THE DYNAMIC RESPONSE OF THE HURRICANE WIND FIELD TO RAINBAND HEATING
PART II: COMPARISONS TO RAINEX OBSERVATIONS AND HIGH RESOLUTION SIMULATIONS

Yumin Moon* and David S. Nolan
Division of Meteorology and Physical Oceanography
Rosenstiel School of Marine and Atmospheric Science
University of Miami, Miami, FL

1. Introduction and Approach

Radar observations of spiral bands (e.g., Senn and Hiser, 1959; Atlast et al., 1963; Barnes et al., 1983, hereafter BZJM83; Powell 1990, hereafter P90; Hence and Houze, 2008, hereafter HH08) show that the upwind region of spiral bands is mostly convective while the downwind region is mostly stratiform with a transition between them. During the transition from the convective upwind region to the stratiform downwind region, they are usually observed to spiral radially inward in a cyclonic fashion. At the same time, their radial structure becomes wider but their vertical structure becomes shallower. BZJM83, P90, and HH08 also have examined the convective-scale circulation within spiral bands and found that there is an overturning secondary circulation in which an updraft is connected with low-level radial inflow and upper-level radial outflow; a mid-level radial inflow that enters spiral bands on their radially outward edge and descends to surface; and a secondary tangential wind maximum located radially outside of spiral bands. Schematic diagrams of the spiral band circulation by BZJM83 and HH08 are shown in Figs. 1 and 2, respectively.

While the accumulation of radar observations of spiral bands clearly has led to the better understanding of their precipitation and kinematic structures, the question of whether spiral bands have a positive or negative influence on the intensity of tropical cyclone remains unanswered. From a thermodynamical viewpoint, spiral bands have a negative impact on the intensity as they intercept some of the moist low-level radial inflow and replace it with cool, dry air originating from downdrafts within spiral bands (e.g., BZJM83; P90). However, they can also be viewed as barriers to protect the storm core from dry air intrusion and environmental wind shear (Kimball 2006). From a fluid dynamical viewpoint, spiral bands are characterized as bands of vorticity sheared with the flow and are believed to have a positive influence on the intensity as they transport angular momentum inward through the axisymmetrization process (e.g., Carr and Williams 1989; Montgomery and Kallenbach 1997; Nolan and Farrell 1999).

To understand the effects of spiral bands on a tropical cyclone, it is necessary to fully incorporate their dynamical and thermodynamical aspects. However, the dynamics and thermodynamics of the bands must be driven in large part by latent heat release in convection embedded within bands. In this study, it is assumed that spiral bands can be interpreted as rotating asymmetric heat sources superimposed on a balanced, axisymmetric vortex and that the effects of spiral bands on the hurricane wind field are caused by the response to diabatic heating in their convection.

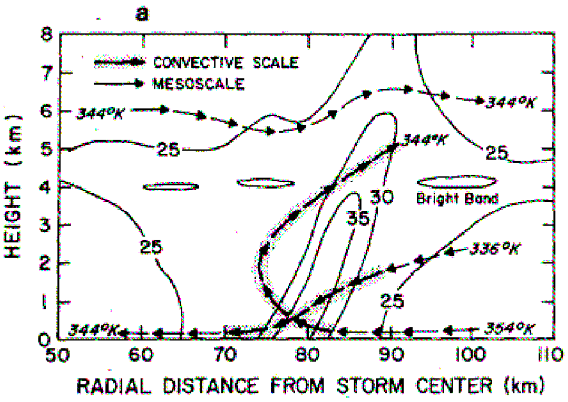

Fig. 1: A schematic diagram of the spiral band circulation, from Barnes et al. (1983).

