Re-Writing the Climatology of the Tropical North Atlantic and Caribbean Sea Atmosphere

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Abstract

The Jordan mean tropical sounding has provided a benchmark reference for representing the climatology of the tropical North Atlantic and Caribbean Sea atmosphere for over 50 years. However, recent observations and studies have suggested that during the months of the North Atlantic hurricane season, this region of the world is affected by multiple air masses with very distinct thermodynamic and kinematic characteristics. This study examined ~6,000 rawinsonde observations from the Caribbean Sea region taken during the core months (July-October) of the 1995-2002 hurricane seasons. It was found that single mean soundings created from this new dataset were very similar to Jordan's 1958 sounding work. However, recently developed multi-spectral satellite imagery that can track low to mid-level dry air masses indicated that the 1995-2002 hurricane season dataset (and likely Jordan's dataset as well) was dominated by three distinct air masses: moist tropical (MT), Saharan Air Layer (SAL) and mid-latitude dry air intrusions (MLDAIs). Findings suggest that each sounding is associated with unique thermodynamic, kinematic, stability and mean sea level pressure characteristics and that none of these soundings is particularly well-represented by a single mean sounding like Jordan's. This work presents three new mean tropical soundings (MT, SAL, and MLDAI) for the tropical North Atlantic Ocean and Caribbean Sea region and includes information on their temporal variability, thermodynamics, winds, wind shear, stability, total precipitable water and mean sea level pressure attributes. It is concluded that the new MT, SAL, and MLDAI soundings presented here provide a more robust depiction of the tropical North Atlantic and Caribbean Sea atmosphere during the Atlantic hurricane season and should replace the Jordan mean tropical sounding as the new benchmark soundings for this part of the world.

1. Introduction

The first atmospheric climatology for the tropical North Atlantic and Caribbean Sea (TNAC) region was presented by Jordan (1958) more than 50 years ago and has served as a benchmark reference since that time. Jordan included a mean core month (July-October) hurricane season sounding in his 10-yr (1946-1955) climatology that has been used extensively as a reference for tropical soundings during the North Atlantic hurricane season and as an initial background state in model simulations. Jordan (1958) mentioned that since the tropics generally exhibit small spatial and seasonal variability, mean atmospheric soundings taken over the summer months in these regions should be robust. However, Carlson and Prospero (1972), Prospero and Carlson (1972) and Karyampudi and Carlson (1988) discussed a phenomenon called the Saharan Air Layer (SAL) and showed that this elevated layer (~1500-5500 m) of extremely warm, dry air and strong mid-level (~2000-4500 m) easterly winds that forms over west Africa can overspread vast areas of the tropical North Atlantic during the summer months. More recently, Dunion and Velden (2004) showed that individual SAL outbreaks can cover areas of the North Atlantic the size of the 48 contiguous United States and migrate as far west as the western Caribbean Sea and Gulf of Mexico. Dunion and Velden (2004) hypothesized that the components of the SAL can contribute to an environment that is hostile to tropical cyclone formation and intensification. They also suggested that in light of their findings related to the SAL, the TNAC is likely characterized by a multiple distribution of distinct environmental moisture soundings [e.g. SAL and non-SAL (moist tropical)] that are not well-represented by a single climatological sounding like Jordan's (1958). They indicated that Jordan may have been unaware that his mean tropical sounding likely contained a mixture of SAL and non-SAL soundings. This suggests that the Jordan mean sounding is substantially drier than the typical moist tropical sounding that exists in the tropical North Atlantic during this time of year.

Dunion and Marron (2008) investigated Dunion and Velden's (2004) hypotheses regarding the possible influence of the SAL on the Jordan mean tropical sounding. They examined over 750 Caribbean rawinsonde soundings from July-October 2002 and presented evidence that the TNAC actually contains a mixture of SAL (~29%) and non-SAL (i.e. moist tropical; ~71%) air masses during these months. Their examination of a portion of Jordan's original dataset showed that a distinct two-peak PDF (SAL and non-SAL soundings) existed, suggesting that although Jordan was likely unaware of it, his dataset probably contained a mixture of SAL and moist tropical soundings. The current study greatly expands on Dunion and Marron's (2008) work and presents new hurricane season mean soundings for the TNAC that are based on 8 years (1995-2002) of Caribbean rawinsonde data (6,000 soundings). Findings from this work also resulted in the identification of an additional air mass that can significantly impact the TNAC during the Atlantic hurricane season: mid-latitude dry air intrusions (MDLAIs). Discussion of the set of three new mean soundings (moist tropical (MT), SAL, and MLDAIs) is presented in detail and includes discussion on aspects of the mean state and temporal variability of their thermodynamics, kinematics and stability. These new soundings represent a new benchmark for the TNAC region and could have important implications related to our understanding of the climatology for this part of the world.

2. Data and Methods

This study examined twice-daily (0000 and 1200 UTC) rawinsonde observations from four Caribbean stations [Owen Roberts Airport, Grand Cayman (WMO index #: 78384); Miami, FL (WMO index #: 72202); San Juan, Puerto Rico (WMO index #: 78526); and La Raizet, Guadeloupe (WMO index #: 78897)] for the period 1995-2002. Figure 1 shows the locations of these rawinsonde stations as well as the geographical center (normalized by the total number of July-October soundings at each of the four stations) of the 1995-2002 dataset (20.1ºN 71.3ºW). GOES multi-spectral infrared satellite imagery developed by Dunion and Velden (2004) (using techniques described by Dunion and Marron (2008)) was used to identify both moist (e.g. MT) and low- to mid-level dry air masses (e.g. the SAL and MLDAIs) that impacted each of the four rawinsonde sites over the the 8-yr study period. The current work also employed the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT; Draxler and Rolph 2010) model running with NCAR/NCEP reanalysis data to identify the origins of the air masses that were observed at these sites. Three-dimensional back trajectories were calculated to track the sources of low to mid-level (850-700 hPa) moisture sampled by each of the rawinsondes in the dataset. Mosaics of total precipitable water from Remote Sensing Systems, GOES and Metesosat visible satellite imagery and aerosol analyses from the Navy Aerosol Analysis and Prediction System (NAAPS; Witek et al. 2007, Christensen 1997) were also used to examine the moisture and aerosol characteristics of the synoptic environments impacting the study region.

Approximately 7,300 (6,000) Caribbean rawinsonde observations for the months of June-October (July-October) were examined in this study. Rawinsondes from June were not included in the calculation of the new mean soundings. However, they were incorporated during the assessment of the spatial and seasonal variability of the three new sounding types. Mean (July-October) atmospheric soundings (presented at mandatory levels from the surface to 50 hPa[1]), stability indices, vertical wind shear, total precipitable water and mean sea level pressure for

[1] Mean thermodynamic, wind, and stability information for 600 hPa (not a mandatory level in routine sounding data) is also presented in this study. This was done because of the relatively large vertical gap (200 hPa) between the 500 and 700 hPa mandatory levels and was accomplished by extracting (from each individual sounding) the single level (if any existed) that was closest to (and within +/- 10 hPa of) 600 hPa. Although not as robust as the mandatory level data, these tight search constraints and large size of the sounding dataset (~6,000 soundings) still produced statistically significant results.

three dominant air masses (MT, SAL and MLDAI) that affect this region during the Atlantic hurricane season are presented. The mean July-October values of vertical wind shear and stability were derived from the ~6,000 individual soundings (not from the single mean MT, SAL and MLDAI soundings) in the 1995-2002 dataset. This methodology helped preserve the true wind vector and stability characteristics of the three sounding types, which would likely have been smoothed out in the averaging. Statistical significance for the various thermodynamic, kinematic and stability parameters that are presented were determined using a Student's T-Test and unless otherwise stated, are highly statistically significant at the 95-99.9% level.

3. Results

a. 1995-2002 Dataset vs Jordan (1958)

The July-October 1995-2002 dataset appears to be strikingly similar to Jordan's 1958 work. Figure 2 and Table 1 indicate that the average moisture sounding created from the ~6,000 1995-2002 rawinsonde observations was quite similar (within 3.5% RH from the surface to 500 hPa) to Jordan's (1958) mean sounding. Mixing ratio differences ranged from 0.1-0.3 g kg^{-1} from the surface to 500 hPa and temperature disparities were <1.0ºC from the surface to 100 hPa (2.5ºC at 50 hPa). Geopotential height differences were <7 m from the surface to 300 hPa and <25 m from 50-250 hPa. It should be noted that Jordan's mean hurricane season sounding did not include information on wind speed and direction. The thermodynamic and geopotential height differences between the two mean soundings suggest that the 1995-2002 and Jordan datasets are quite similar. This is comparable to results found by Dunion and Marron (2008). Although the mean 1995-2002 sounding was similar to Jordan's work and represents the average atmospheric conditions that exist during July-October in the TNAC, it does not appropriately represent the conditions that persist in this region at any particular time and place.

