Validation of Atmospheric Infrared Sounder (AIRS) Data Using GPS Dropsondes

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VALIDATION OF ATMOSPHERIC INFRARED SOUNDER (AIRS) DATA USING GPS DROPSONDDES

By

Edward Hildebrand

A THESIS

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Master of Science

VALIDATION OF ATMOSPHERIC INFRARED SOUNDER (AIRS)
DATA USING GPS DROPSHONDES

Edward Hildebrand

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The vertical structures of tropospheric temperature and moisture over the oceans have not been well observed to date. The Atmospheric Infrared Sounder (AIRS) aboard NASA’s Aqua satellite offers the opportunity to provide observed soundings of these variables. This thesis focuses on the validation and application of AIRS soundings in the tropical troposphere over the Atlantic Ocean, with emphasis on the Saharan Air Layer (SAL). SAL outbreaks occur every few days, producing a warm air mass that is particularly dry at the middle levels. These westward-propagating plumes inhibit convection and are thereby thought to possess a detrimental effect on African easterly waves and tropical cyclones (TCs).

First, AIRS soundings are compared with concurrent Global Positioning System (GPS) dropwindsonde data released from NOAA’s Gulfstream-IV jet aircraft, for three TC cases. In SAL environments, temperature soundings from both instruments are usually consistent. Additionally, AIRS is able to capture the very dry air in the middle levels, but it generally underestimates the moisture in the boundary layer and often misses the sharp vertical moisture gradient at the SAL base (~850 hPa). In the moist tropical boundary layer, AIRS also exhibits a dry bias. Cloud cover also prevents AIRS from accurately sampling the low-level moisture.
Next, total precipitable water is derived from AIRS soundings and averaged over daily, monthly and seasonal timescales. The significant monthly and interannual variability of the moisture distribution is found to be consistent with expectations. A peak in the probability density function of mixing ratio corresponding to dry air is observed in the lower-mid troposphere in early summer, consistent with the increased frequency of SAL outbreaks during this period.

Finally, the relationship between dry air derived from AIRS and TC intensity is explored. As the amount of dry air increases, particularly in the southeast and northeast quadrants of the TC, the TC becomes more likely to weaken. In the presence of high wind shear or low sea surface temperature, the likelihood of weakening increases further. While these results highlight some shortcomings of the AIRS data, their importance and uniqueness are emphasized via new applications of AIRS soundings over data sparse regions.
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Chapter 1

Background and Motivation

The study of tropical cyclones has become an important area of research in recent decades, as they pose a significant threat to increasing coastal populations and to maritime interests (Pielke and Landsea 1998). A thorough understanding of hurricanes can in turn lead to fewer lives lost and less property damaged. The development and sustainability of a tropical cyclone is often a combination of several factors, one of which is its interaction with a dry air mass, such as the Saharan Air Layer (SAL). This hot, dry air that emerges from the west coast of Africa in late spring and early summer can act to suppress convection in a westward moving African Easterly Wave (AEW). Should an AEW encounter the dry SAL, evaporatively driven downdrafts can help suppress sustained updrafts associated with convection (Dunion and Velden 2004). The SAL is often marked by a temperature inversion at its base with a height near ~850 hPa, which acts as a cap to inhibit cumulus convection. SAL outbreaks have also been observed to have anticyclonic rotation in the mid-levels, which would be detrimental to the development of a cyclonically rotating tropical cyclone (Diaz et al. 1976).

Initially, the SAL was only occasionally sampled by in situ measurements from aircraft and radiosondes. Since the satellite era began in the 1960s, the SAL has become much easier to track. Differencing infrared channels (12.0 and 10.7 microns) on GOES and Meteosat satellites can show the presence of low to mid-level dry air. Microwave imagery is also efficient at detecting moisture variability in the middle troposphere where
the SAL is most pronounced. Satellite animations and trajectory analyses must also be considered to distinguish a dry mid-latitude continental airmass from the SAL.

This study in part seeks to assess the reliability of satellite measurements to detect the dry air associated with SAL outbreaks in regions of tropical cyclones. Atmospheric Infrared Sounder (AIRS) temperature and moisture data in the vicinity of three tropical cyclones (Irene 2005, Debby 2006, and Helene 2006) are examined in detail. This study also uses AIRS satellite data to create temporal averages of moisture across the Atlantic basin to show the intraseasonal variability of dry air from SAL outbreaks and mid-latitude intrusions. The performance of AIRS data is also compared with that of microwave data, which is not sensitive to cloud cover. These satellite data are also used to determine the relationship between dry air and tropical cyclone intensity change. Because the intensity of a tropical cyclone is dependent on many variables, vertical wind shear and SST data from SHIPS files are also used in conjunction with the presence of dry air to assess the intensity change. Gaining a more thorough understanding of the role dry air plays in combination with other factors can hopefully lead to better predictions of tropical cyclone intensity change.

1.1 SAL

Before the era of satellites, there was little, if any, skill in tracking SAL outbreaks across the tropical Atlantic. Early studies of vertical soundings in this region were only divided by season, not by airmass. Jordan (1958) compiled a mean hurricane season sounding based on several stations in the western Atlantic basin. It was his belief that there was little spatial and seasonal variation in the tropics during the months of July-

October, and thus a mean hurricane season sounding was typically representative of the conditions on any given day. Later studies (e.g., Dunion and Velden 2004, Dunion and Marron 2008, Dunion 2010) suggest that the Atlantic hurricane season is better represented by a moister atmosphere than the Jordan mean with occasional SAL outbreaks and mid-latitude dry air intrusions that are significantly drier than the Jordan mean. Figure 1.1 shows a mean SAL and mean non-SAL environment from observations around four Atlantic hurricanes (Dunion and Velden 2004). The tropospheric moisture in the mean SAL sounding is significantly drier than that of the mean non-SAL (moist tropical) sounding. During the summer months, the tropical Atlantic is more likely to resemble a mean moist tropical or a mean SAL environment than it is to resemble the Jordan mean. The Jordan mean does not clearly show the presence of occasional dry SAL profiles. Instead, it lies between the mean SAL and mean moist tropical

![Graph showing composite GPS sonde profiles from sondes launched in the environments of Hurricanes Danielle and Georges of 1998 and Hurricanes Debby and Joyce of 2000. SAL and non-SAL environments were determined using GOES SAL-tracking imagery. The Jordan mean tropical sounding for the area of the West Indies for July-October is presented for reference (From Dunion and Velden 2004).](image-url)
environments, but with a slight bias towards moist tropical because that regime is more common in the western Atlantic basin. Additionally, there is a clear bi-modal peak in 700 hPa moisture distribution that was seen in July-October 1995-2002 Caribbean soundings (Dunion 2010). There is a peak in RH frequency around 30-35% (indicating SAL regimes) and a second peak in frequency around 70-75% (non-SAL), with a relative minimum in frequency observed in between (Fig 1.2).

Case studies in Huang et al. (2010) and Kaufman et al. (2005) showed that SAL outbreaks propagate westward at speeds of about 8º-10º longitude per day, reaching the Caribbean (at latitude 10-20N) after about 1 week. The leading edge of the dust outbreak can easily be detected via a strong “dust front”, where there is a large horizontal gradient in dust concentration. Aerosol optical depth gradients were found to be as sharp as 0.5 per longitudinal degree. The dust outbreaks are also accompanied by decreases in mixing ratio (up to -1.0 g kg\(^{-1}\)) and increases in temperature (1.0 K) behind the front in the low-mid levels, as seen in Figure 1.3.

Figure 1.2: Probability distribution functions of the rawinsondes that comprised the mean July-October (1995-2002) moist tropical (MT), SAL, and mid-latitude dry air intrusions (MLDAI) 700 hPa soundings of (a) RH (%) and (b) mixing ratio (g kg\(^{-1}\)) (From Dunion 2010).
A study (Dunion 2010) of over 7000 Caribbean soundings in June-October 1995-2002 showed that SAL outbreaks are most likely to occur from mid-June through mid-August (Fig. 1.4). The overall June through October trend is a moist tropical environment.
with occasional SAL outbreaks. The stronger SAL outbreaks that occur in early summer may be one reason for AEWs to occur less frequently than in the later season when SAL outbreaks are both less frequent and less intense (Dunion 2010). Quantitatively, SAL outbreaks in the tropical Atlantic can be defined as having total precipitable water (TPW) less than 45 mm, and air parcel origins over northern Africa.

The advent of satellites has allowed for more detailed studies of the origin of tropical cyclones and SAL outbreaks. Burpee (1972) noticed the presence of an easterly jet at 700 hPa along the baroclinic zone between the hot, dry Sahara to the north, and cooler moister air to the south over equatorial Africa. African easterly waves developed along the south side of this jet maximum where the flow was unstable. Carlson and Prospero (1972) noted a wind maximum of 21-26 ms\(^{-1}\) (40-50 knots) around 700 hPa associated with SAL outbreaks emerging off the African coast. The air over the Sahara consists of a deep well-mixed layer in the lower half of the troposphere. When this hot and dry airmass reaches the coast, it becomes elevated as it is undercut by denser, cooler, and moister marine air just offshore (Prospero and Carlson 1972). Both the SAL and the AEW move nearly in concert across the Atlantic, with dust outbreaks occurring every summer over the Caribbean and the western portions of the Atlantic. Although far from the source region, these dust outbreaks in the Caribbean are still noticeable, especially at sunset when a hazy and dusty sky is often seen. Aircraft measurements near Barbados have shown aerosol concentrations in the SAL to be higher by a factor of three when compared to concentrations between the SAL base and the surface (Prospero and Carlson 1972). Mineral aerosol concentrations were 61 \(\mu g\) m\(^{-3}\) in the SAL (defined as 1.5 km to 3.7 km altitude), and 22 \(\mu g\) m\(^{-3}\) below the SAL base. Sea salt aerosol concentrations
below the SAL base were only 10 μg m⁻³, which shows that even though its source region is a few thousand kilometers away, dust is the most prominent aerosol in Barbados during the summer months and it is most present in the mid-levels (Prospero and Carlson 1972). Radiative transfer models have shown that this increase in mid-tropospheric aerosol concentration can lead to 1-2K day⁻¹ atmospheric warming (Carlson and Benjamin 1980). This mid-level warming acts to increase atmospheric stability and suppress convection.

Figure 1.5: Three-dimensional conceptual model of the SAL looking westward. The SAL is shown in cutaway, with dashed lines representing individual trajectories. The flow of the SAL is toward the west across the axis of an easterly wave and toward the north curving anticyclonically. The rise of the SAL base toward the west is shown by the base of an inclined plane. On the southern side of the SAL is the middle-level easterly jet (MLEJ; the tubular arrows). Thin solid streamlines represent air flow at the surface; these are shown to be confluent along the intertropical convergence zone (ITCZ), although at higher levels the confluence is along the lateral boundary of the SAL. (Flow lines within the SAL are shown only along the axis of the MLEJ) (From Karyampudi and Carlson 1988).
Karyampudi and Carlson (1988) provided a conceptual model of the SAL (Fig. 1.5). They noted that the SAL typically occurs with latitudinal boundaries of 10-15°N to 25-30°N. During the summer, intense heating of desert air occurs in North Africa, causing a thermal low to form near the surface. When this heated air reaches the west coast of Africa, it is often well-mixed in the lower half of the troposphere (up to around 500 hPa). The base of the SAL rises as it moves across the Atlantic, reaching an altitude of 1.5 km around 25°W and up to 2.5 km in the Caribbean (Karyampudi and Carlson 1988). Because the altitude of the top of the SAL (typically 550-500 hPa) does not change much with westward movement, the SAL is found to be deeper in the eastern Atlantic and shallower in the Caribbean. At the SAL base, there is often a strong potential temperature inversion ranging from a few degrees Celsius to as high as 10°C. A SAL outbreak is often accompanied by a strong mid-level wind maximum centered near 600-800 hPa found on the southern edge of the SAL, resulting from a meridional temperature gradient between the warm SAL and the cooler marine air in the equatorial region. This easterly jet is a result of thermal wind balance between the warm SAL to the north and cooler air to the south. Karyampudi and Carlson (1988) also attempted a 5-day numerical simulation of the SAL with a regional model of 220 km resolution and a 110 km resolution inner domain. Their model was able to capture the top and base of the SAL and its frontlike nature along the leading edge. The mid-level jet was also resolved in the model. However, the authors concluded that the SAL is important in the growth and maintenance of an AEW because of the increased baroclinicity along the edge of the SAL. In one of the cases they simulated a SAL outbreak along with two AEWs (Fig. 1.6a). Wave T-1, the stronger of the two waves, eventually developed into Hurricane
Carmen (1974), while wave T-2, which was closer to the core of the SAL outbreak, dissipated over the mid-Atlantic without developing. Five days later (Fig. 1.6b), wave T-1 is still ahead of the SAL enough for it to intensify, but wave T-2 is more closely surrounded by dry air.

Figure 1.6a: The 700 mb streamline analysis and depiction of deep convection, dust front and the SAL at 1200 UTC 23 August 1974 for Case 1. The shaded region within the serrated line indicates the SAL. Deep cumulonimbus convection with cirrus tops is shown by the stippling within scalloped borders. Dashed lines denote axes of easterly wave disturbances (labeled inside circles) (From Karyampudi and Carlson 1988).

Figure 1.6b: As in Fig. 1.5a except for 1200 UTC 28 August 1974. Heavy arrows denote axes of midlevel easterly jets (From Karyampudi and Carlson 1988).
1.2 SAL and Tropical Cyclones

Recent studies (e.g. Dunion and Velden 2004, Jones et al. 2007) have shown that SAL outbreaks can have a negative effect on AEWs and TCs. While the SAL may enhance convection along its periphery due to strong horizontal temperature gradients and the lifting of its warmer/drier (less dense) air over the cooler/moister (denser) tropical air along its edges, the interior of the SAL contains dry, sinking air which is stable and prevents persistent deep convection necessary for tropical cyclone development and intensification. Dry SAL air can also be wrapped in towards the center of an existing TC. This mid-level dry air leads to convective downdrafts which can cause tropical cyclones to weaken. Vertical wind shear can be enhanced by the easterly jet around 600-800 hPa, which also presents unfavorable conditions for tropical cyclone development.