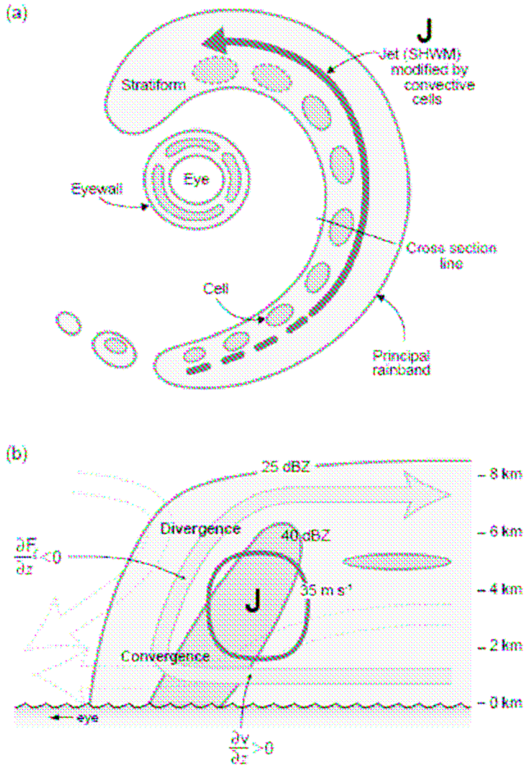

Fig. 2: (a) Horizontal and (b) vertical cross sections of an idealized schematic diagram of the spiral band circulation, from Hence and Houze (2008).

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*Corresponding author address: Yumin Moon
University of Miami, RSMAS/MPO
4600 Rickenbacker Causeway
Miami, FL 33149
ymoon@rsmas.miami.edu

A three-dimensional, nonhydrostatic, but linear model which is based on the vortex-anelastic equations (Hodyss and Nolan, 2007) is used to examine the validity of this approach. Nolan et al. (2007) provides a description of this model. Balanced, axisymmetric state vortices are modeled after real tropical cyclones, and an idealized spiral band heat source is designed to represent diabatic heating within spiral bands.

2. The response to a purely convective band

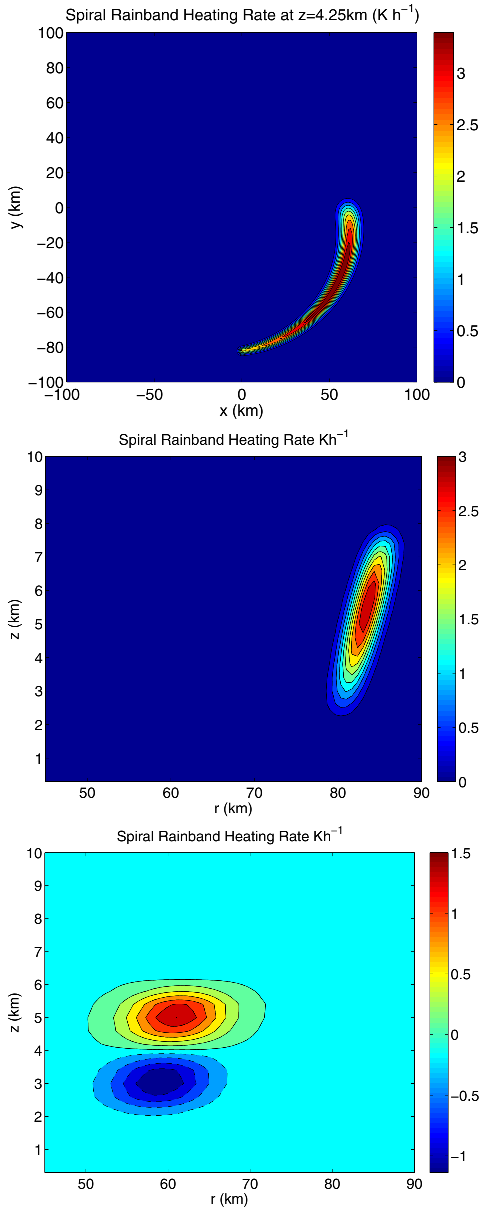
The diabatic heating profile of typical spiral bands have both convective and stratiform characteristics. Fig. 3 is an example of such spiral band heat sources that have mixed structures, which are in accordance with observations. Its upwind region is convective and its downwind region is stratiform, with a transition in between. It spirals radially inward from *r* =80 km to 60 km in a cyclonic direction. During the transition from convective to stratiform, it becomes wider and shallower. Fig. 4 shows vertical cross section of tangential wind field of the basic state vortex.