Analyses of the satellite, model and rawinsonde data described in Section 2 confirmed that three distinct air masses consistently affected the TNAC during the 1995-2002 hurricane seasons and that a single mean atmospheric sounding (like Jordan's) does not adequately represent this variability. Each of these air masses (MT, SAL, and MLDAIs[2]) has very unique temporal variability, thermodynamic and kinematic profiles, stability characteristics and vertical wind shear attributes. As discussed by Dunion and Marron (2008), 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 mid-level easterly jets, lower SAL bases and trade wind inversion levels, and cooler SSTs (surface temperatures).

b. Moist Tropical, SAL, and Mid-Latitude Dry Air Intrusion Soundings

i. Relative Occurrence (Intraseasonal Variability)

GOES split window satellite imagery (Dunion and Velden 2004, Dunion and Marron 2008), visible and microwave satellite imagery, and model analyses of parcel trajectories and atmospheric dust were used to identify various air masses that affected the Caribbean rawinsonde stations utilized in this July-October 1995-2002 study. Figure 3 shows the mean bi-weekly frequency distribution of MT, SAL, and MLDAI soundings for the period June-October (1995-

[2] Dunion and Marron (2008) also identified three unique air masses in their 2002 "hurricane season" study: non-SAL (moist tropical), SAL and MLDAIs. Since MDLAIs made up a relatively small percentage (~10%) of their 2002 dataset, they decided to group these soundings together with the moist tropical soundings in their statistics. However, findings in the current study indicated that MLDAI soundings are actually more prevalent over the tropical North Atlantic Ocean. Therefore, this work presents three distinct soundings instead of just two.

2002) and indicates that the occurrence of each type of air mass varies significantly through the months of the hurricane season. The ~6,000 July-October rawinsondes examined in this study reveal that overall the MT soundings account for ~2/3 (66%) of the soundings in the Caribbean. SAL outbreaks and MLDAIs account for 20% and 14% of the total soundings respectively. Depending on the time of year, SAL frequency ranged from as much as ~ 40% (early summer) to as little as 2-6% (October) of all soundings, while MLDAI frequency was consistently less than that of the SAL for all months except October.

Figure 3 indicates that the SAL is most active (large outbreaks that reach farther west) from mid-June to late July, when it comprises 40% of all Caribbean soundings. This confirms previous findings by Carlson and Prospero (1972) and Dunion and Marron (2008). Although SAL activity begins to gradually wane after July, SAL outbreaks can still impact the Caribbean through October. Not surprisingly, MLDAIs impact the Caribbean more rarely during the hurricane season and are most numerous in June and especially October when mid-latitude frontal passages are relatively more common. Still, MLDAIs do consistently impact the tropical North Atlantic throughout the hurricane season and appear to have sources that primarily originate from the North American continent and around the east side of the mid-Atlantic ridge. HYSPLIT trajectory analyses indicate that this latter source of MLDAIs is often associated with significant subsidence. MLDAIs comprise over 35% of all Caribbean soundings in late October as mid-latitude fronts begin to increasingly affect the subtropical and tropical North Atlantic and Caribbean. Interestingly, the number of October MLDAIs that impacted the Caribbean from 1995-2002 was significantly higher in El Niño years (1997 and 2002) than in non-El Niño years (1995-1996 and 1998-2001; NOAA/Climate Prediction Center, 2009: Oceanic Niño Index). During the non-El Niño years, MLDAIs accounted for ~25% of all October soundings.

However, in 2002 (a moderate El Nino year) 34% of the October soundings were MLDAIs (not shown), which is 1.5 standard deviations above the average for the non-El Niño years. In 1997 (the strongest El Niño on record; NOAA/Climate Prediction Center, 2009: Oceanic Niño Index) 47% of the October soundings were MLDAIs, which is more than 3.5 standard deviations above the average of the non-El Niño years. This suggests the possibility that during strong El Niño years, frontal activity in the tropical western North Atlantic and Caribbean is greatly enhanced in the late summer/early fall and the number of MLDAIs affecting this region increases significantly. Additionally, the following sections show that MLDAIs are associated with thermodynamic, stability and especially vertical wind shear profiles that are hostile to tropical cyclone development. Although beyond the scope of this work, the possible connection between El Niño and increased occurrence of MLDAIs in the tropical western North Atlantic and Caribbean is an intriguing question and warrants further research.

MT environments comprised only 50-60% of the Caribbean atmosphere from June through mid-August, but as SAL activity begins to subside in late July, the MT soundings gradually increase. By mid-August (and continuing through mid-October), MT soundings comprise 70-80% of all Caribbean soundings. This agrees with previous work by DeMaria et al. (2001) who found that during the hurricane season, mid-level moisture in the tropical Atlantic reaches a minimum in mid-July and rapidly increases in mid-August. They surmised that this July moisture minimum might help explain why tropical cyclone genesis in the tropical Atlantic is relatively rare in July, even though vertical wind shear and instability typically become conducive for tropical cyclone development by the first week in July. Additionally, DeMaria and Kaplan (1994) defined a term called “relative intensity” that relates a tropical cyclone’s maximum attained intensity to its MPI (maximum potential intensity). They found that for the months of the hurricane season, relative intensity was lowest in June and July, indicating that early-season storms are less likely to approach their MPI than mid- or late-season storms. This trend may partly relate to the fact that SAL activity peaks in these early summer months.

Interestingly, the mid June to early August peak in SAL activity also corresponds quite well with the precipitation patterns described by Hastenrath (1967) and later termed the midsummer drought, or MSD, by Magaña et al. (1999). Hastenrath (1967) described a pattern of abundant precipitation over Central America and the Caribbean during May and June, followed by an abrupt change around late June that ushered in a period of drier and less cloudy conditions in July and August. Though beyond the scope of this study, the mid-summer peak in SAL activity may contribute to this relative minimum in the region's precipitation patterns and the onset of the midsummer drought.

Although MT soundings are the most prevalent of the three sounding types identified in this study, a significant portion of the core months of the hurricane season (~1/3) is influenced by SAL or MLDAI environments. The following sections show that these two soundings are associated with thermodynamic, wind, and stability profiles that are not conducive to tropical cyclone development. This indicates that only ~2/3 of the time does the TNAC contain an environment (MT) that strongly supports tropical cyclone development and intensification.

ii. Moisture

The mean MT, SAL, and MLDAI soundings that were extracted from the 1995-2002 rawinsonde dataset exhibited distinctly unique moisture characteristics. Although these three sounding types combine to create the "All Soundings" moisture profiles shown in Fig. 2 and Table 1, none of them is particularly well represented by that single mean sounding or the Jordan (1958) mean sounding. Figure 4 shows that the MT sounding is significantly moister than the

SAL and MLDAI soundings for every year in the 8-yr rawinsonde dataset, particularly in the lower to middle levels of the atmosphere. Figure 4 also indicates that the mean MT, SAL and MLDAI soundings are fairly consistent from year to year. Figure 5 shows that at 700 hPa (the approximate vertical center of the SAL) a 3-peak PDF (MT, SAL and MLDAI) exists for RH and mixing ratio in the July-October (1995-2002) dataset. This 3-peak tendency in humidity is also clearly evident at the 500 and 850 hPa levels (not shown). Figure 6 shows the statistical distributions of RH for the MT, SAL and MLDAI soundings in the 1995-2002 Caribbean rawinsonde dataset using contoured frequency by altitude diagrams (CFADs). These CFADs highlight the differences between the three sounding types and their distinct distributions of vertical moisture.

Figure 7 and Table 2 show that the mean July-October (1995-2002) MT, SAL and MLDAI moisture soundings are quite distinct. The SAL and MLDAI soundings are 50-60% (~30-35% RH, 1.3-3.6 g kg^{-1}) drier than the MT sounding from 500-700 hPa and drier at every level below 50 hPa. Although the mean SAL and MLDAI moisture soundings are similar, the MLDAIs are drier than the SAL at every level from the surface to 150 hPa. This difference is most pronounced from the surface to 925 hPa, where the MLDAI mixing ratio is ~5-10% (0.9-1.5 g kg^{-1}) drier than the SAL. This likely relates to the fact that unlike the SAL, MLDAIs are not purely elevated dry layers and are often associated with significant amounts of dry air in the boundary layer and surface layer. It is also worth noting that the RH differences between the SAL and MLDAI soundings are relatively small (<5% RH) from the surface to 925 hPa, even though the mixing ratio differences were relatively large (0.9-1.5 g kg^{-1}). This relates to the fact that MLDAIs are also associated with relatively cool low-level air that originates from mid-latitudes, which acts to boost the RH (see next section). The moisture differences between the

MT, SAL and MLDAI soundings were highly statistically significant levels except 150 hPa (MT-SAL).

iii. Temperature

Figure 5 indicates that the PDFs of the 700 hPa MT, SAL and MLDAI temperatures exhibit distinct Gaussian distributions. The SAL distribution is shifted slightly to the right (relatively warmer temperatures) of the MT and MLDAI distributions, while the MLDAI distribution is broader and not as peaked as the MT and SAL distributions. Although the 700 hPa temperatures for the three sounding types do exhibit a 3-peak PDF, the differences are less striking than the moisture disparities. This was also found by Dunion and Marron (2008) and suggests that temperature is not as robust an indicator for identifying MT, SAL and MLDAI soundings in the central and western tropical North Atlantic. Similar trends were also found at other pressure levels (not shown).