It is hypothesized that the low moisture content associated with the SAL approaches the center of the TC via low to midlevel inflow that follows the cyclonic circulation of the storm (Dunion and Velden 2004). Shu and Wu (2009) showed that tropical cyclones are most affected by the SAL when the dry air is within 360 km from the center. Figure 1.7 shows the progression of dry air into the circulation of Tropical Storm Debby (2006). Initially, the dry mid-level air is present well north and west of Debby, outside the 360 km radius. With time this dry air follows the cyclonic circulation and wraps around the south side of Debby (Fig. 1.7b), then to the east side (Fig. 1.7c), and eventually entering the circle representing 360 km radius from the center (Fig. 1.7d). In cases of vertical wind shear, the shear may act to either accelerate or delay the intrusion of dry air toward the center.
Figures 1.7: Relative humidity field between 600 and 700 hPa retrieved from the AIRS/Aqua suite in the vicinity of Tropical Storm Debby (2006) with a contour interval of 5%. The hurricane symbol shows the tropical cyclone center at the time shown in the left corner of each plot while the circle represents the radius of 360 km from the center. The relative humidity below 40% is shading (From Shu and Wu 2009).

The effects of the SAL on tropical cyclones and cyclogenesis are difficult to predict using forecast models. In 2001, a tropical depression in the eastern Atlantic developed into Tropical Storm Erin, and the National Oceanic and Atmospheric Administration/National Hurricane Center (NOAA/NHC) forecasts called for steady strengthening. However, the effects of a nearby SAL outbreak, strong shear, and mid-latitude dry air created an increasingly hostile environment for the storm, and Erin weakened to an open wave. A few days later it moved away from the dry SAL and high
shear, and quickly reintensified to a category 3 hurricane. NOAA/NHC forecasts underestimated the intensity of the SAL that initially caused Erin to dissipate, and also underestimated the rapid intensification that occurred after Erin moved away from the SAL (Jones et al. 2007). Pratt and Evans (2008) showed that the NCEP-GFS operational model does not accurately capture the effects of the SAL, and this may contribute to false predictions of cyclogenesis in the eastern tropical Atlantic. A better understanding of the SAL and a more complete incorporation of it into statistical and numerical models would act to limit forecast intensity errors.

A recent PSU-NCAR MM5 simulation of the formation of Hurricane Isabel (2003) assimilated observed Atmospheric Infrared Sounder (AIRS) temperature and moisture profiles (Wu et al. 2006). The incorporation of AIRS data in regions not contaminated by clouds led to a more accurate simulation of the track of Isabel versus the control run, which used only NCEP reanalysis data and completely omitted AIRS data (Fig. 1.8). With the AIRS data in the model, the simulated track was more similar to the observed (Fig. 1.8a), whereas without the AIRS data, the model insisted on Isabel curving to the north (Fig. 1.8b). The MM5 with AIRS was also able to better depict the dry SAL in the mid-levels and the increase in zonal wind around 4 km (Fig. 1.9).

### 1.3 Research Questions

The primary investigative questions in this study are as follows:

- Is AIRS temperature and, especially, moisture data reliable in tropical cyclone environments?
Figure 1.8: Comparisons of the observed Isabel track (red) with the simulated tropical cyclone tracks in the numerical experiments (a) with nudging the AIRS data and (b) without. The formation time is indicated for Isabel and the simulated tropical cyclones (From Wu et al. 2006).

- Can AIRS data be used on longer time scales to show seasonal variability in tropical North Atlantic moisture?
- How does AIRS moisture data compare with other measurements of moisture from microwave sensors aboard satellites?
- What role does dry air play in conjunction with other factors such as wind shear and SST in the intensity change of tropical cyclones?

The thesis is organized as follows: Chapter 2 addresses the various data sources and how they can be used to track SAL outbreaks. Chapter 3 is a statistical comparison of AIRS profiles using GPS dropsonde data. In Chapter 4, AIRS data are applied to
Chapter 5 discusses the relationship between dry air, wind shear, sea surface temperature and intensity change of tropical cyclones. Some conclusions and ideas for future work are presented in Chapter 6.
Chapter 2

Data

2.1 GPS Dropwindsondes

Global Positioning System (GPS) dropsonde data were obtained from the NOAA/AOML/HRD field programs in 2005 (Tropical Storm Irene) and 2006 (Tropical Storm Debby and Hurricane Helene). The data consist of Gulfstream IV (high altitude) aircraft GPS dropsonde data measuring tropospheric temperature and moisture profiles from ~175-200 hPa to the surface. The dates of the research flights for each storm are listed in Table 2.1, along with the number of GPS dropsondes released on each flight.

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Table 2.1: Dates of NOAA/AOML/HRD flights into each tropical cyclone and the number of GPS dropsondes released on each flight.

GPS dropsondes, developed by the National Center for Atmospheric Research, were first used in 1996. Their marked improvement over earlier aircraft-deployed instruments such as Omega dropwindsones (Govind 1975, Franklin and Julian 1985) has led to their widespread use around the world over the past 13 years. The GPS dropsondes have a vertical resolution of 0.5 s (~5 m), a wind speed accuracy of 0.5 – 2.0 m s⁻¹, and can measure a standard 10 m surface wind which was not possible with previous aircraft-
deployed instruments. When released from an altitude of 12 km (roughly the tropopause), it has a descent time of 12 minutes (Hock and Franklin 1999).

Pressure, temperature, and humidity sensors in the GPS dropsonde are also more accurate than earlier instruments. Typical errors for pressure, temperature, and relative humidity are 1.0 hPa, 0.2°C, and <5%, respectively (Hock and Franklin 1999). The Airborne Vertical Atmospheric Profiling System (AVAPS) can process four dropsondes simultaneously, and the sondes can be released less than 20s apart. This capability is important when studying the SAL because there are often strong horizontal gradients between the dry SAL and moist tropical regimes, and high temporal and spatial measurements across these gradients are desirable.

2.2 Defining and Tracking SAL Outbreaks

SAL outbreaks were defined and tracked using several methods and sources of data. Because a main characteristic of SAL outbreaks is mid-level dry air, any GPS dropsonde profile with a sharp vertical moisture gradient in the low- to mid-levels is initially suspected to be indicative of a SAL airmass. Additionally, profiles exhibiting a temperature inversion near this vertical moisture gradient are also judged to be possible SAL cases. To track the origins of these outbreaks and to determine if the dry air originated from the Sahara (SAL outbreak) or higher latitudes (mid-latitude dry air outbreak), the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph 2010) was run at 3000m using NCEP/NCAR reanalysis data (examples to be shown in Chapter 3). This model provides backwards trajectories that show the origin of air parcels at a given latitude/longitude point. As a result, mid-level
dry air near the three storms (Irene, Debby, and Helene) could be traced back to its Saharan or mid-latitude origins. The Navy Aerosol Analysis and Prediction System (NAAPS) provide aerosol characteristics over 6-hour periods on each day of the three tropical cyclones. These images highlight areas of sulfates, aerosols (dust), and smoke, making it easy to see if a tropical cyclone and the GPS dropsondes released near it were in a SAL airmass. Additionally, visible satellite imagery from GOES was also used to track the SAL outbreaks near these storms. SAL outbreaks are typically free of deep convection, and the presence of dust often can be seen in the visible image at lower sun angles.

2.3 AIRS

Launched on 4 May 2002, the Atmospheric Infrared Sounder (AIRS) is one of six instruments orbiting on the Aqua satellite, a near-polar orbiter which is part of NASA’s A-Train satellite constellation. The goal of AIRS is to provide data with higher vertical resolution and better accuracy than previous satellites, thus allowing improved medium-range weather forecasts. AIRS crosses the equator at 0130 and 1330 (+/- 15 minutes) local time. The AIRS scanning mirror detects infrared energy emitted from the Earth and its atmosphere across a swath width of ~1650 km. Infrared spectral coverage occurs in three wavelength ranges: 3.74-4.61 μm, 6.20-8.22 μm, and 8.80-15.4 μm. There are 2378 infrared channels, each of which senses energy that is sensitive to temperature and moisture at a particular atmospheric level. Data from all channels were combined to produce vertical profiles (soundings) of the atmosphere. The vertical resolution of AIRS is coarse, with data measured and derived only at the mandatory pressure levels and 600
hPa. In the troposphere, this amounts to 10 levels from 1000-200 hPa. Dense cloud cover presents a problem because it blocks infrared emissions from below, and this becomes particularly an issue for AIRS data around tropical cyclones. Cloudy regions are identified by comparisons to radiance values in a known clear region. To account for the effects of clouds, cloud-clearing algorithms have been developed, and microwave data onboard the Aqua satellite can also be used and combined with the AIRS data to provide nearly global coverage of the atmospheric state.

The required performance of AIRS for temperature data is 1 K RMS in 1 km vertical layers below 100 hPa, and for relative humidity it is 20% RMS (with a goal of 10%) in 2 km vertical layers below 100 hPa (Tobin et al. 2006). Over a given region of the Earth, profiles of temperature and moisture are obtained twice daily with a ~50 km horizontal resolution and 28 vertical pressure levels (Wu et al. 2006).

A number of studies have validated the AIRS data. Tobin et al. (2006) compared AIRS version 4 temperature and moisture retrievals with radiosonde data from the Atmospheric Radiation Measurement (ARM) site in the tropical West Pacific (TWP). Temperature RMS differences were ~1 K or less in 1 km layers below 200 hPa, and moisture RMS differences were 20% or less in 2 km layers below 400 hPa. This corresponds well with the required performance values of AIRS. The authors also found AIRS temperature retrievals were too warm (by about 0.5 K) in the mid-levels and too cold (also by about ~0.5 K) in the upper levels. There were also moisture biases of ~5% below 400 hPa and biases of minus 10% above 400 hPa.

Other studies validating AIRS temperature and moisture retrievals include Hagan et al. (2004), Divakarla et al. (2006), McMillin et al. (2007), and Ho et al. (2007). Hagan
et al. (2004) compared AIRS middle to upper tropospheric (500 to 100 hPa) water vapor retrievals to \textit{in situ} balloon and aircraft data near Costa Rica. For AIRS retrievals within one hour and 100 km from an \textit{in situ} observation, percentage differences between AIRS and \textit{in situ} water vapor amounts were typically 25\% or less. This comparison took place in January 2004, when air mass changes are more common at lower latitudes in the Northern Hemisphere, and AIRS was able to capture an observed 2-day change in upper tropospheric moisture.

Divakarla et al. (2006) considered AIRS data over land and water and compared them with radiosonde observations. Over water, AIRS accuracies for temperature were within 1 K in 1 km layers, and accuracies for moisture were within 15\% in 2 km layers. These results are similar to the expected product accuracies and consistent with other validation studies (e.g. Tobin et al. 2006). Divakarla et al. (2006) and McMillin et al. (2007) both showed that AIRS is more accurate over water than over land because of a higher emissivity of water, so the spectral channels are more sensitive to changes in moisture over oceans. Emissivity over land is more variable because the surface is less uniform, and other effects such as diurnal heating and cooling and differences in surface pressure due to elevation can cause AIRS error estimates to be higher over land.

\section*{2.4 AIRS Standard and Support Data}

As AIRS passes over a region, it measures hundreds of vertical profiles and spatially groups them into granules of 1350 each (arranged in a 30x45 array). Figure 2.1 shows an example of 5 AIRS granules in and near Hurricane Irene and the NOAA/HRD GPS dropsonde locations. The vertical resolution of these profiles is much coarser than
Figure 2.1: Map of AIRS granules and NOAA/HRD dropsonde locations (black asterisks) from Hurricane Irene on 7 August 2005. The center of Irene is represented by the red star, while the initial and final dropsonde locations are indicated by the purple and cyan asterisks. (Figure courtesy: CIRA)

that of the GPS dropsondes, with data measured and derived only at the mandatory pressure levels and 600 hPa. Initially, two types of AIRS products, standard dataset and support dataset, were used. The standard data has 28 vertical levels (10 pressure levels in the troposphere from 1000 hPa to 200 hPa), while the support data has 100 (approximately 45 pressure levels in the troposphere). AIRS data in standard or support form are essentially the same because interpolation is used between the datasets, and no new information is present in the support dataset that cannot be seen in the standard dataset. Additionally, the support product is more experimental in nature, with the increased vertical resolution to help refine AIRS retrieval algorithms (Olsen et al. 2007). The support product also contains data from instances when the algorithms failed to work completely, so some support data may be misleading even though it might look physically reasonable.
Figure 2.2 shows the mean of AIRS temperature profiles that match all SAL GPS dropsondes from Hurricanes Irene, Debby, and Helene. The mean temperature profile from the standard (support) data is in red (blue). It can be seen that the standard and support mean temperature profiles are equal at the mandatory pressure levels and 600 hPa. Slight differences do exist between the mandatory levels and 600 hPa, and this is due to the higher vertical resolution of the support dataset. The greatest differences (support data being warmer than the standard data by as much as 0.5K) are found in the ~750-800 hPa layer.

A similar plot is shown in Figure 2.3 for mixing ratio. As for temperature, mixing ratio values of the support and standard data should be equal at the mandatory pressure levels and 600 hPa. However, this is not the case. Mixing ratio of the standard data is
drier than that of the support data at every level except 1000 hPa. This difference is largest at 800-925 hPa, with the greatest difference near 850 hPa (~9 g/kg in the support data compared to ~6 g/kg in the standard data).