To better understand the combined response to these two heating profiles, it is necessary to first consider the effects of a spiral band heat source that is entirely convective or stratiform. First, the response to a purely convective heat source is examined first. A purely convective heat source is constructed in the same way as in the mixed heat source. The difference is that there is no upwind-to-downwind transition. Fig. 5 shows horizontal cross section of a purely convective heat source. Its vertical cross section is the same as in Fig. 3b. Here, the *response* refers to the sum of the asymmetric and symmetric responses to the purely asymmetric components (n = 1 to 4) and the symmetric response to the symmetric part (n = 0). In addition, all responses are rotated to the same location as the spiral band heat source in Fig. 3a.

The response to purely convective heat source shows that there is a sign of an accelerated tangential flow radially outward of the heat source (arrows in Fig. 6a), mostly at low levels. The existence of an overturning secondary circulation can also be found (arrows in Fig. 6b). However, all cross sections have the excitation of modal structure in the inner core region, and it is difficult to discern whether the response is mainly due to the spiral band heat source. Although it is necessary to examine the sum of asymmetric and symmetric responses to fully understand the response of the hurricane wind field to the heat source, the symmetric response to the azimuthal mean of the heat source can capture a large portion of the full response. Vertical cross section of the symmetric response (Fig. 7) clearly shows an overturning secondary circulation (arrows) and low-level tangential acceleration radially outside of the heat source. Note the absence of inner core mode.

3. The response to a purely stratiform band

Fig. 8 shows horizontal cross section of a purely stratiform heat source. The stratiform response shows that there is a clear sign of an accelerated tangential flow radially outward of the heat source (arrows in Fig. 9a), mostly at low levels. The existence of a mid level radial inflow descending to surface can also be found (arrows in Fig. 9b). This mid level radial inflow is shown more clearly in the symmetric response to the symmetric part of the stratiform band (arrows in Fig. 10). Note that inner core mode is still excited but to a lesser extent.


Spiral Rainband Heating Rate at z=4.25km (K h^{-1})

Spiral Rainband Heating Rate Kh^{-1}

Spiral Rainband Heating Rate Kh^{-1}

Fig. 3: (a) Horizontal cross section of an idealized mixed band heat source; (b) and (c) show vertical cross sections in the convective upwind and stratiform downwind regions, respectively.

4. The response to a mixed band

The response to a mixed band heat source has both convective and stratiform components. At low levels there is an accelerated tangential flow (arrows in Fig. 11a). At mid levels there seems to be a radial inflow that enters the band from its radially outward side and descends to surface (arrows in Fig. 11b). A weak sign of overturning secondary circulation can also be found (arrows in Fig. 11c).

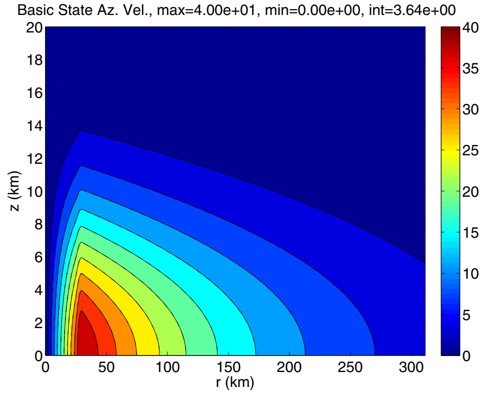


Fig. 4: Vertical cross section of tangential velocity field of the basic state vortex.

