impact of the Saharan air layer (SAL) on the development of tropical cyclones is not well understood. Early studies (e.g., Karyampudi and Carlson 1988) suggested a potential positive influence on the growth of easterly waves and tropical cyclones in the Atlantic. A more recent study by Dunion and Velden (2004, hereafter DV) described several potentially negative influences of the SAL. The reduced Atlantic hurricane activity of 2006 and 2007 compared to 2004 and 2005, particularly as it affected the United States, has led to speculation in the media and in some research papers (e.g., Lau and Kim 2007) that dustiness or dry air from increased SAL activity contributed to the decline in hurricane activity in those two years. Map room tropical weather discussions and even planning of field experiments is often focused on the negative impacts of the SAL. But is this intense focus on the negative impacts of the SAL warranted? Is the SAL a major influence, just one of many factors, or is it only a minor influence on Atlantic hurricane activity? These questions led the authors to use National Aeronautics and Space Administration (NASA) satellite data sets to evaluate the role of the SAL in Atlantic hurricane activity.

Synoptic outbreaks of Saharan dust occur from late spring to early fall and can extend from western Africa across the tropical Atlantic Ocean to the Caribbean (Prospero *et al*. 1970; Prospero and Carlson 1970, 1972). The dust is carried predominantly westward within the SAL, which is caused by strong surface heating as westward moving air crosses the Saharan desert. The heating produces a deep well-mixed layer with warm temperatures and low relative humidity (RH). As the warm, dry air moves off the African coast, it is undercut by cooler, moister air to form the elevated SAL (Karyampudi and Carlson 1988). The vertical thermodynamic structure consists of a well-mixed boundary layer capped by the trade wind inversion up to about 850 hPa, where the SAL begins (Carlson and Prospero 1972; Diaz *et al*. 1976; Prospero and Carlson 1981; Karyampudi and Carlson 1988; Karyampudi *et al*. 1999; Karyampudi and Pierce 2002). The SAL extends from ~800 to 550 hPa near the coast of Africa and is characterized by nearly constant potential temperature and vapor mixing ratio (Carlson and Prospero 1972; Karyampudi and Carlson 1988). The base of the SAL rises while the top of the SAL slowly sinks to the west. Temperatures near the top of the SAL tend to be somewhat cooler than the surrounding tropical atmosphere so that the SAL is typically capped by another inversion (Carlson and Prospero 1972).

The strong horizontal temperature gradients along the leading and southern borders of the SAL give rise to a maximum in the geostrophic wind (due to thermal wind considerations) to produce the mid-level African Easterly Jet (AEJ) along the southern edge of the SAL. This jet is associated with large vertical and horizontal wind shears and an ageostrophic transverse circulation that produces upward motion in the dust-free air to the south of the jet, leading to deep convection there, and downward motion within the SAL (Karyampudi and Carlson 1988; Karyampudi *et al*. 1999; Karyampudi and Pierce 2002).

Karyampudi and Carlson (1988) and Karyampudi and Pierce (2002) suggested that the SAL contributes to easterly wave growth and, in some cases tropical cyclogenesis, by supporting convection along its leading and southern borders. The SAL increases the strength of the AEJ and its associated vorticity patterns. The AEJ leads to weak cyclonic or even anticyclonic potential vorticity (PV) north of the jet, strong positive PV south of the jet, and a significant PV-gradient sign reversal. The latter favors easterly wave growth via barotropic instability. Karyampudi and Carlson (1988) also showed that the baroclinic aspects of the AEJ, via the induced ageostrophic circulation and attendant convection, also contribute to wave growth.

Thus, Karyampudi and Carlson (1988) and Karyampudi and Pierce (2002) conclude that the SAL can aid wave growth and tropical cyclone development.

In contrast, DV focused on mechanisms that generally inhibit tropical cyclone genesis and intensification. They suggested that the SAL negatively impacts tropical cyclones in the following ways: 1) The enhanced low-level temperature inversion, maintained by radiative warming of dust, suppresses convective development; 2) vertical wind shear associated with the AEJ inhibits tropical cyclone intensification, based upon studies that have shown that shear tends to weaken storms (Gray 1968; Merrill 1988; DeMaria and Kaplan 1994, 1999; Frank and Ritchie 2001; Rogers *et al*. 2003; Braun and Wu 2007); and 3) intrusions of dry SAL air into tropical cyclones foster enhanced cold downdrafts (Emanuel 1989; Powell 1990) and lower the convective available potential energy within tropical cyclones. While it was not Dunion and Velden's intention to imply that the SAL's impacts were always negative or were the dominant factor affecting hurricane activity (DV; Dunion and Velden, personal communication), it appears from discussions, media interviews, and research papers (e.g., Jones et al. 2007; Wu 2007) that some people in the research community have adopted that view.

The results of DV contrast with those of Karyampudi and Carlson (1988) and Karyampudi and Pierce (2002) since the former stress mainly a negative impact of the SAL on tropical cyclones, while the latter suggest a positive influence. This disagreement raises questions regarding the role of the SAL in tropical cyclogenesis and intensity change. Our goal with this paper is to assess the negative influences of the SAL on tropical cyclogenesis and evolution and to determine if the main negative influences, if present, are the result of vertical shear, warm air (higher stability), or dry air.

2. Data

Several NASA satellites currently provide information that is critical to assessing the impacts of the SAL on hurricanes. The Tropical Rainfall Measuring Mission (TRMM), launched in November 1997, provides information on the rainfall amount and structure in tropical systems over the ocean. Here, we use the TRMM multi-satellite precipitation product (known as the TRMM 3B42 product, Huffman et al. 2007), which provides rainrate estimates every 3 hours. The Moderate Resolution Imaging Spectroradiometer (MODIS) imager, on both the Aqua and Terra satellites since 2002, provides a measure of the vertically integrated dust concentration, or aerosol optical depth (AOD), within the SAL. The Atmospheric Infrared Sounder (AIRS) and Advanced Microwave Sounding Unit (AMSU) retrieve temperature and humidity profiles that are essential to characterizing the thermodynamic properties of the SAL. Since the satellite data provide little, if any, wind information, National Centers for Environmental Prediction (NCEP) global analyses, available every 6 h, are used to characterize properties of the AEJ and to complement the satellite data sets. The data are summarized in Table 1. Of particular note regarding the AIRS/AMSU data is that the temperature data for a particular pressure level is the temperature at that level while the relative humidity for a specified level is the layer-averaged RH from the specified level to the next level above. For the discussion that follows, AIRS RH data at 850 hPa (700 hPa) is the average over the layer from 850 to 700 hPa (700 to 600 hPa).