The conversion of the moisture product in the support data from ‘molecules/cm²’ to ‘g/kg’ might be a reason for the discrepancies. Two variables need to be approximated in order to make this conversion: a vertical depth between each support pressure layer (‘dz’), and density. Density also requires the assumption of a pressure and temperature value for each layer. For these plots, ‘dz’ was obtained using the height data from nearby GPS dropsonde measurements. It is believed that the differences at the mandatory levels and 600 hPa are not real, and that if a perfect conversion to ‘g/kg’ could be made without assumptions, the values at the mandatory levels and 600 hPa would be equal, as in the
case of temperature. No conversion or approximation is necessary for the standard data, which might be an advantage.

An example of AIRS standard and support data for individual profiles is shown in Figure 2.4. The solid blue line is the temperature profile from a GPS dropsonde released in a SAL environment around Tropical Storm Irene. A slight temperature inversion is seen near 800 hPa where the base of the SAL is located. Two individual AIRS profiles matched this GPS dropsonde within 50 km and 3 hours, but neither the standard nor support version of AIRS is able to capture this shallow temperature inversion at the SAL

Figure 2.4: Temperature profiles of AIRS standard and support data and a SAL dropsonde launched during a NOAA Saharan Air Layer Experiment mission around Hurricane Irene (7 August 2005). Solid blue line is the dropsonde temperature profile. The pink and yellow lines are AIRS standard dataset temperature profiles, while cyan and purple lines are AIRS support dataset profiles.
base. It is not surprising because the inversion lies between AIRS standard pressure levels of 850 and 700 hPa. However, the support dataset has approximately four pressure levels around 800 hPa, yet the AIRS temperature still shows a cool bias compared to the dropsonde temperature at the SAL base.

After examining the standard and support datasets, it was determined that the standard dataset should be used in this study for three reasons. First, there are no issues in obtaining accurate mixing ratio values because they are explicitly provided, while assumptions are needed to calculate mixing ratio in the support dataset. Second, the support dataset contains all results of the retrieval algorithms, even if those algorithms encountered problems. Third, the standard dataset contains mandatory level (plus 600 hPa) data. This makes AIRS comparisons with GPS dropsonde data easier if these simple pressure levels can be used. The support dataset does not contain these specific mandatory pressure levels. Instead, the 100 pressure levels in the support dataset were chosen based on desired accuracies in the algorithm used to calculate radiance values.

### 2.5 AIRS Dust Flag

AIRS offers two methods to track SAL outbreaks. One is to follow the SAL by looking at the moisture distribution across the Atlantic basin, especially in the lower and middle levels. The SAL and mid-latitude dry air intrusion can be identified by low tropospheric mixing ratio. Moist regions, such as those in tropical cyclones, have high tropospheric mixing ratio. Another method to specifically track the SAL is through the dust flag product. This appears to be a more efficient method, as it shows where AIRS is actually sensing dust, not just sampling dry air (e.g. mid-latitude dry air intrusions). The
dust flag is determined by comparing radiance values, and is a 3x3 array for each field of view. Flag values are unitless. They are 0 except when dust detection is confirmed and they become 1. However, dust may still be present when the dust flag value is 0 but the AIRS dust test cannot confirm it. A negative flag value indicates an invalid dust test due to land, high latitude, clouds, or bad input data. The AIRS dust test is only valid in a clear atmosphere over ocean. Cloud cover above the SAL dust, even if it is thin, will prevent AIRS from “seeing” the dust (Olsen et al. 2007).

While the dust flag is a simple tool to use to track the SAL, it must be used with caution. AIRS seems to miss (dust flag of 0 or a negative integer) many regions that are expected to contain dust. Figure 2.5 is an example of this. Blue dots mark locations where AIRS detected dust, and red dots are where the dust test failed because of cloud cover. When compared with the AIRS TPW plot in Figure 2.6a, several differences appear. AIRS does detect some dust in the western Caribbean Sea, but it appears to

![Figure 2.5: AIRS dust flag on 7 August 2005. Positive dust tests are indicated by blue dots, invalid tests due to cloud cover by red dots. The cloud cover associated with Irene is roughly from 15-25\textdegree N and 40-45\textdegree W.](image)
Figure 2.6: (a) AIRS TPW with (b) dust flag values overlaid on 7 August 2005.

underestimates the coverage of dust that is likely present in this region. AIRS shows no
evidence of dust in the dry region to the west of Irene. Near the coast of Africa, AIRS
indicates more dust, but the TPW plot indicates this SAL region is much larger than what
the dust flag shows. Figure 2.6b shows the same AIRS TPW plot, but with the dust flag
test results overlaid. The white dots (found near the coast of Africa and just east of Irene)
indicate where the test for dust was positive. Black dots indicate an invalid dust test due
to the presence of clouds. As expected, clouds were an issue in areas with high TPW,
especially near tropical cyclones, AEWs, and convection along the ITCZ. The three main dry regions (eastern Atlantic, west of Irene, and western Caribbean Sea) all have little cloud cover, but also little dust. Most dust would be expected in the large dry region off Africa, closest to the source of the dust. While dust is detected close to the coast, none is detected in the heart of this dry region. Perhaps the dust flag test is only sensitive to high concentrations of dust, and it might not detect dust as frequently in regions of lower concentrations. To confirm this, a NAAPS plot from the same day (7 August 2005) is presented in Figure 2.7. Indeed, the areas in Figure 2.5 where AIRS detects dust (western Caribbean and the west coast of Africa) are where the NAAPS plot shows the highest concentrations of dust. Based on this, AIRS appears to struggle in capturing dust of relatively less concentration.

There are also times when the presence of dust is strongly indicated by other satellite measurements, but AIRS fails to switch on the dust flag. Figure 2.8a shows a SSM/I TPW map from 15 September 2006 (Hurricane Helene). Helene is centered near 15ºN and 40ºW, with a large region of high TPW air near and to the east of the center. A

![Figure 2.7: NAAPS aerosol from 7 August 2005. The green region represents where dust is detected.](image-url)
large SAL region extends from the northwest coast of Africa westward, surrounding
Helene on the north and west sides. AIRS does not detect dust (Fig. 2.8b) in this region,
but a HYSPLIT back trajectory from the middle of this large region of dry air suggests its
origins from Africa (Fig. 2.9). Also, a NAAPS aerosol plot shows a large area of dust to
the west of Helene (Fig. 2.10). The NAAPS plot also suggests that dust has wrapped
entirely around Helene, which is centered near 15ºN 40ºW. The AIRS dust test has
difficulties in cloudy regions (black dots in Figure 2.8b). Once again this tends to occur
in high TPW areas. The large SAL region on the west side of Helene does not have any failed dust tests due to cloud cover, yet AIRS does not indicate any dust is present.

Figure 2.9: HYSPLIT model 700 hPa backward trajectory ending at 2000 UTC 15 September 2006.

Figure 2.10: NAAPS aerosol from 15 September 2006. The green region represents where dust is detected. Hurricane Helene (blue x) is centered near 16°N and 41°W.
Chapter 3

Statistical Analysis of AIRS Using GPS Dropsondes

3.1 Categorizing GPS dropsondes and their AIRS matches

To assess the performance of AIRS in tropical cyclone environments, a detailed comparison with GPS dropsonde data obtained during NOAA/HRD Saharan Air Layer Experiment (SALEX) aircraft missions was performed. Data from three Atlantic tropical cyclones were considered: Irene (2005), Debby (2006), and Helene (2006). Collocated GPS dropsonde-AIRS temperature and moisture data (in the form of mixing ratio) was obtained for these cases and included a total of eight flights. Individual AIRS profiles that matched each GPS dropsonde were selected based on predetermined criteria. An AIRS profile was determined to match a given dropsonde if criteria of spatial (within 50 km) and temporal (within 3 hours) proximity were met. Additionally, the error flag value for the AIRS profile had to be less than or equal to 3584, meaning there was completeness and confidence in the data for that single AIRS profile (Olsen et al. 2007). Seven of the eight NOAA/HRD flights had AIRS data that met the three criteria listed above.

Table 3.1 shows the number of AIRS matches to GPS dropsondes in each of the three storms and for the total. In all, 209 sondes were released during the 8 flights (average 26 sondes per flight). There were 50 sondes, or 24%, with at least one AIRS match. The total number of AIRS matches was 123, or between 2 and 3 matches on
<table>
<thead>
<tr>
<th>Date</th>
<th>Irene 2005</th>
<th>Debby 2006</th>
<th>Helene 2006</th>
<th>Total</th>
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<tr>
<td>7Aug</td>
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<td>23</td>
<td>25</td>
<td>209</td>
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<td>20Sep</td>
<td>20</td>
<td>23</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: This shows the number of dropsondes released in each flight, the number of sondes with AIRS matches, and the total number of AIRS matches.

average for each of the 50 sondes. Dividing the sondes into two categories (SAL and moist tropical) was done based on HYSPLIT model runs at the GPS dropsonde locations, NAAPS aerosol maps, GOES visible satellite imagery, and a visual inspection of the temperature and moisture profiles of the GPS dropsonde. An example of a HYSPLIT model run is shown in Figure 3.1. The ten-day back trajectories from two GPS dropsondes released into Irene show origins over northern Africa. A NAAPS image (Fig. 3.2) shows these GPS dropsondes were released into a SAL environment.

![Figure 3.1: HYSPLIT back trajectories ending at 16Z on 7 August 2005.](image)

Figure 3.2: NAAPS aerosol plot from 7 August 2005. Green/yellow areas indicate where dust is indicated. Black asterisks indicate the end points of the two HYSPLIT trajectories shown in Figure 3.1, which correspond to GPS dropsonde release points.

GPS dropsondes launched in environments with strong SAL signals originating from the Sahara (sharp vertical moisture gradient and temperature inversion at the SAL base, low TPW) were placed in the SAL category. Strong moist tropical signals (moist profile, high TPW) were placed in the non-SAL category. Table 3.2 shows the number of GPS dropsondes that fall into each category for each storm, while Table 3.3 shows the number of GPS dropsondes in each category for the three storms combined. The

<table>
<thead>
<tr>
<th></th>
<th>Irene</th>
<th>Debby</th>
<th>Helene</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAL</td>
<td>NS</td>
<td>SAL</td>
</tr>
<tr>
<td># of sondes with matches</td>
<td>11</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td># of AIRS matches</td>
<td>27</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3.2: Dropsondes and AIRS matches divided by environment in which the dropsonde was released: SAL or non-SAL (NS).
Table 3.3: Number of sondes with matches and total number of AIRS matches for all three storms combined.

<table>
<thead>
<tr>
<th></th>
<th>SAL</th>
<th>Non-SAL</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td># of sondes with matches</td>
<td>35</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td># of AIRS matches</td>
<td>84</td>
<td>16</td>
<td>123</td>
</tr>
</tbody>
</table>

majority of GPS dropsondes and AIRS matches are found in SAL regions. This does not necessarily mean that AIRS tends to match dropsondes more frequently in SAL regions, but instead is probably a reflection of more dropsondes being in SAL regimes during the SALEX missions.

### 3.2 AIRS and GPS Dropsonde Temperature and Mixing Ratio Analysis

After determining which AIRS profiles matched each GPS dropsonde from each flight, vertical profiles of temperature and moisture for the GPS dropsondes and AIRS data were created. An example of this from Hurricane Helene is shown in Figure 3.3. Above approximately 850 hPa, the GPS dropsonde (blue line) and AIRS (red dashed line) mixing ratios are in close agreement with differences less than 1 g/kg. However, significant differences exist below the 850 hPa level. While AIRS shows a strong increase in moisture in the boundary layer, it is much less than what the GPS dropsonde indicates. At 1000 hPa, for example, AIRS underestimates the mixing ratio by about 3.5 g/kg. This mixing ratio profile is from a SAL environment, and shows a typical SAL profile of high mixing ratios near the surface with a sharp vertical moisture gradient near ~850 hPa. The base of the SAL can also be characterized by a temperature inversion, where the temperature locally increases with height (Fig. 3.4). AIRS also struggles to
Figure 3.3: Example of vertical profile of mixing ratio from a dropsonde (blue line) and matching AIRS (red line) profile in a SAL environment surrounding Hurricane Helene. AIRS performs well in and above the SAL, but struggles near the surface where it underestimates the amount of moisture in the boundary layer.

capture this feature, with the largest AIRS-GPS dropsonde difference being around 1-2K in the 800-900 hPa layer. The rest of the temperature profile shows that AIRS and GPS dropsonde temperature values are very similar.

An average mixing ratio profile for all SAL dropsondes and their matching AIRS profiles is shown in Figure 3.5. Similar to the example from Hurricane Helene just shown, the mean also shows that AIRS underestimates the amount of moisture in the lower levels. The greatest difference in the mean mixing ratio profiles is approximately 3 g/kg at 850 hPa (Fig. 3.6). PDF plots of AIRS mixing ratio bias in SAL cases and all cases (Fig. 3.7) show that dry biases, especially in SAL cases, occur most frequently below ~700 hPa. Specifically, PDF values are highest (~0.25) in the boundary layer,
Figure 3.4: Same as Fig. 3.3, but for temperature.

Figure 3.5: Mean dropsonde and AIRS profiles for all dropsondes launched in SAL environments surrounding Tropical Storms Irene and Debby and Hurricane Helene.
Figure 3.6: AIRS mixing ratio bias (AIRS – GPS dropsonde difference) profile from dropsondes launched in SAL environments surrounding Tropical Storms Irene and Debby and Hurricane Helene.

Figure 3.7: PDF of AIRS mixing ratio bias from (a) SAL dropsondes and (b) all dropsondes in Tropical Storms Irene and Debby and Hurricane Helene.

where biases of 1-2 g/kg are common. At 850 hPa, the PDF values are smaller (~0.15), but this is where the greatest average bias is found around 3 g/kg. It is also at this level that both GPS dropsonde and AIRS data indicate a maximum in mixing ratio standard
deviation (Fig. 3.8). The GPS dropsondes show a higher standard deviation in mixing ratio than AIRS, but both do have the highest values at this level. The most likely reason for this is because in SAL cases, the base is typically near 850 hPa. If the base is just above (below) this level, then 850 hPa moisture values will be high (low).