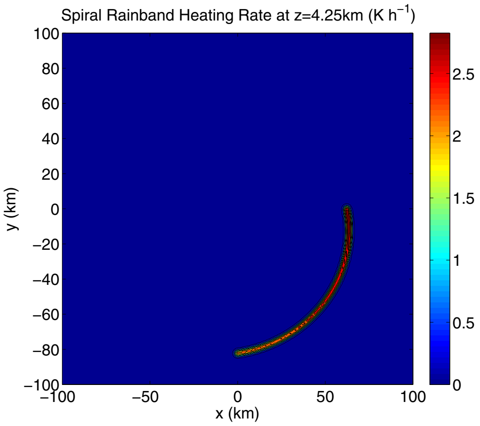


Fig. 5: Same as in Fig. 3a but for an idealized purely convective heat source.

5. Comparisons to observations

The response to the hurricane wind field to an idealized mixed spiral band heat source is able to recover most of the well-known features of the spiral band circulation: an overturning secondary circulation (i.e., low-level radial inflow, updraft located on the radially inward side of spiral bands, and upper-level radial outflow), a cyclonic tangential acceleration located radially outward of spiral bands, and a mid-level radial inflow that enters spiral bands on their radially outward side and descends to surface. The responses to purely convective and stratiform heat sources show that the overturning secondary circulation is mostly due to convective processes while the mid-level radial flow descending to surface is mostly due to stratiform processes. It seems both convective and stratiform processes contribute to secondary tangential wind maximum.

6. The response to a principal band heat source

Fig. 12 shows horizontal cross section of an idealized principal band heat source that has both convective and stratiform components with a smooth transition. It is twice as long as the mixed band heat source. Unlike the simulation of the mixed band heat source, it is prescribed to be stationary. The response is mostly similar to the response to a mixed band heat source, but the cyclonic tangential acceleration wraps around the entire vortex (arrows in Fig. 13).

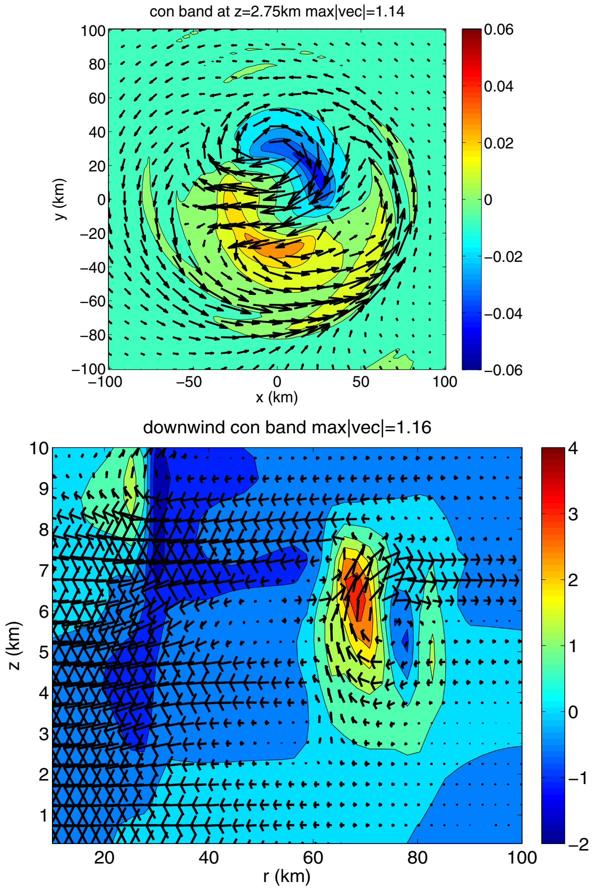


Fig. 6: (a) Horizontal cross section of the response to a purely convective heat source at *z* = 2.75 km; and (b) vertical cross section of the response to a purely convective heat source in the downwind region. Arrows and contours represent [u,v] and [w] fields in (a) but [u,w] and [v] fields in (b).