The satellite data are averaged in time to produce daily and monthly analyses. For precipitation, daily analyses show 24-h rainfall accumulation while monthly analyses give the monthly mean rainfall rate. For MODIS AOD and AIRS/AMSU temperature and RH, daily analyses are created as follows: for grid points with no valid data for a given day, the grid point is assigned a missing value; for one valid data value, the value is taken as the mean value; for multiple valid data values, the average of the values is used. For MODIS data, monthly mean fields are obtained by averaging the daily results. For AIRS/AMSU, we use the level 3 monthly mean product available from the AIRS data archive.

The following results must be viewed with two caveats in mind. First, our examination only includes named storm systems. Consequently, the conclusions cannot be applied to non-developing storms. Second, because of the lack of detailed wind data over the oceans and the relatively coarse resolution of the NCEP data, the NCEP analyses may not capture the magnitude and more detailed structure of the AEJ or the tropical cyclones. As a result, the exact extent to which vertical shear associated with the jet encroaches upon the core of the storms may be difficult to assess. However, the qualitative relationships between the AEJ and tropical cyclones can be addressed.

3. The SAL: A negative influence?

a. Vertical shear and increased stability

Studies by Frank (1970), Burpee (1972), Landsea and Gray (1992), Thorncroft and Hodges (2001), and Ross and Krishnamurti (2007), among others, have demonstrated that the AEJ plays an instrumental role in the formation of tropical cyclones over the Atlantic, with most storms developing to the south of the AEJ axis. The southern side of the jet is characterized by strong cyclonic vorticity, thereby providing a vorticity-rich environment for cyclogenesis. The AEJ is also a source of African Easterly Waves, which grow by baroclinic and barotropic instability. Cumulus convection south of the AEJ, particularly in the Intertropical Convergence Zone (ITCZ), also contributes to wave growth by producing reversals in the meridional gradient of potential vorticity (Mass 1979; Hsieh and Cook 2005). DV suggested that the AEJ may be a source of vertical wind shear that could negatively impact developing cyclones. They show vertical shear estimates for the cases of hurricanes Isaac and Joyce (see their Fig. 6), with peak shear associated with the SAL northeast of Joyce of about 35 m s^{-1} between the 150-350 and 700-925 hPa layers. However, the western edge of the strong shear layer was located more than 2° from the storms and the peak shear more than 5° from the storms. Whether and by which means storms are detrimentally impacted by vertical shear on their periphery has not been established. In most previous studies of vertical-wind-shear impacts on tropical cyclones, the "detrimental" shear was thought to be that existing over the core (the center and out to some specified radius) of the storm (Marks et al. 1992; Franklin et al. 1993; Reasor et al. 2000; Black et al. 2002; Corbosiero and Molinari 2002, 2003; Rogers et al. 2003; Chan et al. 2004; Braun et al. 2006; Chen et al. 2006) and was often assumed to be horizontally uniform in modeling studies (Jones 1995; Bender 1997; Frank and Ritchie 1999, 2001; Wong and Chan 2004; Wu and Braun 2004). For this study, we assume that for the AEJ to negatively impact tropical cyclone development, the jet would need to move over or very near the center of the storm.

Analysis of NCEP fields for all Atlantic tropical cyclone events between 2003-2007 suggests that the AEJ generally does not move over developing disturbances, but in fact, that the jet provides a key source of vorticity and frequently forms the northern portion of the storms. Hurricanes Florence and Helene in 2006 are provided here as typical examples (Fig. 1). On 3 September (Fig. 1a), a broad jet is apparent at 700 hPa extending from the western coast of Africa to ~50°W at a latitude of 17-18°N. A region of enhanced cyclonic vorticity (not shown) that would shortly develop into a tropical depression and later into Hurricane Florence is located south of the jet between 40-50°W and 12°N. By 4 September (not shown), a tropical depression has formed at ~48°W, 13°N, with maximum easterlies concentrated on the northern side of the depression in association with the AEJ and strengthening westerlies on the southern side of the storm. The system becomes Tropical Storm Florence on 5 September (Fig. 1c) with the remnants of the AEJ now comprising the northern part of the storm circulation. Eight days later (Fig. 1e), as Florence moves northeastward off the U.S. East Coast, a new wave has emerged off of the western African coast in association with a strong AEJ. As with Florence, a cyclonic vortex develops south of the jet. Over the next several days (Fig. 1g), Hurricane Helene forms, with the trailing portion of the jet becoming the northern part of the storm circulation.

The relationship between the dust layer, precipitation, the AEJ, and the large-scale meridional circulation is demonstrated in Fig. 2 for 2 September 2006, immediately before the formation of Florence. Strong easterly winds at 700 hPa extend from the African coast to ~50°W with peak winds along or near the southern and leading edges of the dust layer. The heaviest precipitation is located south of the leading portion of the dust outbreak. Meridional cross sections formed by averaging between 20-40°W show the AEJ centered near 16-17°N and ~650 hPa (Fig. 2b). The vertical circulation exhibits low-level convergence and strong ascent on the south side of the AEJ and sinking motion to the north of the jet. Although there is weak rising motion beneath the jet, deep saturated ascent (Fig. 2c) is confined to the region to the south where vertical shear associated with the AEJ is weak. Thus, the deep convection occurs in the cyclonic vorticity-rich region south of the jet, enabling development of the tropical cyclone. Since the jet does not move over the region of deep convection (Fig. 1), the vertical shear associated with the AEJ does not inhibit development. The examples of hurricanes Florence and Helene are typical of most hurricanes developing from African easterly waves in the central and eastern Atlantic based upon NCEP analyses and satellite data for 2003-2007.

The warm SAL air is found to the north of the AEJ (Karyampudi and Carlson 1988), with the developing storms typically located south of the jet very close to the southern edge of the warm layer (see Fig. 1); in other words, near the zone of strong meridional temperature gradient on the southern side of the SAL. To the extent that the air flow is in geostrophic balance with the thermodynamic field (Cook 1999), the fact that the jet usually forms the northern side of developing storms implies that the warmer air, and hence greater thermodynamic stability, is usually confined to areas north of developing storms (see the right columns of Figs. 1 and 3 for examples). As a result, this higher stability air would not be expected to impact precipitating regions of the storms.

