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ON THE SENSITIVITY OF TC INTENSIFICATION UNDER UPPER-LEVEL TROUGH FORCING

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1. INTRODUCTION

Issues to accurately predict tropical cyclone (TC) intensification using NWP models remain, stressing out the need to unravel or clarify some of the mechanisms leading to TC spinup, and/or better resolve multiscale processes in prediction models; indeed, both large-scale (e.g., Molinari et al. 1995, 1998; Hanley et al. 2001; Davidson et al. 2008) and vortex-scale (e.g., Emanuel 1986; Willoughby et al. 1982; Montgomery and Kallenbach 1997) processes have been demonstrated to control rapid intensification (RI), defined in the North Atlantic by an increase of the maximum sustained surface winds above 30 kt (15.4 m s^{-1}) in the course of 24 hours (Kaplan and DeMaria 2003).

Understanding TC intensity changes under upper-level trough forcing, in particular, remains one of the strongest challenges of operational forecasting. The various perturbations of the large-scale environment induced by a trough have already been documented, together with their possible impact on storm intensity: significant vertical wind shear (usually detrimental, Kaplan and DeMaria 2003), increased upper-level divergence and enhanced outflow poleward of the storm (beneficial, Ritchie and Elsberry 2007), as well as cyclonic eddy angular momentum import (Molinari et al. 1995) and cyclonic potential vorticity (PV) advection toward the TC core, beneficial below the level of the outflow anticyclone ("PV superposition principle", Molinari et al. 1998). However, to help forecasters tackle the "bad trough/good trough" (Hanley et al. 2001) issue, further investigation is needed to clarify the physical and dynamical processes involved in TC-trough interactions and accurately predict the systematic impact of an upper-level trough on TC intensity.

As Molinari et al. (1998) concluded: "A great need exists for systematic study of hurricane-trough interactions with a hierarchy of numerical models that isolate the various mechanisms and for observation of the upper troposphere during such interactions." The present study attempts to address this request by examining the sensitivity of TC intensification in the presence of a nearby trough. Relevant questions include: Why can some TCs intensify in moderate to high shear conditions while others decay? Are the initial relative positions and intensities of the trough and the TC important in favoring a good trough interaction? What is the dynamic impact of an outside upper to midlevel PV anomaly in vortex intensification?

2. DATA AND TOOLS

Many observational studies and numerical modeling have documented TC-trough interaction. Kimball and Evans (2002) in particular ran numerical simulations in an idealized framework to modify the intensity and size or depth of a cold core upper-level low approaching a same initial vortex. Shapiro and Möller (2005) used piecewise PV inversion to modify the trough approaching a real hurricane and quantify its contribution to storm intensification. The idea now is to a use a real case of TC-trough interaction and run sensitivity experiments in which only the initial position and intensity of the TC are modified, leaving the trough untouched.

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a. *TC Dora*

TC Dora (2007) is an interesting case to study TC-trough interaction. Its deepening occurred in the southwest Indian ocean under hardly conducive conditions: ambient wind shear was large (above $9\,\mathrm{m\,s^{-1}}$ during 36 hours, peaking at $12\,\mathrm{m\,s^{-1}}$), and ocean heat content was below the $50\,\mathrm{kJ\,cm^{-2}}$ threshold that has been shown to promote high rates of intensity change. Rapid intensification occurred between 1800 UTC 31 January and 0000 UTC 3 February with a 50 hPa pressure fall from 975 hPa (see Fig. 1 of Leroux et al. 2013). From late 1 to early 2 February, the intensification was temporarily slowed down by an ERC "eyewall replacement cycle" (ERC, Willoughby et al. 1982) clearly identified on passive microwave imagery.

b. *The reference experiment*

A control run (hereafter called "reference experiment") of TC Dora was previously examined by Leroux et al. (2013). This 60-h forecast, starting at 0600 UTC 31 January 2007 (12 hours prior to the onset of RI), was carried out using the limited-area model Aladin-Reunion in its 2011 operational version (domain shown in Fig. 1, hydrostatic, 70 vertical levels, 8-km horizontal resolution, cf. Montroty et al. 2008). The forecast was initialized and coupled with ECMWF global analyses, and Aladin's 3D-Var assimilation of cyclone wind bogus was used to get a realistic vortex structure at the basetime of the forecast. Fig. 1 indicates that Dora was approached by an upper-level trough associated with a planetary Rossby wave train originating from the mid-latitudes. A high negative (cyclonic) PV anomaly associated with a cutoff cyclone formed during the isentropic equatorward advection of stratospheric air into the troposphere; It is located some 12 degrees southeast of Dora's center at the basetime of the forecast (Fig. 1).