Looking at moist tropical cases, AIRS also underestimates the amount of moisture at all pressure levels except 925 hPa (Fig. 3.9). The mean GPS dropsonde mixing ratio profile for moist tropical cases is moister than the mean SAL profile because no significant region of dry air is present. AIRS also shows more moisture than it does for SAL environments, but it is generally drier than the GPS dropsonde profile at nearly all pressure levels (Fig. 3.10). The only positive AIRS mixing ratio bias for moist tropical cases is at 925 hPa, which may be a result of small sample size (only 5 moist tropical
Figure 3.9: Mean dropsonde and AIRS profiles for all dropsondes launched in moist tropical environments surrounding Tropical Storms Irene and Debby and Hurricane Helene.

Figure 3.10: AIRS mixing ratio bias profile from dropsondes launched in moist tropical environments surrounding Tropical Storms Irene and Debby and Hurricane Helene.
soundings with AIRS matches from flights into Irene, Debby, and Helene). A possible reason for the general dry bias in moist tropical environments is cloud cover. Moist tropical environments are moister and more unstable than SAL environments, so there is generally thicker cloud cover in these regimes. Clouds can negatively affect AIRS infrared retrievals by absorbing returning radiation from below the cloud layer.

The ability of AIRS to capture the SAL environment around a tropical cyclone can also be seen in histogram plots of mixing ratio. One might suspect that a mixing ratio histogram at 850 hPa would contain many moist tropical soundings, along with some dry SAL soundings. This is what occurred in an AIRS granule (1350 individual soundings, Fig. 2.1) taken in and around Hurricane Irene on 7 August 2005 (Fig. 3.11). This 850 hPa histogram shows a distinct bimodal peak in mixing ratio. The moist tropical

![Histogram of 850 hPa mixing ratio from one AIRS granule (1350 individual profiles) covering Hurricane Irene on 7 August 2005. A PDF curve is indicated by the green line, while a Gaussian curve is represented by the red line.](image)

Figure 3.11: Histogram of 850 hPa mixing ratio from one AIRS granule (1350 individual profiles) covering Hurricane Irene on 7 August 2005. A PDF curve is indicated by the green line, while a Gaussian curve is represented by the red line.
soundings are seen by the mixing ratio peak around 10 g/kg. Dunion (2010) showed the mean moist tropical mixing ratio to be closer to 12 g/kg. This makes sense given the ~1-2 g/kg AIRS dry bias in moist tropical cases (Fig. 3.10). There is a second (and even higher) peak in the PDF around 6-7 g/kg. This is a result of the large SAL outbreak that was located in a significant portion of this granule. Additionally, the northern fringes of this granule appear to contain areas of mid-latitude dry air. Dunion (2010) showed mean SAL mixing ratios at 850 hPa are ~10 g/kg, much moister than the peak PDF shown on this day (7 August 2005). Part of the reason for the difference may be attributed to the dry bias in the AIRS data in the low-mid levels. Between the peaks in Figure 3.11 is a local minimum in occurrence which is seen in the histogram and the green PDF curve, indicating that a distinct moist tropical or dry SAL (with some mid-latitude dry air) is more likely rather than a combination of the two. It is easy to see the effect of the SAL at this pressure level. At 700 hPa, the SAL is also usually seen, but on this particular day there was no bimodal peak in the histogram and PDF of mixing ratio (Fig. 3.12). Dunion (2010) shows that the average 700 hPa mixing ratio for SAL and moist tropical cases are ~3.5 g/kg and ~6.7 g/kg respectively. It is likely that the PDF of 700 hPa mixing ratio for the entire granule masks the SAL and moist tropical peaks. PDFs of only SAL or only moist tropical profiles from this granule would likely show independent peaks closer to the Dunion (2010) values. The bimodal peak seen at 850 hPa may be a result of AIRS having a larger dry bias at this level compared to 700 hPa (~1.5 g/kg versus 0.5 g/kg). At 1000 hPa, the mixing ratio histogram for the same AIRS granule (Fig. 3.13) shows no evidence of the SAL. Nearly all soundings appear to be moist with a peak around 15 g/kg at this low level, which makes sense because this is below the base of the SAL.
Figure 3.12: Same as Fig. 3.11, but for 700 hPa.

Figure 3.13: Same as Fig. 3.11, but for 1000 hPa.
Overall, AIRS is able to show the presence of the SAL in its mixing ratio profiles. While the AIRS data does not agree exactly with GPS dropsonde data, it is generally able to capture whether or not a given airmass is SAL or moist tropical. AIRS biases in SAL cases were as large as ~3 g/kg at 850 hPa, while in moist tropical cases biases were ~1.5 g/kg at 850 hPa and ~2.5 g/kg at 600 hPa. Features on smaller scales, such as the base of the SAL, are generally not captured by AIRS. AIRS temperature profiles tend to agree well with GPS dropsonde data, except for a 1-2 K cool bias in the AIRS data near the SAL base. One hypothesis to explain these differences is that the initial distance criterion of 50 km separation between a GPS dropsonde and AIRS profile may not be strict enough, and refining this criterion to smaller values may lead to a more consistent comparison between AIRS and GPS dropsondes.

3.3 Sensitivity to Distance Criterion

One of the three initial criteria to determine which AIRS profiles matched each GPS dropsonde was distance. The distance between the two had to be 50 km or less. While this is a strict criterion, it is necessary for it to be small, especially along SAL edges where there can be strong horizontal temperature and moisture gradients. To see if the performance of AIRS is better or worse at different distances, the distance criterion was adjusted down to 25 km and up to 75 km. Figure 3.14 shows the average dropsonde and AIRS mixing ratio for profiles within 25 km of each other. Figure 3.15 is the same but within 75 km. There is not much difference between the two, as correlation coefficients are ~0.97-0.98 (Table 3.4). AIRS still disagrees with the GPS dropsondes around 850 hPa, near where the SAL base is typically located. This may be a surprising
Figure 3.14: Mean SAL mixing ratio profiles for AIRS and GPS dropsonde profiles within 25 km and +/- 3 hours of each other.

Figure 3.15: Mean SAL mixing ratio profiles for AIRS and dropsonde profiles within 75 km and +/- 3 hours of each other.
result, as it is intuitive that AIRS should perform better when the AIRS/GPS dropsonde distance criterion is less. However, if clouds and/or dust are affecting the AIRS retrievals, then adjusting the distance criterion will not meaningfully change the performance of AIRS because the clouds and dust will still be present.

This result is also supported by the root mean square error (RMSE) calculations and correlation coefficients shown in Table 3.4. RMSE values for low-level (1000-850 hPa), mid-level (850-400 hPa), and deep layer (1000-300 hPa) take into account the variance and bias of the estimator (in this case, the AIRS data). RMSE values for mid-level and deep layer do not show much improvement with a lower distance criterion, though values for the 25 km distance criterion are slightly lower (by about 0.3-0.4) than the values for the 75 km criterion. The greatest effect of the changing distance criterion is seen in the low-levels, where RMSE values are ~1 g/kg lower for the 25 km criterion compared with 75 km, suggesting AIRS may show a slight improvement in the boundary layer when the distance criterion is small. Correlation coefficients for three pressure layers for each distance criterion are also very close (0.97 to 0.99), suggesting that the AIRS and GPS dropsonde data are highly correlated for each distance criterion.

It has been shown that adjusting the distance criterion from 50 km down to 25 km and up to 75 km does not result in a meaningful improvement (except possibly in the boundary layer) in AIRS/GPS dropsonde comparisons. Now that AIRS and GPS

<table>
<thead>
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<th>Correlation Coefficients</th>
<th>RMS Error</th>
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<tr>
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<td>25 km</td>
<td>50 km</td>
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<tr>
<td>Low-level</td>
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<td>0.975</td>
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<tr>
<td>Mid-level</td>
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<td>0.968</td>
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<tr>
<td>Deep layer</td>
<td>0.985</td>
<td>0.987</td>
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Table 3.4: AIRS-dropsonde correlation coefficients and RMS errors for low-level (1000-850 hPa), mid-level (850-400 hPa), and deep layer (1000-300 hPa) pressure layers.
dropsonde mixing ratio profiles have been compared, it may be important to use these values in calculating the total precipitable water (TPW) of the AIRS and GPS dropsonde data.

### 3.4 Total Precipitable Water

TPW is defined as the amount of water vapor contained in a vertical column of air extending from the surface to the top of the atmosphere. TPW is calculated by integrating mixing ratio (MR) values from the bottom to the top of the atmosphere and dividing by the force of gravity, which is equal to 9.8 ms\(^{-2}\) (Equation 1). Units of TPW

\[
TPW = \frac{1}{g} \int (MR) \, dp \tag{Equation 1}
\]

are technically kg m\(^{-2}\). To convert this to millimeters, a TPW value is divided by the density of water (10\(^3\) kg m\(^{-3}\)), then multiplied by 10\(^3\) to arrive at millimeters. This part of the process essentially cancels out, so a value of 1 kg m\(^{-2}\) is equal to 1 mm. In this study, mixing ratio values from 1000 hPa to 250 hPa were considered. Unfortunately, 1000 hPa is the lowest pressure level in the AIRS dataset, and there are no surface mixing ratio values. Any moisture between 1000 hPa and the surface is therefore not included, leading to an automatic dry bias in TPW values calculated from the AIRS data. Dunion (2010) showed that 4.7% (moist tropical cases) and 6.0% (SAL cases) of atmospheric moisture is located between 1000 hPa and the surface. This will generally lead to a ~2-3 mm dry bias in TPW values calculated from AIRS data. In the upper troposphere, especially above 250 hPa, mixing ratio values are orders of magnitude smaller than those at 1000 hPa. These small values would contribute little to the TPW value. Additionally, most of the dropsondes were released between 200 hPa and 250 hPa, which limits the
amount of moisture data available above 250 hPa. These are the two reasons why mixing ratio values above 250 hPa were ignored. Dunion (2010) showed that 99.6% (moist tropical cases) and 99.5% (SAL cases) of moisture is located below 250 hPa, so neglecting moisture values above 250 hPa is not a large issue.

AIRS TPW plots were created for Tropical Storms Irene and Debby and Hurricane Helene. An example from Irene is shown in Figure 3.16. This AIRS granule overlapped Irene around 1630 UTC on 7 August 2005. At this time, Irene was a minimal tropical storm (35 knots) and centered near 21N 45W. Near and to the east of the center there are some missing TPW values. This is likely due to cloud cover preventing AIRS from sampling much of the troposphere and leading to either missing or erroneous data. A couple of other interesting features can be seen. To the north of Irene is dry, low TPW air that is getting wrapped into the circulation along the west and south sides. There is

Figure 3.16: AIRS Total Precipitable Water (TPW) plot from Irene on 7 August 2005. The center of Irene is denoted by the black x located near 21N 46W.
also more dry air further to the southwest that is impinging on the high TPW air. Figure 3.17 shows a broader TPW map of the region surrounding Irene. This includes all AIRS passes (day and night) on 7 August 2005. It is clearer here how broad the dry SAL regions are to the east, north and west of Irene (with some mid-latitude dry air also impinging from the north), and how some of that dry air is wrapping into the circulation. The broader plot also shows the high TPW values associated with Tropical Storm Harvey, centered near 35N 55W. There is also a broad region of high TPW south of 15N that is likely associated with convection in the Intertropical Convergence Zone (ITCZ). In this region there are also some missing or likely erroneously low TPW values, especially over South America, either due to elevation (which reduces TPW) or deep cloud cover that is preventing AIRS from sampling the lower troposphere.

Figure 3.17: AIRS TPW plot with NOAA/HRD flight track (black line) and GPS dropsonde TPW values (colored dots) from 7 August 2005. The center of Irene is denoted by the black x.
Figure 3.17 also shows TPW values (colored circles) calculated from GPS dropsonde data along the NOAA/HRD flight track (black line) from 7 August 2005. GPS dropsonde #1 was released at 1542 UTC, while GPS dropsonde #26 was released at 2125 UTC. The ascending AIRS pass over Irene (oriented SSE-NNW in Figure 3.17) was around 1630 UTC. The AIRS TPW values generally agree with the GPS dropsonde values on the location of dry and moist environments, but there appears to be a slight dry bias in the AIRS TPW values. This can be seen in the GPS dropsonde (#9) just northwest of the center of Irene. The GPS dropsonde shows a TPW value that is about 5-10 mm higher than surrounding AIRS TPW values. A likely cause of this dry bias might be due to AIRS underestimating the amount of moisture in the lower levels. Because the low levels contain the most moisture, an erroneous measurement will lead to sizeable differences when TPW is calculated. Also, the lack of a surface mixing ratio in AIRS also may be contributing to a dry bias. The slight dry bias is also seen from GPS dropsondes 15-19 on the east side of Irene. Nonetheless, both AIRS and GPS dropsondes show a moist environment (TPW 50-60 mm) to the south of Irene, and a drier environment (TPW 25-35 mm) on the west and east sides of Irene.

Expanding the map a little further, Figure 3.18 shows AIRS TPW values across the Atlantic basin on 7 August 2005, and Figure 3.19 shows SSM/I TPW values from the same day. The ability of AIRS in capturing horizontal TPW gradients is quite good. It does well in capturing the AEW, the SAL regions, the dry mid-latitude (polar) airmass, and the moisture associated with Irene, all of which are labeled in Figure 3.19. The AIRS plots contain both day and night satellite passes, so the gaps in swath coverage are minimal. AIRS does seem to have a problem along the ITCZ, where convection is
Figure 3.18: AIRS TPW plot with NOAA/HRD flight track (black line) and GPS dropsonde TPW values (colored dots) from 7 August 2005.