Figure 7 and Table 2 show that the mean July-October (1995-2002) MT, SAL and MLDAI temperature soundings exhibit subtle differences. Similar to findings by Dunion and Marron (2008), the SAL sounding is as much as 0.5ºC warmer than the MT sounding from 500-700 hPa, which relates to the SAL's origins over the hot Sahara Desert and to the fact that the SAL's warmth is partly preserved by solar heating of its suspended mineral dust (Carlson and Benjamin 1980, Dunion and Velden 2004, Dunion and Marron 2008). Surface temperatures in the SAL sounding were 0.8ºC warmer than the MT sounding and may be due to the fact that the reduction in tropical convection associated with the relatively drier, more stable SAL environment is conducive to diminished cloud cover and increased overland surface heating.

Figure 7 and Table 2 also indicate that the MLDAI sounding is associated with the coolest lower tropospheric temperatures and is related to the mid-latitude origins of this air mass.

These differences are most pronounced from the surface to 850 hPa, where the MLDAI sounding is 1.2-1.3ºC cooler than the MT and SAL soundings. The temperature differences between the MT, SAL and MLDAI soundings were highly statistically significant for all levels except 50 hPa (MT-SAL), 250 hPa (SAL -MLDAI), and 500 hPa (SAL-MLDAI).

iv. Winds and Vertical Wind Shear

Figure 5 shows that the PDFs of the 700 hPa MT, SAL and MLDAI wind speeds exhibit distinct Gaussian distributions (though each distribution is slightly positively skewed). The SAL distribution is shifted markedly to the right (relatively stronger mid-level winds) of the MT and MLDAI distributions and likely relates to the SAL's associated mid-level easterly jet. The MLDAI distribution indicates that mid-level winds in these air masses tended to be the weakest of the three sounding types.

Figures 6 and 7 and Table 2 indicate that the wind profiles and vertical distributions of wind speed are quite different for the three sounding types. The MT sounding is associated with a deep layer (surface to 400 hPa) of light (~1-5 m s^{-1}) easterly trade winds overlaid by weak (~1-3.5 m s^{-1}) northwest winds from 150-300 hPa. Consequently, the 200-850 hPa vertical wind shear in the MT sounding is a moderate 8.2 m s^{-1} at 298 degrees (Table 3).

In contrast to the MT sounding, the mean SAL sounding is associated with a slightly deeper layer (surface to 300 hPa) of easterly trades (Fig. 7 and Table 2). The SAL's low to mid-level (500-850 hPa) winds were ~2-3x stronger and more easterly than the MT sounding. These enhanced easterly winds are associated with the SAL's mid-level easterly jet and were also discussed in Dunion and Marron's (2008) study. Although the winds overlaying this trade wind profile are slightly shallower (150-250 hPa) than in the MT sounding, they are similarly weak (~1-2 m s^{-1}) and from the northwest. The 200-850 hPa vertical wind shear in the SAL sounding is a moderate to high 9.8 m s^{-1} and is primarily being driven by the SAL's mid-level easterly jet (Table 3). It should be noted that although the 200-850 hPa shear direction for the SAL sounding (277 degrees) indicates westerly shear, it is actually the strong 850 hPa easterlies that are dominating the direction of this shear vector. Also, unlike the MT tropical sounding, the magnitude of the 200-700 hPa vertical wind shear in the SAL is nearly identical to the 200-850 hPa wind shear (Table 3). This is likely related to the deep easterly wind surge that is associated with the SAL.

The MLDAI sounding exhibits a relatively shallow layer (surface to 500 hPa) of light (~2-5.5 m s^{-1}) northeast to east-northeast winds under a deep layer (100-400 hPa) of northwest winds (Fig. 7 and Table 2). Above 300 hPa, these northwesterly winds are quite strong and peak at 200 hPa (7.5 m s^{-1}). This 200 hPa maximum is likely related to the fact that MLDAIs are often associated with mid-latitude troughs and the upper-level jets that accompany these troughs. Although the low-level winds in the MLDAIs are fairly weak, the deep layer of relatively strong northwest winds in this profile results in a high value of mean 200-850 hPa vertical wind shear (12 m s^{-1}, Table 3). The 200-850 hPa shear direction for the MLDAI sounding is also westerly (280 degrees), but in contrast to the SAL sounding, the MLDAI shear vector is being driven by strong 200 hPa winds. The wind speed differences between the MT, SAL and MLDAI soundings were highly statistically significant at all levels except 300 hPa (MT-SAL) and 500 hPa (MT-MLDAI).

v. Stability and Total Precipitable Water (TPW)

The MT, SAL and MLDAI soundings exhibited distinct differences (highly statistically significant for all parameters except Level of Free Convection (SAL-MLDAI)) in stability and TPW and are discussed in detail in this section.

1. Lifted Condensation Level (LCL)

The LCL is defined as the height at which an air parcel being lifted dry adiabatically will become saturated because of adiabatic cooling and approximates the height of cloud base when there is mechanical forcing. Table 4 indicates that the MT sounding exhibits the lowest LCL (944 hPa) of the three soundings presented here, the result of its relatively high moisture content from the surface to 850 hPa. The SAL and MLDAI soundings exhibit relatively elevated LCL values (935 and 928 hPa respectively), which relates to the drier lower tropospheric air present in these soundings. The LCL values for these two soundings indicate that it is more difficult to form clouds in these environments (i.e. parcels must be lifted higher in the atmosphere to form clouds).

2. Level of Free Convection (LFC)

The LFC is the height at which a parcel of air lifted dry adiabatically until it is saturated and lifted moist adiabatically thereafter would first become warmer than the surrounding environment. The LFC also represents the point where the air parcel becomes positively buoyant and accelerates upward without further need for forced lifting. Table 4 indicates that the MT sounding has the lowest LFC (880 hPa) of the three soundings. The LFC in the SAL sounding is ~17 hPa higher (863 hPa) than the MT sounding and relates to the SAL's dry lower tropospheric air and low- to mid-level warmth. The MLDAI sounding has the highest LFC (860 hPa; ~20 hPa higher than the MT sounding), which relates to its dry lower tropospheric air and relatively cooler surface temperatures.

3. Convective Available Potential Energy (CAPE)

CAPE is defined as the amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. Table 4 shows that the CAPE in the MT sounding is 1922 J kg^{-1}, indicating a moderately unstable environment. The CAPE in the SAL sounding is ~10% less (1731 J kg^{-1}) and also indicates a moderately unstable environment. However, there are several competing effects present in the SAL soundings that combine to produce a net reduction in CAPE (relative to the MT sounding): 1) the SAL is warmer from the surface to 1000 hPa, which would help boost CAPE; 2) the SAL's LCL is higher, so a parcel will be relatively cooler when lifted to its LFC (<CAPE); 3) the SAL's LFC is higher, which would equate to potentially less CAPE; 4) the SAL's low to mid-level warmth would tend to reduce CAPE; 5) SAL soundings are associated with a dry middle layer aloft that is often closer to dry adiabatic, which would boost CAPE. Although these various competing effects result in a SAL sounding that has relatively less CAPE, the details are certainly more complex.

The CAPE in the MLDAI sounding is only 1046 J kg^{-1}, indicating an only marginally to moderately unstable profile. This relatively low CAPE likely relates to the fact that this sounding is associated with the highest LCL and LFC and is substantially drier than the MT sounding and somewhat drier than the SAL sounding.

4. Convective Inhibition (CIN)

CIN is a measure of the amount of energy needed to lift an air parcel from the surface to the LFC and can be quite pronounced when a layer of relatively warm air is located above the surface layer (i.e. a temperature inversion exists). Table 4 shows that CIN is smallest (less negative) in the MT sounding (-22.9 J kg^{-1}), indicating a fairly unstable environment. Since the SAL is associated with warm temperatures in the lower to middle levels (~500-850 hPa) and typically has a strong temperature inversion at its base, it is not surprising that CIN values for this sounding are the largest (-32.8 J kg^{-1}). Since the mean height of the LFC is 863 hPa in the SAL and the low-level temperature inversion at the SAL's base is typically found near 800-850 hPa, CIN is probably only capturing the stabilizing effects of the SAL's low-level temperature inversion and warmth a portion of the time. The CIN for the MLDAI sounding (-28.0 J kg^{-1}) was 5.1 J kg^{-1} larger than for the MT sounding and is in part related to the fact that this sounding has the most elevated LFC (860 hPa). Additionally, the extreme lower tropospheric dryness of the MLDAI sounding would promote nighttime radiational cooling and help to enhance the formation of low-level nocturnal temperature inversions, which would also act to enhance CIN.

