Assessing The Coast's Influence on Tropical Cyclone Miniature Supercell Mesocyclones.

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ABSTRACT

Supercells in the outer bands of tropical cyclones (TCs) are often smaller than their midlatitude counterparts. They are often difficult to observe via weather radar due to their small size and rapid evolution. Yet, they are capable of producing damaging winds and tornadoes upon arrival onshore. The potential to develop tornadoes and the production of severe winds are associated with a strong mesocyclone present in an individual supercell. Mesocyclones have been observed to intensify rapidly as they cross the coastal boundary. It is hypothesized that the mesocyclone responds to an increase in vertical wind shear afforded by the onshore change in surface roughness. In order to assess the individual mesocyclone response to the coastal boundary, this study characterizes individual supercells as they move from the ocean onto land. Specifically, the changes in azimuthal shear are examined through a local, linear, least-squares derivative of single-Doppler velocity observations often termed "AzShear." Relative to more spatially limited dual-Doppler analysis domains, this study affords a large area over which numerous supercells can be examined. Two cases will be examined, including Irene (2011) and Irma (2017), which were characterized by numerous observed supercells and confirmed tornadoes.

1. Introduction

Miniature supercells embedded in the outer rain bands of tropical cyclones (TCs) exhibit many of the same characteristics as their midlatitude counterparts. However, the spatial scale of these miniature supercells in TCs is much smaller than what is considered a typical supercell (McCaul 1991; McCaul and Wesiman 1996; Baker et al. 2009; McCaul et al. 2004; Carroll-Smith et al. 2019). Hence, identifying these supercells is difficult due to their small appearance when observed by most weather radars. Exacerbated by the difficulties associated with identifying supercells in the outer rainband of TCs, recognizing characteristics of the attendant small mesocyclones associated with even strong supercells is even more difficult (McCaul 1991). Commonly used radar characteristics used to identify miniature supercells can include identifying regions of high reflectivity, overshooting cloud tops, persistent cloud to ground lightning, or strong gate-to-gate shear (Spratt et al. 1997; Edwards 2012). Identifying regions with such characteristics can convey potential supercells with strengthening mesocyclones.

Being able to identify potential supercells embedded in the outer rain bands of TCs poses a challenge to forecasters. Typically, miniature supercells associated with TCs evolve rapidly over short periods of time. Because of the difficulty in identifying miniature supercells as they cross the coastal boundary, it can be challenging to forecast the potential hazards associated with a landfalling miniature supercell, such as forecasting the probabilities of dam-

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aging winds and the potential to spawn tornadoes. This has led to inaccuracies in the ability to forecast potentially hazards phenomena such as tornadic events associated with these miniature supercells. Resulting from these challenges, the false alarm ratio associated with TC tornadoes is considerably higher than that associated with all other tornadic events (Nowotarski et al. 2021).

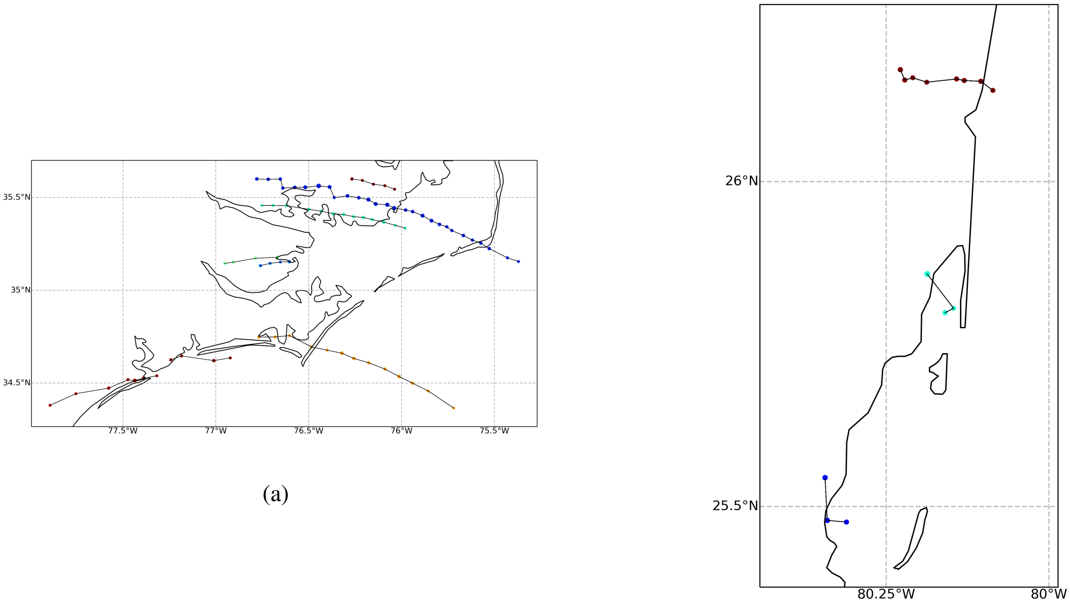
Previous works have examined TC production of tornadoes. However there are less studies directed at investigating the boundary layer interactions and assessing how miniature supercells associated with TCs are impacted by landfall. Spratt et al. (1997) investigated the rotational velocity (a measure of mesocyclones intensity) to the diameter of cell size. In a typical midlatitude supercell the distance from the radar has a slight impact on the ability to detect mesocyclone strength. However, a typical supercell in the outer rain bands of a TC is on average less than one-third the size of a standard supercell. Given typical WSR-88D azimuthal and range resolutions, this results in a more severe decrease in radar ability to measure the mesocyclone strength (characterized by rotational velocity) (Spratt et al. 1997). Although there is a large discrepancy in size between a midlatitude supercell and a miniature supercell associated with a TC, there is evidence that the conventional parameters used in identifying potentially tornadic midlatitude supercell, such as CAPE, storm relative helicity and the supercell composite index, can also be used in differentiating potential tornadic events in TCs (Baker et al. 2009). However, these parameters are difficult to measure in a landfalling TC due to limited radiosonde sampling.