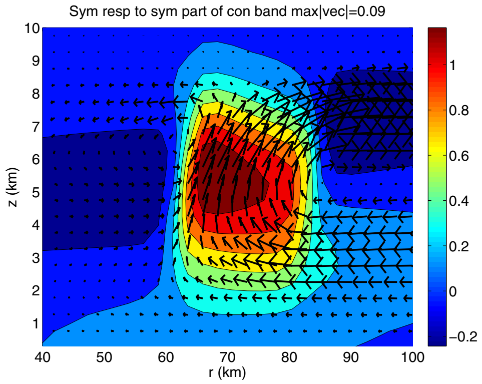


Fig. 7: Symmetric response to the azimuthal mean of a purely convective heat source. Arrows and contours represent [u,w] and [v] fields.

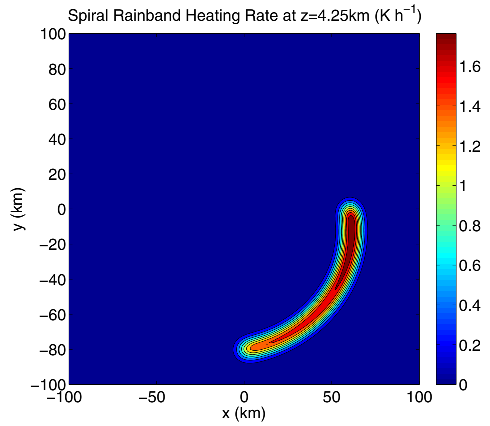


Fig. 8: Same as in Fig. 3a but for an idealized purely stratiform heat source.

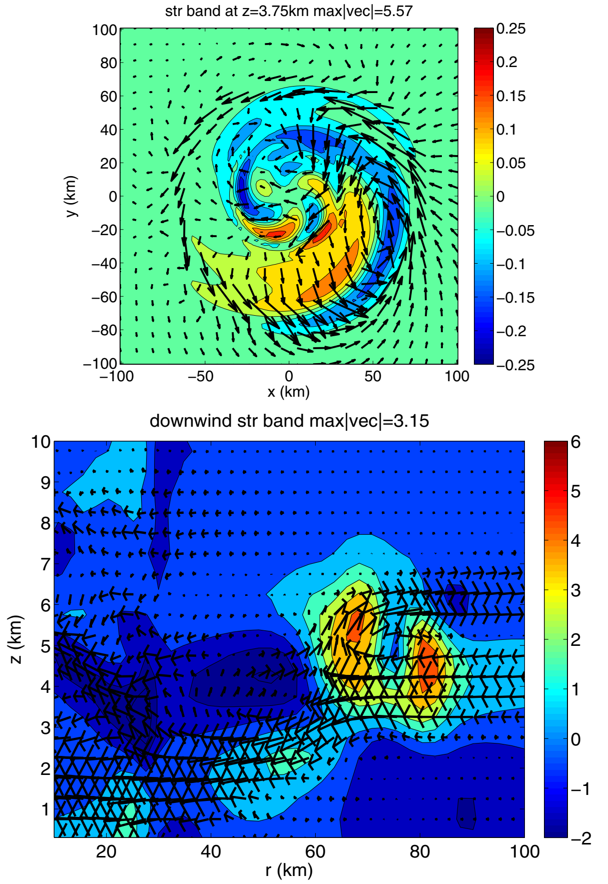


Fig. 9: Same as in Fig. 6, but for the response to a purely stratiform heat source; (a) is taken at z = 3.75 km

7. Comparisons to full-physics simulations

It is not difficult to find the response of the hurricane wind field to similar diabatic heat sources in full-physics numerical simulations. Fig. 14 is an example of a mostly convective diabatic heating (contours), and there is a clear sign of overturning secondary circulation (arrows). There is great resemblance between this and the response to a purely convective heat source.