The results in this section are, of course, dependent on the reliability of the NCEP analyses in representing the structure of the AEJ and its relationship to developing tropical cyclones. We have assumed that the qualitative relationship between the jet and the storms is correct even if the magnitude of the winds is in error. Comparison of high-resolution aircraft and satellite observations (e.g., from the 2006 NAMMA field campaign) are needed to determine if this assumption is correct.

b. Intensification within the SAL

Assessing the degree to which the SAL is having a negative impact on storm development is difficult without detailed modeling of all the relevant processes and being able to add or remove those processes to determine their impacts. It may be enticing to assume that a storm that struggles to intensify in the presence of SAL air did so because of the SAL, but one risks neglecting other processes that may affect, and perhaps even dominate, intensification. Consider the following four scenarios: 1) No SAL air is present and a storm fails to intensify, 2) no SAL air is present and the storm intensifies, 3) SAL air is present and the storm fails to intensify, and 4) SAL air is present and the storm intensifies. Obviously, in cases (1) and (2), the SAL is not an issue and other processes (vertical shear, other sources of dry air, lack of convective organization, etc.) control whether or not intensification occurs. If one starts with the hypothesis that the SAL represents a negative influence on tropical cyclone development, then because of cases (1-2), the presence of the SAL near a storm struggling to intensify does not necessarily prove the hypothesis. However, a storm that intensifies in the presence of SAL air would suggest that the SAL may not always, or even often, be a major factor in determining the evolution of a tropical cyclone. Here, we use Hurricane Fabian (2003) as an example of case 4. Other storms in this class include Isabel in 2003, and Frances, Ivan, and Karl of 2004.

A portion of the life cycle of Hurricane Fabian (2003) is shown in Fig. 3 using TRMM, MODIS, and AIRS observations. On 26 August 2003 (top row), a dust outbreak has recently emerged from the African coast. A convective system at the eastern end of the ITCZ is the seedling for the genesis of Fabian late on 27 August. An AEJ wind maximum (not shown) was located directly on the north side of this convection centered near 21°W, 16°N. The relative humidity pattern in the 850-700 hPa layer shows a narrow zone of maximum RH at the leading edge of the dust with weak precipitation extending northward from the ITCZ within this moist tongue. Air within the dust outbreak possesses lower humidity (~20-40%). Very warm air at 850 hPa extends from Africa to nearly 40°W to the north of the ITCZ and the seedling disturbance. Two days later (second row), the dust has pushed westward, with the greatest concentration just north and ahead of Fabian, now a tropical depression. The moist tongue is still at the leading edge of the dust outbreak, with more enhanced precipitation occurring at the northern end of the moist tongue. Dry air (30-40% relative humidity) surrounds the tropical depression from east to north and west. Fabian is situated on the southern edge of the warm SAL air, about 10° longitude behind the leading edge of the SAL. By 30 August (third row), dust concentrations have diminished with AOD values of ~0.3-0.4 surrounding Fabian, which at this time has intensified into a category 2 hurricane. Relative humidity in the northern half of the storm's environment ranges from between 40-60%. Fabian remains along the southern edge of the warm air, which is gradually cooling and whose area is shrinking with time. Finally, by 1 September (bottom row), Fabian has intensified into a category 4 hurricane. It continues to be surrounded by low to moderate concentrations of dust (again, AOD between 0.3-0.4). Relative humidity is as low as 30% to the east of the storm, 40-60% to the west, and Fabian is now to the east of what is left of the warm air. Fabian peaks in intensity at the beginning of 2 September and maintains category 4 strength through much of 3 September. By that time (not shown), a new dust outbreak is just beginning at the African coast, where soon another convective disturbance will emerge and evolve under similar circumstances to become Hurricane Isabel with category 5 intensity.

The storms highlighted by DV presented examples in which dry SAL air may have limited or suppressed hurricane development, although other potential causes for storm intensity change were not fully examined. The examples described above, however, emphasize that the presence of dry SAL air surrounding a tropical disturbance does not necessarily imply that the storm will struggle to intensify. Based upon examination of AIRS-derived 850-600 hPa RH data for 2003-2007, we find that dry air in the immediate vicinity of developing tropical cyclones is a rather common occurrence (see below). The puzzle, then, for atmospheric scientists to solve is determining what factors make some storms more susceptible to dry air and others rather immune to it? Is it related more to characteristics of the environment such as vertical wind shear, to characteristics of the vortex (size, strength), or to other factors such as the recently proposed marsupial hypothesis of Dunkerton et al. (2008), in which a protective "pouch" forms around an incipient disturbance when its parent AEW moves with the speed of the mean flow?

c. Dry air over the Atlantic Ocean and within the SAL

Dry air associated with the SAL would appear to be the main potentially negative influence on tropical cyclone genesis and evolution, although as mentioned, some storms are more susceptible to this negative influence than others. However, a climatology of the Atlantic moisture distribution, given below, suggests that the moisture distribution is, to first order, determined by the large-scale flow and only secondarily by the influences of the Sahara. In this section, we use the NASA satellite data and NCEP analyses averaged over the month of August 2006 to highlight climatological aspects of the SAL. This month (in terms of monthly mean characteristics) is qualitatively representative of all other months from June-September 2003-2007.

