A Reexamination of the Jordan Mean Tropical Sounding Based on Awareness of the Saharan Air Layer: Results from 2002

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ABSTRACT

The Jordan mean tropical sounding has provided a benchmark for representing the climatology of the tropical North Atlantic and Caribbean Sea since 1958. However, recent studies of the Saharan air layer (SAL) have suggested that the tropical atmosphere in these oceanic regions may contain two distinct soundings (SAL and non-SAL) with differing thermodynamic and kinematic structures and that a single mean sounding like Jordan's does not effectively represent these differences. This work addresses this possibility by examining over 750 rawinsondes from the tropical North Atlantic Ocean and Caribbean Sea during the 2002 hurricane season. It was found that a two-peak bimodal moisture distribution (dry SAL and moist non-SAL) exists in this region and that the Jordan sounding does not represent either distribution particularly well. Additionally, SAL soundings exhibited higher values of geopotential height, unique temperature profiles, and stronger winds (with an enhanced easterly component) compared to the moist tropical non-SAL soundings. The results of this work suggest that the Jordan mean tropical sounding may need to be updated to provide a more robust depiction of the thermodynamics and kinematics that exist in the tropical North Atlantic Ocean and Caribbean Sea during the hurricane season.

1. Introduction

About 50 years ago, Jordan (1958) presented mean monthly and "hurricane season" (July–October) soundings of geopotential height, temperature, and humidity in the western tropical North Atlantic Ocean and Caribbean Sea. Since that time, these soundings have served as benchmarks for moist tropical soundings in the tropical regions of the Atlantic basin for observational (Frank 1977) and theoretical (Brown and Bretherton 1995; Gray and Craig 1998; Ooyama 2001) studies. Jordan, however, may have been unaware of an atmospheric phenomenon that could affect the reliability of his moist tropical soundings. That feature is the Saharan air layer (SAL) that Carlson and Prospero (1972) first described using soundings from Barbados and the central and eastern North Atlantic Ocean. Soundings of the SAL reveal warm, dry, and dusty air between 500 and 850 hPa and the presence of an embedded midlevel (~600–800 hPa) easterly jet. The SAL is most active (larger outbreaks that reach farther west into the North Atlantic) in the late spring and early summer, has been shown to sometimes cover areas larger than the contiguous United States, and can reach as far west as the western Caribbean Sea and Gulf of Mexico (Dunion and Velden 2004).

Jordan (1958) suggested that "the relatively small geographical and seasonal variability found in the tropics makes the mean atmospheric soundings for these areas much more representative of the conditions that may be expected at any given time and place." However, Dunion and Velden (2004) suggested that the tropical North Atlantic Ocean is likely characterized by a multiple distribution of soundings that include non-SAL (moist tropical) and SAL. It seems likely that numerous SAL events may have been sampled in Jordan's 10-yr mean hurricane season sounding. Here, we examine the hypothesis that the SAL had a significant effect on these soundings. The results presented here could

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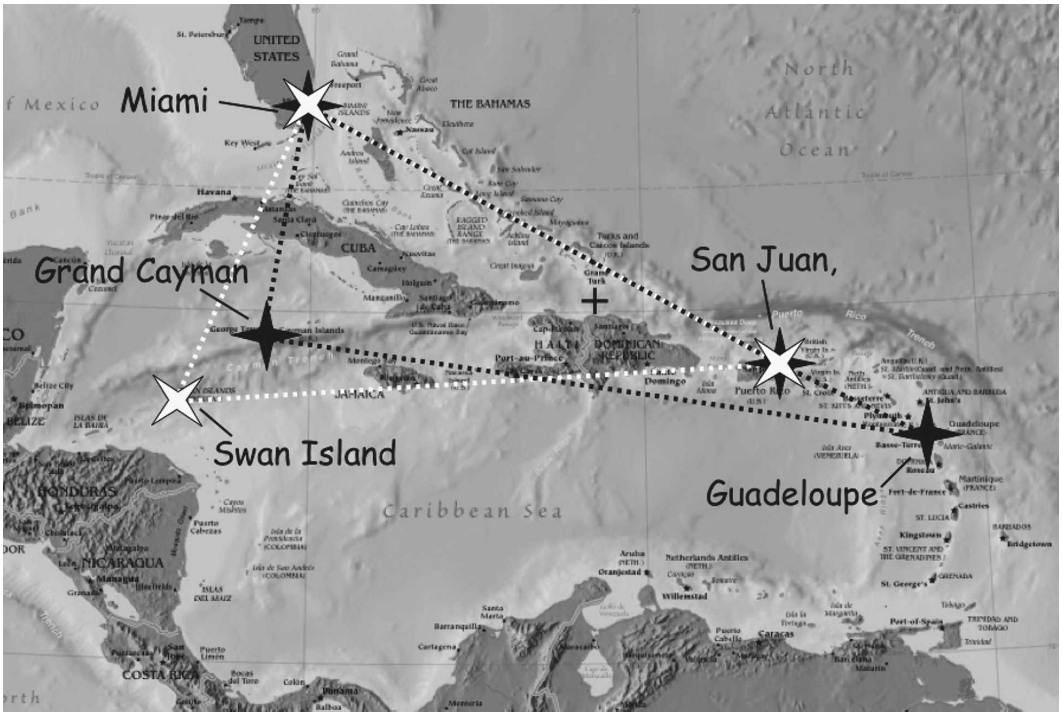

Fig. 1. Rawinsonde stations used in the Jordan (1958) study (white markers) and the current 2002 study (black markers). The black crosshair located north of Hispaniola (20.2°N, 71.6°W) indicates the geographic center of the 770 rawinsondes used in the 2002 dataset (normalized by the number of soundings that were included from each of the four stations).

have important implications related to our understanding of the climatology of the tropical North Atlantic and Caribbean and whether or not the use (e.g., in climate and modeling studies) of the Jordan (1958) "hurricane season" sounding as a standard background state for this region is appropriate.

2. Background

a. Jordan mean tropical sounding

Jordan (1958) compiled a mean tropical sounding for the West Indies "hurricane season" (July–October) using rawinsonde data for the 10-yr period from 1946 to 1955. He selected three rawinsonde stations to develop his climatology (Fig. 1)—Miami, Florida (WMO index: 72202); San Juan, Puerto Rico (WMO index: 78526); and Swan Island[1] (WMO index: 78501)—and used only nighttime (0300 UTC) soundings to generate his statistics, citing inhomogeneities in the daytime (1500 UTC) soundings that related to the different methods for correcting radiative effects in the 1946–55 dataset. Jordan also mentioned that in his dataset "the processing of humidity data required special consideration because of the fact that reports are always missing when the humidity is low." From 1945 to 1965, the United States utilized a lithium chloride hygrometer in its rawinsondes (Wade 1994). Low humidity values were transmitted and recorded in the low frequency region of the 10–200-Hz audio range and, because of the slope of the hygristor's response curve, low RH values (<15%–20%) could not be evaluated (Wade 1994). Below this limit, the rawinsonde humidity was unmeasurable and said to be "motorboating," a term named after the sound heard through the monitoring speaker of an audio-modulated rawinsonde that resembled the sound of a motorboat (Wade 1994). Jordan referred to rawinsonde motorboating in his 1958 study and used the "motorboating average threshold" humidity values for these situations (Jordan 1958). Presumably, his lower-limit threshold values would have been ~15%–20% RH, though he does not specifically state this. Jordan's methodology for dealing with low RH values, com-