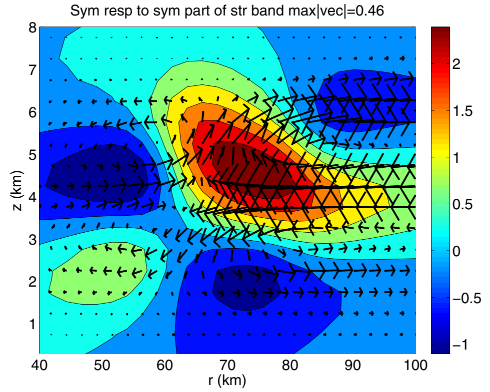


Fig. 10: Same as in Fig. 7, but for the response to a purely stratiform heat source.

8. Summary and Future Work

A large portion of the spiral band circulation was captured by simulating the response of the hurricane wind field to the diabatic heating field of spiral bands by using a simple linear model. Therefore, a large part of their dynamics and thermodynamics must be driven by the response to latent heat release within embedded convection. This approach is similar to that of Pandya and Durran (1996) in which the mesoscale circulation around squall lines was approximated by the direct response to steady thermal forcing that resembles the latent heat release in a convective leading line. Additional simulations will be performed to see whether the response to an idealized heat source is sensitive to any particular parameters. Preliminary results show that the results are insensitive to the radial structure of the basic state vortices. All simulations had the excitation of an inner core mode, and a method to reduce the influence of this modal structure will be explored.

A cyclonic tangential acceleration was simulated to encircle the entire vortex (Fig. 13) in simulating the response to a principal band heat source. This may suggest a possible triggering mechanism for secondary eyewall formation, which is not well understood. The role of spiral bands on the formation of secondary eyewall could be explored in the future, by using the linear model, a full-physics numerical model (WRF), or even a new framework which simplifies the problem but retains the essential processes.

A natural next step of this work is to extend this approach to different frameworks by gradually increasing the complexity of numerical models. The simple linear model and the full-physics numerical model represent the two extreme ends of numerical methods. Simplifications of the linear model used in this study can be removed one at a time, until a balance is reached between retaining essential processes and computing efficiency and cost.

Acknowledgements

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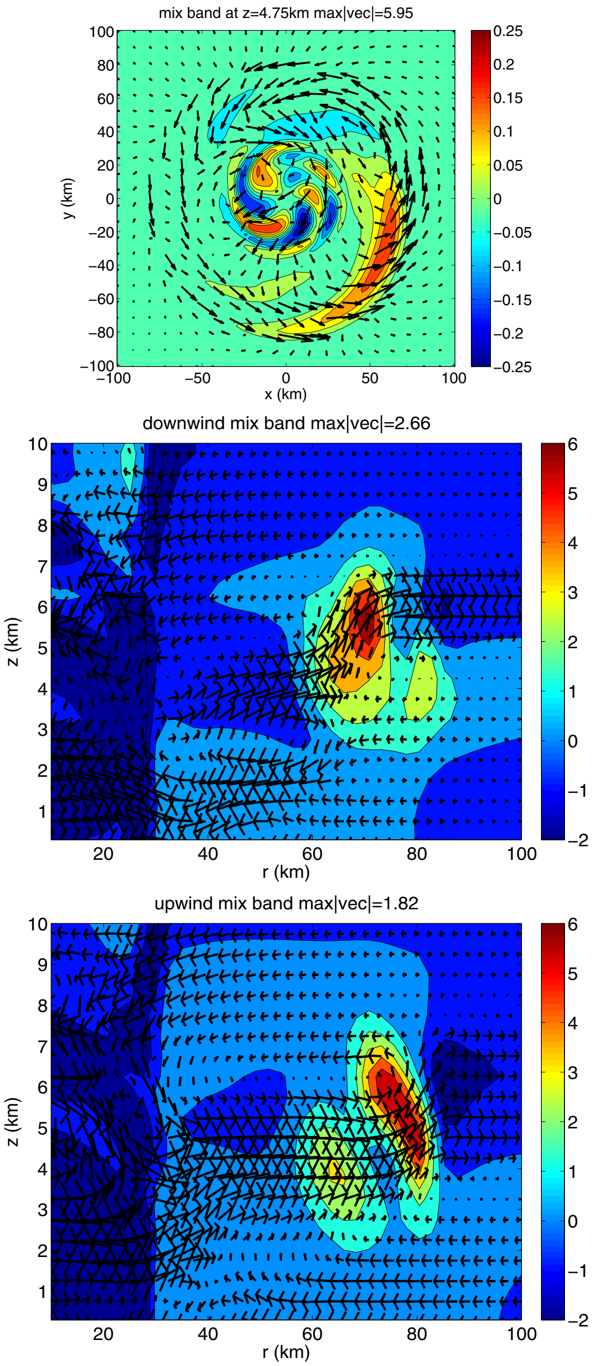