Beyond the traditional scope of investigating the structures of miniature super cells in the rainbands of TCs, less studies have investigated the response of an individual supercell to the coastal boundary. Morin and Parker (2011) used a numerical simulation of Hurricane Ivan in order to investigate the landfalling process of miniature supercells in the outer rainbands of TCs. Most notably, the work emphasized the impacts of a sea-to-land transition of miniature supercells. Ultimately, it was concluded that the increase in surface friction over land benefits the development of high wind shear (Morin and Parker 2011). In addition to this numerical research on the transition from sea-to-land, there is support that the orientation in which a cell interacts with the coastal boundary plays a role in how the cell develops as it makes landfall. Miniature supercells making landfall perpendicularly to the coastline may maximize the effects of the frictional convergence associated with landfall (Spratt et al. 1997). In addition to the evolution of the miniature supercell mesocyclones as they move across the coastline, prior work has been done on assessing how the inland strengthening process can affect tornadogenesis. Characterized by an increase in low level vertical vorticity, a relative increase in miniature supercell strength can be identified in the sea-to-land transition. This numerical increase can further be supported by identifying characteristics in the structure of the cell, such as the development of hook appendages (Carroll-Smith et al. 2019).

In order to reduce the uncertainty associated with forecasting hazards from miniature supercells, this study attempts to understand the miniature supercell response to the coastal boundary. More specifically, this study focuses on the response of the mesocyclone within individual miniature supercells and understanding how the coastal boundary influences the potential strengthening of the mesocyclone. It is thought that the change in surface roughness associated with making landfall (such as an increase in friction associated with transitioning from a relatively smooth water surface to a comparatively rougher land boundary) can lead to an increase in the mesocyclone strength of a miniature supercell (Alford et al. 2020). As air parcels in the hurricane boundary layer (HBL) approach the coastline, substantial modification of the low-level horizontal winds are observed, with comparatively little adjustment in upper-level winds above the HBL (Alford et al. 2020). These changes suggest an increase in vertical wind shear, particularly within the first 20-30 km inland from the coast (Alford et al. 2022a,b, 2023). In order to characterize how supercell mesocyclones respond to the near-shore vertical wind shear increase, a single-doppler observation known as Azimuthal Shear (AzShear; Mahalik et al. 2019) is used. AzShear is commonly used over several radar volume scans, where it then can be used as a rotational tracks product. However, AzShear can also be used to quantify storm scale rotation in supercells (Mahalik et al. 2019). This analysis would improve understanding of the mesocyclone response to the coastal boundary, which would ultimately allow for more accurate forecasting of the potential severe weather events associated with the landfall of miniature supercells in the outer rain bands of tropical cyclones.

2. Data and Methods

In this study, landfalling outer rainbands were studied in two separate TCs, Irma (2017) and Irene (2011). In order to minimize radar distance from miniature supercells, data were taken from WSR-88D radars (Crum and Alberty 1993) that were in the closest proximity to the landfalling outer rain bands, rather than the location of the landfalling eye of the TC. Since mesocyclones associated with TC miniature supercells only reach an average diameter of around 1.85 km, a scan from a WSR-88D can typically resolve a mesocyclone within 111 km range of the radar (Spratt et al. 1997). Spratt et al. (1997) show in conjunction with the diameter limitations, the mesocyclone of a typical supercell associated with a TC is approximately 3.5 km tall. At this height, a half degree radar tilt can detect the circulations associated with the mesocyclone up



(a)

(b)