[1] The Swan Islands are a small three-island chain located at ~17°N, 83°W, approximately 145 km north of Honduras in the western Caribbean Sea. The U.S. Weather Bureau established a weather station on Great Swan Island in 1938 and sovereignty of these islands was transferred from the United States to Honduras in 1972. The Swan Island weather station no longer provides daily rawinsonde reports.

bined with the limitations of the rawinsondes of the time, could have introduced a moist bias in Jordan's mean sounding statistics.

b. The Saharan air layer

A deep well-mixed, dry adiabatic layer forms over the Sahara Desert and Sahel regions of North Africa during the late spring, summer, and early fall. As this air mass advances westward and emerges from the northwest African coast, it is undercut by cool, moist low-level air and the SAL mixed layer becomes elevated. The SAL contains very dry air and substantial mineral dust lifted from the arid desert surface over North Africa and is often associated with a 10–25 m s^{-1} midlevel easterly jet (Carlson and Prospero 1972; Karyampudi and Carlson 1988). Recently developed multispectral Geostationary Operational Environmental Satellite (GOES) infrared satellite imagery detects the presence of dry and/or dusty air in the lower to middle atmosphere (e.g., the SAL) (Dunion and Velden 2004). Therefore, this imagery can be used to track the SAL as it moves westward over the North Atlantic. Dunion and Velden used this new type of GOES imagery to identify global positioning system (GPS) dropwindsondes that inadvertently sampled the SAL during several recent operational NOAA Gulfstream-IV hurricane surveillance missions. They examined these GPS dropwindsonde data and found large differences in atmospheric moisture between dropwindsondes launched in moist tropical (non-SAL) versus SAL environments. They noted that the RH (mixing ratio) in the SAL was ~25%–35% (~1.5–3.5 g kg^{-1}) lower than the non-SAL sounding in the layer from 500 to 850 hPa. The Jordan mean (July–October) moisture sounding was found to lie between these two soundings, suggesting that Jordan's original dataset may have contained a mixture of both SAL and non-SAL soundings. This implies that the Jordan mean sounding may, in fact, contain bimodally distributed moisture data, a detail that he may have been unaware of when he published his original atmospheric sounding work in 1958. SAL and non-SAL soundings are also likely associated with distinct vertical profiles of geopotential height, temperature wind speed, and wind direction, which may have also influenced Jordan's mean soundings.

3. Methodology

To examine the possibility that the Jordan mean "hurricane season" sounding is actually the average of two distinct environments (SAL and non-SAL) that tend to dominate the tropical North Atlantic and Caribbean Sea region, we attempted to recreate Jordan's original work by examining rawinsondes from the 2002 Atlantic hurricane season. Four tropical sounding stations were selected for this study (Fig. 1): Owen Roberts Airport, Grand Cayman (WMO index: 78384); Miami, Florida (WMO index: 72202); San Juan, Puerto Rico (WMO index: 78526); and La Raizet, Guadeloupe (WMO index: 78897). During 2002, the sounding systems at these four sites utilized VIZ-B2 (United States), Vaisala RS80–57H, VIZ-B2 (United States), and Vaisala RS90/Star (Finland) rawinsondes, respectively. The set of stations used in this study differ slightly from the stations used by Jordan. It should be noted that Swan Island, used in Jordan's 1958 study, is no longer an active rawinsonde station. For the current study, we chose Grand Cayman and Guadeloupe to supplement this missing station. It should also be noted that Guadeloupe is located farther east than any station that Jordan used in his dataset. Owing to its eastward location, the inclusion of this station could equate to a relatively greater number of detected SAL soundings in the 2002 dataset. However, although this could impact the relative number of SAL versus non-SAL soundings, it is unlikely that the thermodynamics and kinematics of the SAL and non-SAL soundings at this site would be significantly different from those at the other three sites.

Twice daily (0000 and 1200 UTC) rawinsondes were collected from July to October 2002. GOES SAL tracking imagery (Dunion and Velden 2004) was used to distinguish between rawinsondes launched in SAL versus non-SAL environments. This satellite imagery is sensitive to the presence of dry, dusty low- to midlevel air (~600–925 hPa) via the enhancement of the brightness temperature (BT) differences between the 12- and 10.7-μm channels ($BT_{12} - BT_{10.7}$) on the GOES satellites (Dunion and Velden 2004). We followed the criteria presented by Dunion and Velden and used differences in BT values between -4 ($\sim-2°C$) and $+4$ ($\sim+2°C$) to represent SAL environments, while BT differences $>+4$ ($\gtrsim+2°C$) were selected to represent moist non-SAL regions.

Animations of the GOES SAL tracking satellite imagery allows one to distinguish dry air associated with the SAL from dry air associated with intrusions of midlatitude fronts. A small percentage (<5%) of the rawinsondes in this study were launched in continental or polar dry air environments; these soundings were identified as non-SAL soundings in the dataset. Occasional rawinsonde failures coupled with the fact that not all rawinsonde stations reported twice per day, especially in the early summer months (e.g., Grand Cayman), also reduced the size of the rawinsonde dataset.

Nevertheless, over 750 soundings were analyzed from the four rawinsonde stations for the period from July to October 2002.

It should be emphasized that the compositing of hundreds of soundings in this study likely smoothed out some of the finer-scale thermodynamic (e.g., small-scale temperature inversions at the SAL top and base and steep lapse rates above the SAL base) and kinematic (e.g., the SAL's midlevel easterly jet) features that are often present in individual SAL soundings. Additionally, this work examined mandatory level rawinsonde data only, which limited the vertical resolution of the mean soundings that were created. Again, this would likely act to "wash out" some of the finer-scale thermodynamic and kinematic features that are found in some of the individual soundings. Still, this methodology does replicate, as closely as possible, Jordan's original sounding work. It should also be noted that the mean soundings presented in this study are more applicable to the tropical western and central North Atlantic and Caribbean Sea regions. The atmospheric conditions and SAL characteristics found over the eastern North Atlantic are quite unique and mean soundings in this part of the basin would likely be slightly different from those presented here (e.g., stronger temperature inversions at the SAL top and base, warmer temperatures in the SAL layer, stronger midlevel easterly jets, and lower SAL bases).