5. K-index (KI)

KI is measure of the thunderstorm potential based on the vertical temperature lapse rate, moisture content of the lower troposphere and the vertical extent of the moist layer (George 1960). Table 4 shows that the KI for the MT sounding is 31.5, indicating an environment that is conducive for scattered thunderstorm activity. The extreme low to mid-level dryness in the SAL and MLDAI soundings (and mid-level warmth of the SAL sounding) equate to much lower KI values of 19.2 and 14.6 respectively. It should be noted that KI values of <20 suggest an environment with little to no thunderstorm activity.

6. Lifted Index (LI)

LI is calculated by taking a representative low level air parcel and lifting it adiabatically to 500 hPa. The temperature difference between this air parcel and the ambient environment at 500 hPa denotes the LI. Table 4 shows that the LI for the MT sounding is -4.4, indicating an unstable environment with thunderstorm development likely. The LI for the SAL sounding is slightly more stable (-3.7) and is also indicative of an unstable environment with thunderstorm development likely. Since LI utilizes the LCL in its calculation, it does inherently account for low-level moisture, but does not adequately account for mid-level dryness. Therefore, since the SAL is only slightly drier than the MT sounding below ~850 hPa and its LCL is only ~9 hPa higher, LI differences between the two soundings are not exceptionally large. The LI for the MLDAI sounding is -1.6, indicating a marginally unstable atmosphere with thunderstorms possible. This sounding is ~1.0-1.5°C cooler and ~1.0-2.0 g kg^{-1} drier than the MT and SAL soundings from the surface to 850 hPa and likely why its LI is significantly more stable than the MT and SAL soundings.

7. Total Precipitable Water (TPW)

TPW is a measurement of the amount of water vapor in a column extending from the surface to the top of the atmosphere. This quantity can be reliably derived from satellites using the 19, 22 and 37 GHz microwave channels (e.g. from the Special Sensor Microwave/Imager (SSM/I)) and is one of the most accurate and robust of the microwave-derived satellite products (Alishouse et al. 1990, Petty 1993, Hawkins et al. 2007). One significant advantage of microwave-derived TPW over the GOES split window algorithm developed by Dunion and Velden (2004) is that it can detect atmospheric moisture through clouds. Therefore, it is an ideal tool for tracking air masses such as MT, SAL and MLDAIs. Table 5 indicates that ~90-95% of the total column moisture is below 500 hPa in all three sounding types. Since such a large percentage of the column moisture is contained in the lower to middle levels (surface to 500 hPa) of the atmosphere, TPW is an extremely robust proxy for detecting dry air masses like the SAL and MLDAIs. In fact, moisture variability in these parts of the vertical column can result in large differences in TPW. Table 4 shows that the TPW in the MT sounding is 51.5 mm, indicating a relatively moist low- to mid-level environment. The SAL sounding contains ~20% less TPW (~40 mm) than the MT sounding, while the MLDAI sounding contains ~25% less moisture (~37.5 mm) than the MT sounding. The SAL's 500-850 hPa dryness is responsible for the low TPW values in the SAL sounding, while the even lower TPW in the MLDAI sounding is being driven by both its mid-level dryness and its relatively drier air from the surface to 850 hPa. The means and standard deviations of TPW for these three air masses (not shown) suggest that 45 mm is a reasonable threshold value for discerning MT air masses from environments with substantially dry air in the lower to middle levels (e.g. SAL and MLDAI air masses).

vi. Geopotential Height and Mean Sea Level Pressure

Table 1 indicates that the mean sea level pressure for the TNAC is 1015.3 hPa. However, significant surface pressure differences exist between the three sounding types that comprise this mean value. Table 2 indicates that below 250 hPa the SAL sounding exhibited the highest geopotential heights of the three sounding types, while the MLDAI sounding had the lowest heights from 50-700 hPa. Not surprisingly, the SAL sounding was associated with the highest mean surface pressure (1016.5 hPa), while the MLDAI sounding had a relatively lower mean surface pressure (1015.7 hPa). The mean surface pressure was lowest for the MT sounding (1014.8 hPa), indicating that in terms of pressure, it is the most conducive environment for tropical cyclone development.

The relatively high pressure of the SAL sounding (1.8 and 0.8 hPa higher than the MT and MLDAI soundings respectively) is related to the fact that it is typically positioned in the ridge that is located either in front of or more typically behind African easterly waves that propagate across the North Atlantic during the summer. Karyampudi and Carlson (1988) noted a "curious" clockwise rotation of the SAL in their three-dimensional conceptual model of the SAL, which is probably related to this ridge positioning. The SAL's higher pressure may equate to relatively stronger subsidence within this unique environment and might help explain why the mean SAL sounding is so dry at levels well above its typical upper extent (~500 hPa). Since SAL outbreaks take several days to cross the basin, this subsidence-induced drying would be particularly evident in soundings taken well west of the SAL's source over Africa (i.e. the soundings used in this study). The MLDAI sounding's lower pressure (relative to the SAL) is likely related to the fact that these air masses are often associated with mid-latitude troughs (i.e. relatively lower pressure). However, the relatively cooler temperatures of the MLDAI sounding may somewhat offset this lower pressure, producing slightly higher pressure compared to the MT sounding.

4. Concluding Remarks

A new set of mean soundings representing the core months of the North Atlantic hurricane season (July-October) is presented for the tropical North Atlantic and Caribbean Sea region. This dataset includes ~6,000 Caribbean rawinsonde observations for the 8-yr period 1995-2002 and was shown, in the mean, to be very similar to the sounding work presented by Jordan in 1958. However, GOES multi-spectral satellite imagery, 3-dimensional HYSPLIT model trajectories, mosaics of total precipitable water, GOES and Metesosat visible satellite imagery and aerosol analyses from the NAAPS model indicated that the 1995-2002 sounding dataset was dominated by three distinct air masses: moist tropical (MT, 66% of all soundings), Saharan Air Layer (SAL, 20% of all soundings), and mid-latitude dry air intrusions (MLDAIs, 14% of all soundings). These three sounding types were each associated with distinct temporal (intraseasonal) variability, thermodynamics, kinematics, wind shear, stability attributes and surface pressures and none is particularly well-represented by a single climatological sounding like Jordan's (1958). It is concluded that the new MT, SAL, and MLDAI soundings presented here provide a more robust depiction of the tropical North Atlantic and Caribbean Sea atmosphere during the Atlantic hurricane season and should replace the Jordan mean tropical sounding as the new benchmark soundings for this part of the world.

The new atmospheric sounding information presented here represents a new standard for the tropical North Atlantic and Caribbean Sea region and could have important implications related to our understanding of the climatology for this region of the globe. Additionally, this work could help enhance our understanding of intra- and inter-annual climate variability in the region and has relevancy to tropical cyclone forecasting and modeling.

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1. Rawinsonde stations comprising the 1995-2002 rawinsonde dataset. The black cross located at 20.1ºN 71.3ºW indicates the geographic center of the ~6,000 rawinsondes used in the July-October 1995-2002 dataset (normalized by the number of soundings that were included from each of the four stations).

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(right) wind speed (m s^{-1}) at each level using bin sizes of 5% RH and 2 m s^{-1} respectively.

7. Mean July-October (1995-2002) MT, SAL and MLDAI soundings of (a) temperature (C), (b) RH (%), (c) mixing ratio (g kg^{-1}), (d) theta-e (K), (e) wind speed (m s^{-1}) and (f) wind direction (degrees).

Table 1: Jordan [1958, (italic)] and 1995-2002 [combined average, (standard font)] July-October mean atmospheric soundings from the current study.