Figure 3.19: SSM/I TPW plot with NOAA/HRD flight track and dropsonde release points from 7 August 2005. Labeled are Hurricane Irene, three SAL regions, one dry mid-latitude (polar) region, and one African Easterly Wave (AEW). Mid-latitude dry air is also present north and northeast of Irene at this time (not labeled). TPW image courtesy of NRL-Monterey.

deeper and more widespread. Many values along this region are either missing or erroneously low. The low TPW values (around 10 mm) in the ITCZ are probably a result of clouds causing AIRS to have invalid data in the low levels, which would contribute to a significant reduction in the vertically integrated TPW values. The missing AIRS TPW values near Irene are also in regions of cloud cover, as seen in the GOES-12 visible satellite image (Fig. 3.20). There is a significant amount of cloud cover associated with
Irene, especially on the east side of the center where there is the most missing AIRS data (seen in Fig. 3.18). To the west of the center, the visible satellite image shows little if any deep convection. This is likely due to the presence of a SAL airmass on the west side of Irene.

For a stronger tropical cyclone, such as Hurricane Helene on 18 September 2006, AIRS appears to be less effective at capturing the moisture near the core. Figure 3.21 shows TPW values from two AIRS granules that passed over Hurricane Helene around 1630 UTC 18 September. Dry air is seen wrapping into the center on the south side of the storm. An even drier airmass is seen along the east side of the granules, east of the center of Helene. Near the center there is a large circular gap in data, likely due to the thick, central dense overcast (CDO) of the hurricane. Surrounding the outer edges of this gap are many extremely low TPW values (under 15 mm). These are suspected to be anomalously low given their proximity to the deep convection associated with this strong
tropical cyclone and were not supported by the NOAA P-3 Orion and G-IV aircraft observations that were collected in these regions of the storm. The intensity of Helene on this day was approximately 100 knots and 960 hPa. It is possible that the CDO prevented AIRS from sampling the low levels, which would result in very low integrated TPW values. This idea is supported by an aircraft (NOAA P-3) radar image from the same time (~1630 UTC) during the NOAA/HRD SALEX flight into Irene on 18 September 2006 (Fig. 3.22). The northern and eastern side of the eyewall is where the strongest reflectivity is seen, coinciding with where AIRS shows anomalously low TPW values near the core (Fig. 3.21). AIRS is most likely to miss sampling the low-level moisture in these areas with the deepest convection. A TPW map from AMSR-E (Fig. 3.22) also shows that the low TPW values calculated from AIRS data are likely incorrect.
A broader view of the environment surrounding the storm on 18 September (Fig 3.23) shows a plume of dry air extending westward into the Caribbean, and a narrow meridional band of dry air with TPW values around 30-35 mm to the west of the center. The NOAA/HRD SALEX flight on this day sampled this dry air, and GPS dropsonde TPW values were similar to those of AIRS. On the east side of the center, the dropsondes sampled a very moist airmass (TPW in excess of 60 mm), but this was the region where AIRS indicated incorrect TPW values (~20 mm) due to dense cloud cover affecting retrievals.

The AIRS basin-scale plot from 18 September (Fig. 3.24) agrees well with the SSM/I plot from the same day (Fig. 3.25). AIRS is able to capture the SAL 1 region in the Caribbean, and the extension of the dry air in narrow bands to the west and south of Helene. An interesting feature is seen in the AIRS plot along 40W where overlapping AIRS swaths show a thin line of rather moist (~50 mm) and dry (~30 mm) pixels running NNW-SSE. The moist TPW values are likely from a nighttime satellite pass, and the dry
Figure 3.23: AIRS TPW plot with NOAA/HRD flight track (black line) and dropsonde TPW values (colored dots) from 18 September 2006.

Figure 3.24: AIRS TPW plot with NOAA/HRD flight track (black line) and dropsonde TPW values (colored dots) from 18 September 2006.
Figure 3.25: SSM/I TPW plot with NOAA/HRD flight track and dropsonde release points from 18 September 2006. Labeled are two SAL regions, one dry polar region, and one African Easterly Wave (AEW). Thick black line and black dots are dropsondes along the NOAA/HRD G-IV flight path. Thin black line and white dots are dropsondes along the NOAA/HRD P-3 flight path. TPW values are from a daytime pass ~12 hours later when the tropical cyclone and SAL region have advanced further westward. AIRS also captures the high TPW air in AEW 1 and along the ITCZ. Similar to the Irene case on 7 August 2005, there are also gaps in data in the ITCZ where clouds have led to missing or unrealistic TPW values. The AIRS and SSM/I plots also show an expansive dry environment between Helene and the northwest coast of Africa. HYSPLIT trajectory analyses in Figure 3.26 show that this dry air might be of mid-latitude origin as well and not entirely dry SAL air.

The disadvantage of using TPW is that it provides an integrated total amount of water in a column, but it says little about how that water is distributed vertically. Dunion (2010) showed that 90-95% of the column moisture is below 500 hPa. To look at the vertical moisture structure in more detail, cross-sections were made through Irene, Debby, and Helene and their surrounding environments. Such cross-sections can show how the mixing ratio values change on a given pressure level along the cross-section. Figure 3.27 is a plot of AIRS TPW from 7 August 2005. Irene is located around
Figure 3.26: HYSPLIT trajectory analyses ending at 18Z on 18 September 2006. The three trajectories ending in the dry airmass in the east Atlantic (east of Helene) show possible mid-latitude origins and not entirely dry SAL air. The center of Helene is indicated by the black asterisk near 23°N and 50°W.

Figure 3.27: AIRS TPW map from 7 August 2005. The black line along 21N represents the mixing ratio cross-section.

20°N and 45°W. The thin black line represents where the mixing ratio cross-section was taken, in this case along 21°N. The cross-section extends along this latitude from 75°W to 20°W. It samples the southern border of a SAL region in the eastern Atlantic, and
continues west through Irene and into another region of dry air west of Irene. HYSPLIT analyses (Fig. 3.28) show the dry air to the east of Irene has Saharan origins (trajectory ending just east of Irene), while the dry air west of Irene may be a mix of SAL and mid-latitude dry air (trajectory ending just west of Irene). A vertical mixing ratio profile along 21N should have low values extending closer to the surface in the dry SAL regions, and more moisture present in and around Irene. This is depicted in Figure 3.29. Indeed the eastern Atlantic (~20-40W) along 21N is quite dry, with 850 hPa mixing ratios as low as 3-4 g/kg. Near Irene the mixing ratios are higher (where there is data). Around 50W the 850 hPa mixing ratio approaches 10 g/kg, a significant increase from the dry SAL area to the east. The SAL area west of Irene (around 60W) does not look as intense on the TPW map when compared to the eastern Atlantic SAL outbreak. This is also confirmed by higher mixing ratio values in the cross-section.

Figure 3.28: HYSPLIT back trajectories ending at 12Z on 7 August 2005.
Figure 3.29: Mixing Ratio Cross-Section from Irene on 7 August 2005. The cross-section was done along 21N from 75W to 20W (see black line in Figure 3.27).

After analyzing AIRS TPW values, the general SAL/mid-latitude dry air vs. moist tropical environments can be differentiated easily. AIRS TPW values are most likely to be unreliable in regions of deep convection, such as centers of tropical cyclones or along the ITCZ. When compared with SSM/I and GPS dropsonde TPW values, the AIRS TPW values appear to have a dry bias of around 5 mm. This could be due to cloud cover or to the lack of AIRS moisture data between 1000 hPa and the surface. Even though this layer would be shallow, its proximity to the moisture source (the surface) would mean that an important percentage (~5%; Dunion 2010) of the TPW would come from this layer. This would lead to an AIRS dry bias of ~2-3 mm. Despite these shortcomings, AIRS moisture data is important because of the vertical resolution it provides. The next step after examining mixing ratio and TPW data from specific SALEX flight dates is to expand the use of AIRS data to longer-term averaging of TPW.
Chapter 4

AIRS Climatology

4.1 Temporal Averaging of Total Precipitable Water

Monthly and seasonal plots of average TPW were also created using AIRS moisture data across the Atlantic. All data in the box from 0-40°N and 15-90°W were considered for these temporally-averaged plots. Figure 4.1 shows an average TPW map from August 2005, the month in which Hurricane Irene occurred. The driest air over water is off the northwest coast of Africa, nearest the origin of SAL outbreaks and mid-latitude dry air intrusions from the Mediterranean and Western Europe. Moist air is seen along the ITCZ south of 15°N, and in the western Atlantic basin. AIRS is even able to capture local minima in average TPW in regions of high terrain, such as Hispaniola and

Figure 4.1: AIRS average TPW (mm) map from August 2005. Also shown are NOAA/HRD flight paths from 7 August (black line) and 8 August (blue line) 2005 with dropsonde TPW values. The small black (blue) X marks the center of Irene on 7 August (8 August).
the higher terrain of North, Central, and South America. The two NOAA/G-IV flight paths from Hurricane Irene are also plotted, along with individual GPS dropsonde TPW values. Many of the dropsondes sampled air that was either moister or drier than the monthly mean. It is important to note that the mean monthly values in the region where Irene was located are not as likely to occur with the same frequency as dry air outbreaks or moist tropical regimes. This region is typically moister than the mean in August, with periodic SAL outbreaks that are drier than the mean.

Figure 4.2 shows the average TPW map from September 2006, the month in which Hurricane Helene occurred. The September 2006 map shows a few differences from the August 2005 map (Figure 4.1). More dry air is present at higher latitudes in September 2006, in line with the onset of fall. There is also somewhat less moisture in the western Atlantic basin in September 2006. These features are seen in the TPW difference map (September 2006 – August 2005) shown in Figure 4.3. Figure 4.2 also

Figure 4.2: AIRS average TPW (mm) map from September 2006. Also shown are NOAA/HRD flight paths from 15 September (black line), 16 September (blue line), and 18 September (pink line) 2005 with dropsonde TPW values. The center of Helene on each flight day is shown by the black, blue, and pink X, respectively.
Figure 4.3: AIRS TPW (mm) difference field between September 2006 and August 2005. Positive (negative) values indicate regions where September 2006 (August 2005) had higher average TPW.

shows that AIRS is able to capture local minima in TPW in areas of high terrain (e.g. Central America, Columbia, and Venezuela). Three flight tracks and GPS dropsonde TPW data from Hurricane Helene are also shown in Figure 4.2. The GPS dropsonde TPW values along the eastern half of each flight are very moist (~50-60 mm), while the western half of each flight sampled much drier air (TPW ~30-40 mm).

Monthly mean sea level pressure plots from NCEP/NCAR reanalysis are shown in Figure 4.4. The subtropical high pressure in the eastern Atlantic is stronger in August and September 2005 than it was in August and September 2006. This could have caused more subsidence and a stronger anticyclonic flow coming from the mid-latitudes and northern Africa into the eastern Atlantic, and might help explain why the eastern Atlantic contained more moisture in September 2006 than in August 2005. AIRS TPW plots for the months of August and September 2005-2006 are shown in Figure 4.5. August 2005 was generally moister than August 2006 in the central and western tropical Atlantic.
September 2005 also shows higher TPW than September 2006 in the Caribbean and along the ITCZ.

Monthly averages of TPW were also used throughout the lifetime of AIRS (2003-2008). Figure 4.6 shows the average and standard deviation of TPW for the month of June from 2003-2008. In the early summer, SAL outbreaks and mid-latitude dry air intrusions are more frequent and more intense. This can be seen by the very dry air (< 25 mm) that is usually present off the northwest coast of Africa (likely a combination of SAL and mid-latitude dry air) and in the southeast United States (mid-latitude dry air).
Figure 4.5: Monthly mean TPW calculated from AIRS data for (a) August 2005, (b) August 2006, (c) September 2005, and (d) September 2006.

Figure 4.6: Average and standard deviation of June TPW using AIRS data from every June in the years 2003-2008.
High TPW in the ITCZ lies on an axis along 5-10N this time of year. The western portion of the Atlantic basin is moderately moist, as the transition to summer is still taking place. There is a local maximum in standard deviation of TPW over western Africa which could be indicative of a moist airmass (e.g. AEWs) with periodic SAL outbreaks. The average and standard deviation of July TPW from 2003-2008 (Fig. 4.7) shows both a smaller and weaker westward extent of the dry air near Africa. There is a slight northward shift in the ITCZ as the Northern Hemisphere continues to warm. Additionally, eastern North America and the western Atlantic basin tend to have higher TPW air compared to June. This moister air also extends further northward along the Gulf Stream. Standard deviation increases slightly over western Africa in July, which
could either mean a moister airmass because it is further into the Northern Hemisphere summer season, or more frequent/more intense SAL outbreaks. By August (Fig. 4.8) the average TPW off the coast of Africa has continued to increase, and the ITCZ has moved further northward. The average TPW in the western Atlantic basin is also at its highest point of the summer (~45 mm across the Gulf of Mexico, for example). TPW values over the eastern United States are also at their peaks. The standard deviation plot continues to show a local peak in western Africa. Average September TPW values from

![AIRS Average August TPW 2003-2008](image)

![AIRS TPW Standard Deviation (August 2003-2008)](image)

Figure 4.8: As in Fig. 4.6, but for August.
2003-2008 (Fig 4.9) show the transition from summer to fall. By September, cold fronts start reaching further equatorward, bringing drier air down behind them. The ITCZ and Caribbean are still quite moist, however. By October (Fig 4.10), the ITCZ has begun to move equatorward. Even drier air is seen in the mid-latitudes as the summer season has ended. The tropical latitudes remain very moist, with average October TPW values as high as 50 mm in the southwest Caribbean and in parts of the tropical east Atlantic. Standard deviations of TPW in October show a weakening maximum over western

Figure 4.9: As in Fig. 4.6, but for September.
Figure 4.10: As in Fig. 4.6, but for October.

