11C.4 THE INFLUENCE OF TROPICAL CYCLONE OUTFLOW ON THE NORTHERN HEMISPHERE SUBTROPICAL AND TROPICAL GENERAL CIRCULATION

Ross A. Lazear* and Michael C. Morgan

University of Wisconsin – Madison
Madison, Wisconsin

1. INTRODUCTION

Throughout the lifetime of a tropical cyclone (TC), attention is primarily focused on the track and intensity of the TC's lower tropospheric cyclonic circulation (hereafter, LTC) as it is to this circulation that TC damage (wind, storm surge, and inland flooding) is directly attributed. From a potential vorticity (PV) perspective, this lower tropospheric circulation is associated with a cyclonic PV tower that extends from just above the surface to the upper troposphere. This PV tower is surmounted by a lens of anticyclonic PV in the upper troposphere (i.e., an elevated dynamic tropopause) that is a manifestation of PV redistribution associated with convective heating. This lens of locally anomalous anticyclonic PV defines the TC *outflow*. Situated in the divergent flow above the cyclonic PV tower, TC outflow tends to expand away from TC center during TC intensification (Rappin 2004). Wu and Kurihara (1996, hereafter WK) showed that after the hurricane's cyclonic PV anomaly weakens, the upper tropospheric negative PV anomaly associated with the outflow often lingers for several days.

While attention is typically focused on the TC's potentially damaging cyclonic circulation, the morphology and evolution of TC outflow is also of practical importance for a number of reasons. Prior to the demise of the LTC, the wind field attributed to the outflow can affect the vertical wind shear experienced by the LTC; if the outflow of the hurricane is asymmetric with respect to the hurricane center, vertical wind shear induced by the outflow's anticyclonic circulation will be stronger than if the outflow were symmetric. Similarly, upper tropospheric winds associated with an asymmetric outflow can also alter the steering flow of the LTC (WK).

An additional distinction between the LTC and the TC outflow is that the outflow has a spatial scale much larger than that of the hurricane's LTC, and as a consequence, can have long-lasting effects (an outflow "footprint") on the upper tropospheric large-scale circulation following the spin-down of the LTC. This outflow footprint can be advected by the upper tropospheric flow until gradual diabatic redistribution of the PV weakens the anomaly. Prior to the dissipation of the outflow PV anomaly, the height perturbations attributed to the anomaly can be realized as substantial anomalies in the climatology of the subtropics and middle latitudes. Hoskins et al. (1985) suggest that radiative cooling in the upper troposphere attenuates upper tropospheric low PV anomalies on time scales of about a week. Furthermore, if the outflow from a TC extends to a mid-latitude PV gradient, downstream Rossby waves may be excited. If the outflow PV differs from that of the ambient upper tropospheric PV, an outflow jet forms along the PV gradient.

In this presentation, we document the structure and evolution of outflow from Hurricanes Ophelia and Rita (2005) and attempt to identify both hurricanes' outflow "footprints" as well as their contribution to the upper tropospheric circulation using analyzed data, observations, and numerical simulations. Particular attention will be placed on the excitation, by the outflow of Ophelia, of a Rossby wave train downstream that appears to have created a favorable environment for development of Hurricane Rita.

The data used are described in Section 2, as well as an analysis of the case study. An outline for future work can be found in section 3.

2. CASE STUDY

a) Data

The analyzed data sets used in the following discussion are the National Centers for Environmental Prediction (NCEP) global tropospheric final analysis data, available from the National Center for Atmospheric Science Data Support Services as data set DS083.0.

b) Synoptic Overview

Hurricane Ophelia developed off the coast of southern Florida on 6 September 2005 and strengthened to category 1 hurricane status while moving northward along the southeast coast of the United States. By 1200 UTC 16 September (Fig. 1a), Ophelia had begun to weaken off the North Carolina coast. Ophelia's outflow, as seen on the dynamic tropopause as a region with tropopause potential temperatures[1] (hereafter, TPT) exceeding about 350 K, had expanded to encompass an area extending northeastward from the northeast Gulf of Mexico to Halifax, NS, and from the Ohio Valley to just east of Bermuda. At this time, the cyclonic portion of Hurricane Ophelia was depicted as a small area (approximately 300 km in diameter) of high lower tropospheric PV off of the North Carolina coast. A smaller area of TPT exceeding 370 K was also positioned downstream from the hurricane. Downstream from the large outflow-

*Corresponding author's address: Ross A. Lazear, 1225 W. Dayton St., Madison, WI 53706; email: ralazear@wisc.edu

[1] These tropopause analyses were constructed using the contour (fill) superposition method described by Morgan and Nielsen-Gammon (1998).