Pressure (hPa)	GPH (m)	Temp. (C)	Dewpoint (C)	RH (%)	MR (g kg^{-1})	Theta (K)	Theta E (K)	Speed (m s^{-1})	Direction (degrees)
50	*20743* 20723	*-60.6* -63.1	*n/a* -73.8	*n/a* 25.4	*n/a* 0.04	*500.0* 494.5	*n/a* 495.5	*n/a* 12.9	*n/a* 88
100	*16568* 16588	*-73.5* -74.4	*n/a* -81.4	*n/a* 32.9	*n/a* 0.01	*386.0* 383.7	*n/a* 384.5	*n/a* 4.0	*n/a* 70
150	*14177* 14199	*-67.6* -67.0	*n/a* -74.8	*n/a* 33.9	*n/a* 0.01	*354.0* 354.5	*n/a* 354.8	*n/a* 3.4	*n/a* 321
200	*12396* 12414	*-55.2* -54.4	*n/a* -63.7	*n/a* 34.2	*n/a* 0.04	*345.0* 346.4	*n/a* 346.6	*n/a* 3.8	*n/a* 304
250	*10935* 10946	*-43.3* -42.6	*n/a* -53.2	*n/a* 34.8	*n/a* 0.13	*342.0* 342.6	*n/a* 343.2	*n/a* 2.4	*n/a* 302
300	*9682* 9689	*-33.2* -32.6	*n/a* -44.9	*n/a* 34.5	*n/a* 0.29	*338.0* 339.3	*n/a* 340.5	*n/a* 1.1	*n/a* 313
400	*7595* 7597	*-17.7* -17.3	*n/a* -31.2	*n/a* 37.5	*n/a* 0.94	*332.0* 332.5	*n/a* 335.9	*n/a* 1.2	*n/a* 81
500	*5888* 5888	*-6.9* -6.5	*-16.9* -20.4	*45.0* 41.7	*2.10* 1.94	*324.0* 325.0	*332.0* 331.8	*n/a* 2.3	*n/a* 93
600	*4442* 4439	*1.4* 1.7	*-7.9* -10.3	*50.0* 48.8	*3.61* 3.47	*318.0* 318.0	*328.0* 329.5	*n/a* 3.2	*n/a* 100
700	*3182* 3180	*8.6* 9.1	*0.6* -1.0	*57.0* 54.4	*5.83* 5.60	*312.0* 312.5	*329.0* 330.3	*n/a* 4.3	*n/a* 100
850	*1547* 1543	*17.3* 17.4	*12.6* 12.9	*74.0* 76.4	*11.12* 11.34	*304.0* 304.4	*334.0* 338.5	*n/a* 5.3	*n/a* 101
925	*n/a* 813	*n/a* 21.7	*n/a* 18.6	*n/a* 83.2	*n/a* 14.89	*n/a* 301.5	*n/a* 345.5	*n/a* 5.4	*n/a* 100
1000	*132* 128	*26.0* 26.4	*22.5* 22.9	*81.0* 81.4	*17.92* 18.06	*299.0* 299.6	*345.0* 352.6	*n/a* 3.3	*n/a* 92
P_{MSL} *1015.1* 1015.3	- -	*26.3* 26.9	*23.4* 23.3	*84.0* 81.3	*18.54* 18.26	298.0 298.9	*345.0* 352.3	*n/a* 2.0	*n/a* 91
Layer Mean (500-850)	- -	*n/a* 6.7	*n/a* -2.8	*n/a* 57.5	*n/a* 6.30	*n/a* 314.0	*n/a* 333.5	*n/a* 3.9	*n/a* 99

Table 2: MT (standard font), SAL (bold), and MLDAI (italic) July-October mean atmospheric soundings.

Pressure (hPa)	GPH (m)	Temp. (C)	Dewpoint (C)	RH (%)	MR (g kg^{-1})	Theta (K)	Theta E (K)	Speed (m s^{-1})	Direction (degrees)
50	20726	-63.0	-73.8	25.5	0.04	494.5	495.4	12.7	88
	20733	**-63.0**	**-72.2**	**28.6**	**0.05**	**494.6**	**496.4**	**15.6**	**89**
	20696	*-63.2*	*-75.4*	*21.5*	*0.04*	*494.1*	*495.1*	*9.5*	*88*
100	16590	-74.5	-81.3	33.8	0.01	383.5	384.4	4.1	67
	16593	**-73.7**	**-80.4**	**32.5**	**0.01**	**385.0**	**386.7**	**6.0**	**86**
	16572	*-75.2*	*-83.1*	*29.2*	*0.004*	*382.2*	*382.8*	*1.8*	*356*
150	14203	-67.2	-74.7	35.3	0.01	354.2	354.5	3.6	330
	14196	**-66.8**	**-74.5**	**32.6**	**0.01**	**354.8**	**355.5**	**1.1**	**329**
	14182	*-66.6*	*-75.6*	*29.0*	*0.01*	*355.2*	*355.6*	*6.6*	*292*
200	12418	-54.3	-63.2	35.9	0.04	346.6	346.8	3.6	309
	12413	**-54.7**	**-64.2**	**31.6**	**0.04**	**346.0**	**346.2**	**2.1**	**300**
	12395	*-54.5*	*-65.3*	*28.2*	*0.03*	*346.3*	*346.5*	*7.5*	*293*
250	10949	-42.3	-52.4	37.0	0.14	343.0	343.6	2.1	305
	10947	**-43.1**	**-54.2**	**31.4**	**0.11**	**341.9**	**342.2**	**0.9**	**323**
	10930	*-43.1*	*-55.9*	*27.6*	*0.09*	*341.9*	*342.3*	*6.2*	*292*
300	9690	-32.3	-43.5	38.7	0.34	339.8	341.1	0.9	309
	9693	**-33.1**	**-47.4**	**27.3**	**0.21**	**338.6**	**339.5**	**1.1**	**57**
	9676	*-33.3*	*-48.5*	*25.4*	*0.20*	*338.3*	*339.2*	*4.3*	*297*
400	7596	-17.1	-28.7	44.4	1.12	332.7	336.8	0.8	100
	7604	**-17.5**	**-35.1**	**25.7**	**0.61**	**332.1**	**334.4**	**3.5**	**83**
	7590	*-17.8*	*-37.2*	*22.2*	*0.52*	*331.8*	*333.8*	*1.6*	*342*
500	5887	-6.6	-16.9	51.8	2.41	325.0	333.3	1.8	111
	5897	**-6.4**	**-26.4**	**23.5**	**1.09**	**325.1**	**329.1**	**5.0**	**84**
	5883	*-6.3*	*-28.5*	*20.1*	*0.95*	*325.3*	*328.7*	*1.7*	*38*
600	4437	1.6	-7.1	57.7	4.11	317.9	331.4	2.7	113
	4451	**1.5**	**-16.5**	**30.7**	**2.13**	**317.8**	**325.0**	**6.7**	**88**
	4430	*2.2*	*-18.9*	*25.9*	*1.92*	*318.6*	*325.2*	*1.8*	*54*
700	3178	8.9	2.5	65.7	6.74	312.3	333.6	3.6	112
	3190	**9.4**	**-6.6**	**33.5**	**3.51**	**312.8**	**324.3**	**7.8**	**91**
	3173	*9.2*	*-9.5*	*30.7*	*3.17*	*312.7*	*323.0*	*3.1*	*69*
850	1541	17.6	13.8	79.5	11.96	304.6	340.5	4.7	109
	1553	**17.5**	**11.3**	**69.5**	**10.29**	**304.5**	**335.5**	**7.6**	**92**
	1542	*16.4*	*10.6*	*71.4*	*9.92*	303.3	*331.1*	*5.0*	*79*
925	810	21.9	19.0	84.2	15.27	301.7	346.9	4.9	108
	823	**21.6**	**18.2**	**81.7**	**14.53**	**301.4**	**344.3**	**7.1**	**92**
	815	*20.6*	*17.1*	*80.8*	*13.60*	*300.4*	*340.5*	*5.6*	*81*

1000	124 **138** *133*	26.5 **26.7** *25.8*	23.3 **22.7** *21.1*	83.3 **78.9** *76.2*	18.50 **17.81** *16.28*	299.6 **299.9** *298.9*	354.0 **352.3** *346.6*	3.0 **4.4** *3.5*	98 **86** *74*
P_{MSL} 1014.8 **1016.5** *1015.7*	- - -	26.8 **27.6** *26.2*	23.7 **23.2** *21.8*	83.3 **77.2** *77.6*	18.65 **18.04** *16.65*	298.8 **299.5** *298.1*	353.5 **352.5** *346.7*	1.8 **2.7** *2.0*	97 **84** *74*
Layer Mean (500-850)	- - -	6.7 **6.8** *6.4*	-0.2 **-7.2** *-9.0*	65.7 **42.2** *40.9*	7.04 **4.97** *4.70*	314.0 **314.1** *313.7*	335.8 **329.6** *328.3*	3.4 **6.8** *3.2*	111 **89** *69*

Table 3: 200-850 hPa and 200-700 hPa vertical wind shear for the MT (standard font), SAL (bold), MLDAI (italic) and combined average (i.e. all soundings; underline) July-October mean atmospheric soundings. Both the shear magnitude and shear vector are shown.

	Vertical Wind Shear (200-850 hPa)	Vertical Wind Shear (200-700 hPa)
Speed [m s^{-1}]	8.2 **9.7** *12.0* <u>8.9</u>	7.1 **9.8** *10.0* <u>7.9</u>
Direction (degrees)	298 **278** *280* <u>290</u>	300 **277** *281* <u>291</u>

Table 4: Stability and moisture indices from the MT (standard font), SAL (bold), MLDAI (italic) and combined average (i.e. all soundings; underline) July-October mean atmospheric soundings. Lifted condensation level (LCL), level of free convection (LFC), convective available potential energy (CAPE), convective inhibition (CIN), K-index, lifted index (LI), and total precipitable water (TPW) are shown.