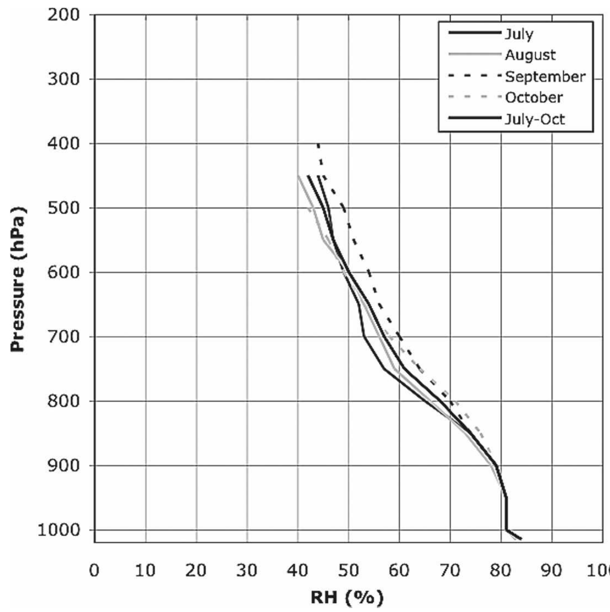

FIG. 2. The Jordan (1958) mean tropical moisture soundings for the months of July, August, September, and October and the mean for July–October.

4. Results

a. *Mean tropical soundings: Jordan versus 2002*

Jordan's original work in 1958 showed that the mean July, August, September, and October tropical moisture soundings were very similar (Fig. 2). These results may have led Jordan to conclude that a mean July–October "hurricane season" moisture sounding would exhibit a fairly low standard deviation. However, since the SAL is active throughout the summer months and often extends well into the Caribbean Sea (Carlson and Prospero 1972; Dunion and Velden 2004), Jordan's sounding is likely a mixture of both SAL and non-SAL (moist tropical) soundings. To confirm this hypothesis, Jordan's mean July–October sounding was compared with the mean sounding calculated from all of the 770 soundings from July to October 2002. Figure 3 shows that these two mean "hurricane season" soundings are quite similar (RH differences were <3.5% between 450 hPa and the surface). Similar consistencies between the 2002 data and Jordan's mean sounding were noted in values of temperature, geopotential height, and mixing ratio (differences of $\leq 0.7°C$, ≤ 10.0 m, and ≤ 0.5 g kg^{-1}, respectively) and are not shown. Figure 3 also shows that, similar to Jordan's original work in 1958 (Fig. 2), the 2002 mean July, August, September, and October tropical moisture soundings were markedly alike. The next section will show that the 2002 mean "hurricane season" sounding is actually a mixture of SAL and non-SAL soundings.

b. *SAL versus non-SAL tropical soundings (2002)*

GOES SAL-tracking satellite imagery was used to identify over 750 SAL and non-SAL soundings throughout the four-month period of this 2002 study. Figure 4 shows an example of the GOES SAL tracking imagery used to distinguish between the SAL and non-SAL soundings. This figure indicates a significant Saharan air layer outbreak extending from Africa to the central Caribbean Sea at 0000 UTC 30 July 2002. Here, San Juan and Guadeloupe were located in the SAL, whereas Grand Cayman and Miami were in a region of moist tropical (non-SAL) air. Figure 5 shows the biweekly frequency distribution of these two distinct moisture soundings for the period June–October 2002 determined from the GOES SAL tracking imagery. The SAL comprised ~50%–70% of the Caribbean soundings during the early summer, which corresponds well with results from Carlson and Prospero (1972) who found that SAL outbreaks are typically more frequent during the early months of the summer. Figure 5 also shows that by the late summer, though the SAL was still reaching the western North Atlantic and Caribbean Sea

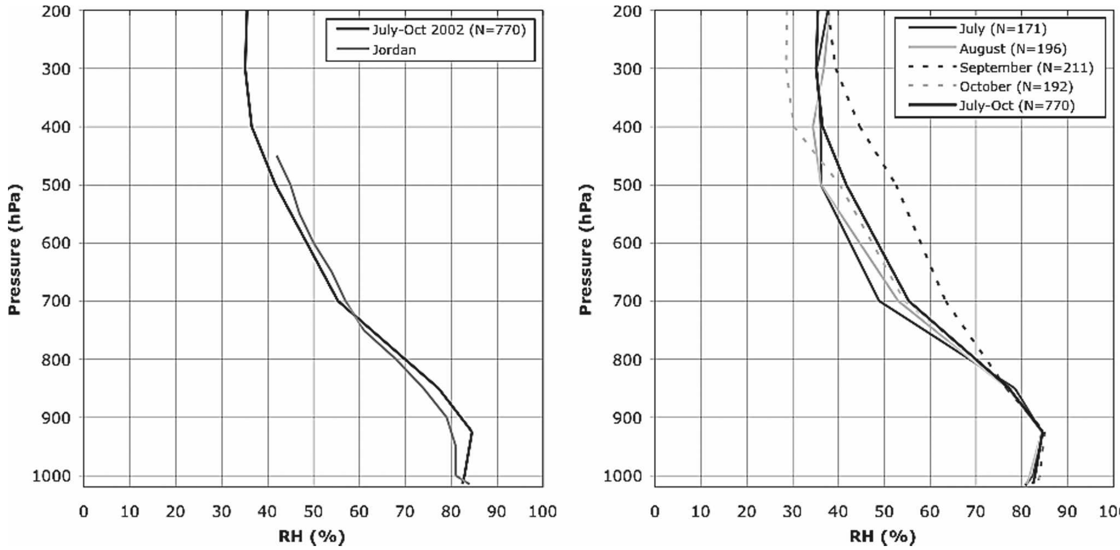

FIG. 3. (left) The mean July–October 2002 sounding vs the Jordan (1958) mean tropical sounding (July–October) and (right) the mean soundings for the months of July, August, September, and October 2002, and the July–October 2002 mean.

sounding stations, moist soundings (non-SAL) began to dominate the region (~70%–95% of the soundings). This corresponds well with results from DeMaria et al. (2001) who found that, during the hurricane season, midlevel moisture in the tropical North Atlantic is climatologically near its minimum value from July to mid-August and rapidly increases in the late summer and early fall. These results suggest that early summer SAL activity (larger outbreaks that reach farther west into the North Atlantic) may contribute to the relatively few African easterly waves that develop into tropical cyclones during this time of year. Figure 5 also indicates that approximately 30% of the 2002 June–October soundings were identified as SAL. This suggests that the SAL is an important consideration when compiling a climatology for the tropical North Atlantic Ocean and Caribbean Sea.

