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An Observational and Modeling Study of Tropical Cyclone Outer Rainbands

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1. INTRODUCTION

When a tropical cyclone threatens an area, the general aviation community within that area must typically respond before the arrival of the first outer rainband if aircraft are to be safely evacuated. This leads to at least two forecast questions that must be answered. First, will your particular location be affected by the intense central portion of the storm such that you should, in fact, evacuate to avoid damaging winds? And second, if damaging winds are anticipated, when will the first outer rainband arrive and begin making the safe evacuation of general aviation aircraft problematic? Understanding the behavior and dynamics of these outer rainbands is, therefore, crucial to answering the second question.

Theoretical modeling studies suggest the formation and evolution of rainbands can be understood in terms of potential vorticity (PV) dynamics (e.g., Guinn and Schubert, 1993). One rainband generation mechanism suggested by these studies is vortex merger. Specifically, if a high-PV vortex, representative of the inner circulation of the storm, interacts with pre-existing PV structures on the periphery of the circulation, PV structures that strongly resemble rainbands (i.e., band-like PV structures) will result.

This investigation, therefore, focuses on vortex merger as a possible mechanism for outer rainband development (i.e., our hypothesis is vortex merger does lead to the formation of outer rainbands in nature). Both an observational and modeling approach has been taken and is described in the following section.

2. METHOD

An overview of our approach is as follows. Cases of possible rainband formation and evolution through the vortex merger process were identified using PV analyses from the GFS model initialization and forecasts. These selected cases are then compared with the evolution of similar but idealized PV structures as forecast by a shallow-water model to confirm that vortex merger was likely taking place. We then compared the evolution of the PV structures observed in the GFS model data to satellite imagery to identify the presence of actual rainbands associated with the relevant PV band-like structures.

The specific GFS model grids used had 0.5^{o} resolution and were obtained for every 6 hour forecast cycle for the period 1 July through 31 October 2011. This was done using the NOMADS data access web page (http://nomads.ncdc.noaa.gov/data.php). This data was then read into the Integrated Data Viewer (IDV) visualization tool to calculate and view the evolution of PV at 700 mb for several tropical cyclone events in the tropical Atlantic, eastern Pacific, and western Pacific ocean basins. Both initial and 3-hour forecast grids were used giving us PV images every 3 hours.

By examining the evolution of PV for these events, as well as IR satellite imagery obtained from the GIBBS: ISCCP Global Browse System (http://www.ncdc.noaa.gov/gibbs/), three cases of apparent vortex merger were selected for modeling with a shallow-water model. These were Hurricane Irene in the Atlantic from 21 August at 12 UTC to 22 August at 06 UTC (note Irene was a strengthening tropical storm at this time), Hurricane Hilary in the eastern Pacific from 23 September at 12 UTC to 26 September at 12 UTC, and Typhoon Nesat in the western Pacific from 24 September at 06 UTC to 26 September at 00 UTC.

The shallow-water model that was used in this study is discussed in detail in Guinn and Schubert (1993). For each case, the model was initialized with an idealized distribution of PV approximating the PV distribution observed using the GFS model data (compare Figures 1 and 4, for example). The maximum value of the initial vorticity used in the shallow-water model was carefully chosen to produce similar wind speeds to those observed in the GFS data. The shallow-water model was then run for the same length of time as the selected storm, and the vortex merger event was observed. If, to some degree, the GFS simulation replicated the apparent vortex merger event in the idealized shallow-water model simulation, it strengthened the argument that vortex merger had, in fact, occurred in nature.

The satellite imagery used in this study was standard IR imagery obtained as described above and locally generated satellite images that used combined data from the visible, IR, and

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water vapor channels of the satellite. Examples of this locally produced imagery are shown in Figures 7 through 9. This latter type of imagery was developed to more easily view the deep, active convection that would be associated with a particular rainband.

3. SELECTED RESULTS

While we identified and studied three cases of vortex merger, we will only present detailed results for the case of Hurricane Irene in the Atlantic basin. This vortex merger event occurred as Irene was strengthening from a relatively weak tropical storm with maximum wind speeds of 45 knots to a stronger storm with sustained winds of 60 Knots. The time period examined was 21 August at 12 UTC to 22 August at 06 UTC.