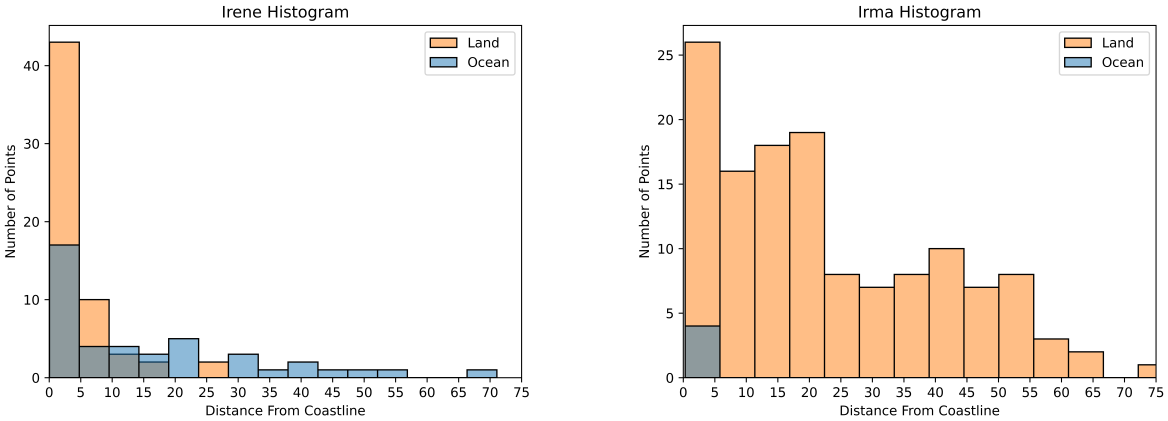
FIG. 1: Tracks of mesocyclones identified by the mesocyclone tracking algorithm are shown for both (a) Hurricane Irene (2011) and (b) Hurricane Irma (2017).

to 160 km from the radar. With these limitations in mind, data collected at a 0.5-degree elevation from radars in the closest proximity to the landfall of the outer bands were retained for this study.

The data used from the radars in closest proximity to the landfalling outer rainbands were half degree tilt reflectivity and AzShear (Mahalik et al. 2019). AzShear is calculated using a linear, least squares derivative of single radar Doppler velocity (Mahalik et al. 2019). AzShear can be understood as a gradient of radial velocity and is often used to highlight regions of significant azimuthal wind shear. Here, AzShear is used as a quantitative measure of mesocyclone intensity and is an optimal tool to do so, as it well-captures the storm-scale changes in Doppler velocity (Mahalik et al. 2019). Both reflectivity and AzShear were used in order to create plots demonstrating the movement of the outer rainbands from the ocean onto shore. In addition, data from a mesocyclone detection algorithm (of which AzShear is a critical component) was also used in order to track individual mesocyclones for miniature supercells. Specifically, the local maxima in AzShear were primarily used to characterize the location of mesocyclones.

The aforementioned data were interpreted in two separate ways. To start, the reflectivity and AzShear radar data were plotted by time in order to make a series of images that showed the movement of the outer rainbands onto shore in chronological order. These series of images were then examined subjectively, and individual miniature supercells were identified and followed over time. This individual analysis allowed for a manual detection of a mesocyclone present in a cell. Conducting a manual analysis of individual cells is consistent with methods described in Spratt et al. (1997), as miniature supercells associated with TCs can be difficult to assess with an algorithm. Following the identification of individual cells, the mesocyclone of the cell was then manually identified and recorded. This process allowed for a characterization of each mesocyclone to be formulated over time and provided insight into the transformation it may undergo as it moves across the coastal boundary.

Supplementing the manual analysis of each mesocyclone, a mesocyclone tracking algorithm was used. This algorithm identified regions of at least four neighboring radar gates that exhibited an AzShear value greater than 0.006 s^{-1} to identify ”storm objects”. The objects are fur-



(a)

(b)

Fig. 2: Histograms of mesocyclone objects as a function of distance from the coastline over the ocean (blue) and over land (orange) for both (a) Hurricane Irene and (b) Hurricane Irma.

ther constrained by a 20 dBZ dilation filter with despeckling (Thea Sandmael, personal communication). The cutoff value was determined based on a value of 0.006 s^{-1} as this value is understood to represent a strong rotational value consistent with mesocyclones likely to produce a tornado. Once an AzShear value surpassed the threshold for classification by the algorithm, it was given an identification number and was subsequently tracked as it moved over time and sustained an AzShear value that was greater than the threshold value. Using the mesocyclone tracking algorithm, a dataset was generated and was organized by time. From this dataset, the location of each mesocyclone object was classified as being over ocean or over land. A storm must at least have existed over land to be retained in the dataset. For all storms meeting the above criteria, the maximum value of AzShear was recorded as a function of time. In total, eight cells in Irene and three cells in Irma were identified as moving across the coastal boundary. However, this was not the entirety of the objective dataset, rather just the cells that met criteria that allowed for a useful analysis to be conducted using the data points-such as moving onto land from the ocean, or being initially tracked very closely to the coastline.

After the processing of data from the mesocyclone detection algorithm, the data points were connected, demonstrating the path a cell took over its lifespan (Figures 1a, 1b). Then a subjective and objective analysis of individual cells was conducted where the subjective data were used to verify the objectively identified mesocyclone tracks.

Using two methods of analysis allowed for the data to be assessed in a conducive manner. Due to the subjectivity associated with the analysis, the objective object tracking was able to confirm patterns recognized subjectively. Similar to how the subjective analysis was supplemented by the object tracking algorithm, the inverse was done as well. Due to the threshold of AzShear used by the algorithm, if a cell fell below the 0.006 s^{-1} the algorithm moved onto the next cell. This caused some identified cells to be remnants of an older cell. This was combated by manually recognizing whether or not a data point was a part of a previously named cell. Along with this, the algorithm was only able to follow cells that had achieved a mesocyclone strength of $\geq$0.006 s^{-1}. This threshold prohibited the algorithm from following cells while they were weaker. This was also supplemented with the manual analysis. Using images created from the reflectivity and AzShear and comparing them with the images created from the mesocyclone algorithm dataset, cells that only appeared on land were tracked back over the ocean and recorded. Ultimately, the two methods used to analyze the data were used in correspondence with each other in order to provide a complete dataset.