1) SAL VERSUS NON-SAL SOUNDINGS: MOISTURE

Grouping the 2002 rawinsonde data used to create Fig. 3 (left) into SAL versus non-SAL monthly averages produced striking results. Figure 6 shows that the mean SAL monthly soundings were consistently drier than the Jordan mean, whereas the non-SAL soundings were moister. This figure suggests that the SAL and

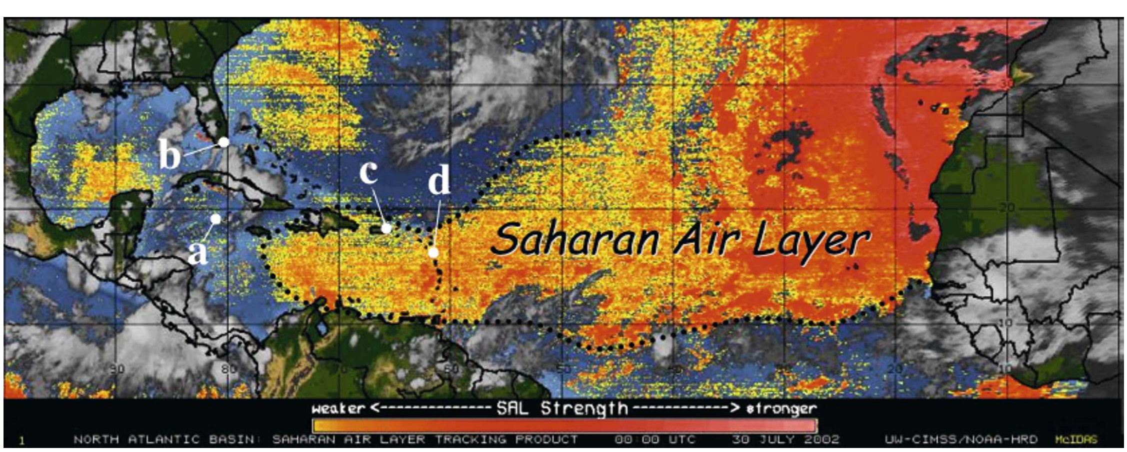

FIG. 4. GOES SAL-tracking imagery for 0000 UTC 30 Jul 2002 indicating a large SAL outbreak spanning from the western Caribbean Sea to the eastern North Atlantic (black dashed curve). The yellow–red shading depicts increasing amounts of dust content and dry lower-tropospheric air, as detected by the GOES imagery. The (a) Grand Cayman, (b) Miami, (c) San Juan, and (d) Guadeloupe rawinsonde stations are indicated for reference.

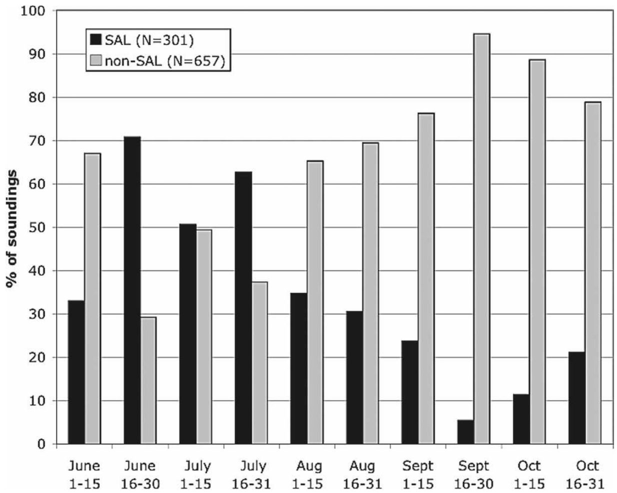

FIG. 5. Biweekly occurrences of SAL and non-SAL soundings from June to October 2002 at the Grand Cayman, Miami, San Juan, and Guadeloupe rawinsonde stations. Approximately 70% of the June–October soundings were moist tropical (non-SAL) while ~30% were SAL.

non-SAL July–October mean soundings would be significantly different from the Jordan mean tropical sounding. Indeed, Fig. 7 shows that at 700 hPa (the approximate vertical center of the SAL), two-peak probability distribution functions (PDFs) (dry SAL and moist non-SAL) exist for RH and mixing ratio in the mean 2002 July–October rawinsonde dataset. In fact, ~90% of the 700-hPa SAL soundings from 2002 were drier than 50% RH, while ~90% of the non-SAL soundings were moister than 50% RH. This two-peak tendency in humidity is also clearly evident at the 500-hPa (typical upper extent of the SAL) and 850-hPa (typical SAL base) levels (not shown). Figure 8 reflects these bimodal PDFs and shows that the mean July–October 2002 SAL and non-SAL moisture soundings are quite distinct. The 2002 combined mean moisture sounding (and Jordan "hurricane season" sounding, not shown) lies in between these two discrete soundings, though it is skewed toward the non-SAL sounding. This is not surprising since the ratio of non-SAL to SAL soundings in the July–October 2002 dataset was about 2.5:1 (~70% and ~30% of the 770 soundings respectively).

Figure 8 also shows that the moisture differences between the SAL and non-SAL mean soundings extend well above the typical vertical extent of the SAL (~500 hPa). This suggests that mid- to upper-level dry air, perhaps associated with the climatological mid-Atlantic anticyclone (i.e., Bermuda high), is preferentially associated with SAL outbreaks. It may also suggest that, because the SAL is associated with suppressed convection, it is consequently associated with less deep atmospheric moisture than the typical non-SAL environment. This aspect is beyond the scope of this study and requires further investigation. Certainly, the largest differences between the SAL and non-SAL soundings were in the ~500–850-hPa layer, as would be expected. Here, differences in RH (mixing ratio) between the two 2002 soundings were as high as 33% (2.8 g kg^{-1}; Fig. 8). The mixing ratio differences between the two soundings were also highly statistically significant (99.9% from a Student's t test) for the 500-, 700-, and 850-hPa

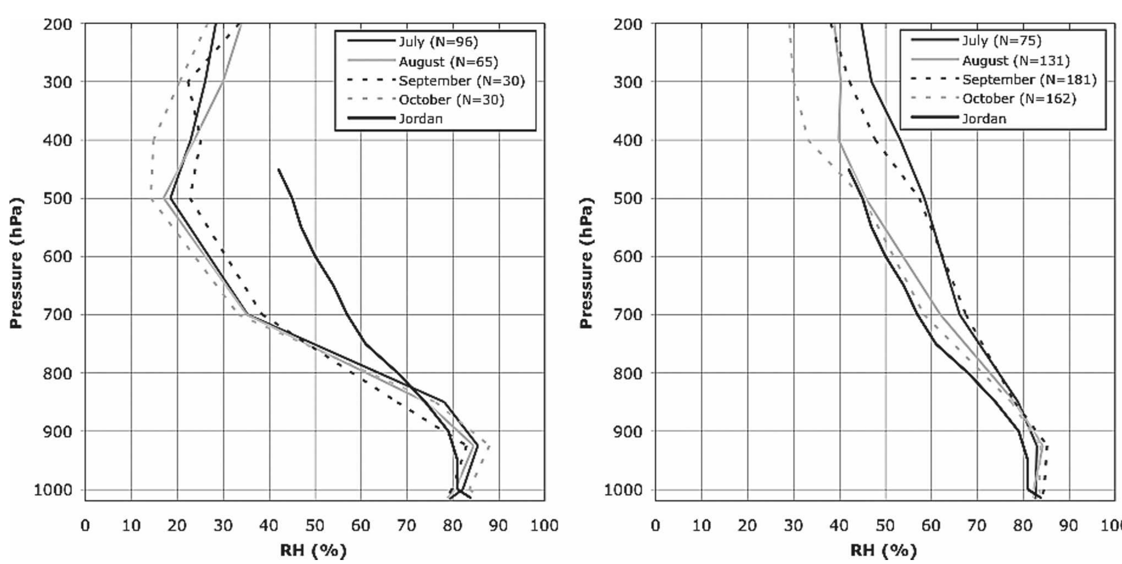

FIG. 6. Monthly mean moisture soundings of (left) SAL vs (right) non-SAL rawinsondes for July, August, September, and October 2002. The Jordan (1958) mean "hurricane season" moisture sounding (July–October) is included for reference.