In the reference simulation, the model captured the PV interaction as well as the two periods of RI (see Fig. 4 of Leroux et al. 2013). The main mechanisms identified for vortex intensification were PV superposition between about 33 and 40 h, followed by secondary eyewall formation induced by eddy angular momentum flux convergence, eddy PV fluxes, and vertical velocity forcing from the trough.

c. *Sensitivity tests*

An ensemble of 98 other experiments was run with the same numerical setup as the reference experiment. Using Aladin's bogus routine, the storm was moved 1, 2, 3 or 4 degrees away from the best track position in 8 different quadrants, as illustrated in Fig. 1 (red dots). 1 degree is realistic and close to an operational analysis error; 4 degrees is approximately one third of the initial distance separating Dora from the cutoff cyclone. Also, some 10 hPa difference being within the range of initial intensity error from observations or model analyses, three values were tested to initialize the vortex central pressure: 975 hPa (the best track value used in the reference experiment), as well as 990 and 960 hPa. The latter were experienced by the storm at other times of its life cycle, and therefore chosen in order to constrain the bogussed vortex with realistic values of RMW and MSLP pressure (obtained from the best track data).

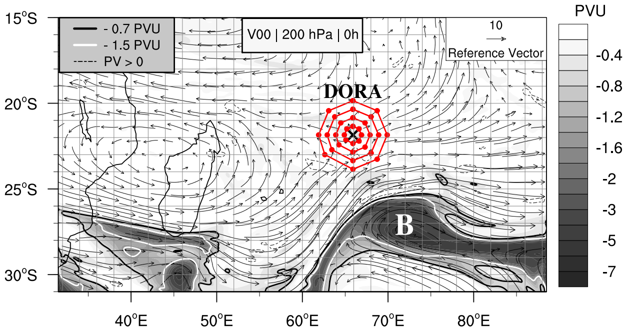

FIG. 1. Wind vectors (arrows) and PV field (PVU; negative, shaded with -0.7 PVU and -1.5 PVU contours; positive, 0.2 PVU and 1 PVU dotted contours) at 200 hPa at the initial time of the reference simulation. A cross indicates Dora's best track center. Red dots delineate the various initial vortex positions in the sensitivity experiments. Label "B" indicates the coherent structure (cutoff low) approaching TC Dora.

3. RESULTS

Weaker initial vortices systematically deviate to the east due to a smaller vertical extension of the vortex, lowering the depth of the steering flow that affects the storm track. Therefore, we will focus on the other intensity experiments, whose tracks are similar to that of the reference experiment with a general movement of the vortex to the south, then southeast, before veering to the south-southwest. To stay in realistic conditions, all simulations are initialized with the same operational sea surface temperature (SST) field (not shown). This field is not uniform: depending on its track, a vortex will move over warmer or colder SSTs than in the reference experiment, which will be quantified below.

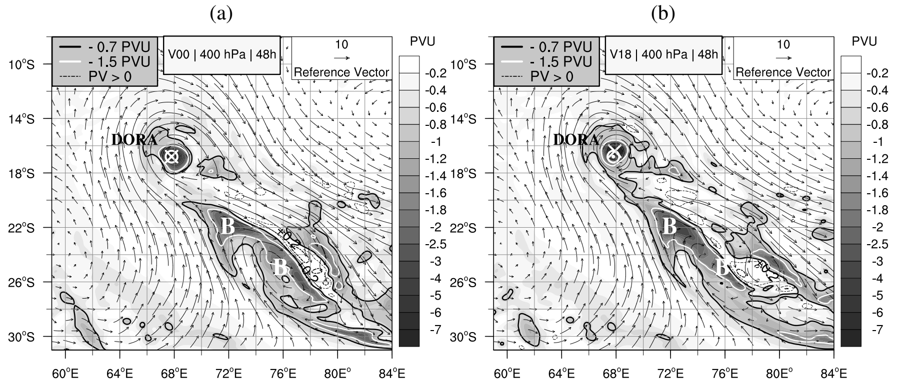

FIG. 2. As in Fig. 1 but at level 400 hPa after 48 hours of model integration for (left) the reference simulation and (right) a stronger initial vortex positioned at the same initial location. A cross (resp. circle) indicates the vortex predicted center in the simulation (resp. in the reference experiment).

a. *Central experiments*

The evolution of the predicted pressure along the 60-h forecast shows that a stronger initial vortex placed in the same location as Dora has a greater intensification rate after 36 hours (not shown). With a track almost identical to that of the reference experiment, and less than 0.05° C SST difference on average over a 300-km radius area and over the 60-h period, this intensification is most likely related to a favored interaction of the two cyclonic PV anomalies in the 500-300 hPa layer. At 400 hPa (Fig. 2), cyclonic PV advection from the trough into the TC core begins at 33 h, like in the reference experiment, but lasts longer (at least 8 more hours).