Satellite-derived properties of the SAL for August 2006 are shown in Figs. 4 and 5. The largest dust amounts over the ocean (Fig. 4) are found immediately off of the west African coast between 12-28°N latitude, falling off dramatically by 40°W longitude, roughly 2300 km west of the African coast. This dust layer coincides with very warm 700-hPa and 850-hPa temperatures (Figs. 5c, e), with the warmest air over the African land mass and with temperatures diminishing rapidly westward. This result is consistent with Carlson and Prospero (1972) who estimated longwave radiative cooling rates of about 1.5-2 K per day. Precipitation is heaviest in the ITCZ south of the main dust region and also diminishes substantially by 40°W. Two possible reasons for this close relationship between dust/warm air and precipitation are (1) the frontogenetic properties of the warm SAL provide an indirect vertical circulation that favors cloud development, as proposed by Karyampudi and Carlson (1988), and 2) precipitation systems routinely track due westward in this narrow latitudinal band, but westward of 40°W, possess tracks that diverge and range from due westward to northward. If the former is true, then the

SAL would be expected to have a positive influence on cyclone development by fostering mean ascent to its south.[1]

The mean environment of the SAL can be ascertained by examining AIRS-derived temperature and humidity data at multiple levels. For example, the temperature (relative humidity) at 500 hPa (500-400 hPa,) in Fig. 5a (5b) represents conditions at, or just above, the top of the SAL. Here, we find three primary dry regions unrelated to the SAL, one over the eastern Mediterranean and northern Egypt, another over the eastern Atlantic northwest of the West African coast, and the third over the central Atlantic Ocean. Each of these dry regions is associated with a weak warm anomaly in the 500-hPa temperature field, suggesting the prevalence of large-scale subsidence in these regions. High humidities are found in the ITCZ and also extend northward over western Africa, further indication of the weak or absent Saharan drying influence at this level.

The relative humidity in the 700-600 hPa layer (Fig. 5d) is nearly identical to that at 500-400 hPa, but with somewhat higher humidities. Three characteristic moisture regimes are found in the eastern Atlantic: a moist zone in the tropical precipitation belt, a very dry region on the northern side of the dust layer, and an intermediate humidity region within the SAL. This zone of intermediate humidity within the SAL can be partly explained by Fig. 2c, where southerly flow just above the AEJ transports moister air from south to north. In addition, dry convective mixing over the Sahara produces profiles of constant potential temperature and mixing ratio up to about 500 hPa. The result is a profile of relative humidity with the driest air near the surface and increasing humidities toward the top of the mixed layer (Carlson and Prospero 1972).

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[1] This fact does not preclude the SAL from simultaneously having negative influences as well, particularly as a result of dry air.

At 700 hPa, the influence of the Sahara becomes apparent in the temperature field (Fig. 5c), with air temperatures over Africa 3-5 K greater than air over nearby Atlantic waters. If one holds the vapor mixing ratio constant, a temperature variation of 3-5 K at this level would account for only a few percent relative humidity variation. Therefore, the observed relative humidity variability seen in Fig. 5d arises largely from variations in the vapor mixing ratio, whose horizontal distribution is qualitatively similar to that above 500 hPa, or above the SAL.

In the 850-700 hPa layer (Fig. 5f), the zone of intermediate humidity is absent, replaced by very dry air. The 850-hPa temperatures (Fig. 5e) show strong warming over the Sahara, with temperatures as much as 10-12 K warmer than air over nearby Atlantic waters. Again, holding vapor mixing ratios constant would suggest a drop in relative humidity of 10-15%. The decrease in relative humidity seen over northern Africa is consistent with the expected drop caused by strong surface warming. Thus, the impact of the Sahara on the mean moisture field is seen primarily below 700 hPa over Africa, but fades quickly as the air cools as it moves westward.

The relative humidity in the 700-600 hPa layer from NCEP global analyses (Fig. 5g) is nearly identical to that from AIRS. The monthly mean streamline pattern and vertical velocities (Fig. 5h, depicting only downward motions) show that the driest regions are located at the terminus of northerly descending airflow associated with midlatitude troughs on either side of a Saharan midlevel high-pressure system. Over the Atlantic, the dry tongue that extends from northwest Africa to the central Atlantic is associated with descending flow on the northern side of the AEJ, suggesting that the jet may contribute to this descending flow. Results presented are typical of other months as well.

We can further expand our view to look at the global distribution of observed monthly averaged (again, Aug. 2006) relative humidity and precipitation (Fig. 6a), and NCEP fields (Figs.

6b, c). Similar to the Atlantic, regions of dry air can be found in the eastern portions of major ocean basins in both the northern and southern hemispheres. For example, over the northeastern Pacific Ocean, dry air occurs from the coast of California and toward the southwest into the tropical Pacific.[2] Monthly averaged streamlines (Fig. 6b, c) reveal that these dry regions are the product of semi-permanent pressure systems, including the Pacific and Bermuda highs, a Saharan high, a monsoonal low over northern India, and high pressure regions in the southern hemisphere. The dry oceanic areas are also zones of large-scale subsidence on the eastern and equatorward sides of the high pressure systems. Figure 6 should not be interpreted as saying that mid-latitude dry air moving around the oceanic high pressure systems is the source of dry tropical air. While some midlatitude dry air does intrude into the tropics and move westward, much of the dry mid-level air in the tropics derives from subsiding tropical air equatorward of the highs. These results suggest that large-scale processes dominate the distribution of moisture over the oceans, including the Atlantic. They also imply that the Sahara is likely only a smaller modulating influence, not the main determinant, of the tropical Atlantic moisture distribution.

Not only does the AEJ mark the region of strong temperature gradient on the southern side of the SAL (Karyampudi and Carlson 1988), it also lies within the zone of strong meridional moisture gradient over the Atlantic and Africa. Because the AEJ is barotropically unstable, easterly waves readily form and move westward across the tropics. These waves, lying in this zone of strong moisture gradient, then produce perturbations in the moisture field with dry (moist) air westward (eastward) of trough axes. The implication of these results is that the dry SAL air is, to first order, the dry sector of an easterly wave that happens to contain dust. This

[2] Although speculative, we suspect that the lack of dry air in the main development region of the Eastern Pacific compared to the Atlantic is related to the orientation of the coastlines, i.e., northwest to southeast along the eastern side of the Pacific compared to northeast to southwest along the eastern side of the Atlantic (Fig. 6a).

dryness is enhanced below 700 hPa by surface heating over the Sahara, but this enhancement diminishes as the air cools while moving westward. Dry air further westward over the Atlantic must be maintained by subsidence.