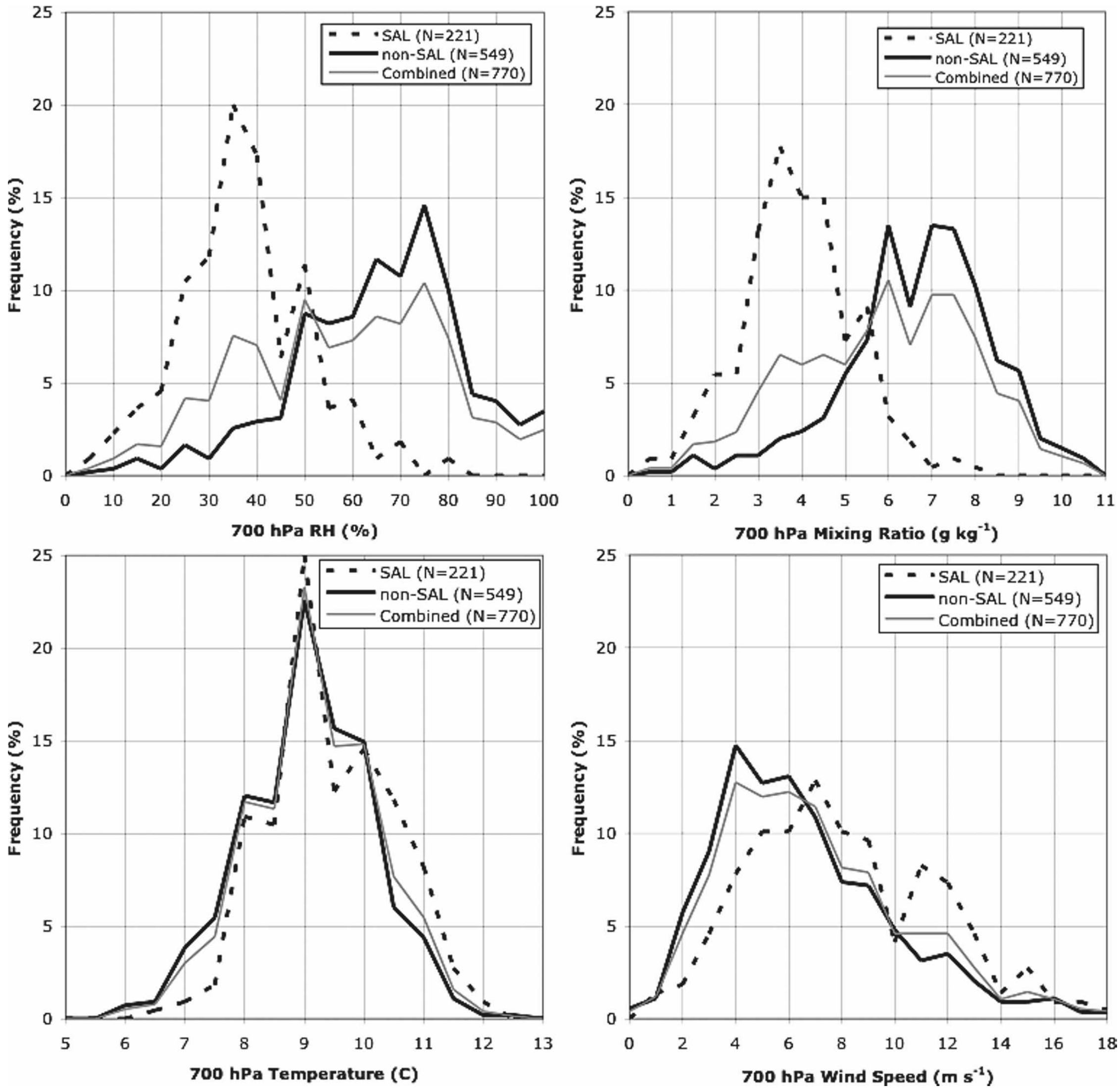

FIG. 7. Probability distribution functions of the mean July–October 2002 SAL, non-SAL, and combined (SAL and non-SAL) 700-hPa soundings of (top left) RH (%), (top right) mixing ratio (g kg^{-1}), (bottom left) temperature (°C), and (bottom right) wind speed (m s^{-1}).

levels. Additionally, Table 1 shows that above the base of the SAL (~850 hPa) the standard deviations of the mean July–October SAL and non-SAL moisture soundings at 500 and 700 hPa were lower than those of the mean combined dataset. This suggests that much of the variability associated with the combined 2002 sounding was due to the fact that it contained a bimodal distribution (two-peak PDF) of moisture soundings (SAL and non-SAL).

2) SAL versus non-SAL soundings: Temperature

Figure 7 indicates that the PDFs of the 700-hPa SAL and non-SAL temperatures both exhibit Gaussian distributions and that the SAL distribution is shifted slightly to the right (warmer temperatures) of the non-SAL distribution. However, the SAL and non-SAL 700-hPa temperatures do not have the same distinct bimodal (two-peaked) distributions that were evident in the 700 hPa humidity distributions. This suggests that the SAL's unique temperature characteristics may not be as robust as those of humidity, especially after it has traveled for thousands of kilometers from its source over the Sahara Desert.

Figure 8 and Table 2 show that the SAL was slightly cooler (0.2°–0.8°C) than the non-SAL sounding from 200 to 400 hPa. This may be related to the relatively drier air found to exist in the 200–400-hPa layer of the