3. Results

First, the coast-relative location of objectively identified storm objects is examined. The processed data provided individual cells that made landfall, and allowed mesocyclone locations to be tracked as the cells moved over time. For each cell and mesocyclone location (i.e., mesocyclone objects), the distance from the coastline was determined. The coastal distance of mesocyclone locations was partitioned in 5 km intervals relative to the nearest point on the coast. Overall, it was found that of the majority of objects identified by the mesocyclone identification algorithm fell within 0-25 km inland of the coastline (Fig. 2). In contrast,

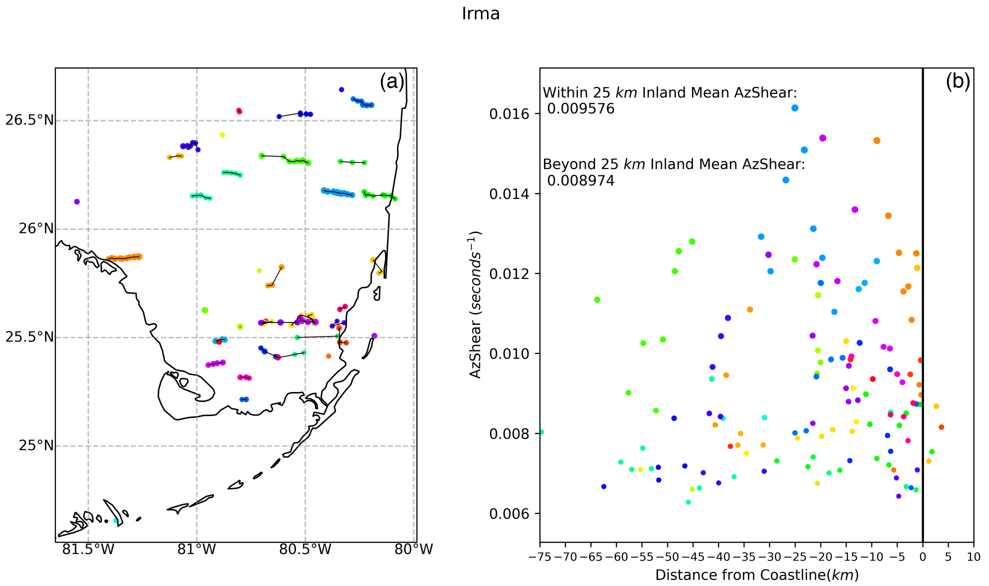


FIG. 3: (a) All objectively tracked points in Hurricane Irma that were recorded over land, or moving over land. (b) Corresponding cell location compared to the coastline vs. AzShear value at that location with mean for locations within 25 km and outside of 25 km of the coastline.

very few mesocyclone objects were identified ≥10 km offshore by the algorithm, particularly in the Hurricane Irma case (Fig. 2b). The data were further examined subjectively to determine the algorithm did not miss cases. There were few readily identifiable prominent supercell mesocyclones offshore. In Hurricane Irene the overwhelming majority of cells identified were within 5 km of the coastline (Fig. 2a; both onshore and over the ocean). In Hurricane Irma there is a vast decrease in the number of mesocyclones identified >25 km inland from the coastline, but again there were clearly more mesocyclone objects over land than there were over water.

Next, the distribution of mesocyclone intensity was examined as a function of coast-relative distance. For each mesocyclone object, the value of AzShear was examined as a quantitative measure of the low-level mesocyclone intensity. In Hurricane Irene, the mean AzShear offshore (onshore) was approximately 0.00963 s^{-1} (0.01069 s^{-1}). Likewise, an increase in variance of AzShear on land was noted and was an order of magnitude greater than the variance of AzShear over the ocean (Fig. 3). Notably, the increase in variance was associated with a positive trend in AzShear increase, such that it can be concluded that the increase in variance was a direct result of cells strengthening as they moved across the coastal boundary (Fig. 3). Attempting to replicate these results for Hurricane Irma yielded similar results. The objective data for Hurricane Irene included eight miniature supercells that moved from the ocean onto land. These eight cells yielded seventy-eight mesocyclone objects (Fig. 1a). On the other hand, the objective data for Hurricane Irma only included three cells that moved from the ocean onto land, yielding fourteen total points (Fig. 1b). However, this was due to the limitation imposed on the minimum AzShear criterion (0.006 s^{-1}). Based on only the cells identified, there is clearly a substantial increase in the range of AzShear values onshore. Since all other AzShear were <0.006 s^{-1}, there is a clear tendency for cells to exhibit stronger mesocyclones over land in the Irma case. Figure 3 shows that within approximately 25 km of landfall, cells exhibit a higher AzShear value than when further inland, suggesting mesocyclones in Irma were strongest between the coast and ∼25 km inland.