b. *975-hPa experiments*

To see how environmental parameters evolve with initial vortex position for all quadrants and distances, area and time averages are computed over the 60-h period of the forecast. Fig. 3 shows PV values averaged over a 200-800-km annulus region surrounding the storm predicted center, and over a 335-350-K layer to take into account the vertical extension of the PV anomaly approaching Dora. The x-axis gives the initial distance from the best track center from 1 to 4 degrees and the 8 quadrants are plotted with different colors, a grey color corresponding to the reference experiment (best track position). Results show, in most quadrants, a quasi-linear evolution of the PV with the initial distance from the storm: such parameter is therefore a good indication of the trough proximity. Secondly, the storm is surrounded by more cyclonic potential vorticity when it is initially moved to the south, southeast, southwest, and eastern quadrants to a lesser extent, which is summarized in Fig. 4 (red dots).

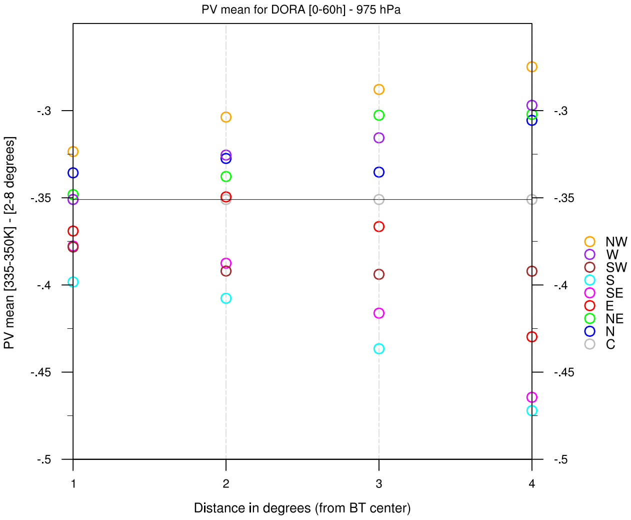

FIG. 3. Mean PV values averaged over a 60-h period, a 335-350-K layer and a 200-800 annulus region surrounding the storm predited center, for experiments initialized with a 975 hPa central pressure.

Briefly, Fig. 4 summarizes the favorable (red) and unfavorable (blue) quadrants for the most important large-scale parameters influencing TC intensity. SSTs are colder in the south, southeastern and eastern quadrants (up to 0.35°C) which is consistent with the latitudinal gradient of SSTs and may be observed in most TC-trough interaction cases in the southern hemisphere. Divergence increases at 200 hPa when the vortex is moved towards the south, southeast, east and northeast, while vortices displaced further north, southwest and south experience less vertical wind shear from a trough originally located in the southeastern quadrant of the vortex. Note that both the divergence and shear are conducive to TC intensification when the vortex is initially moved to the south. It is important to stress the fact that the shear and the divergence, both computed over a 200-800 annulus region, do not systematically evolve in the same way: in most cases, i.e. in most quadrants here, when the shear increases, the divergence increases (not shown). However, in the case of a cutoff low originally located southeast of the storm, we notice that, when the vortex is moved to the south, the shear abates while the divergence increases compared to the reference experiment; when moved to the west instead, the shear amplifies and the divergence decreases (except for an initial 1-degree distance).

Pressure forecasts indicate that no vortex initialized at 975 hPa intensifies more than the reference experiment, for an initial distance greater than one degree, albeit higher SSTs in some quadrants (not shown), or favorable shear and divergence conditions in the southern quadrant. This suggests that the trough interaction has a major role to play in storm intensification. However, after 60 hours, 4 vortices initially displaced by one degree are deeper than the reference experiment, due to a greater intensification rate after 36 h: the one shifted to the northwest, with the help of higher SSTs, and all the 3 vortices that benefit from lower SSTs in the south, southeast and eastern quadrants. The southeastern quadrant in particular deepens by more than 10 hPa. Once again, this result seems correlated with a longer (at least 14 more hours) and greater PV superposition at 400 hPa when the TC is initially displaced 1 degree in the direction of the cutoff low.

4. CONCLUSION

Diagnostics confirm the importance of the relative positions and strength of a TC and a cutoff cyclone interacting together to promote TC intensification. In the case of TC Dora, when the vortex is initially stronger and located at the best track position, the merging of the two cyclonic PV anomalies associated with the trough and the TC is favored at midlevels (330 K, or about 400 hPa) which helps strengthening the TC inner-core even more. It also occurs for a vortex initially as strong as Dora, positioned one degree closer to the cutoff low, originally located 12 degrees southeast: it intensifies more after 36 hours from longer PV advection into the TC core, albeit colder SSTs.