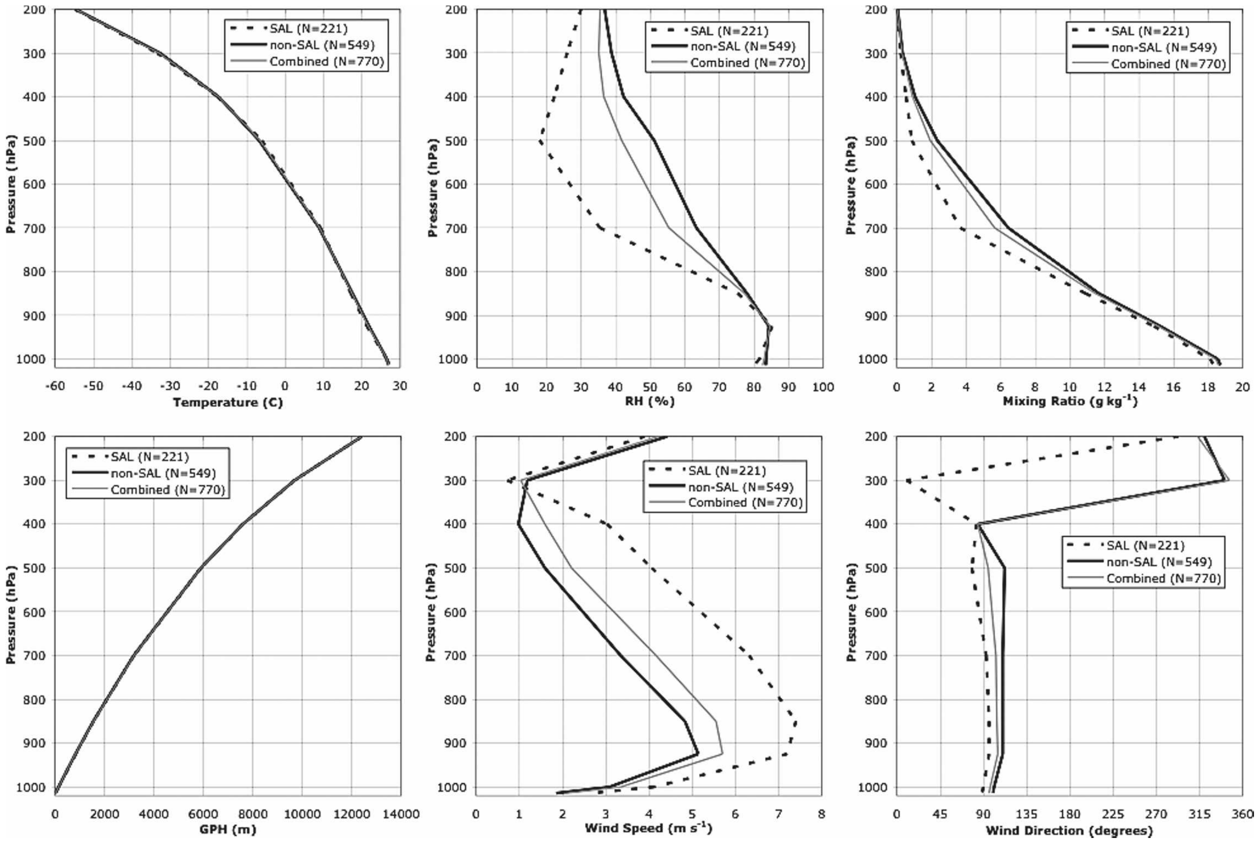

FIG. 8. Mean July–October 2002 SAL, non-SAL, and combined (SAL and non-SAL) soundings of (top left) temperature (°C), (top middle) RH (%), (top right) mixing ratio (g kg^{-1}), (bottom left) geopotential height (m), (bottom middle) wind speed (m s^{-1}), and (bottom right) wind direction (degrees).

mean SAL sounding. Radiational cooling above the SAL would likely be greater (more net cooling) in this relatively drier mid- to upper-level layer. Another possible explanation for this temperature difference is that the SAL sounding, because of its warmth, experiences some vertical ascent that pushes the air above it upward, thereby cooling it. In the middle levels of the atmosphere, (~500–700 hPa), the SAL sounding was warmer (0.3°–0.7°C) than that of the non-SAL. This relates to the SAL origins over the hot Sahara Desert and to the fact that the SAL warmth is partly preserved by solar heating of the SAL's suspended mineral dust (Carlson and Benjamin 1980; Dunion and Velden 2004). Diaz et al. (1976) described the temperatures at the base of the SAL to be ~5°–10°C warmer than the Jordan (1958) mean tropical sounding. The low to midlevel temperature differences between the 2002 SAL and non-SAL soundings were fairly modest compared to those suggested by Diaz et al. However, their earlier study was based on data collected several hundred kilometers east of Barbados, while the rawinsonde stations used in this 2002 study ranged from ~4500 to 6500 km west of the coast of North Africa. The geographic center point of the 2002 dataset (normalized by the number of soundings that were included from each of the four stations) was 20.2°N, 71.6°W—a point just north of Hispaniola. Therefore, it is likely that the SAL outbreaks sampled in this study had relatively more

TABLE 1. Standard deviations of the July–October 2002 mean combined dataset (regular font), SAL (bold), and non-SAL (italic) soundings from 500 to 850 hPa.

Pressure (hPa)	RH std dev (%)	Mixing ratio std dev (g kg^{-1})
500	28.0	1.27
	12.9	**0.58**
	26.9	*1.23*
700	20.9	2.03
	13.2	**1.28**
	17.9	*1.70*
850	13.8	1.89
	16.5	**2.14**
	12.6	*1.74*

TABLE 2. Mean Jordan (1958) (regular font), SAL (2002) (bold), and non-SAL (2002) (italic) "hurricane season" (July–October) atmospheric soundings.

Pressure (hPa)	Geopotential height (m)	T (°C)	RH (%)	Mixing ratio (g kg^{-1})	θ (K)	θ_e (K)	Wind speed (m s^{-1})	Wind direction (°)
200	12 396	−55.2	—	—	345.0	—	—	—
	12 410	**−54.9**	**30.0**	**0.03**	**345.6**	**345.9**	**3.9**	**293**
	12 412	*−54.6*	*36.8*	*0.04*	*346.4*	*346.6*	*4.4*	*320*
300	9682	−33.2	—	—	338.0	—	—	—
	9693	**−33.4**	**26.0**	**0.20**	**338.2**	**339.1**	**0.7**	**10**
	9687	*−32.6*	*38.8*	*0.32*	*339.1*	*340.6*	*1.2*	*341*
400	7595	−17.7	—	—	332.0	—	—	—
	7607	**−17.6**	**22.3**	**0.53**	**332.1**	**334.1**	**3.1**	**83**
	7596	*−17.4*	*42.3*	*1.05*	*332.2*	*336.2*	*1.0*	*84*
500	5888	−6.9	45.0	2.10	324.0	332.0	—	—
	5898	**−6.1**	**18.0**	**0.86**	**325.6**	**328.7**	**4.1**	**78**
	5888	*−6.8*	*51.1*	*2.33*	*324.6*	*332.8*	*1.6*	*112*
700	3182	8.6	57.0	5.83	312.0	329.0	—	—
	3190	**9.2**	**35.4**	**3.66**	**312.7**	**324.5**	**6.3**	**93**
	3181	*8.9*	*63.3*	*6.45*	*312.3*	*332.6*	*3.3*	*110*
850	1547	17.3	74.0	11.12	304.0	334.0	—	—
	1554	**17.1**	**75.3**	**10.92**	**304.1**	**336.9**	**7.4**	**96**
	1545	*17.6*	*78.0*	*11.69*	*304.3*	*339.7*	*4.8*	*110*
925	—	—	—	—	—	—	—	—
	825	**21.3**	**85.2**	**14.87**	**301.1**	**345.0**	**7.2**	**96**
	814	*21.8*	*84.3*	*15.23*	*301.4*	*346.7*	*5.1*	*110*
1000	132	26.0	81.0	17.92	299.0	345.0	—	—
	141	**26.4**	**81.6**	**18.10**	**299.6**	**352.8**	**4.1**	**90**
	129	*26.5*	*83.5*	*18.56*	*299.6*	*354.1*	*3.1*	*101*
P_{MSL}								
1015.1	—	26.3	84.0	18.54	298.0	345.0	—	—
1016.9	—	**27.3**	**79.9**	**18.35**	**299.1**	**352.9**	**2.6**	**88**
1015.1	—	*26.9*	*83.4*	*18.70*	*298.8*	*353.6*	*1.9*	*100*
Layer mean (500–850)	—	—	—	—	—	—	—	—
	3537	**6.8**	**43.0**	**5.17**	**304.0**	**330.1**	**7.4**	**96**
	3539	*6.5*	*64.2*	*6.82*	*304.3*	*335.0*	*3.3*	*110*