To corroborate the results of the objective algorithm, supercells were also examined subjectively. Like in the former objective analysis, many cells were seen to have undergone strengthening processes as they made landfall during the subjective analysis. In Irma, nineteen supercells were identified that moved from over the ocean onto land and included the three that were tracked objectively (discussed above). Thus, sixteen other storms that were not tracked by the objective algorithm moved from over the ocean onto land. Approximately fourteen of the nineteen identified different cells were found to have undergone a noticeable increase in AzShear as they made landfall. However, this does not indicate that the other five cells weakened as they crossed the coastline. Rather they did not exhibit a noticeable increase in AzShear, but rather maintained similar values as they moved over land. With the exception of the three objectively-identified storms, all mesocyclone were found to have maximum AzShear values $< 0.006\ \mathrm{s}^{-1}$ while over the ocean. In support of this, the cells identified using the objective analysis supported what was found in the subjective analysis.

This same analysis yielded similar results for Hurricane Irene as well. Of the thirteen cells identified during the subjective analysis, nine showed a noticeable increase in AzShear during their transition onto land. Of these cells, only one was identified as weakening as it made landfall. Again, these results were consistent with what was determined with the objective tracking algorithm.

4. Discussion

Overall, there was significant evidence supporting our hypothesis that the interaction with the coastal boundary aids in the intensification of miniature supercells in the outer rainbands of TCs. It was found that of the objects that were identified by the mesocyclone tracking algorithm, the majority were within close proximity of the coastline. In the case of Hurricane Irma, of the 139 points identified by the algorithm, 83 were found within 25 km inland of the coastline. Figure 4 demonstrates a reduction in the proportion of points detected beyond a 25 km range of the coastline. Additionally, only 4 out of the 139 points were over the ocean. This data showed that during Hurricane Irma, the mesocyclones of individual miniature supercells that exhibited AzShear values strong enough to be tracked objectively occurred almost exclusively during the transition of the cell onto the coastal boundary. Since there is little detection of mesocyclones prior to arriving on land, the detection inland conveys that the mesocyclones increased in intensity as they moved across the coastline.

The proportion of mesocyclone objects (both onshore and offshore) found within 10 km of the coastline is even more drastic in Hurricane Irene. Of the 103 objects identified, approximately 70% of them were within 10 km of the coastline. Although the difference between points on land versus points over the ocean was smaller in Hurricane Irene than in Hurricane Irma (Fig. 2), the majority of identifiable mesocyclone points had crossed the coastal boundary. The decrease in identifiable cells further inland of the coastline that was seen in Hurricane Irma was also seen in Hurricane Irene. This supporting evidence indicates that the most prominent mesocyclones in miniature supercells in the outer rainbands of TCs may generally occur within the first 30 km inland of the coast.

Prior studies such as Schenkel et al. (2020) have pointed to a large proportion of observed tornadoes in TCs occurring within the first 50 km of the coast. While Alford et al. (2022a,b) showed the vertical wind shear immediately inland of the coastline was more supportive for mesocyclone intensification, no study has yet examined the individual mesocyclone intensity response of supercells as they move inland into a more favorable shear environment. Using dual-Doppler radar derived vertical wind shear in Hurricane Irene, the intensification of mesocyclones can be interpreted and can be examined in an environmental context. Figure 5 demonstrates the change in dual-Doppler derived vertical wind shear relative to coastal distance. The average shear vector magnitude nearly doubled over land versus over water (Fig. 5). This increase in shear is a direct indication of the HBL response to the coastal boundary. Thus, it is likely that supercells moving onshore into a more favorable vertical wind shear environment are more likely to intensify.

shWith more objects identified over the ocean, Hurricane Irene provided more insight into the quantitative strengthening of individual mesocyclones as they moved onto land. Figure 6 shows the distribution in AzShear values over the ocean versus on land. This revealed that there is a 50% increase in standard deviation in the AzShear values of cells that move across the coastline. While this variability does not indicate that a cell will see an increase in mesocyclone strength as it moves onshore, it does show that there is a higher likelihood that a cell will undergo a mesocyclone strengthening upon making landfall, rather than remaining at the same strength.

Likewise in Irma, Figure 4 demonstrates a strong mesocyclone response to the coastal boundary that is supported by both the subjective and objective analyses. While the cell is over the open ocean approximately 30 km from its landfall, it is just a slightly organized region of high reflectivity that exhibits low AzShear values. As the area approaches the coastline, there is an increase in AzShear associated with the proximity to the coast and an organization of reflectivity. At 1620 UTC, the objective algorithm classifies the organized mass of high reflectivity as a supercell with a strong mesocyclone. This takes place just off the coastal boundary at roughly 2.5 km away from the coastline when the forward flank of the supercell structure is indeed over land. By 1623 UTC the entire cell had moved across the coastal boundary and was on land, at this time the objective and subjective analysis both identified that the cell had attained its maximum value of AzShear. Figure 7a shows the path of the cell, along with the AzShear values of the cell relative to its proximity to the coastline. This verifies the increase in AzShear that can be identified in Figure 7b. Overall, this is a reasonable example of a mesocyclone exhibiting an increase in strength in response to the coastal from this dataset.