Figure 1 shows the PV and wind structure at 700 hPa about the storm on 21 August at 12 UTC. The main high-PV vortex at the center of Irene's circulation is associated with an easterly wave-like structure (indicated by the black line) and has PV values greater than 2 PVU. Three weaker PV maxima surround this main vortex. One exists due east, is circled in red in the image, and is labeled 'A'. A second sits to the northwest, is circled in orange, and is labeled 'B'. The third is located south through southwest of the main vortex, is circled in yellow, and is labeled 'C'. Figures 2 and 3, presented to illustrate the evolution of the PV and wind fields during this event, present the same type of analyses as Figure 1 but are for the dates 21 August at 21 UTC and 22 August at 06 UTC, respectively.

Collectively these figures indicate that vortex merger did occur. Two of the three PV maxima surrounding the storm's main circulation seemingly evolve into band-like structures as they are entrained in to the storm. These were maxima 'B' and 'C'. One does not, however. This was maximum 'A'.

The details of this PV evolution are as follows. Maximum 'A', initially located due east of the main vortex, is embedded in strong southeasterly flow that extends from the east around to north of the storm (i.e., the northeastern portion of the domain). This strong flow advects "A' toward the northwest with 'A' never fully merging with the storm's inner circulation. Maximum "B", located to the northwest of the storm, sits in a region of relatively strong northeasterly flow that lies to the northwest of the axis of the easterly wave. This leads to an apparent deformation zone south of 'B,' towards which 'B' is advected. As 'B' interacts with this deformation zone, it is stretched northeast and southwest producing a rainband-like structure. Maximum 'C', located along the axis of the easterly wave with southerly flow to the east and northeasterly flow to the west, also seemingly experienced deformation; in this case, along a north-northeasterly, south-southwesterly axis. Maximum 'C' would also appear to be drawn into Irene's inner circulation forming a rainband-like PV structure.

The behavior of maxima 'B' and 'C' during this time period strongly suggests vortex merger is occurring and leading to possible rainband development. The shallow-water model results (Figs. 4-6) help confirm this. An 18 hour simulation was carried out consistent with the time period that Irene was observed. Results from the simulation are shown at initialization, 9 hours, and 18 hours thereby corresponding to the GFS analyses for 21 August at 12UTC and 21 UTC and 22 August at 06 UTC.

When comparing the results of the shallow-water model to the GFS analyses, we see the results are quite similar between the two. The PV maxima we have labeled 'B' and 'C' in the shallow-water model simulation behave in a very similar manner to the maxima we labeled 'B' and 'C' in the GFS analyses. They deform and are drawn toward the center of the storm. The maxima we labeled 'A' in the model simulation is advected towards the northwest, as it was in the GFS analyses, but in the case of the shallow-water simulation, it experiences a greater amount of deformation and entrainment into the storm vortex (i.e., it forms more of a band-like structure associated with the storm's inner circulation). The shallow-water model therefore confirms that some form of vortex merger was taking place with Irene.

After we compared the shallow-water model simulations to our GFS analyses, we then looked more closely at the relationship of the PV structure in the GFS analyses to actual rainbands. This was done using the satellite imagery presented in Figs. 7-9. These are images for 21 August at 12 UTC and 21 UTC and 22 August at 06 UTC; once again, consistent with the times of the GFS analyses. In this portion of the study, results provide less support to the hypothesis that vortex merger leads to actual rainband formation in nature. As can be seen when comparing the relevant PV analysis to the satellite imagery, actual rainband structures are not exactly coincident with the band-like PV structures. While high PV regions are somewhat related to areas of convection, the convection is not always organized into clear bands.

While not shown, results for Hurricane Hilary and Typhoon Nesat were similar to that of Irene. Vortex merger was apparent in the GFS analyses, and shallow-water model simulations supported the presence of vortex merger process during these events. However, when comparison was made to the satellite imagery, a strong relationship between the band-like PV structures and actual rainbands or distinct lines of convection, once again, was not evident.

4. SUMMARY AND CONCLUSIONS

Analyses of PV at 700 hPa during portions of three tropical cyclone events shows that a vortex merger-like process can occur leading to PV structures that strongly resemble rainbands. Idealized modeling of these events using a shallow-water model also resulted in band-like features forming consistent with the occurrence of the vortex merger process. When PV analyses were compared to satellite imagery, however, the relationship between the band-like PV structures and actual rainbands was not that strong.