time to cool to temperatures that were closer to the surrounding ambient tropical atmosphere. Finally, the SAL was cooler (0.1°–0.5°C) than the non-SAL environment from ~850 to 1000 hPa. This may be due to the SAL suspended mineral dust attenuating the amount of solar energy that reaches the 850–1000-hPa layer below it. Also, the depth of the moist layer in the non-SAL environment was greater than that in the SAL. Therefore, when condensation occurs at these low levels, the non-SAL environment will experience more latent heating. The 500-, 700-, and 850-hPa temperature differences between the SAL and non-SAL soundings were highly statistically significant (99.9% from a Student's t test).

As previously mentioned, some of the temperature characteristics associated with the SAL (e.g., small-scale temperature inversions at the SAL top and base and steep lapse rates above the SAL base) are inherently smoothed in our mean soundings (see methodology section). Therefore, individual soundings that better represent the SAL's unique temperature profile would likely exhibit higher static stability near the SAL base and lower static stability above the SAL base than would be indicated in our mean SAL sounding.

3) SAL versus non-SAL soundings: Winds

Figure 7 indicates that the PDFs of the 700-hPa SAL and non-SAL wind speeds both exhibited Gaussian distributions and that the SAL distribution was shifted to the right (stronger winds) of the non-SAL distribution. Similar to 700-hPa humidity, the SAL and non-SAL 700-hPa wind speeds had a discernable (though less striking) two-peak bimodal distribution. This suggests that the SAL's unique wind speed characteristics may not be as robust as those for humidity, especially well west of the Sahara Desert. This tendency may also be partly explained by the fact that the SAL midlevel easterly jet has a relatively narrow vertical extent (often only 100–200 hPa thick). The SAL, while markedly warmer than the surrounding environment at its base, cools rapidly with altitude and actually becomes cooler than its surroundings just above the jet level. Thus, the thermal wind vector quickly reverses itself by 180° above the jet, resulting in a relatively shallow midlevel jet feature. The magnitude of these rather subtle midlevel jets may not be sufficiently represented in soundings that contain only mandatory level data.

Figure 8 and Table 2 suggest that the lower to middle tropospheric winds (surface to 400 hPa) in the SAL sounding tended to be stronger and more easterly than the non-SAL sounding. This was evident in the 500–850-hPa layer mean winds (Table 2) and was most pronounced at 700 hPa (the approximate vertical center of the SAL). The layer mean 500–850-hPa and 700-hPa winds in the SAL sounding were approximately two times stronger and had a more easterly component than the non-SAL sounding. This is likely related to the SAL midlevel easterly jet that is maintained by the temperature contrasts that exist between the SAL and the relatively cooler tropical air to its south through thermal wind balance. The 500-, 700-, and 850-hPa wind speed differences between the SAL and non-SAL soundings were highly statistically significant (99.9% from a Student's *t* test).

c. *Evidence of SAL soundings in the Jordan 1946–55 rawinsonde dataset*

The 2002 rawinsonde dataset utilized in this study indicates that approximately 30% of the atmospheric soundings recorded in the Caribbean from July to October contained Saharan air. Additionally, the SAL and non-SAL soundings that were identified in these soundings were associated with distinct vertical moisture profiles. The 2002 rawinsonde data also showed that by averaging all of the July–October 2002 rawinsonde moisture profiles together, the resulting profile was very similar to the Jordan mean "hurricane season" sounding, suggesting that Jordan's 1946–55 dataset may have contained a mixture of SAL and non-SAL soundings. Since the Jordan 1946–55 rawinsonde dataset predates the satellite era, an objective technique for identifying SAL versus non-SAL soundings using GOES SAL-tracking imagery could not be applied to his dataset. Therefore, a simple method for objectively identifying the presence of SAL and non-SAL soundings in Jordan's dataset was developed using statistics from the current 2002 study. We examined a 5-yr subset of the Jordan dataset (San Juan, Puerto Rico; 1948–52) and used the following criteria to identify SAL and non-SAL soundings: 1) only San Juan nighttime (0300 UTC) soundings for the months of July and August were examined (in order to reduce the likelihood that midlatitude dry-air intrusions would be present in any of the soundings); 2) a sounding with a mean 600–800-hPa RH that was within one standard deviation of the mean 600–800-hPa RH in the 2002 SAL sounding was designated as a SAL sounding (37.5% RH ± 9% RH); 3) a sounding with a mean 600–800-hPa RH that was within one standard deviation of the mean 600–800-hPa RH in the 2002 non-SAL sounding was designated as a non-SAL sounding (63.7% RH ± 14% RH).

Using the criteria described above, 288 soundings (130 SAL and 158 non-SAL) were identified in the Jordan 1948–52 rawinsonde dataset for San Juan, Puerto Rico, for the months of July and August. Figure 9 shows that at 700 hPa (the approximate vertical center of the SAL) two-peak PDFs (dry SAL and moist non-SAL) exist for RH in the Jordan rawinsonde dataset. Similar to the 2002 dataset, ~90% of the SAL soundings identified in Jordan's dataset were drier than 50% RH at 700 hPa, while ~90% of the non-SAL identified soundings were moister than 50% RH at 700 hPa. Figure 9 also shows that the mean SAL and non-SAL moisture soundings in Jordan's dataset are quite distinct. The combined (SAL and non-SAL) mean moisture sounding lies in between these two discrete soundings, though it is skewed slightly toward the non-SAL sounding since there were slightly more non-SAL soundings than SAL soundings that were identified for this period. This objective analysis of a subset of Jordan's original sounding dataset strongly suggests that, similar to the 2002 dataset, his mean "hurricane season" sounding likely contained a significant number of SAL soundings. The PDFs of 700-hPa RH (Fig. 7) and mean SAL, non-SAL, and combined soundings (Fig. 8) for the 2002 dataset and a subset of Jordan's 1946–55 dataset (Fig. 9) were also strikingly similar.