4. Conclusions

Previous studies on the impact of the Saharan Air Layer on tropical cyclone genesis and intensification have yielded mixed results, with some studies (Karyampudi and Carlson 1988; Karyampudi et al. 1999; Karyampudi and Pierce 2002) suggesting that the SAL can have a positive influence on development, while other studies (Dunion and Velden 2004; Jones et al. 2007) have suggested that the SAL may be a negative influence. Dunion and Velden (2004) described several ways by which the SAL can inhibit tropical cyclone growth including low-level vertical wind shear associated with the African Easterly Jet, increased thermodynamic stability caused by the elevated warm layer, and impacts of dry mid-level air, particularly in terms of the production of cold downdrafts. Since the DV study, the SAL has been emphasized by some as a primary negative influence on Atlantic tropical cyclogenesis and evolution (Lau and Kim 2007; Jones et al. 2007; Wu 2007). To determine whether this emphasis is warranted, in this study, we used NASA satellite remote sensing data and NCEP global analyses to evaluate the negative impacts proposed by DV.

Key findings are as follows:

- NCEP wind fields suggest that the AEJ generally does not produce inhibiting amounts of vertical wind shear over developing disturbances. Instead, convective systems typically form on the southern side of the AEJ, where the background cyclonic vorticity is high and the large-scale meridional circulation favors upward motion. The jet often forms the northern part of the developing cyclonic storms and, hence, does not move over the core of the storms. As a result, little vertical shear is felt over the center of the storms. The impact of shear on the periphery of storms is unknown. Consequently, the negative influence caused by vertical wind shear associated with the AEJ is either small or indeterminate. This conclusion is dependent on the reliability of the NCEP fields in representing the AEJ and tropical cyclone circulations and may be proven incorrect in some cases by analysis of higher-resolution aircraft data. The conclusion also applies to storm systems that developed into tropical storms and hurricanes. It is not known to what extent this result applies to non-developing storm systems.

• The warm SAL air is found to the north of the AEJ, with the developing storms typically located south of the jet. To the extent that the air flow is in geostrophic balance with the thermodynamic field, the fact that the jet usually forms the northern side of the storms implies that the warmer air, and hence greater thermodynamic stability, is usually confined to areas north of developing storms. As a result, this higher stability air generally does not impact precipitating regions of the storms that lie mostly south of the jet.

• The dry air of the SAL is likely its key negative influence. However, the presence of dry air in the environment of storms is not necessarily a good indicator of whether or not a storm will intensify. While some storms appear to be weakened by the presence of dry SAL air, cases can be found in which storms readily intensify despite the presence of dry air in their immediate surroundings. The question to be addressed in future research is why some storms are susceptible to the dry air while others are not.

• The dry "SAL" air, to some extent, is not necessarily unique to the Saharan region, at least in a climatological sense. Outside of the Atlantic ITCZ, the subtropical and eastern Atlantic regions are characteristically dry, with dry regions collocated with areas of large-scale descent on the eastern and equatorward sides of the Bermuda high pressure system. The impact of the Sahara is evident primarily at low levels (below 700 hPa) over the Sahara where warming from the surface reduces the relative humidity substantially. Furthermore, an examination of the moisture distribution across the globe shows similar patterns of relative humidity and descending air flow in all major oceans basins, suggesting that the Atlantic moisture distribution is primarily driven by the large-scale flow rather than by processes that are uniquely Saharan in nature. In other words, the environment over the Atlantic is hostile (i.e., dry) to cyclogenesis even before consideration is given to the effects of the Sahara.

• Since the AEJ occurs in a region of strong relative humidity gradient and is the source of African Easterly Waves (AEWs), the AEWs produce perturbations in the moisture distribution much like developing extratropical systems produce temperature perturbations along frontal zones. The AEWs bring dry air southward ahead of the trough and moist air northwards behind the trough. Many of the pockets of dry air associated with the SAL may simply be the dry zone of the AEW, but with some enhancement of the drying below 700 hPa caused by heating over the Sahara.

Thus, the answer to the question posed in the title is that it is a bit of both: the SAL has been overhyped by some in the research community as a dominant negative influence on tropical cyclone genesis and evolution, but evidence to date also points to an occasional negative influence (Dunion and Velden 2004), mainly due to the effects of the dry SAL air. The picture is further complicated by evidence of a positive influence through the induced vertical circulation associated with the AEJ. As suggested by DV, the SAL is just one of many factors influencing tropical cyclogenesis and evolution in the Atlantic. Each storm must be examined carefully in the context of the larger-scale wind and thermodynamic fields (either from global analyses or satellite data), particularly in terms of other sources of vertical wind shear and dry air (i.e., subsidence drying vs. warming over the Sahara). The impact of African dust has not been evaluated here. Recent studies by Evan et al. (2007) and Lau and Kim (2007) have suggested a link between dust activity and seasonal hurricane activity, although it is not yet clear whether this link is causative or merely correlative (Evan et al. 2007). The impact of dust on microphysical processes and on hurricane intensity and evolution is even less clear, so caution should be taken before attributing to African dust a broad negative influence on seasonal hurricane activity or the development of individual storms.

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FIGURE CAPTIONS

Figure 1. (Left column) NCEP analyzed isotachs and streamlines at 700-hPa for the indicated days and times. Plots show the evolution of the easterly jet for hurricanes Florence and Helene (indicated by white dots) in September 2006. (Right column) The corresponding AIRS 850-hPa temperature and TRMM 24-h accumulated rainfall analyses.

Figure 2. (a) MODIS AOD, TRMM 24-h accumulated rainfall, and NCEP 700-hPa winds (isotachs, contours at 4 m s^{-1} intervals starting at 8 m s^{-1}) for 12 UTC 2 September 2006. (b-c) Vertical cross sections of meridional circulation (streamlines) and (b) zonal wind and (c) RH averaged between 20-40°W longitude. The location of the AEJ is indicated while arrows highlight the direction of the mean circulation.

Figure 3. TRMM 24-h accumulated rainfall (orange color shading) and (left) MODIS AOD, (middle) AIRS 850-700-hPa RH, and (right) AIRS 850-hPa temperature for (top row) 26 August 2003, (second row) 28 August, (third row) 30 August, and (bottom row) 1 September.

Figure 4. Monthly mean distribution of aerosol optical depth and surface rainfall rate for August 2006.