Africa. This is possibly due to the air generally being drier there with the onset of Northern Hemisphere fall.

AIRS is also able to capture the year-to-year seasonal variability in TPW across the Atlantic. Figure 4.11 shows the average and standard deviation of TPW for the summer months (JJA) in 2005. The highest concentration of moisture is in the western Atlantic basin and along the ITCZ (TPW around 45 mm on average). Dry air is also seen in the northeast Atlantic near Africa. TPW standard deviation for JJA 2005 shows a peak
over western Africa, much like what was seen in the individual monthly means. Figure 4.12 shows the summer average and standard deviation of TPW for 2006. The western Atlantic basin and the United States appear to be drier on average during the summer of 2006. There is also a slight southward and westward extension of dry air in the northeast Atlantic. The ITCZ axis in JJA 2006 looks to be slightly further south than in summer 2005. Additionally, the standard deviation in the Caribbean and the northwest tropical Atlantic (near Bermuda) are both higher in summer 2005 than in summer 2006. A final
interesting feature is the stronger standard deviation maximum over west Africa in JJA 2006 compared to JJA 2005. This maximum in standard deviation is also further northward in 2006, suggesting that SAL outbreaks might have been more frequent and more intense in this region in 2006.

The effects of mid-level dry air from the SAL are also evident in histograms and PDFs of AIRS data on longer timescales. The summer (JJA) PDF of mixing ratio at 700 hPa (Fig. 4.13) and 1000 hPa (Fig. 4.14) show the same differences as above. These
PDFs were created using unfiltered AIRS mixing ratio data from over 3 million soundings covering 0-40N, 10-90W during the summer of 2005. At 700 hPa, the peak is quite rounded, while at 1000 hPa there is a much narrower peak. The broader peak shows a wider range of mixing ratio values are more likely at 700 hPa than 1000 hPa.
Additionally, the 1000 hPa PDF tails off slowly on the low mixing ratio side and very rapidly on the high mixing ratio side. PDF plots of mixing ratio may be important in showing how the vertical distribution of moisture in the tropical North Atlantic varies during the summer and fall seasons. This will be examined in the next section.

### 4.2 Mixing Ratio PDF

In an attempt to determine the seasonal variation in SAL outbreaks and mid-latitude dry air intrusions, PDF plots of AIRS mixing ratio data were created for each month. The AIRS data used covered the Atlantic basin from 0-40N 20-80W. An example of a mixing ratio PDF plot from the month of June is shown in Figure 4.15. Only the lower half of the troposphere (1000-500 hPa) was considered, as this is where 90-95% of the moisture in the atmosphere is located (Dunion 2010). At levels above 500 hPa, the mixing ratio values are at least 1-2 orders of magnitude smaller than at the surface. The highest PDF contours (~0.2) are noted for mixing ratio values under 1 g/kg at 500 hPa (Fig. 4.15), and this trend would continue in the upper troposphere. Of greater importance are the PDF contour values in the lower troposphere. At 1000 hPa, mixing ratio values near 15 g/kg are most common. The axis of maximum PDF decreases slowly with height until around 900 hPa, where a sharper decrease is present. Near 850 hPa, the most common mixing ratio values are around 5 g/kg, but below 900 hPa it is 10 g/kg or more. This is a sign of a shallow area of very moist air in the boundary layer, with a significantly drier airmass in the mid-levels above ~900 hPa, coinciding with the base of the SAL (typically ~850-900 hPa). After removing the mean (Fig 4.15b), there is a local maximum in PDF around 800-850 hPa. The PDF maximum here is slightly negative,
meaning the occurrence of drier than normal air (such as that of the SAL) is common at these levels. Previous studies (e.g. Dunion and Marron 2008, Dunion 2010) have shown the SAL and mid-latitude dry intrusions to be more common in the second half of June. A mixing ratio PDF plot during this time period is shown in Figure 4.16. The shape of the PDF is very similar to Figure 4.15, and the contour values of PDF are slightly higher.
in the moist boundary layer and the dry mid-levels compared to the full monthly average. This indicates an increased likelihood of the mid-levels being significantly drier than the boundary layer, a sign that dry air is frequently present in the mid-levels during this time period. Additionally, removing the mean (Fig. 4.16b) shows a PDF maximum at negative values around 800-850 hPa, again a sign that drier than average airmasses occur frequently during this time period.

Figure 4.16: As in Fig. 4.15, but for June 16-30.
Moving further into the Northern Hemisphere summer season, this SAL signal becomes masked due to the increasing frequency of AEWs and decreasing frequency of SAL outbreaks. Figure 4.17 shows the August mixing ratio PDF plot over the same geographical domain. Similar to June, 1000 hPa mixing ratio values are typically around 15 g/kg. However, this time there is no discontinuity in PDF values near the SAL base. Removing the mean shows that mid-level mixing ratios tend to be close to the mean in

Figure 4.17: As in Fig. 4.15, but for all Augusts.
August, with no local PDF maximum on the negative (drier than normal) side (Fig. 4.17b). By August, SAL outbreaks are more infrequent, so any signal of them likely becomes masked when taking a monthly average. Looking at an October mixing ratio PDF (Fig. 4.18), the discontinuity appears again around 850-900 hPa, but this is likely a sign of dry mid-latitude air associated with the onset of the Northern Hemisphere autumn
season and probably not SAL-related. The presence of mid-tropospheric dry air in June and October, along with cooler SSTs, might be reasons why westward moving AEWs tend not to develop in the eastern part of the Atlantic basin during these months. More mid-level moisture in August coincides with the increased likelihood of tropical cyclone development in the eastern Atlantic during this month.

The mixing ratio PDF plot from June (early summer) represents the SAL the most. PDF values in the boundary layer are highest for mixing ratio values ranging from 13-15 g/kg, and there is another local maximum in PDF around 5 g/kg near 800-850 hPa. Even the June-October 2003-2008 PDF (Fig. 4.19) shows a distinct secondary peak in PDF just above where the SAL base is usually located, though the PDF maximum is slightly lower (0.14 versus 0.12) than the June value. August mixing ratio PDF also does not show as strong of a peak as June in this 800-850 hPa layer. By October, the mid-levels tend to be quite dry, most likely due to autumn intrusions of mid-latitude dry air.

![June-October 2003-2008 Mixing Ratio PDF](image)

Figure 4.19: As in Fig. 4.15, but for all June-October months.
It has been shown that AIRS is able to capture the monthly and seasonal variability of tropical Atlantic moisture. Additionally, the advantage of AIRS being able to depict vertical moisture distribution shows the increased likelihood of SAL outbreaks in early summer. The final part of this study is to examine the role this dry air (SAL and mid-latitude) plays in the intensity change of tropical cyclones.
Chapter 5

Relationship between Dry Air and Intensity Change

Having examined the ability of AIRS to capture the vertical and horizontal distribution of tropical Atlantic moisture on short and long time scales, it is important to investigate how this dry air relates to tropical cyclone intensity change. Initially the relationship between dry air and intensity change will be explored using TPW data derived from AIRS and microwave sensors. Because intensity change is a result of several factors, other parameters such as vertical wind shear and sea surface temperature will also be considered.

5.1 Unfiltered AIRS Data

To examine relationship between dry air and tropical cyclone intensity change, AIRS TPW data were gathered from all Atlantic basin tropical cyclones for the years 2003-2008. During these six years, there were 100 named storms in the Atlantic basin. This number was trimmed by removing the few subtropical storms and storms whose lifetime was entirely outside the domain in Figure 5.1. The remaining 57 named storms (with at least one storm day inside the domain) combined for a total of 327 storm days after removing days when the TC was centered over land. Using National Hurricane Center Best Track data, these storm days were categorized by intensity change according to wind speed. Over half (176 days) of the 327 storm days were marked by
intensification. The remaining days were nearly split between weakening (84 days) and steady strength (67 days).

AIRS TPW was calculated on each storm day using all mixing ratio profiles within 400 km of the center of each storm. This 400 km radius was chosen to cover the TC and its immediate surrounding environment. This radius agrees well with previous studies, such as Shu and Wu (2009) who showed that dry air associated with the SAL begins to affect tropical cyclones when it intrudes within 360 km from the center. At radii larger than ~400 km, the presence of dry air is less likely to have a strong effect on tropical cyclone intensity. Dry air intrusions inside 400 km radius are more likely to impact intensity. An example of TPW values within 400 km of Hurricane Dean (2007) is shown in Figure 5.2.

The total number of TPW values within 400 km radius was counted in each earth-relative quadrant on each storm day. Dry profiles were defined by having TPW less than 45 mm (Dunion 2010). This tends to be a critical value separating moist TC air (TPW greater than 50 mm usually) from dry air that may be present around the storm (TPW generally less than 40 mm). Dry quadrants were then determined by the percentage of
Figure 5.2: TPW values (mm) within 400 km radius for each day that Hurricane Dean (2007) was centered within the domain.

The total TPW values in that quadrant that were less than 45 mm. Figure 5.3 shows the intensity change tendency based on how dry a quadrant is. For example, a quadrant was

Figure 5.3: Percentage of storms that are intensifying (left) and weakening (right) based on the amount of dry air present in each quadrant. Blue bars (25-50% dry) mean 25-50% of the total AIRS TPW values in that quadrant were < 45 mm.
said to be 25-50% dry if that percentage of the TPW values in that quadrant were less than 45 mm (and similarly for 50-75% and >75% dry). When either the northwest or northeast quadrants are dry, intensification happens approximately 50% of the time, while weakening happens much less frequently. As would be expected, weakening occurs somewhat more frequently for drier quadrants (>75% dry vs. 25-50% dry). In the southwest and southeast quadrants, intensification is more likely when the quadrant is 25-50% dry, but weakening becomes more likely if the quadrant is at least 75% dry. Table 5.1 shows the number of cases when dry air was present in each quadrant. Not surprisingly, as the percentage of dry air increases, there will be a reduction in the number of cases that meet this more rigorous criterion. Nonetheless, there was still a decent sample size (36 or more cases) for quadrants containing at least 75% dry air, though it is significantly less than the number of cases in which the quadrants were 25-50% dry.

When two quadrants have dry air present, it would be expected that weakening gradually becomes more common as the percentage of dry TPW values increases. Figure 5.4 shows this to be the case. When both the northwest and northeast quadrants are 25-50% dry, intensification still occurs nearly 50% of the time, with weakening only 25% of the time. If both northern quadrants are at least 75% dry, intensification is occurring in

<table>
<thead>
<tr>
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<th>Number of Cases</th>
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<tbody>
<tr>
<td></td>
<td>25-50%</td>
</tr>
<tr>
<td>NW</td>
<td>61</td>
</tr>
<tr>
<td>SW</td>
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<tr>
<td>SE</td>
<td>83</td>
</tr>
<tr>
<td>NE</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 5.1: Number of cases of dry air in each quadrant. For example, there were 61 cases in which 25-50% of AIRS profiles in the northwest quadrant of a storm were dry.
only one third of the cases and weakening in over half of the cases. Interestingly, when the southern quadrants are both dry, there is only a slight decrease in the likelihood of intensification between 25-50% dry and >75% dry quadrants. When the western quadrants are dry, the trend is similar to the northern quadrants, but the change is slightly less dramatic. The number of cases (Table 5.2) still show a large enough sample size to yield meaningful results.

<table>
<thead>
<tr>
<th>Quadrants</th>
<th>25-50%</th>
<th>50-75%</th>
<th>&gt;75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW/NE</td>
<td>66</td>
<td>31</td>
<td>19</td>
</tr>
<tr>
<td>NW/SW</td>
<td>68</td>
<td>31</td>
<td>27</td>
</tr>
<tr>
<td>SW/SE</td>
<td>58</td>
<td>22</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 5.2: Number of cases of dry air in each quadrant. For example, there were 66 cases in which 25-50% of AIRS profiles in the northwest and northeast quadrants of a storm were dry.
With three dry quadrants (northwest, northeast, southwest, chosen because of the typical path of intrusion for dry air along the north, west, and finally south sides), weakening becomes much more common as the three quadrants progressively get drier (Fig. 5.5). When all four quadrants are 25-50% dry, intensification and weakening occur with about the same frequency. In the cases where all four quadrants are 50-75% or at least 75% dry, weakening is more dominant. Table 5.3 shows that there are not many cases where three or four quadrants are 75% dry (13 and 11 cases, respectively).

Classifying dry quadrants based on the percentage of TPW values less than 45 mm is important. It appears that some storms can still intensify when there is some dry

![Figure 5.5: As in Fig. 5.3, but for three and four dry quadrants.](image)

<table>
<thead>
<tr>
<th>Quadrants</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW/NE/SW</td>
<td></td>
</tr>
<tr>
<td>25-50%</td>
<td>51</td>
</tr>
<tr>
<td>50-75%</td>
<td>15</td>
</tr>
<tr>
<td>&gt;75%</td>
<td>13</td>
</tr>
<tr>
<td>All</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
</tbody>
</table>

Table 5.3: Number of cases of dry air in each quadrant. For example, there were 51 cases in which 25-50% of AIRS profiles in the NW/NE/SW quadrants of a storm were dry.
air present (25-50% dry). This is especially true when considering single quadrants (Fig. 5.3), where intensification is much more common than weakening for those 25-50% dry cases. Even when dry air is somewhat present in all quadrants, intensification still occurs. Only when the percentage of dry TPW values meets and exceeds 50% does weakening become more common. This complicates the relationship between dry air and intensity change, because it is not the simple presence of dry air, but rather how much dry air and its proximity to the core, that affects the intensity. Some dry air often leads to strengthening, whereas too much dry air leads to weakening. Complicating matters even further are the roles other factors such as shear, SST, and storm size play in TC intensity change. Often it is a combination of factors that determine whether a given storm will intensify or weaken.