5. Conclusions and future work

This 2002 study attempted to replicate the Jordan (1958) mean "hurricane season" tropical sounding. Temperature, relative humidity, and mixing ratio differences (200 hPa to the surface) between the Jordan mean sounding and the 2002 mean sounding presented here ranged from only 0.1° to 0.7°C, 1.6% to 3.3%, and 0.01 to 1.49 g kg^{-1}, suggesting that the two soundings were quite highly correlated. GOES SAL-tracking satellite imagery was then used to separate the 2002 rawinsonde dataset into dry SAL and moist non-SAL

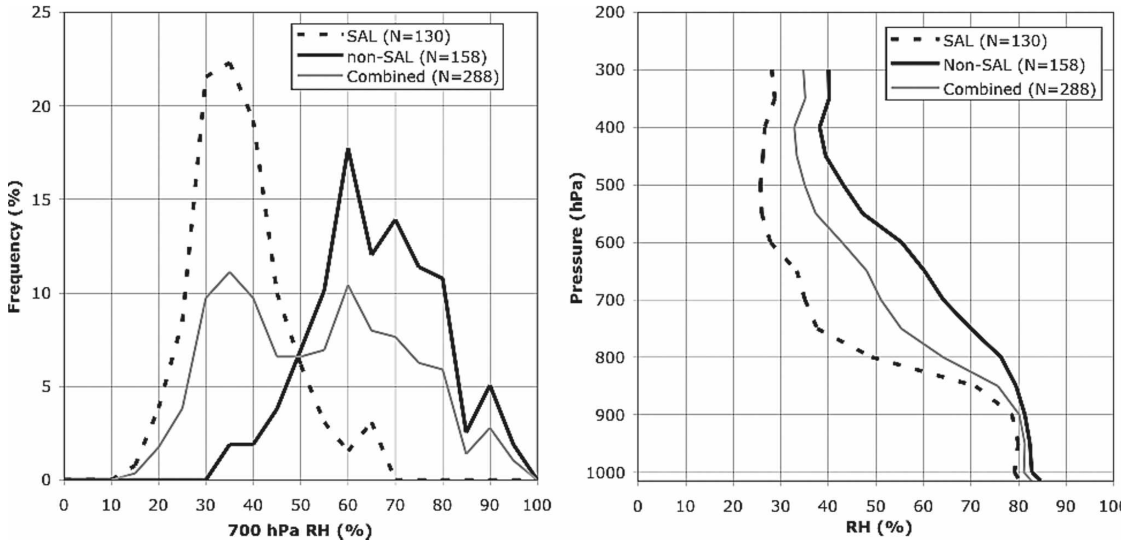

FIG. 9. (left) PDFs of the mean July–August (1948–52) SAL, non-SAL, and combined (SAL and non-SAL) 700-hPa soundings of RH (%) for San Juan, Puerto Rico. (right) Mean July–August (1948–52) SAL, non-SAL, and combined (SAL and non-SAL) soundings of RH for San Juan, Puerto Rico.

mean soundings. Results showed that a two-peak bimodal distribution (70% non-SAL, 30% SAL) of moisture existed in the tropical North Atlantic Ocean and Caribbean Sea from July to October 2002. Statistics from the 2002 dataset were then used to develop an objective method for identifying SAL and non-SAL soundings in a subset of Jordan's original dataset. This analysis showed the existence of a distinct two-peak bimodal distribution of moisture (dry SAL and moist non-SAL) in Jordan's dataset and also indicated that the mean SAL and non-SAL relative humidity profiles present in his data were strikingly similar to those found to exist in the 2002 rawinsonde dataset that was presented in this study. These findings suggest that Jordan's mean sounding may have unknowingly contained a mixture of SAL and non-SAL soundings. The information presented here also suggests that the SAL appears to influence values of humidity, temperature, wind speed, wind direction, and pressure height (Table 2). Specifically,

- The SAL appears to have a profound affect on the atmospheric moisture over the tropical North Atlantic Ocean and Caribbean Sea. The mixing ratio of the 2002 mean SAL sounding was ~40%–60% drier than the mean non-SAL sounding at 500 and 700 hPa and was drier at every level from 200 hPa to the surface. The mixing ratio of the layer mean (500–850 hPa) SAL sounding was ~25% drier than the equivalent non-SAL sounding.
- The SAL sounding had cooler 200–400-hPa temperatures than the non-SAL sounding. This may be due to the relatively drier air found to exist in the 200–400-hPa layer of the mean SAL sounding. Radiational cooling above the SAL would likely be greater (more net cooling) in this relatively drier mid- to upper-level layer. It is also plausible that the SAL sounding, because of its warmth, experiences some vertical ascent, which pushes the air above it upward, thereby cooling it.
- The SAL sounding had warmer 500–700-hPa temperatures than the non-SAL sounding. The SAL's warm midlevel temperatures are related to its origins over the hot Sahara Desert and are partly preserved by solar heating of its suspended mineral dust.
- The SAL sounding had cooler 850–1000-hPa temperatures than the non-SAL sounding. One possible explanation is that the SAL suspended mineral dust attenuates the amount of solar energy that reaches the 850–1000-hPa layer below it. Also, the depth of the moist layer in the non-SAL environment was larger than that in the SAL. Therefore, when condensation occurs at these low levels, the non-SAL environment will experience more latent heating.
- The lower to middle tropospheric winds in the SAL sounding (associated with the SAL midlevel easterly jet) tended to be stronger and more easterly than the non-SAL sounding. This was evident in the 500–850-hPa layer mean winds and was most pronounced at 700 hPa (the approximate vertical center of the SAL). At this level, winds in the mean SAL sounding were nearly two times stronger and had a more easterly component than the non-SAL sounding. This is

likely related to the SAL midlevel easterly jet that is maintained by the temperature contrasts that exist between the SAL and the relatively cooler tropical air to its south through thermal wind balance.

- Below 200 hPa the SAL sounding exhibited higher geopotential heights than the non-SAL sounding, indicating that it was associated with higher atmospheric pressure.

Although this work represents sounding data from only one hurricane season, it does contain several hundred observations and strongly suggests that the tropical North Atlantic Ocean and Caribbean Sea contain a two-peak bimodal distribution of moisture soundings (dry SAL and moist non-SAL) from the early summer to middle autumn. Significant differences between these two distinct soundings were also noted in values of temperature, wind speed, wind direction, and geopotential height. The results of this study have implications related to improving our understanding of the kinematic and thermodynamic climatology of the North Atlantic Ocean and Caribbean Sea. Furthermore, tropical cyclone forecasting and modeling in these regions can potentially benefit from the findings presented here. Future work related to this study will involve performing a longer-term (~8 yr) analysis of the Jordan mean tropical sounding for the months of the Atlantic hurricane season. This effort will include generating mean SAL and non-SAL soundings that extend from 50 hPa to the surface as well as performing detailed analyses of the atmospheric stability associated with these two distinct soundings. This revised set of atmospheric soundings will provide a more robust representation of the kinematics and thermodynamics that exist over the tropical North Atlantic Ocean and Caribbean Sea during the hurricane season.

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