LCL (hPa)	LFC (hPa)	CAPE (J kg^{-1})	CIN (J kg^{-1})	K-index	LI	TPW (mm)
944.0	879.5	1922	-22.9	31.5	-4.4	51.5
935.3	**862.8**	**1731**	**-32.8**	**19.2**	**-3.7**	**40.1**
927.7	*860.0*	*1046*	*-28.0*	*14.6*	*-1.6*	*37.6*
<u>940.0</u>	<u>873.6</u>	<u>1765</u>	<u>-25.7</u>	<u>26.7</u>	<u>-3.9</u>	<u>47.3</u>

Table 5: Percentage of moisture below a given pressure level for the MT, SAL, MDLAI, and combined average (i.e. all soundings) July-October mean atmospheric soundings. Percentages were weighted according to the thickness of each layer.

Pressure (hPa)	MT (%)	SAL (%)	MLDAI (%)	All Soundings (%)
50	99.996	99.994	99.996	99.996
100	99.9	99.8	99.9	99.9
150	99.8	99.8	99.8	99.8
200	99.8	99.7	99.7	99.7
250	99.6	99.5	99.5	99.6
300	99.1	99.0	99.1	99.1
400	96.5	97.2	97.3	96.7
500	91.2	94.0	94.4	92.2
600	83.0	88.7	89.3	84.7
700	71.1	80.6	81.4	73.7
850	43.8	55.1	54.3	46.6
925	26.3	33.0	32.9	28.1
1000	4.7	6.0	5.9	5.1
Surface	0	0	0	0

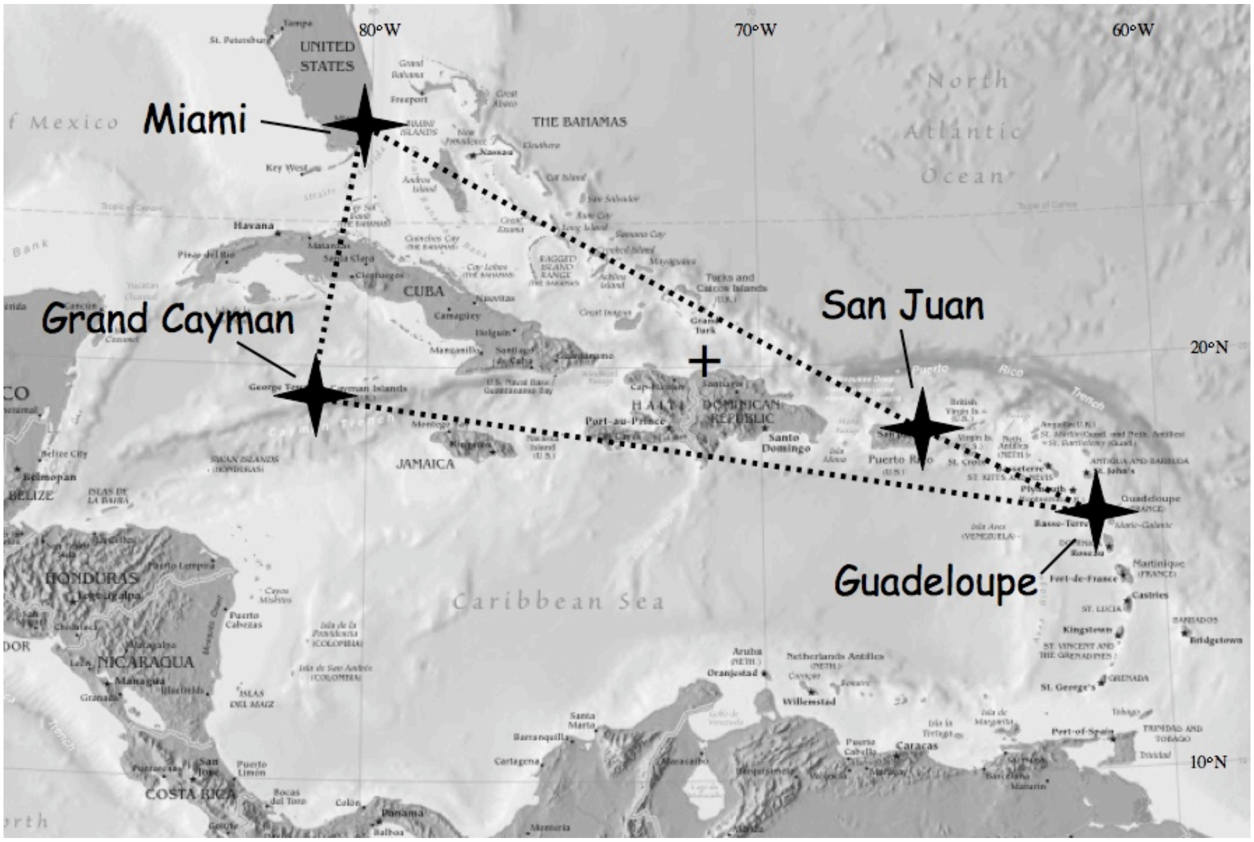

Figure 1: Rawinsonde stations comprising the 1995-2002 rawinsonde dataset. The black cross located at 20.1ºN 71.3ºW indicates the geographic center of the ~6,000 rawinsondes used in the July-October 1995-2002 dataset (normalized by the number of soundings that were included from each of the four stations).

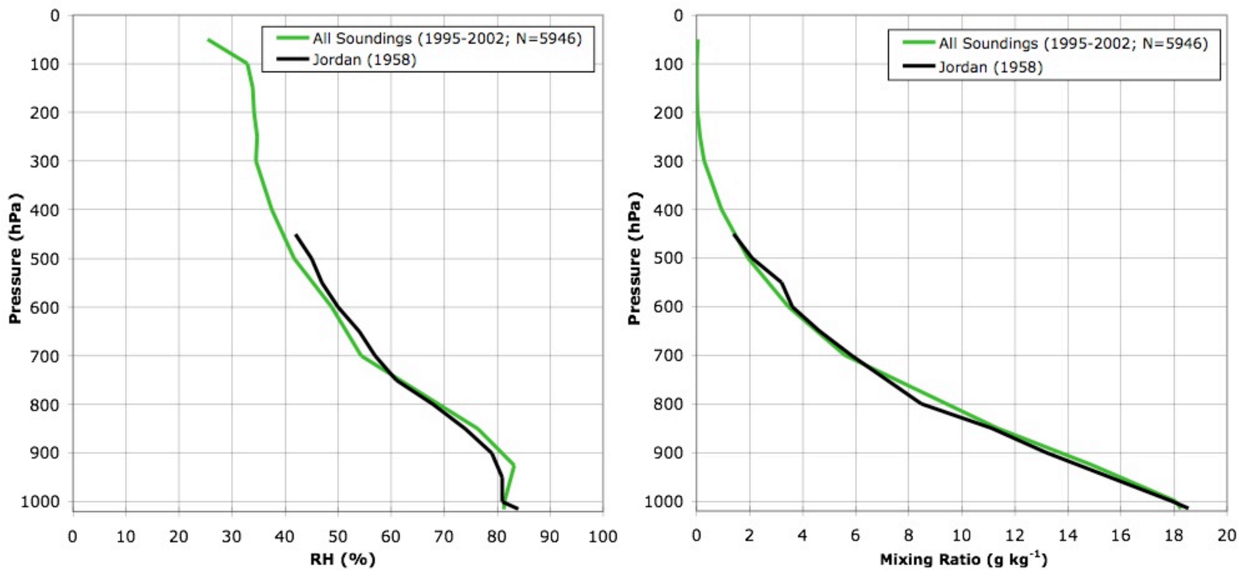

Figure 2: Mean 1995-2002 (July-October) sounding versus the Jordan (1958) mean tropical sounding (July-October) for (left) RH (%) and (right) mixing ratio (g kg^{-1}).