Another interesting aspect is that the southern quadrant of a TC approached by an upper-level low located to the southeast has favorable conditions in terms of divergence, shear and mean cyclonic potential vorticity. In the context of TC-trough interaction, it was shown that the divergence and the shear do not necessarily evolve in the same way. They are asymmetric processes that we try to estimate using symmetric averaged quantities. This might be part of our difficulty to forecast good trough/bad trough interactions in a systematic way.

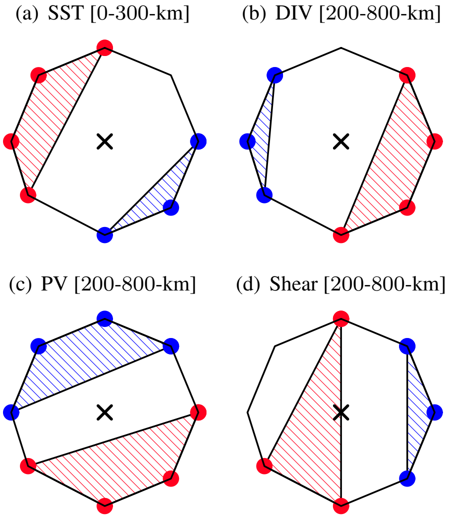

FIG. 4. Systematic favorable (red) and unfavorable (blue) quadrants for storm intensification at each initial distance, in the case of middle intensity experiments. Quadrants are left blank if favorability varies among initial distances. 4 distinct large-scale parameters are examined: (a) the SST, (b) the divergence at 200 hPa (DIV), (c) the potential vorticity averaged over a 335-350-K layer (PV), and (d) the shear computed between 200 and 850 hPa (Shear). Values are also averaged over the 60-h forecast and over a 200-800-km annulus region surrounding the storm predicted center, except for the SST averaged over a 300-km radius area.

Future work is planned to compute PV budgets and Eliassen-Palm flux diagrams for several interesting experiments and see how the processes identified in the reference experiment (Leroux et al. 2013) are modified. Is it possible to elaborate a conceptual model for TC-trough interaction?

REFERENCES

Davidson, N. E., C. M. Nguyen, and M. Reeder, 2008: Downstream development during the rapid intensification of hurricanes Opal and Katrina: the distant trough interaction problem. *28th Conf. on*

Hurricanes and Tropical Meteorology, Orlando, FL, CD-ROM, 9B.4.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585–604.

Hanley, D., J. Molinari, and D. Keyser, 2001: A compositive study of the interactions between tropical cyclones and upper-tropospheric troughs. *Mon. Wea. Rev.*, **129**, 2570–2584.

Kaplan, J. and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Wea. Forecast.*, **18**, 1093–1108.

Kimball, S. K. and J. L. Evans, 2002: Idealized numerical simulations of hurricane-trough interaction. *Mon. Wea. Rev.*, **130**, 2210–2227.

Leroux, M.-D., M. Plu, D. Barbary, F. Roux, and P. Arbogast, 2013: Dynamical and physical processes leading to tropical cyclone intensification under upper-level trough forcing. *J. Atmos. Sci.*, **70**, 2547–2565.

Molinari, J., S. Skubis, and D. Vollaro, 1995: External influences on hurricane intensity. Part III: Potential vorticity structure. *J. Atmos. Sci.*, **52**, 3593–3606.

Molinari, J., S. Skubis, D. Vollaro, F. Alsheimer, and H. E. Willoughby, 1998: Potential vorticity analysis of tropical cyclone intensification. **55**, 2632–2644.

Montgomery, M. T. and R. J. Kallenbach, 1997: A theory of vortex Rossby waves and its application to spiral bands and intensity changes in hurricanes. *Quart. J. Roy. Meteor. Soc.*, **123**, 435–465.

Montroty, R., F. Rabier, S. Westrelin, G. Faure, and N. Viltard, 2008: Impact of wind bogus and cloud- and rain- affected SSM/I data on tropical cyclone analyses and forecasts. *Quart. J. Roy. Meteor. Soc.*, **134**, 1673–1699.

Ritchie, E. A. and R. L. Elsberry, 2007: Simulations of the extratropical transition of tropical cyclones: Phasing between the upper-level trough and tropical systems. *Mon. Wea. Rev.*, **135**, 862–876.

Shapiro, L. J. and D. Möller, 2005: Influence of atmospheric asymmetries on the intensification of GFDL model forecast hurricanes. *Mon. Wea. Rev.*, **133**, 2860–2875.

Willoughby, H. E., J. A. Clos, and M. G. Shoreibah, 1982: Concentric eyewalls, secondary wind maxima, and the evolution of the hurricane vortex. *J. Atmos. Sci.*, **39**, 395–411.