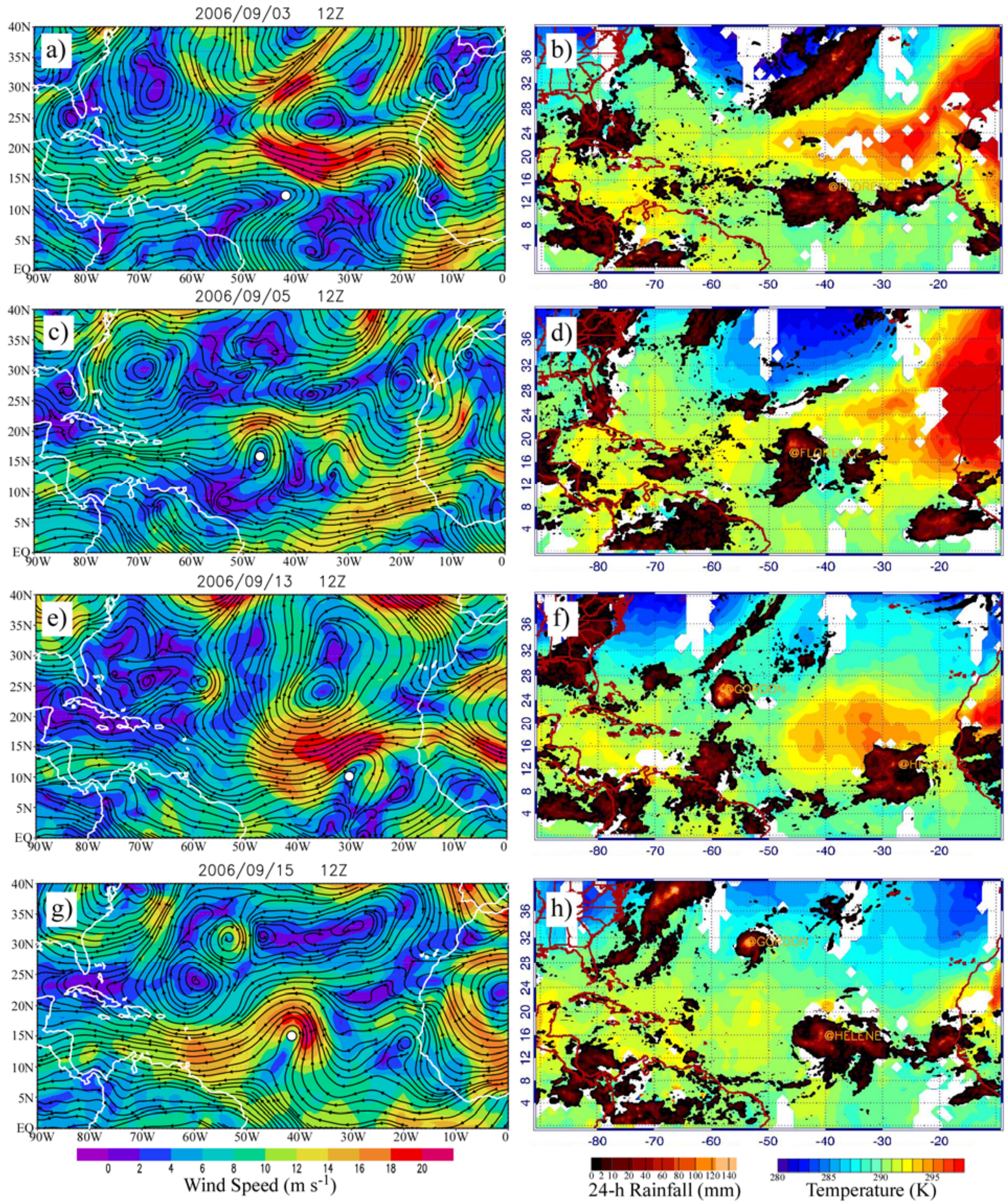
Figure 5. Regional monthly mean distribution for August 2006 of AIRS-derived (a, c, e) temperature at 500, 700, and 850 hPa, respectively, and (b, d, f) relative humidity for the 500-400, 700-600, and 850-700 hPa layers, respectively. (g) NCEP derived 700-600 hPa relative

humidity and layer-averaged streamlines and (h) 700 hPa vertical motion and streamlines. Black lines are streamlines while white contours are isotachs at 2 m s^{-1} intervals starting at 8 m s^{-1}.

Figure 6. Global monthly mean distribution for August 2006 of (a) AIRS-derived relative humidity for the 700-600 hPa layer, (b) NCEP derived 700-600 hPa relative humidity and streamlines and (c) 700 hPa vertical motion and streamlines. Red circular arrows in (a) represent the approximate locations of semi-permanent high and low pressure systems.

Table 1. Summary of the data used in this study.

Data Set	Measurement	Horizontal Resolution	Frequency	Description
TRMM	Rainfall rate (mm h^{-1})	0.25°	3 h	TRMM multi-satellite precipitation product (3B42) (Huffman et al. 2007)
MODIS	Aerosol optical depth	1°	24 h	MODIS Level 3 product (Salomonson et al. 1989)
AIRS/ AMSU	Temperature, relative humidity profiles	1°	12 h	AIRS Level 3 product, 13 vertical levels in troposphere (Aumann et al. 2003)
NCEP	3-D winds, temperature, relative humidity	1°	6 h	NCEP final analyses archived at NCAR