One likely problem with this study was that the grid resolution of the data used to diagnose PV (i.e., 0.5°) was not sufficient to make adequate comparison to actual rainbands in nature (as viewed in satellite imagery, for example). Further study using higher resolution full-physics model data to diagnose PV and more clearly resolve "rainbands" in the PV field may be warranted (e.g., initialization and forecast grids from the WRF model could be used). PV vortex merger may still be a potential pathway to rainband formation, but the appropriate high resolution data set is needed for confirmation.

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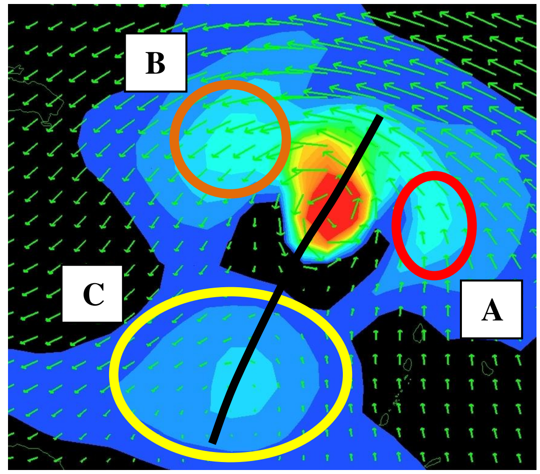

Figure 1. PV at 700 hPa contoured every .02 PVU in the range from .2 to 2 PVU and wind vectors for 21 August at 12 UTC.

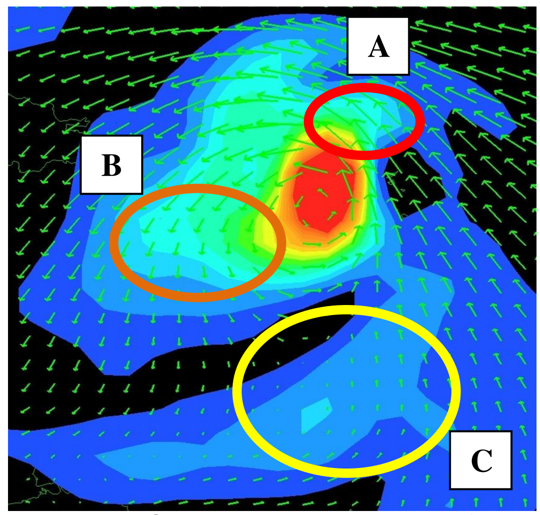

Figure 2. Same as Figure 1 except for 21 August at 21 UTC.

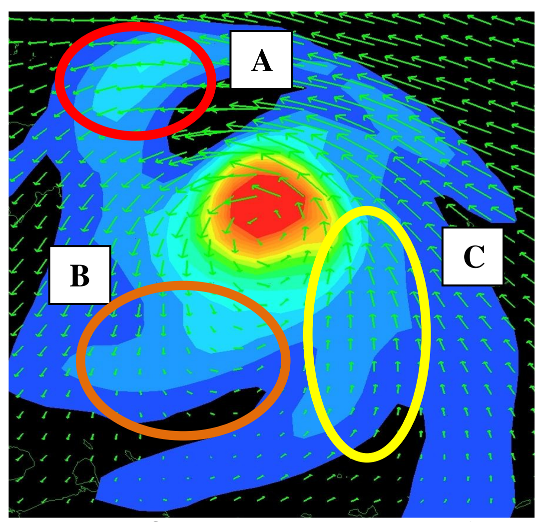

Figure 3. Same as Figure 1 except for 22 August at 06 UTC.

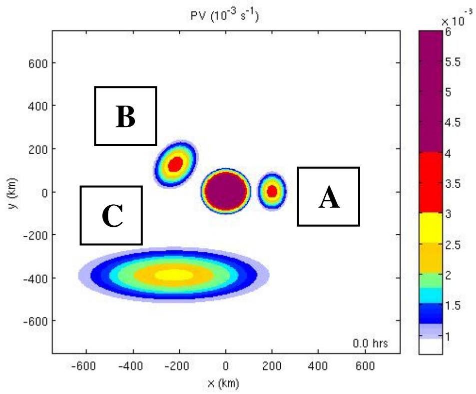

Figure 4. Initialization of PV (s^{-1}) for the 18 hour shallow water model simulation of hurricane Irene.