Fig. 11: same as in Fig. 6, but for the response to a mixed band. (a) is at z = 4.75 km, and (b) and (c) are taken in the downwind and upwind regions

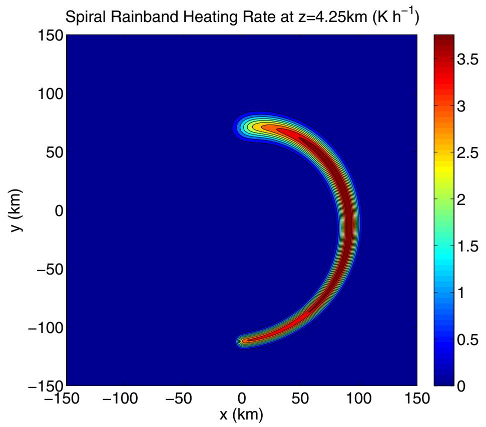

Fig. 12: Horizontal cross section of an idealized mixed principal band heat source.

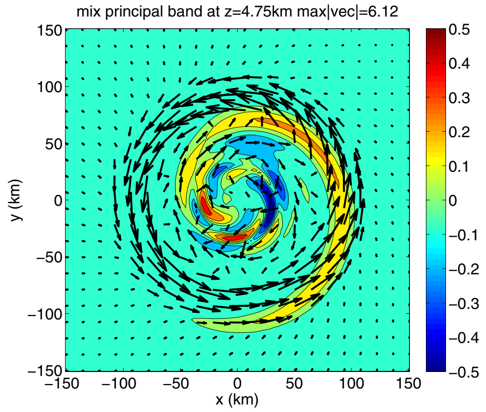

Fig. 13: Horizontal cross section of the response to a principal band heat source at *z* = 4.75 km. Arrows and contours represent [u,v] and [w] fields.

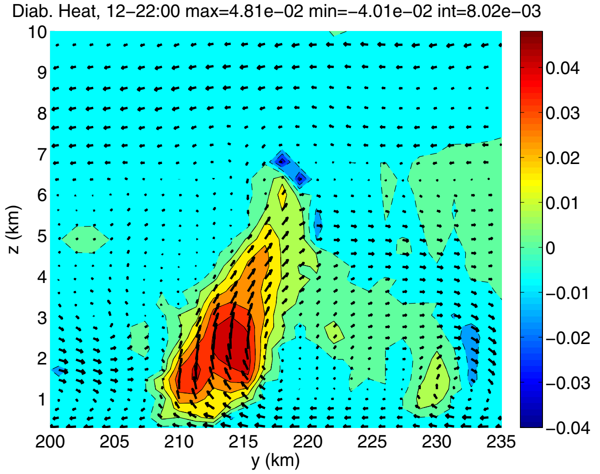

Fig. 14: Diabatic heating (contours) and [u,w] (arrows) seen in a full-physics WRF simulation of Hurricane Isabel (2003).

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