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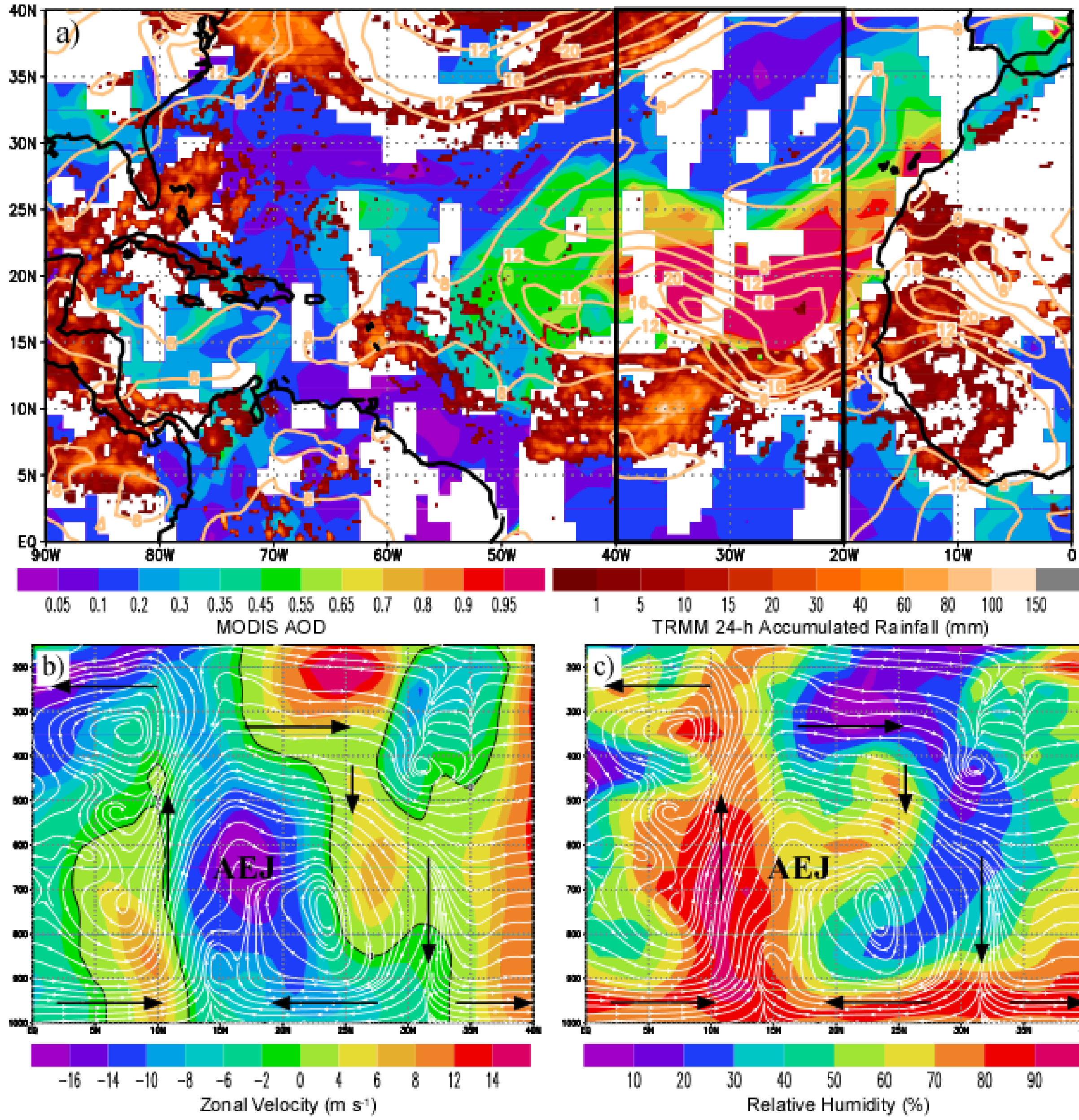

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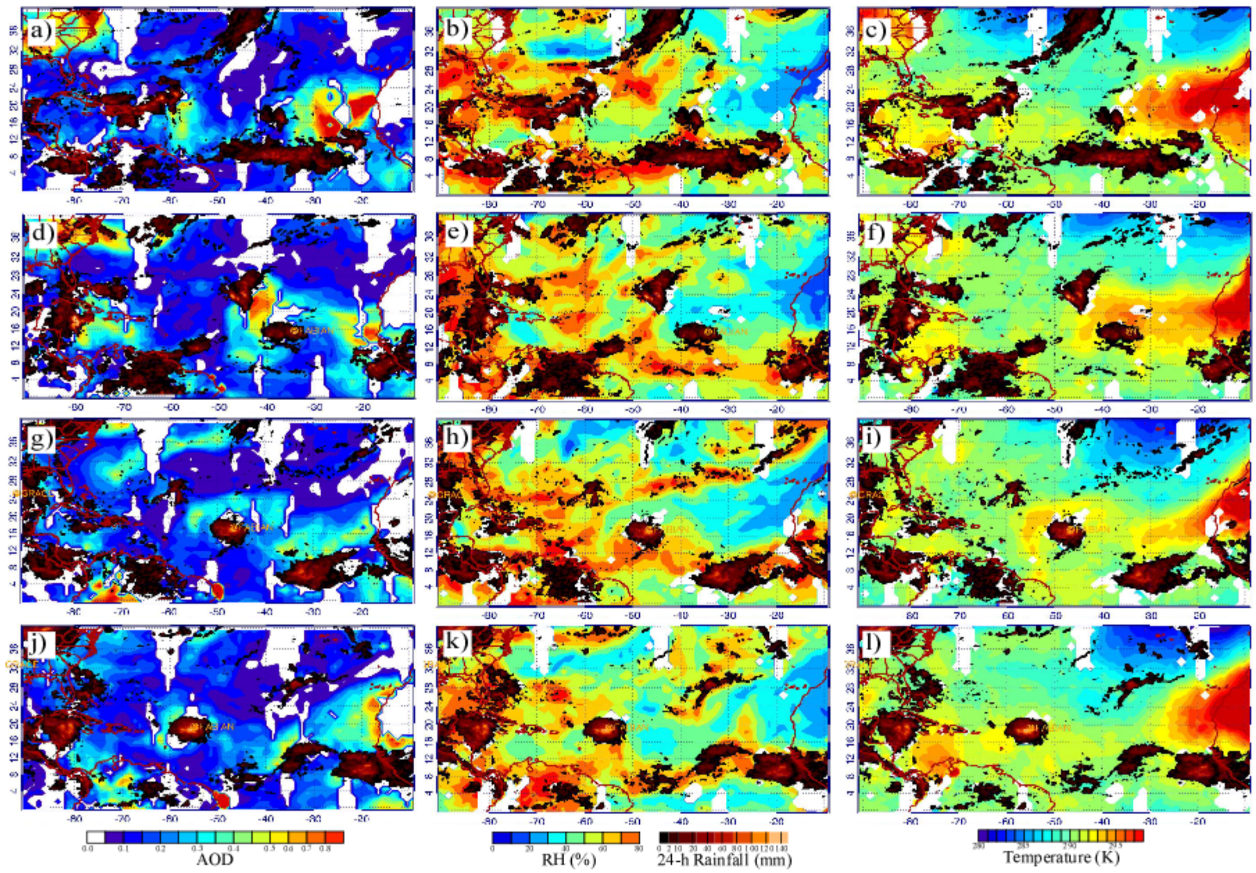

