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DOWNSTREAM DEVELOPMENT DURING THE RAPID INTENSIFICATION OF HURRICANES OPAL AND KATRINA: THE DISTANT TROUGH INTERACTION PROBLEM

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1. Introduction

Environmental interaction during Rapid Intensification (RI) of hurricanes has been the subject of numerous studies. A history of this work is described in Hanley et al. (2001), hereafter HMK01. They have made a comprehensive study of upper trough interactions and described 4 categories of interaction. These include (1) Favorable Superposition (FS), (2) Unfavorable Superposition (US), (3) Favorable Distant Interaction (FDI), and (4) Unfavorable Distant Interaction (UDI). HMK01 note that Categories 3 and 4 are rather similar and suggest that a subtle difference in wind shear is the main distinguishing feature. The terminology "good trough – bad trough" was adopted to describe troughs associated with intensification and those that were not.

We then ask the question: Why might the shear and the upper ridge structure be different in the FDI and UDI composites? We propose that, although the latent heat release within the intensifying storm is a contributor the differences can be linked to the presence or absence of a Downstream Development (DD) event, with large-amplitude, long waves passing over and to the north of the storm. Such downstream events could easily change the environmental wind shear affecting the storm and influence the extended ridge and outflow structure noted by HMK01.

Hurricane Opal is one of the most intensely studied storms ever, but no consensus has been reached on the mechanisms of the RI (Shapiro and Moller, 2003, and the references contained therein). Essentially three schools of thought exist: 1. Based on diagnostics from objective analyses, Bosart et al. (2000) suggest the intensification could be linked to a trough interaction. 2. Based on diagnostics from a skilful GFDL 15km-resolution forecast, Persing et al. (2002), Moller and Shapiro (2002) and Shapiro and Moller (2003) suggest that there was limited or no interaction although we note here that the interaction may have already commenced at the base time of the GFDL forecast. 3. Based on the very likely influence of a Warm Core Ocean Eddy (WCE) which Opal passed over during its intensification, Shay et al. (2002) suggested that this was a significant determinant of the RI. Our numerical experiments suggest (not illustrated here) that #3 was almost certainly true, but we also propose that the environment evolved in such a way as to enable the storm to tap into this energy source.

We will show that a downstream event occurred during the RI of Opal and that favorable environmental conditions had begun to develop from 0000UTC 3 October, approximately *18 hours before RI commenced.* Further we will provide evidence that there *was* an environmental interaction during Opal's RI, but it was not necessarily associated with the approaching upper trough, but with the group propagation of a long, large-amplitude Rossby wave over the top of the storm.

HMK01 indicate that Opal belongs to the FDI category. Our analysis suggests that Katrina may also belong to this group, although the large-scale structures are a little different. So the aim of the current study is to use Opal to (a) illustrate that it had large-amplitude, long waves develop as part of a DD event in its near vicinity during rapid intensification, and (b) explore how the DD may have changed the storm's environment to a favorable setting for RI. For brevity we will focus here on Opal. Very similar processes seem to have occurred for Katrina (e.g., McTaggart-Cowan et al., 2007).

2. Observational Analysis during the Rapid Intensification of Hurricane Opal

Figure 1 shows for Opal and based upon ERA40 analyses, ribbons of 200 hPa Potential Vorticity (PV) with values between 1.0 and 3.0 PV units. The evolution of PV clearly shows the DD with the first major trough-ridge structure developing far to the west on 1 October, with successive troughs and ridges developing eastward and equatorward. The ellipse highlights the leading trough-ridge amplification and the eastward group propagation. The ellipse moves faster than the individual troughs and ridges and is indicative of the group propagation of a planetary Rossby wave. The event propagates southeastward at approximately 23 ms^{-1}, the group speed (Cg) of the wave. The actual synoptic-scale troughs and ridges are slow-moving with phase speed,

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Cp, of approximately 4 ms^{-1}. Note that the waves are long with large-amplitude. Their zonal and meridional wavelengths (Lx, Ly) are approximately 6000 km and 4000 km.

Figure 2 illustrates the troughs and ridges, marked with 'T' and 'R' on the hovmoller diagram, which developed eastward in time, with a major ridge amplifying near Gulf longitudes (280^0E) at the time of Opal's RI. Note that because of the southwest – northeast orientation of the ridge the amplification at this latitude occurs east of Opal's RI location. The zonal wavelength is approximately 6000 km, and indicative of the large zonal scale of the wave.