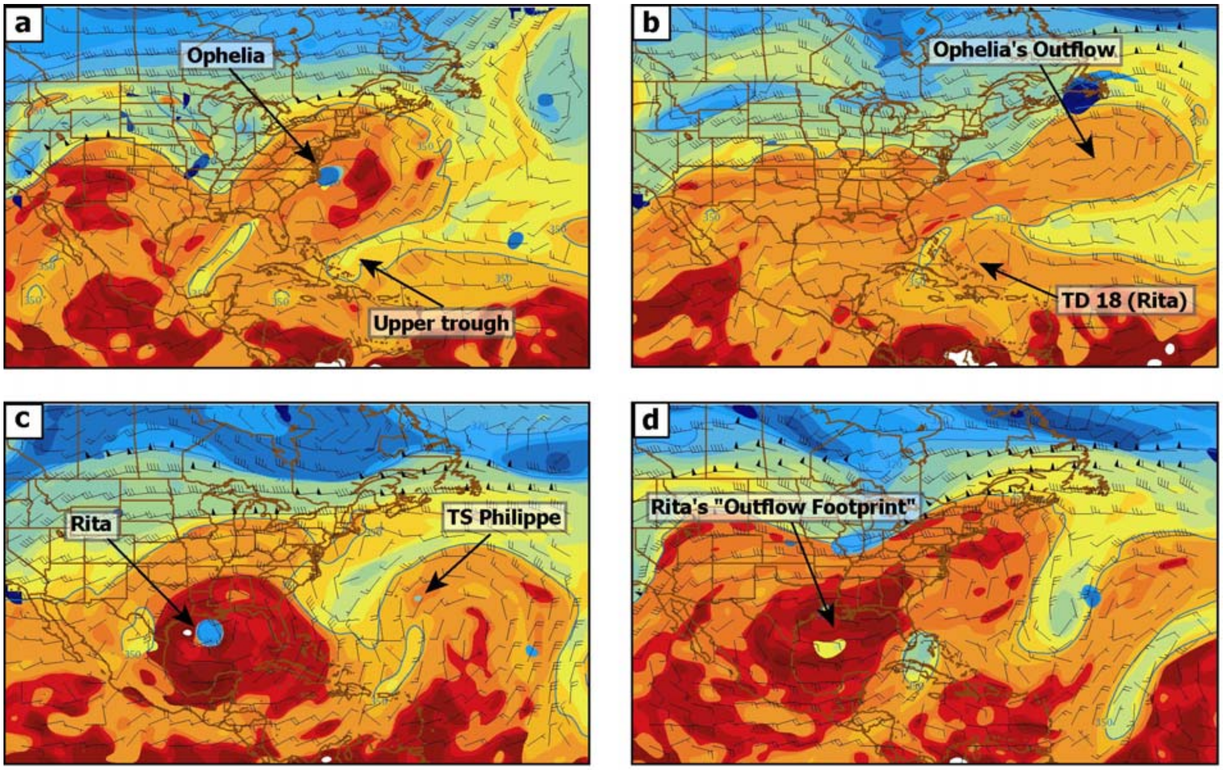

Figure 1. Isentropes (interval 5 K) and winds (ms^{-1}) on the dynamic tropopause (1.5 PVU surface) for a) 1200 UTC 16 September 2005, b) 1800 UTC 18 September 2005, c) 1200 UTC 23 September 2005, and d) 1800 UTC 26 September 2005.

induced anticyclonic circulation was a weak anticyclonically breaking trough, extending east-northeast from the Bahamas.

By 1800 UTC 18 September (Fig. 1b), Hurricane Ophelia had already transitioned into an extratropical storm, leaving behind a broad, elliptical upper tropospheric anticyclonic circulation over the northwest Atlantic. Meanwhile, a portion of the anticyclonically breaking trough had become cut off and was located over the Bahamas. Positioned in a favorable location for ascent downstream from this cut-off upper wave was Tropical Depression 18, a precursor to Hurricane Rita. On the tropopause, the only evidence for the nascent tropical storm was a region of locally higher TPT north of eastern Cuba and the island of Hispaniola.

At 1200 UTC 23 September (Fig. 1c), Hurricane Rita was a category 4 hurricane with its center positioned approximately 300 km south of Morgan City, LA. Unlike Hurricane Ophelia at its maximum intensity, Rita's outflow was associated with a very broad region (nearly 2500 km at its greatest diameter) of TPT over 370 K. Downstream of the outflow was an upper trough off the east coast of the United States. As had occurred with Hurricane Ophelia's outflow, this upper trough broke anticyclonically and became cut off by the northeastwardly expanding anticyclonic circulations associated with both Hurricanes Rita and Philippe (the latter located in the northwest Atlantic, also seen on the dynamic tropopause as a broad region of anticyclonic circulation).