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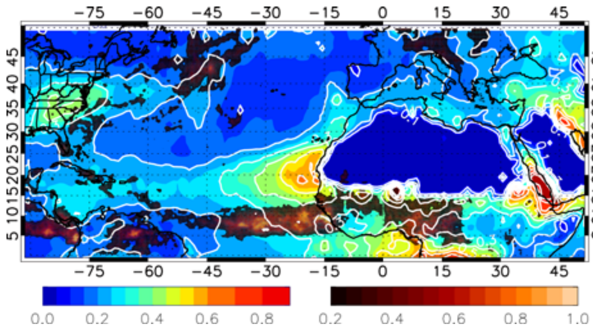
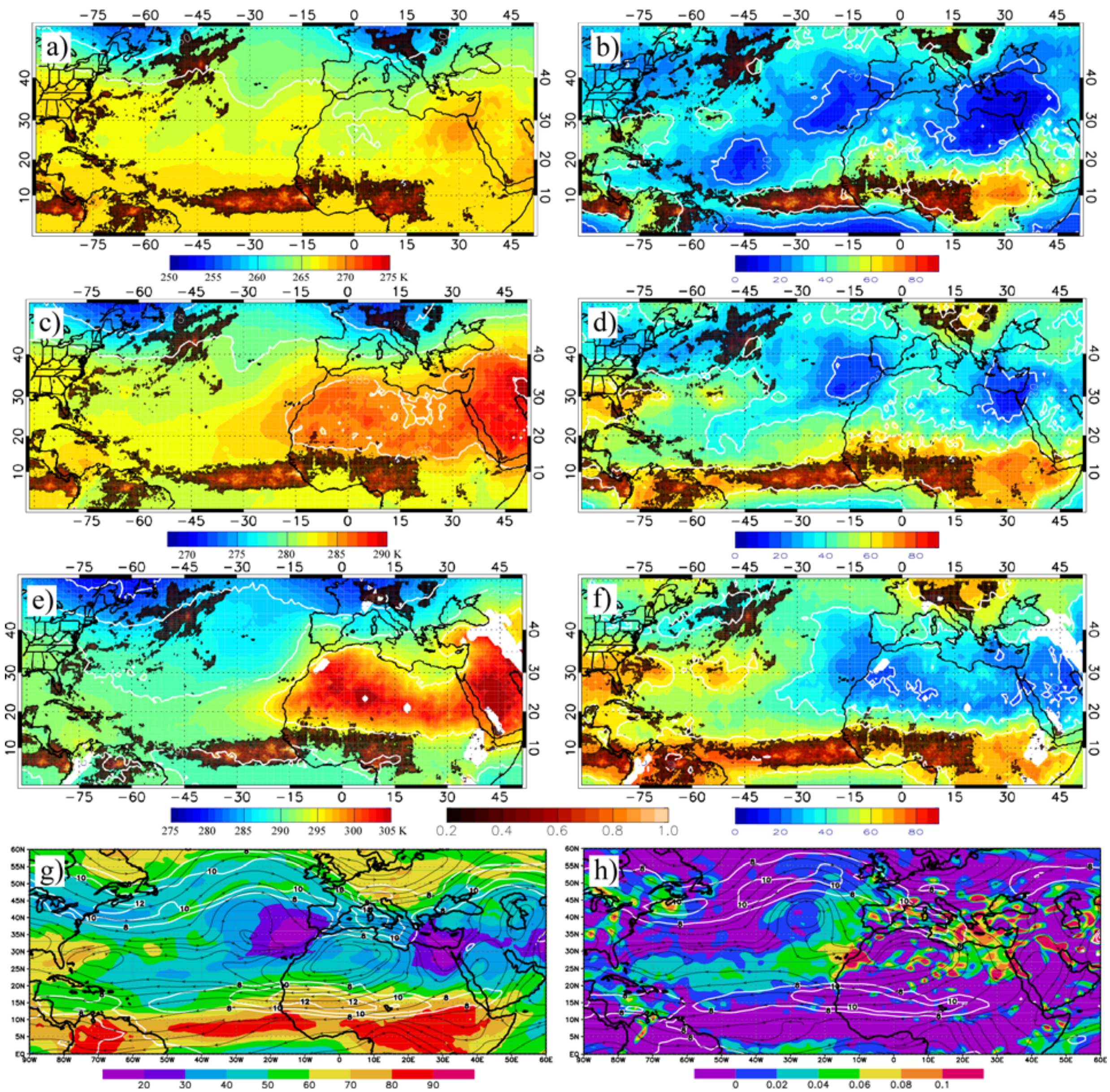


Figure 4. Monthly mean distribution of aerosol optical depth and surface rainfall rate for August 2006.



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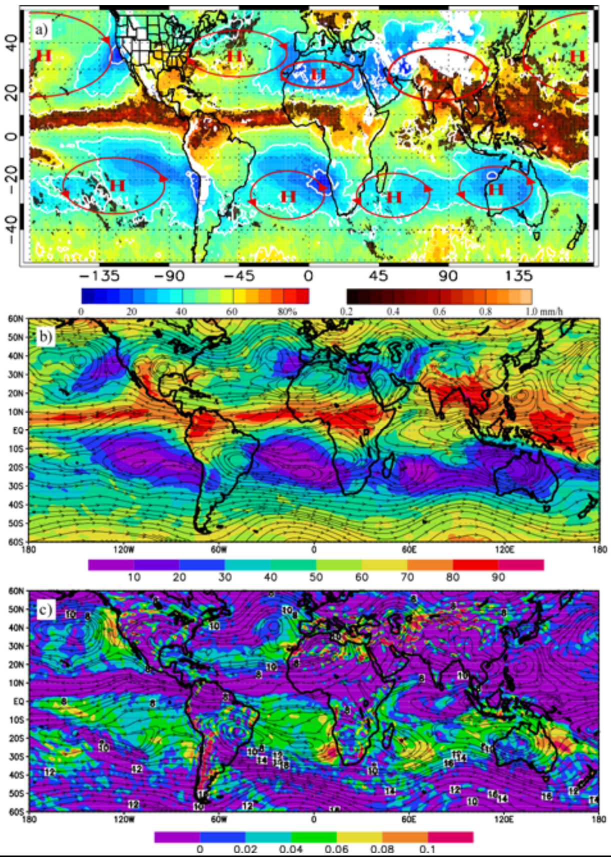

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