Figure 8 demonstrates a mesocyclone decreasing in strength as a response to the coastal boundary. While the cell is approaching the barrier islands to the east of the coastline, the mesocyclone associated with the cell is considered to be rather strong as it has an AzShear value nearing $0.01\ \mathrm{s}^{-1}$. However, as the cell crosses the coastal

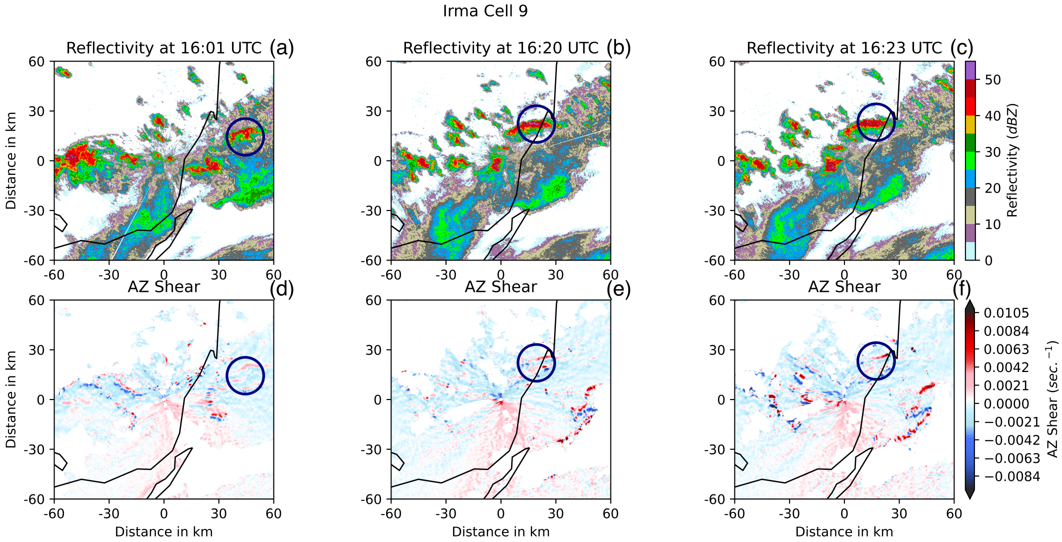


FIG. 4: Hurricane Irma cell 9 (a-c) reflectivity and (d-f) corresponding AzShear at three different locations. (a & d) First identification using subjective cell tracking. (b & e) First identification using objective cell tracking. (c & f) Subjective and objective maximum AzShear associated with the cell.

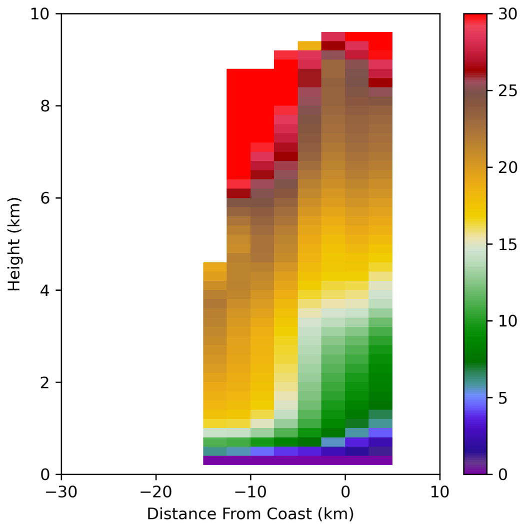


FIG. 5: Magnitude of the 0.25-z km vertical wind shear (m s^{-1}) with respect to coastal distance (km) and height z (km).

boundary the structure and organization of the reflectivity deteriorates coinciding with a decrease in AzShear. As the cell has moved approximately 20 km inland, it has nearly disappeared as both the reflectivity and AzShear signatures used to track the cell are no longer present. The objective analysis of this cell is limited. Since the dataset removed any cells that did not cross land under a common identification, the cell was not tracked as it moved from just outside the barrier islands, and then onto land. This limitation was addressed previously in the data and methods. Using the subjective analysis, the missing information was able to supplement the lack of objective analysis for this cell. Overall, we found that there is a higher probability that the mesocyclone of a miniature supercell in the outer rainbands of a TC strengthens as it makes landfall. Because of these findings, even though this cell sees a decrease in mesocyclone strength as it moves across the coastal boundary, it is not indicative of our results as a whole. Rather, this instance demonstrates it is possible that mesocyclones weaken as they cross the coastal boundary. However, such cases were few and is likely an effect of the state of the supercell lifecycle as it approaches the coastal boundary.