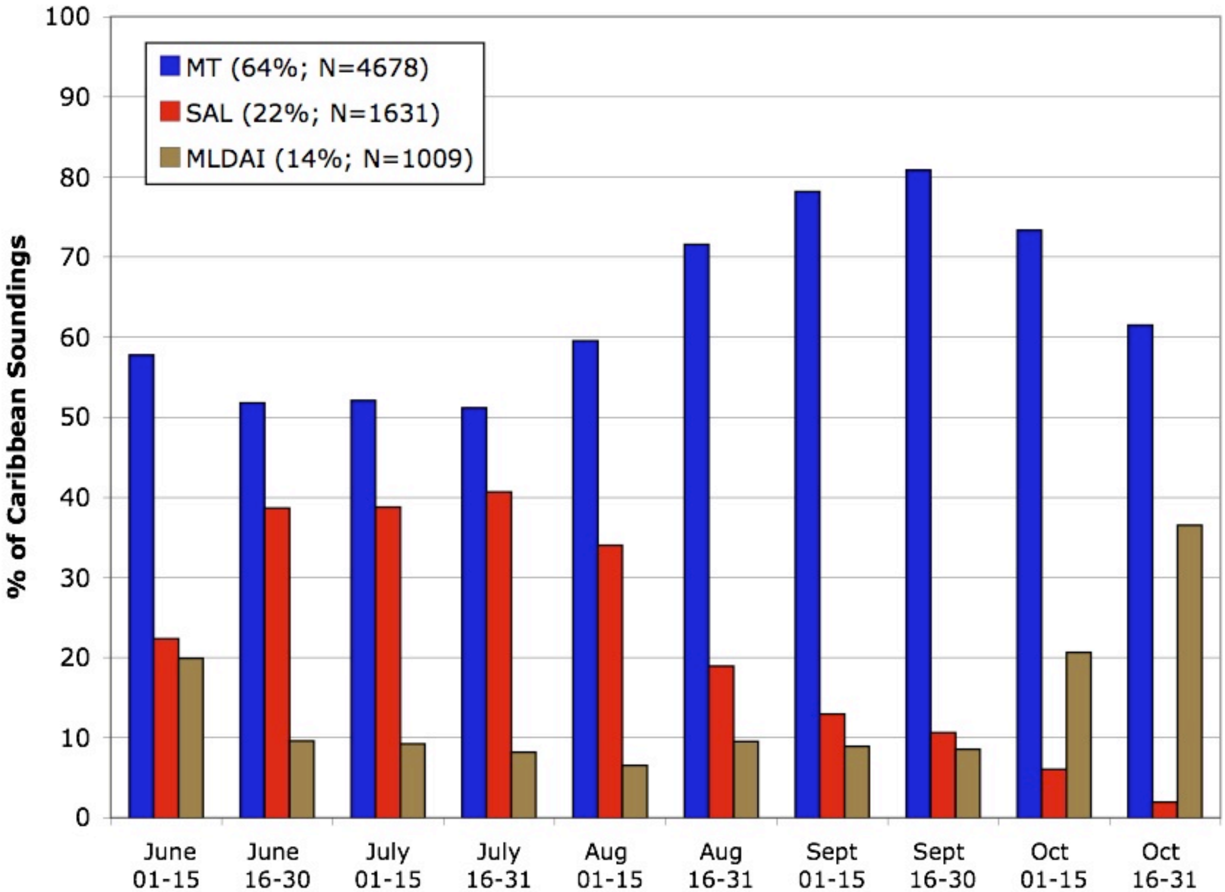

Figure 3: Bi-weekly occurrences of MT, SAL and MLDAI soundings from June-October (1995-2002) at the Grand Cayman, Miami, San Juan, and Guadeloupe rawinsonde stations. For the core months of the hurricane season (July-October) the occurrence of each sounding type (66% MT, N=3927); 20% SAL, N=1212); and 14% MLDAI, N=807) was similar to the June-October period (see legend).

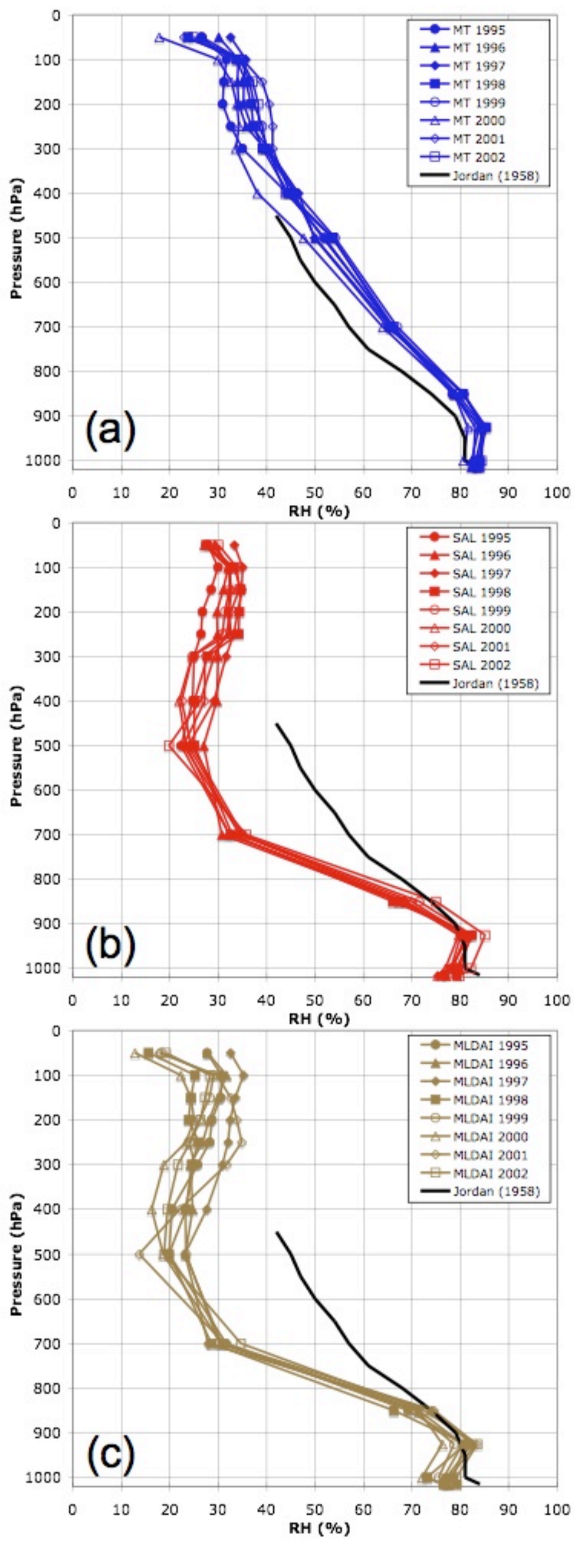

Figure 4: Mean July-October soundings (for the years 1995-2002) of RH (%) for (a) MT, (b) SAL and (c) MLDAI air masses.

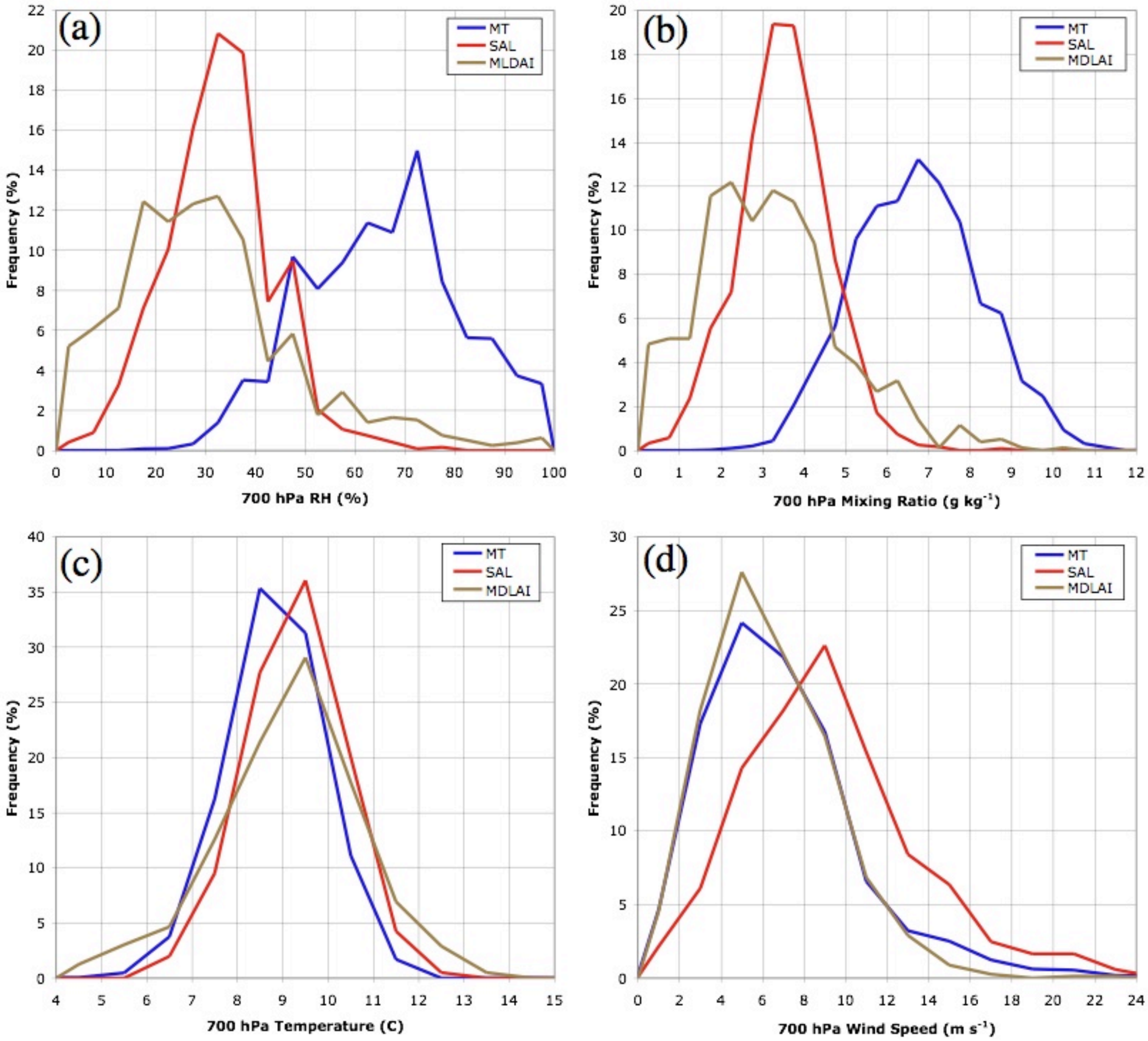

Figure 5: Probability distribution functions of the rawinsondes that comprised the mean July-October (1995-2002) MT, SAL, and MLDAI 700 hPa soundings of (a) RH (%), (b) mixing ratio (g kg^{-1}), (c) temperature (C) and (d) wind speed (m s^{-1}).