Histograms of TPW were also created for each quadrant of intensifying and weakening storms (Fig. 5.6). In the northwest quadrant, there is not much difference in TPW between intensifying and weakening cases. Both have a peak around 50 mm, with a sharp decrease on the high side and a more gradual decline on the left. The peak does look to be slightly sharper for intensifying cases, and broader for weakening cases. For dry air in the northeast quadrant, the histograms of intensifying and weakening storms are also similar. Dry air seems to be present more in weakening cases than intensifying ones. In the southwest quadrant, the intensifying storms have a very smooth histogram, gradually increasing to a peak around 50 mm, then decreasing sharply for larger values. The histogram of weakening storms shows a minor peak around 30 mm for the southwest quadrant. When compared to the intensifying cases, it is seen that lower TPW values (30 mm for example) are more likely to be found in storms that are weakening. This is also
Figure 5.6: Histograms of AIRS TPW for all cases and for intensifying and weakening storms.
seen in the southeast quadrant. The intensifying cases have a much sharper decrease to low TPW values than do the weakening cases, again showing that weakening storms are more likely to have low TPW values (< 45 mm). Effects of dry air on intensity are more easily seen in these two southern quadrants than in the northern quadrants. This suggests that storms can survive and even intensify if dry air is present in the northern quadrants. Typically dry air first encounters the circulation of a TC in the northern quadrants, while the southern quadrants remain very moist (see Fig 1.7). During this stage storms can still intensify. However, as this dry air follows the cyclonic circulation into the storm and reaches the southern quadrants, weakening is more likely.

Table 5.4 shows mean TPW values and standard deviation of TPW for each quadrant based on the intensity change of the tropical cyclones. The mean TPW value in each quadrant is higher (albeit only slightly in the northwest quadrant) for intensifying storms than for weakening storms. This follows the intuition that intensifying storms would tend to have more moisture (at least a higher TPW) than weakening storms. Standard deviation values are quite similar for intensifying and weakening cases, though yet again intensifying storms exhibit a higher standard deviation in TPW in all quadrants.

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>Intensifying Storms</th>
<th>Weakening Storms</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Mean TPW</td>
<td>Std Dev</td>
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<tr>
<td>Northwest</td>
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<td>Southwest</td>
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<tr>
<td>Southeast</td>
<td>43.50</td>
<td>13.71</td>
</tr>
<tr>
<td>Northeast</td>
<td>41.86</td>
<td>14.49</td>
</tr>
</tbody>
</table>

Table 5.4: Mean (mm) and standard deviation of AIRS TPW for intensifying and weakening storms based on quadrant.
5.2 Microwave Satellite Moisture Data and Intensity Change

One of the shortfalls with AIRS is the blocking of the infrared retrievals in cloudy regions. Of course this is important to consider when using AIRS data in regions of tropical cyclones. Figure 5.2 showed TPW values within 400 km on each day Hurricane Dean (2007) was within the domain. It is clear that every day has missing or very low TPW values near the center. TPW values such as these (less than 25 mm) are likely to be incorrect, and not indicative of a strong dry air intrusion. In the thick cloud cover, AIRS cannot sample the low levels. Because the highest mixing ratios are located in the boundary layer, this would lead to extremely low TPW values if the mixing ratios are not vertically integrated down to the surface.

To assess the importance of this problem, microwave TPW data from SSM/I frequencies of 19.35, 22.235, and 37.0 GHz were also used. This microwave dataset has been shown to be an accurate (when compared to dropsondes) estimator of atmospheric TPW (Alishouse et al. 1990). It has the advantage of not being affected by thick cloud cover. Additionally, the microwave data is at higher resolution (1/4 degree and then interpolated to 1/10 degree, compared to ~50 km horizontal resolution in AIRS). This microwave dataset typically includes TPW information in areas of deep convection and heavy rain (e.g. the inner core of tropical cyclones). It should also be noted that microwave TPW retrievals are subject to a high bias in areas of heavy rain. Figure 5.7 shows histograms for each quadrant of intensifying and weakening storms, similar to Figure 5.6 for AIRS data. Despite the struggles AIRS has with cloud cover, there are some similarities with the microwave dataset. The peaks of the histogram are around 50-55 mm, and the peaks look broader in the weakening cases, especially in the northwest.
Figure 5.7: As in Fig. 5.6, but for microwave data.
quadrant for example. This peak looks to be slightly higher than the AIRS data, perhaps because AIRS may have a slight dry bias because of issues with cloud cover and its restricted vertical extent of 250-1000 hPa, while the microwave-derived TPW represents an integration from the surface to the top of the atmosphere. The tail to the left of the peak shows that weakening cases tend to have a greater percentage of low TPW values. This is seen best in the southwest and southeast quadrants. All quadrants for intensifying and weakening storms show a sharp decrease to the right of the peak, with TPW values over 70 mm quite rare. It is important also to note that the microwave data has very few values less than 25 mm, supporting the idea that extremely dry AIRS TPW values near storm centers are likely an effect of cloud cover preventing a complete retrieval of moisture data.

Table 5.5 shows the mean and standard deviation of microwave TPW data. The mean values are noticeably higher than the AIRS mean values (Table 5.4), most likely because of the dry bias that has been shown with AIRS moisture data. Like AIRS, the microwave data shows that TPW is on average higher in each quadrant of intensifying storms. Standard deviation values are significantly lower than AIRS. This is easily seen in the histograms of microwave data in Figure 5.7, which show few if any TPW values less than 20 mm, and very sharp peaks around 50 mm. The AIRS TPW histograms in

<table>
<thead>
<tr>
<th></th>
<th>Intensifying Storms</th>
<th>Weakening Storms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean TPW</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Northwest</td>
<td>51.20</td>
<td>6.44</td>
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<td>Northeast</td>
<td>52.68</td>
<td>5.12</td>
</tr>
</tbody>
</table>

Table 5.5: Mean (mm) and standard deviation of microwave TPW for intensifying and weakening storms based on quadrant.
Figure 5.6 had a significantly greater percentage of TPW values less than 20 mm (generally 1-3%, compared to ~0% for the microwave data).

Bar graphs of intensity change based on dry air are shown in Figure 5.8. Similar to the AIRS data (Fig. 5.3), the microwave data also shows that weakening generally becomes more likely as the amount of dry air in each quadrant increases. However, the microwave data does not show as high of a percentage of intensifying cases compared to the AIRS data. Conversely the percentage of cases that exhibit weakening is higher according to the microwave data. The sample size of dry air with microwave data (Table 5.6) is less than half the sample size of AIRS dry air (Table 5.1). Interestingly, Figures 5.9 and 5.10 do not show much of a change in the likelihood of weakening when there is more dry air. It should be expected that an increase in the amount of dry air in two, three,
Table 5.6: Number of cases of dry air in each quadrant. For example, there were 32 cases in which 25-50% of microwave profiles in the northwest quadrant of a storm were dry.

<table>
<thead>
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<th>50-75%</th>
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</tr>
</thead>
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<td>NW</td>
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</tr>
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<td>SW</td>
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</tr>
<tr>
<td>NE</td>
<td>12</td>
<td>10</td>
<td>14</td>
</tr>
</tbody>
</table>

Figure 5.9: As in Fig. 5.8, but for two dry quadrants.

or four quadrants of a storm would result in greater chances of weakening, but this is not clearly the case in the microwave data. The AIRS data, complete with erroneous values, actually shows this better. Perhaps this is due to sample size issues. Because the microwave data show dry air (TPW < 45 mm) occurring much less frequently, it only has a range of ~10-40 cases (Table 5.7) for each bar graph in Figures 5.9 and 5.10. On the other hand, the AIRS data had up to 126 cases for each bar graph in Figures 5.4 and 5.5,
an increase by as much as a factor of 10. The increase in sample size in the AIRS data is probably because of all the incorrectly low TPW values near tropical cyclone centers. Perhaps more cases of dry air in the microwave data would have yielded the expected results.

The most noticeable difference between the unfiltered AIRS data and the microwave satellite data is the amount of profiles that are very dry (TPW < 20 mm). The unfiltered AIRS data shows a much higher likelihood of these dry profiles, though this is likely unrealistic. Perhaps filtering the AIRS data to remove some effects of cloud cover would allow for a better comparison with the microwave data.
<table>
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<th>Quadrant</th>
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<th>50-75%</th>
<th>&gt;75%</th>
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<tr>
<td>SW/SE</td>
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<td>NW/NE/SW</td>
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</tr>
<tr>
<td>All</td>
<td>6</td>
<td>5</td>
<td>13</td>
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</table>

Table 5.7: Number of cases of dry air in each quadrant. For example, there were 8 cases in which 25-50% of microwave profiles in the northwest and northeast quadrants of a storm were dry.

5.3 Filtered AIRS Data

A significant issue with AIRS data near tropical cyclone centers is missing or incorrect moisture values in regions of cloud cover. While AIRS does correctly flag some pixels as cloud-contaminated, there are often pixels surrounding these regions that are also affected by clouds. One way to account for this is to filter the AIRS data to remove incorrect pixels immediately surrounding cloud-flagged regions. Neighboring pixels with TPW values less than 25 mm were removed, using the assumption that these pixels were also affected by cloud cover, and a lack of boundary layer sampling did not allow for an accurate TPW calculation. This process removed most (but probably not all) of the flawed pixels. A recreation of Figure 5.2 with these erroneous pixels removed is shown in Figure 5.11. This includes more data gaps in Figure 5.2, but here the majority of incorrect TPW pixels have been removed, leaving only the ones that are most likely to be unaffected by clouds.

Bar graphs were then recreated using this modified AIRS dataset. Figure 5.12 shows the likelihood of intensification or weakening based on the amount of dry air in each quadrant. There is a sharp increase in the likelihood of weakening as the amount of
dry air increases from 25-50% dry to >75%. This is especially seen in the northeast quadrant, probably because dry air has wrapped fully around the storm in most of those

Figure 5.11: As in Fig. 5.2, but with pixels with < 25 mm TPW that also had neighboring cloudy pixels removed.

Figure 5.12: As in Fig. 5.3, but with dry pixels removed (see text for explanation).
situations. The rate of intensification also decreases as dry air increases, except in the northwest quadrant. This is typically the quadrant that first sees a dry air intrusion, so it is likely that storms can still intensify if dry air is just beginning to enter the circulation. Table 5.8 shows the sample size for this filtered AIRS data. Despite the filtering, there are still a substantial amount of cases, especially when quadrants are 25-50% dry. Unfortunately the sample size of cases where dry air was present in multiple quadrants was not large enough to produce a meaningful plot of intensity change based on the amount of dry air.

Modified histograms of TPW in each quadrant with dry pixels removed are shown in Figure 5.13. The peaks are nearly the same for all intensifying and weakening cases in each quadrant (around 50 mm). Additionally, all have a sharp decrease toward higher values, with TPW values over 70 mm very unlikely. Differences lie on the left side of the histograms. Weakening cases, especially when the southwest and southeast quadrants are dry, are more likely to have lower TPW values in those quadrants. The histograms of TPW in the northwest quadrant for intensifying and weakening storms are very similar. This is probably because dry air in the northwest quadrant is less likely to affect intensity than dry air in other quadrants.

<table>
<thead>
<tr>
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<th>Number of Cases</th>
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<tbody>
<tr>
<td></td>
<td>25-50%</td>
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<td>NW</td>
<td>64</td>
</tr>
<tr>
<td>SW</td>
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<td>SE</td>
<td>60</td>
</tr>
<tr>
<td>NE</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 5.8: Number of cases of dry air in each quadrant. For example, there were 64 cases in which 25-50% of filtered AIRS profiles in the northwest quadrant of a storm were dry.
Figure 5.13: As in Fig. 5.6, but with dry pixels removed.
Histograms of all TPW values within 400 km of the center of each storm on each day (327 storm days) are shown in Figure 5.14. The top two panels are using the AIRS data with dry pixels removed. The peak is shifted slightly to the left for weakening cases and, as would be expected, the peak is also broader. To the right of the peak, the shape of the histogram is quite similar for intensifying and weakening cases. In the bottom two panels are histograms for the microwave data. Clearly there is some disagreement between the microwave and AIRS datasets (partly due to AIRS data being from 1000-250 hPa and microwave data the full atmosphere), but there are also a couple of similarities to point out. First, the peak also shifts to the left by ~3 mm, like what was seen with the AIRS data. The peak for the weakening cases is also broader than intensifying cases, meaning that a wider range of TPW values are likely in weakening cases. Also, to the right of the peak, there is little difference between intensifying and weakening cases. On the left side of the peak, the tail is larger in the weakening cases, which is to be expected. The main discrepancy with the AIRS data lies on the low TPW side of the histogram. AIRS shows a much higher occurrence of dry TPW values (under 45 mm). It appears that removing the extremely low TPW values (under 25 mm) does not eliminate major differences with the microwave data. It is quite possible that even reasonable AIRS TPW values may still have a dry bias due to cloud cover. This becomes difficult to correct, as it is impossible to determine if a logical dry TPW value around 40 mm is actually correct, or if it has been slightly affected by cloud cover. Another important point to remember is AIRS TPW values represent an integration from 250-1000 hPa, so the percentage of column moisture between 1000 hPa and the surface (~5%) is missed (Dunion 2010). To correct this, a 5% increase in the column moisture was introduced, and 2 g/kg was added
Figure 5.14: Histograms of TPW within 400 km for intensifying and weakening storms using AIRS (top) and microwave (bottom) data.
to 850 hPa mixing ratio values based on the AIRS dry bias at this level (Chapter 3). With these rough approximations, TPW was recalculated using the unfiltered AIRS data. Figure 5.15 shows the peaks of the histograms are shifted to the right with this adjustment to the AIRS moisture and are more in line with the location of the histogram peaks from the microwave TPW data. Despite the adjustments to the AIRS data, there are still unrealistically low TPW values within a 400 km radius of the storm center. It is likely that the presence of cloud cover is affecting some retrievals more than others, so the application of a broad correction for cloud cover does not fully solve the problem. In the end, it looks like AIRS TPW values must be used with caution, likely more so than microwave TPW values.