As illustrated by WK, when the region of anomalously low PV associated with the outflow nears a mid-latitude upper tropospheric jet, it becomes stretched along the axis of the jet. This scenario occurred with Hurricane Rita after it made landfall and weakened over the south central United States. This southwest-northeast tilt of the anticyclonic region can be seen at 1800 UTC 26 September 2005 (Fig. 1d). Two days after hurricane Rita made landfall and its cyclonic PV tower eroded, the broad region of anomalously warm TPT (370 K) which was once associated with Rita's outflow remained over the southern United States and western Gulf of Mexico. Another piece of this circulation had been advected northeastward toward eastern Atlantic Canada. Over time, the area of relatively high TPT over the southern United States was gradually advected westward into the eastern Pacific, and eventually cooled diabatically (not shown). The upper tropospheric circulation in Fig. 1d also illustrates how the outflow "footprint" left over from tropical cyclones can drastically alter the circulation of the tropics and subtropics. From animations of the dynamic tropopause (not shown), it appears that the outflows from Hurricanes Rita and Philippe contributed to the amplification of downstream Rossby waves.

A time-height cross section of PV and relative humidity from Shreveport, LA (KSHV) is shown in Fig. 2. At approximately 0000 UTC 23 September, the PV in the 125-300 hPa layer decreases sharply, while the relative humidity in the layer increases to near

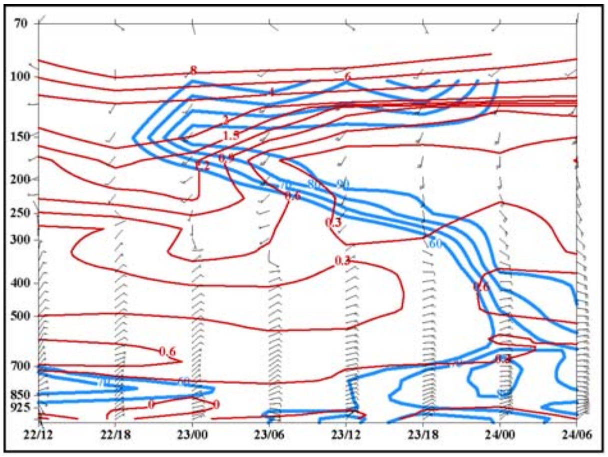

Figure 2. Time-height section of PV (red, interval 0.3 PVU less than 1.5 PVU; interval 2 PVU for 2 PVU and above) and relative humidity (blue, interval 10% above 60%) for Shreveport, LA (KSHV) from 1200 UTC 22 September 2005 through 0600 UTC 24 September 2005.

saturation. This time corresponds with the passage of the "outflow front" on the dynamic tropopause over Shreveport, LA (Fig.1c). The front is also characterized by a shift to stronger southerly winds within the outflow. The "lens" of low PV characterizing the outflow extends over a depth spanning from about 300 hPa to 125 hPa.

3. FUTURE WORK

To further characterize and define TC outflow, we propose to run a set of numerical simulations of Hurricane Rita: a control, "full physics" run and a "no latent heat" run to compare differences in the upper tropospheric circulation with and without the hurricane outflow. As in Shi et al. (1990), the simulations will also allow us to conduct trajectory analyses to identify the full horizontal and vertical extent of the outflow, and evaluate the Lagrangian tendencies of PV in the outflow layer following the demise of the LTC. Additionally, using piecewise PV inversion, we will quantify the magnitude of geopotential height perturbations attributed to the outflow's anomalously low PV.

4. REFERENCES

Hoskins, B., M. McIntyre, and, W. Robertson, On the use and significance of isentropic potential vorticity maps, *Quart. J. Roy. Meteor. Soc.*, **111**, 877-946.

Merrill, R. T., 1993: "Tropical Cyclone Structure" - Chapter 2, *Global Guide to Tropical Cyclone Forecasting*, WMO/TC-No. 560, Report No. TCP-31, World Meteorological Organization; Geneva, Switzerland.

Morgan, M., and J. Nielsen-Gammon, 1998: Using tropopause maps to diagnose midlatitude weather systems. *Mon. Wea. Rev.*, **126**, 2555-2579.

Rappin, E., 2004: The role of environmental inertial stability on tropical cyclone intensification. M.S. thesis, Dept. of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison.

Shi, J-J., S. W-J. Chang, and S. Raman, 1990: A numerical study of the outflow layer of tropical cyclones. *Mon. Wea. Rev.*, **118**, 2042-2055.

Wu, Chun-Chieh, and Y. Kurihara, 1996: A numerical study of the feedback mechanisms of hurricane–environment interaction on hurricane movement from the potential vorticity perspective, *J. Atmos. Sci.*, **53**, 2264–2282.

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