In Hurricane Irma, the landfalling process of the cells in the outer rainband was almost exclusively perpendicular to the coastline. In Fig. 9 it can be seen that the rainbands were oriented perpendicular to Florida's east coast (Fig. 3a). Contrary to this, many cells in Hurricane Irene did not move perpendicularly across the local coastline. Rather some moved parallel to the local, more complex coastal boundary at times. This phenomenon was accounted for when processing the data, as cells that moved parallel to the coastline were removed from the dataset in order to ensure consistency across both cases. Although not directly addressed in this study, the orientation of a cell relative to

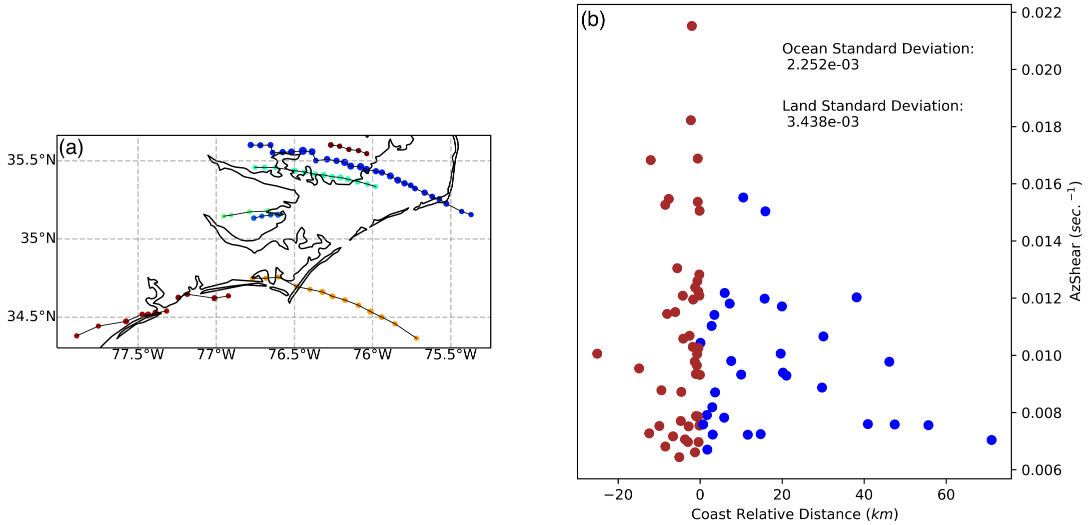


Fig. 6: (a) All cells in Hurricane Irene that moved across the coastal boundary using the objective analysis. (b) Cell relative location to the coastline vs. AzShear. Included in (b) plot is the standard deviation in cell AzShear on land and over the ocean. Cell location on land are brown points, cell location off land are blue points.

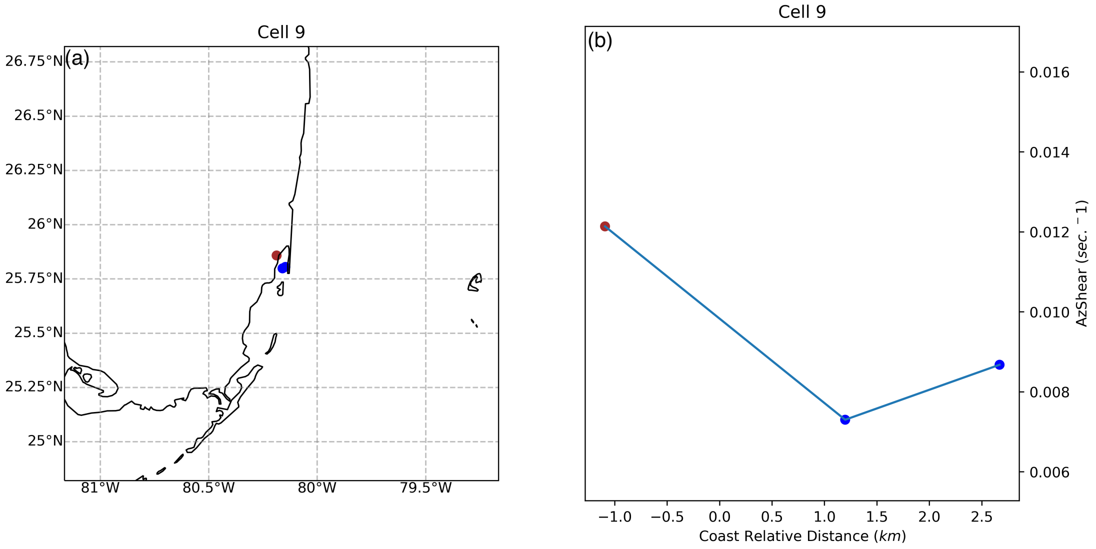


Fig. 7: (a) Hurricane Irma cell 9 cell locations tracked objectively. (b) Corresponding AzShear values and distance from the coastline for the objectively tracked cell locations.

the coastline could potentially elicit a different response to the boundary layer interactions seen in this study. Further work could be done with an emphasis on the role that the orientation of landfall has on the mesocyclone evolution of an individual cell.