Figure 5.15: Histograms of adjusted AIRS TPW within 400 km for intensifying and weakening storms.
5.4 SHIPS Wind Shear and SST

Dry air is one of several factors that can affect the intensity of tropical cyclones. Wind shear and sea surface temperature (SST) often play large roles in the development or weakening of a storm. Wind shear (850-200 hPa) and SST data were obtained for each of the 327 storm days. Figure 5.16 shows the individual relationships between these variables and intensity change. When the shear was less than 10 knots/5.1 m s\(^{-1}\) (90 total cases), the majority of storms (~69%; 62 total) exhibited intensification. Conversely, when shear was over 30 knots/15 m s\(^{-1}\) (24 total cases), over half (~63%; 15 total) of the storms exhibited weakening. This agrees with many previous studies that have shown that high wind shear is detrimental to a tropical cyclone. Perhaps not surprisingly, with the SST data, waters warmer and cooler than 28°C can both still have intensifying storms.

Figure 5.16: Intensity change due to 850-200 hPa wind shear and SST. Numbers above each bar graph indicate sample size.
Adjusting the SST threshold to greater than 30°C, all storms exhibit intensification, but there are only 5 storm days meeting this SST criterion. A downward adjustment of the threshold for SST to less than 26°C shows that intensification, steady-strength, and weakening occur with nearly equal frequency. However, of the 327 total storm days, only 16 met this criterion of SST under 26°C. It is possible that the geographical domain being used leaves out storms occurring in cooler waters outside the domain. Perhaps a larger dataset with more cases above 30°C and below 26°C would more accurately show the effects of SST on intensity change. Another important note is that SST is only a sea surface skin temperature, and does not provide information about the depth of the warm water. Variables such as ocean heat content might shed more light on the relationship between water temperature and TC intensity change.

Because the intensification or weakening of a storm is often a result of several factors, it is important to consider the presence or lack of dry air and shear combined. It is hypothesized that when shear is held constant, the amount of dry air present will have an effect on intensity change. For example, low shear and little dry air should be more conducive to intensification than low shear and a large amount of dry air. To test this, all storm days with shear less than 15 knots (7.7 m s⁻¹) were considered (168 days met this criterion). This threshold matches closely to the mean 850-200 hPa shear (17 knots/8.9 m s⁻¹) found in the tropical North Atlantic and Caribbean during the hurricane season (Dunion 2010). Figure 5.17 shows that despite the amount of dry air (<25% dry, 25-50% dry, and >50% dry) intensification occurred most frequently. However, there are a couple of interesting features to note that highlight the role dry air plays in intensity change. In all four quadrants, the percentage of cases that exhibit intensification
Figure 5.17: Percentage of storms that intensify (left) or weaken (right) based on amount of dry air present while 850-200 hPa wind shear is < 15 knots.

decreases from when there is little dry air present (<25% dry) to a lot of dry air present (>50% dry). Also, the likelihood of weakening goes from 10% of cases or less when there is little dry air (<25% dry) to over 35% when dry air is present (>50% dry). The sample size for each of these bar graphs ranges from 19 to 80 cases (Table 5.9). Unfortunately, there were not enough cases where shear was less than 15 knots and quadrants were >75% dry, though it is suspected that a further increase in the amount of dry air would continue the trend of lower likelihood of intensification and higher likelihood of weakening.
Table 5.9: Number of cases of dry air in each quadrant. For example, there were 46 cases in which less than 25% of AIRS profiles in the northwest quadrant of a storm were dry when the 850-200 hPa wind shear was < 15 knots.

When wind shear is above 15 knots (130 cases), however, the results are not as consistent. In the northeast and southeast quadrants, an increase in dry air from <25% dry to >50% dry results in an increase in the percentage of weakening cases, but this does not hold true for the northwest and southwest quadrants (Fig. 5.18). In fact, the opposite

Figure 5.18: As in Fig. 5.17, but for wind shear > 15 knots.
is true in these quadrants when wind shear is above 15 knots. More dry air actually results in a slight increase in the likelihood of intensification. This seems counterintuitive, but it might indicate that storms can survive the presence of dry air on the western side of the storm, but once dry air wraps around to the eastern side, the chances of weakening become greater, especially if the dry air reaches the northeast quadrant. It may also suggest that the shear vector is important, and perhaps weakening is dependent on whether the dry air is being advected toward the storm. Table 5.10 shows that the sample size of dry air and wind shear greater than 15 knots is similar to that in Table 5.9 when wind shear was less than 15 knots.

Figure 5.19 shows the likelihood of intensification and weakening based on dry air and SST criteria. There were 199 storm days when SST was above 28C. When the amount of dry air was varied, the percent of cases exhibiting intensification was almost always greater than the percent exhibiting weakening. The lone exception was when very dry air (>50% dry) was present in the southeast quadrant. Here weakening occurred in over half of the cases. This is probably due to the likely presence of dry air in other quadrants of the storm on these days. Dry air generally follows the cyclonic circulation around the north, west, and south sides, so if dry air is in the southeast quadrant, it is usually present in other quadrants as well. With the exception of the northwest quadrant,

<table>
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<th>25-50%</th>
<th>&gt; 50%</th>
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<tr>
<td>SW</td>
<td>50</td>
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<tr>
<td>NE</td>
<td>25</td>
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<td>12</td>
</tr>
</tbody>
</table>

Table 5.10: Number of cases of dry air in each quadrant. For example, there were 43 cases in which less than 25% of AIRS profiles in the northwest quadrant of a storm were dry when the 850-200 hPa wind shear was > 15 knots.
Figure 5.19: Percentage of storms that intensify (left) or weaken (right) based on amount of dry air present while SST is > 28C.

Figure 5.19 also shows that as the amount of dry air increases, the chances of weakening also increase when SST is over 28C. Looking at the likelihood of intensification, all quadrants see a decrease in intensification with an increase in dry air. Table 5.11 shows the number of cases when storms met both the dry air and SST (> 28C) criteria. The greatest number of cases were when there was little dry air in each quadrant (< 25% dry). Very few cases occurred when SST was over 28C and a quadrant was over 75% dry, so those cases have been excluded here due to the small sample size.

For the days when SST was less than 28C (103 days), the same trends appear when the amount of dry air varies (Fig. 5.20). The likelihood of storms intensifying decreases as the amount of dry air increases from < 25% dry to > 50% dry. For weakening storms, an increase from <25% dry to >50% dry results in a large increase in
Table 5.11: Number of cases of dry air in each quadrant. For example, there were 82 cases in which less than 25% of AIRS profiles in the northwest quadrant of a storm were dry when the SST was > 28°C.

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>&lt;25%</th>
<th>25-50%</th>
<th>&gt;50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>82</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>SW</td>
<td>91</td>
<td>43</td>
<td>24</td>
</tr>
<tr>
<td>SE</td>
<td>60</td>
<td>37</td>
<td>12</td>
</tr>
<tr>
<td>NE</td>
<td>48</td>
<td>36</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 5.20: As in Fig. 5.19, but for SST < 28°C.

the likelihood of weakening, except in the southwest quadrant. However, in only the southeast quadrant does weakening become more likely than strengthening when the quadrant is greater than 50% dry. This is somewhat surprising, as these are for the storm days with SST < 28°C. It would have made more sense to see weakening more likely when other quadrants are >50% dry. Tweaking the SST threshold resulted in a relatively small number of cases. A longer AIRS dataset with more cases of cooler SSTs (< 28°C)
and more dry air (>50% or >75% dry) might show more clearly the increased chances of weakening in these situations. Table 5.12 shows the sample size when SST was less than 28°C and dry air was present. Not surprisingly, the fewest number of cases this time are when there is a combination of cool SST (< 28°C) and little dry air (< 25% dry). This is intuitive, as cooler SSTs (usually at higher latitudes) would be more likely to correlate with a drier airmass. This might explain why there are more cases with cool SST and dry air, as seen in the two right columns of Table 5.12.

In all likelihood, dry air acts in concert with other factors such as low SST and especially high wind shear to weaken a tropical cyclone. Conversely, the lack of dry air may coincide with a light shear environment and sufficiently warm waters to provide an environment conducive to strengthening. Dry air outbreaks from the SAL can have a mid-level jet and can have high shear along the SAL edge. Mid-latitude outbreaks can bring increase shear to lower latitudes. The presence of dry air appears to be one of several factors that determine the intensity change of tropical cyclones.

<table>
<thead>
<tr>
<th></th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 25%</td>
</tr>
<tr>
<td>NW</td>
<td>12</td>
</tr>
<tr>
<td>SW</td>
<td>25</td>
</tr>
<tr>
<td>SE</td>
<td>24</td>
</tr>
<tr>
<td>NE</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 5.12: Number of cases of dry air in each quadrant. For example, there were 12 cases in which less than 25% of AIRS profiles in the northwest quadrant of a storm were dry when the SST was < 28°C.
Chapter 6

Summary and Conclusions

The main goals of this study were to examine the reliability of AIRS moisture and temperature data in tropical cyclone environments, to show the seasonal variability of moisture in the tropical North Atlantic, to compare AIRS TPW data with that of microwave satellite measurements, and to investigate the role dry air plays along with other factors in the intensity change of tropical cyclones. Main results include:

- AIRS can detect the difference between a dry (SAL or mid-latitude dry air intrusion) environment and a moist tropical one.

- AIRS/GPS dropsonde comparisons show AIRS struggles most with mixing ratios in the low to mid-levels. In SAL cases, AIRS mixing ratio dry bias peaks at ~3 g/kg at 850 hPa, where the greatest standard deviation is also found. Moist tropical cases also show a dry moisture bias in the AIRS data, with a peak around 2.5 g/kg at 600 hPa. Upper level (250-400 hPa) dry biases were small (~0.3 g/kg or less) in SAL and moist tropical cases. At 1000 hPa, dry biases were around 1.3 g/kg and 0.7 g/kg for SAL and moist tropical cases respectively.

- RMSE values in the mid-levels and deep layer do not show a great dependence on the AIRS/GPS dropsonde distance criterion, though in the low-levels the RMSE value was ~1 g/kg lower for a 25 km criterion compared to a 50 km criterion.

- AIRS TPW can be used on individual days and for temporal averaging to determine the monthly and interannual variability of the moisture distribution across the tropical Atlantic.
• AIRS struggles in regions immediately surrounding cloud-flagged pixels. TPW values in these areas are often too low.

• Dry air often combines with other factors (high wind shear and/or low SST) to induce weakening in a tropical cyclone.

There are several advantages and disadvantages that users of AIRS data must consider. The benefits of AIRS include its good spatial coverage over oceans where observational networks are sparse. Additionally, its good coverage allows for an examination of the vertical moisture distribution across the Atlantic. While it is useful to have many vertical profiles of temperature and moisture in data-sparse regions, the fact that AIRS data is only given at the mandatory pressure levels and 600 hPa means that it misses shallow features between each pressure level. One such feature is the base of the SAL, typically around 850 hPa. This is a shallow phenomenon where the vertical gradient of mixing ratio is high, and AIRS does not have sufficient vertical resolution at these levels to consistently and accurately capture it.

Despite this issue with vertical resolution, AIRS still displays an ability to capture the general moisture environment surrounding a tropical cyclone. Integrating mixing ratio to obtain TPW shows that AIRS can accurately depict areas that are moist tropical (high TPW) versus SAL/mid-latitude dry environments (low TPW). This has operational implications too, as the entrainment of dry air into the circulation of a tropical cyclone can affect its intensity. AIRS TPW data can also be used for temporal averaging across the tropical Atlantic basin. Monthly averages can show the strength and westward extent of dry air originating from Africa. For example, in June there is drier air that extends further westward across the Atlantic than it does in August.
One of the biggest problems with the use of AIRS data is its performance in regions with thick cloud cover. This cloud cover blocks or diminishes infrared emissions to the satellite from levels below the cloud layer, thereby making a complete, accurate sampling of the vertical profile impossible. This is seen especially in individual profiles near tropical cyclone centers, where moisture data from the boundary layer can be missing. In turn, this causes a dry bias in the AIRS moisture retrieval, especially in the lower troposphere. The resulting TPW value calculated from this retrieval is erroneously low, because most of the contribution to TPW comes from the boundary layer. Also, the lack of moisture data between 1000 hPa and the surface will also contribute to a dry bias in AIRS TPW. In the end, however, AIRS data can and should be used to assess the atmospheric conditions surrounding tropical cyclones, but there are a few points of caution that need to be taken into account.

The role dry air plays on the intensity of tropical cyclones was also investigated, using all named storms during the first six years of AIRS (2003-2008). It was shown that dry air typically is not the only cause of intensity change, with other factors such as vertical wind shear and SST playing important roles as well. Wind shear and SST data was obtained from SHIPS files. In this 6-year sample of storms, the combination of dry air and high wind shear (> 15 knots) was more likely to induce weakening than the combination of dry air and low SST (< 28°C). Also, greater coverage of dry air in each quadrant of the storm was generally, but not always, more likely to result in weakening.

Future work in this area might involve obtaining more cases of dry air surrounding storms, especially when that dry air is present in more than one quadrant. Increasing the sample size will lead to more accurate results of how dry air, wind shear
(not just the magnitude but the vector), and SST all interact to intensify or weaken a tropical cyclone. Considering the wind shear vector would be important because the direction of the shear may accelerate or delay the process of dry air approaching the tropical cyclone center. This study can also be expanded to include other ocean basins as well. Though dust outbreaks are most commonly seen in the Atlantic, there may be regional features such as mid-latitude dry air outbreaks in other basins that could affect the performance of AIRS. Finally, an adjustment to the moisture data by accounting for the unsampled region between the surface and 1000 hPa, and accounting for the dry bias in the lower levels may improve the performance of AIRS.