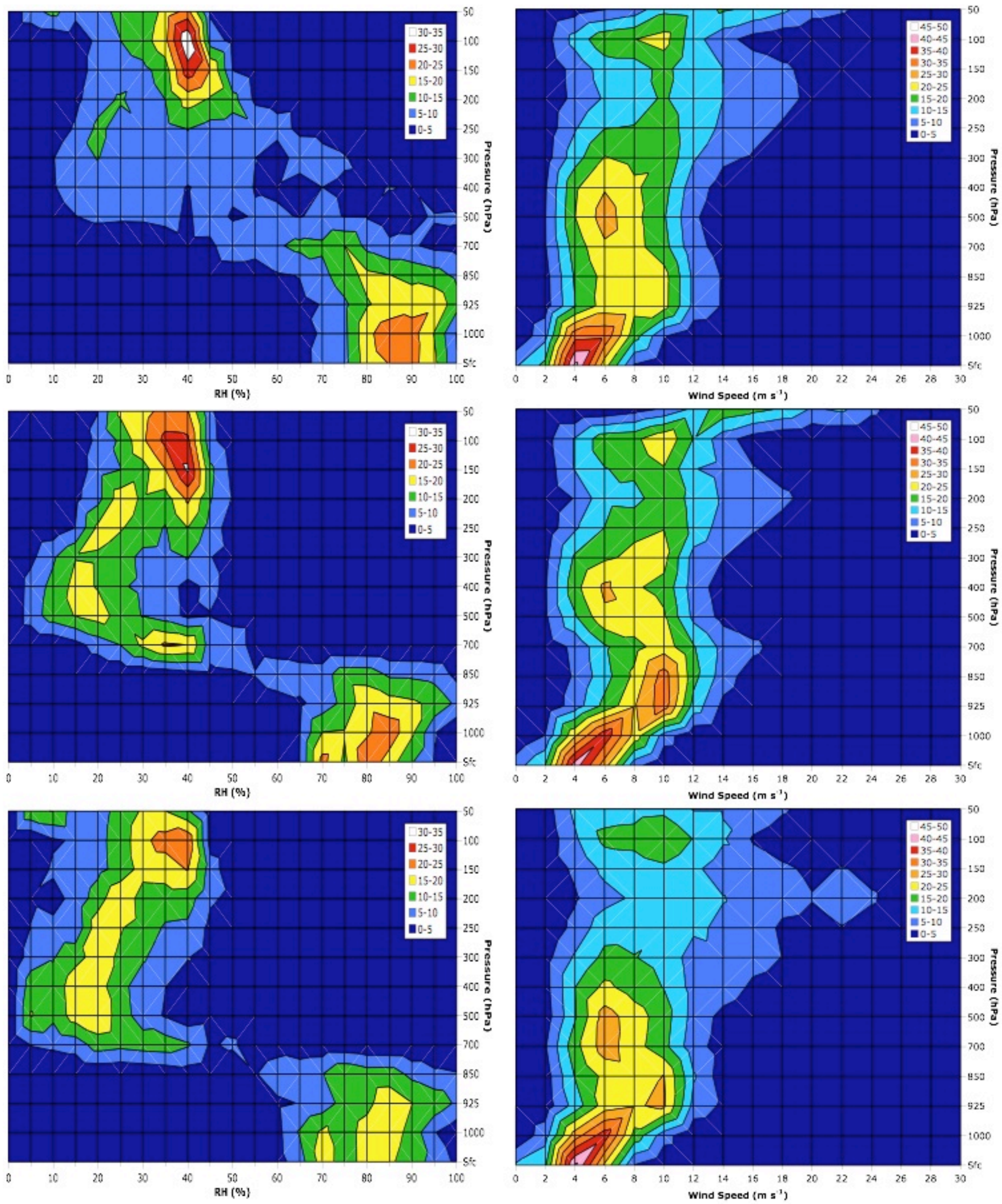

Figure 6: Contoured frequency by altitude diagrams (CFADs) of (top) MT, (middle) SAL and (bottom) MLDAI soundings *as* calculated from the 1995-2002 Caribbean rawinsonde dataset. Contours represent the frequency of occurrence (see legend) of (left) RH and (right) wind speed (m s^{-1}) at each level using bin sizes of 5% RH and 2 m s^{-1} respectively.

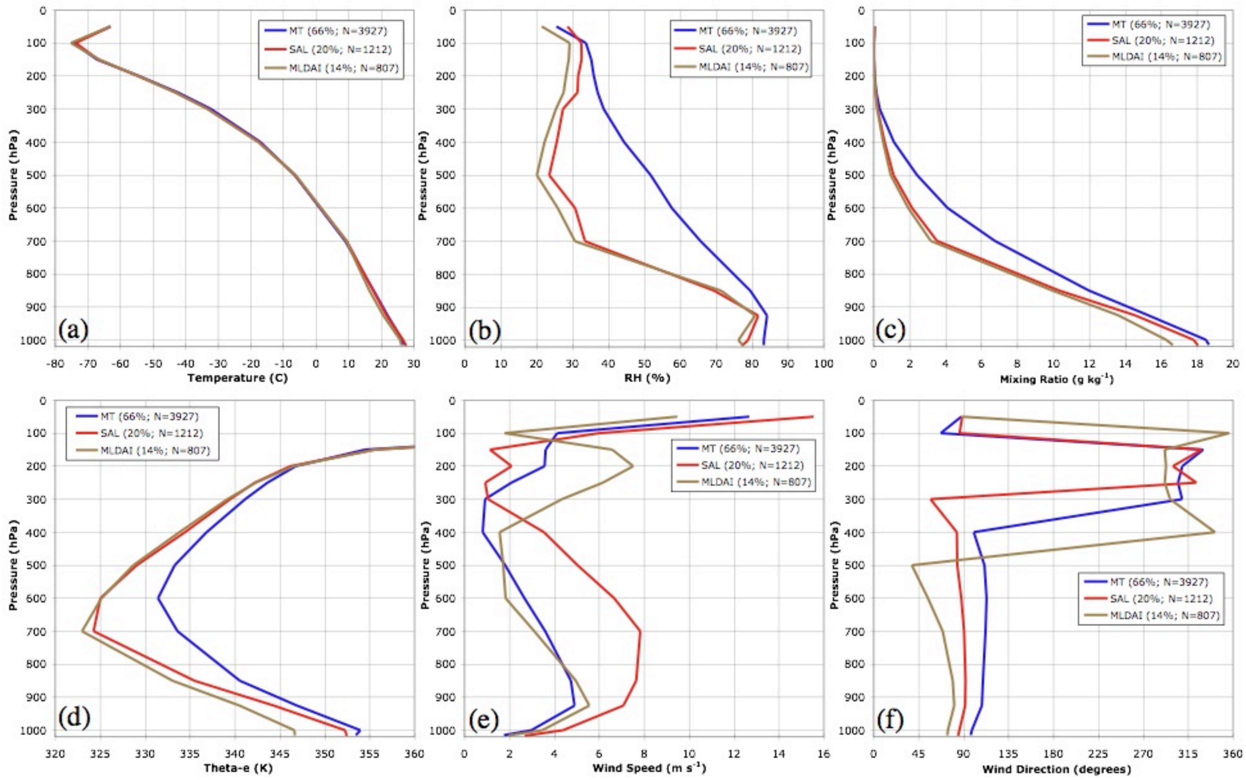

Figure 7: Mean July-October (1995-2002) MT, SAL and MLDAI soundings of (a) temperature (C), (b) RH (%), (c) mixing ratio (g kg^{-1}), (d) theta-e (K), (e) wind speed (m s^{-1}) and (f) wind direction (degrees).