Furthermore, there were geographic regions of land in both Hurricane Irma and Hurricane Irene outside of the

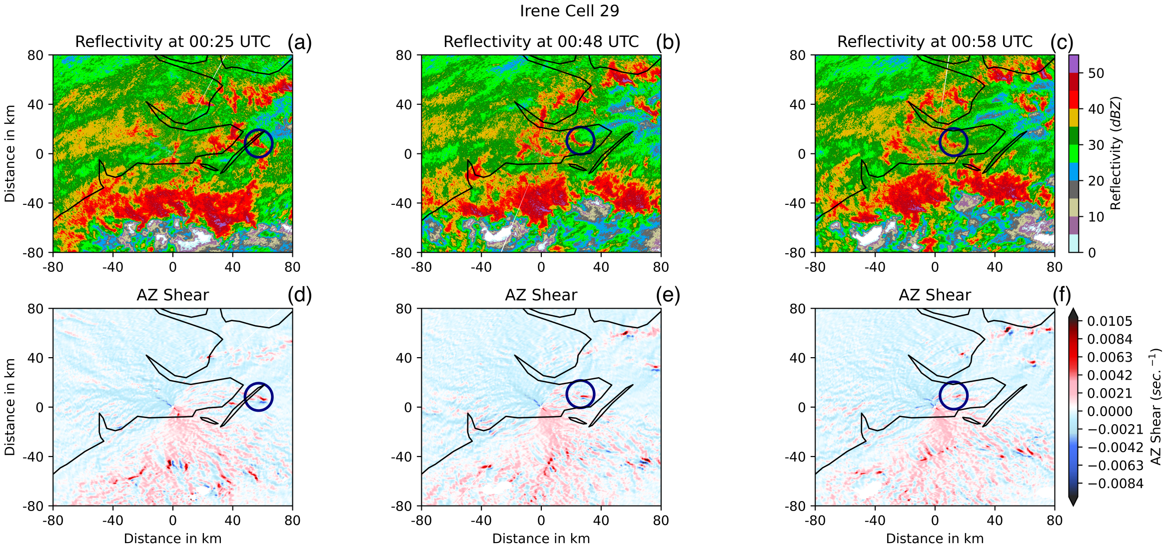


FIG. 8: Hurricane Irene cell 29 reflectivity and corresponding AzShear at three different locations. (a & d) First identification using subjective cell tracking. (b & e) First identification using objective cell tracking, and the maximum AzShear for the cell identified both objectively and subjectively. (c & f) Last identification of the cell subjectively.

coastline that could play a role in the mesocyclone evolution of miniature supercells in the outer rain bands of landfalling TCs. Barrier islands in Irene (in the case of Hurricane Irma, the Florida Keys) may incite a similar mesocyclone response that was found during the continental landfalling process. However, these boundary layer interactions had little impact on our assessment of mesocyclone evolution during the primary landfalling process. Since the cells move briefly over these smaller regions of land, it is thought that the boundary layer interactions may not be significant enough to impact our study. Indeed, we found little evidence for mesocyclone intensity changes when the supercells approached a barrier island. Furthermore, the distance between the barrier islands and the true coastline may allow for the boundary layer to recover as it continues to move across the ocean and closer to the continental coastline (Hirth et al. 2012). Overall, the effect of barrier islands and other narrow geographic land regions were not primarily analyzed in our study. Thus, further investigation into the mesocyclone response to non-primary landfall is needed in order to identify the implications barrier islands have on the mesocyclone evolution, if any exist.

5. Conclusions

Using AzShear to classify the strength of individual mesocyclones we were able to evaluate the strength of an individual miniature supercell as it made landfall. Analyzing each cell using an objective and subjective analysis allowed us to conclude that there is higher variability in mesocyclone strength immediately following landfall than while a cell is over the ocean. This variability conveys the result that the mesocyclone of an individual cell is more likely to see an increase in strength as it moves on land, rather than if it were to continue over the ocean all else being equal. These results pose implications into both the research of TCs and TC tornadoes, and the operational fore-

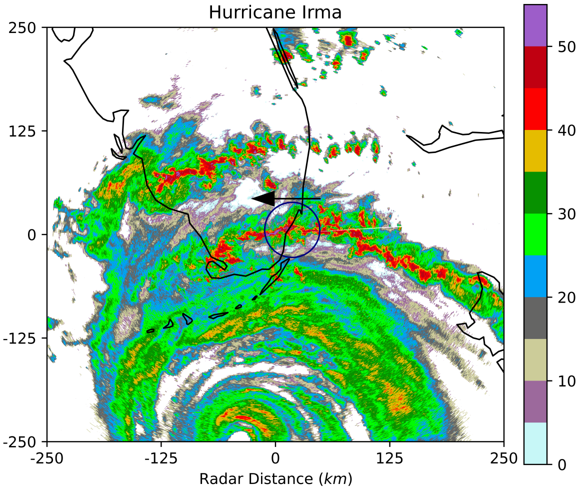


FIG. 9: Outer rainbands of Hurricane Irma making landfall at 233145 UTC with the arrow denoting the direction of propagation of the rainbands, and the circle highlighting the perpendicular angle of landfall.

casting of potentially hazardous conditions as TCs make landfall. Based on evidence from two landfalling TCs, TC miniature supercells can intensify in a more favorable vertical wind shear environment just inland of the coast. Not only are these conditions favorable over land, but also the observed mesocyclone response appears to be a result of the HBL transition across the coastal boundary. Knowledge of the vertical wind shear environment immediately inland of the coastal boundary and how individual storms may respond to such an environment is important for operational forecasters. Likewise, it is important to address numerical simulations of such scenarios in the future.

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