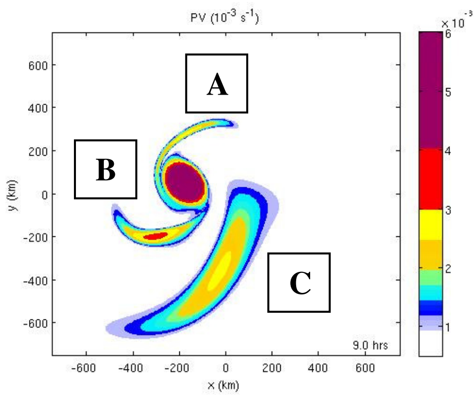

Figure 5. PV (s^{-1}) for the shallow water model simulation of hurricane Irene at 9 hours.

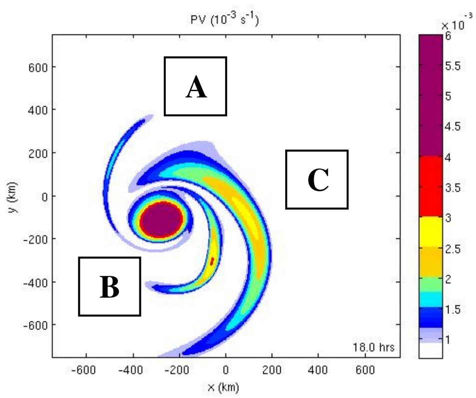

Figure 6. PV (s^{-1}) for the shallow water model simulation of hurricane Irene at 18 hours.

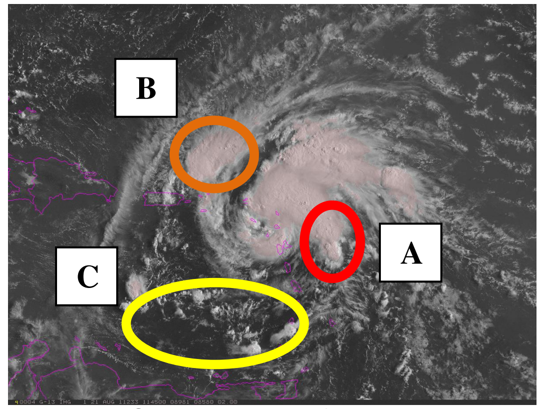

Figure 7. Satellite imagery for 21 August at 12 UTC.

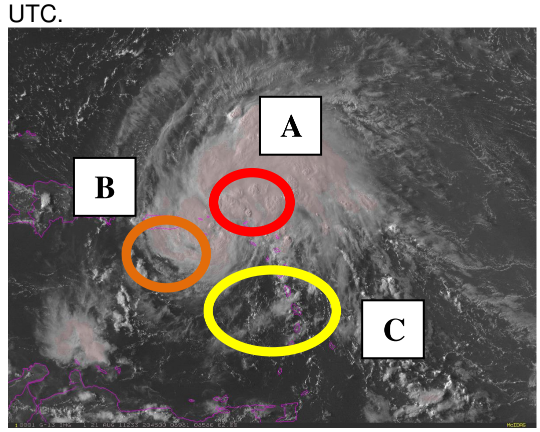

Figure 8. Satellite imagery for 21 August at 21 UTC.

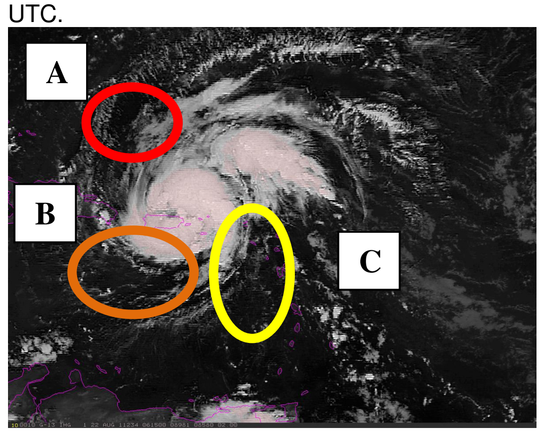

Figure 9. Satellite imagery for 21 August at 21 UTC.