It is possible to show theoretically using barotropic dynamics that for large-amplitude, long waves (small zonal and meridional wave numbers, k and l), the phase speed of waves, Cp, is small and the difference (Cg – Cp) is large. If β_* , the meridional gradient of absolute vorticity, also increases – a situation associated with jet structures – then Cp will decrease still further. In this situation the amplification eastward of troughs and ridges (Cg >> 0) provides the possibility of enhancing the upper level ridge over the storm and either reducing the wind shear or prolonging the period of low wind shear. In this case, since Cp is small and even negative, the high wind shear region associated with the near-stationary upstream trough does not inhibit the intensification, or at least delays the interaction of the storm with the high wind shear region of the trough. If of course the trough was mobile (Cp >>0), the storm's intensity would be influenced by increasing wind shear much earlier.

3. Diagnosis of Environmental Flow Changes

Analysis of the observed and theoretical behavior of Rossby waves suggests a link between downstream events and rapid intensification. To understand how such events may alter the environment of storms, beyond just reducing the wind shear, methods have been devised to isolate the environment from the storm.

Partitioning problems arise when studying the influence of environmental changes on TC behavior. It is difficult to separate the environmental evolution from the PV dilution induced by the storm.

To isolate the environment, at least to a first approximation, we have designed a hierarchy of numerical simulations that can be used to provide clues on how the environment would have evolved without the presence of the storm and its embedded convection. The hierarchy ranges from high-resolution, full physics forecasts with Vortex Specification and Diabatic Nudging Initialization (DNI) (Davidson and Weber, 2000) through to coarse-resolution, dry simulations with the analysed vortex removed. The method of vortex removal is described in Davidson and Weber (2000). For brevity and to highlight just the large-scale processes in action, we will only show coarse-resolution simulations here. The domain covers the large region from 40^0S to 65^0N, and 170^0W to 20^0W.

Note that the DD events are large-scale and so we have chosen a very coarse resolution (1.5^0 latitude-longitude and 29 levels) to represent only the synoptic and larger scales in order to isolate the environment. This limitation can cause a slight degradation of the forecast in terms of the phase and amplitude of weather systems, but has the advantage of eliminating details that are less important to this part of our investigation. Long-term monthly-mean or NCEP re-analysis Sea Surface Temperatures (SSTs) are used in all experiments and held fixed during model integrations.

4. Preliminary Results from Numerical Experiments

Figure 3 shows initial conditions (left panels) and 72 hour simulations (right panels) of 850 hPa wind (lower panels) and 200 hPa wind (upper panels) from a coarse-resolution, full physics run, together with Opal's observed locations. Note: (i) the track simulation is reasonably skilful, but slightly slow, and (ii) the observed amplification of the upper ridge to Opal's northeast is reproduced in the simulation. Figure 4 is similar to Fig. 3 but is from a simulation with the initial vortex removed and run without any latent heating. Note: (i) the initial condition and 48-hour simulation of 850 hPa wind shows no evidence of the Opal circulation; (ii) the simulated environmental flow at 850 hPa over the Gulf shows the evolution from easterly to south and southwesterly flow, consistent with the observed track for Opal; and (iii) even in the absence of convection and the Opal circulation, the simulation reproduces the amplifying upper level ridge to the north of the Gulf. Evidence presented here suggests that environmental flow changes associated with Opal's recurvature and the amplification of the upper ridge to Opal's north may have been part of a downstream development event that influenced Opal's track and possibly its intensity.

To further explore how Opal's environment changed during its RI, Fig. 5 shows from a No-Vortex-No-Heating (NVNH) simulation (top panels) and with full physics (lower panels), time series of vertical motion and absolute vorticity over a 300 km circle centered on the forecast location (from the full physics simulation) of the moving storm. Note: (i) both simulations show the amplifying ridge at upper levels; (ii) at the time of Opal's RI (1800 UTC 3 October), the NVNH simulation shows an enhancement in environmental low to midlevel vorticity; (iii) during the overlaying of the upper ridge, the vertical motion field shows a period of environmental descent and then a period of ascent as the storm passes beyond the ridge axis; (iii) the period of enhanced ascent corresponds approximately with the period of enhanced environmental low to midlevel vorticity; (iv) comparison of the upper and lower panels shows the imprint of the diagnosed environment in the full physics simulations; and (v) there is explosive development of ascent, but not in vorticity at this resolution, in the full physics simulation as the (environmental) inhibition to ascent eases. With regard to the last point, we note, but do not illustrate here, that higher resolution simulations indicate intensification, but not quite at the rate observed.

5. Synthesis and Conclusion

Evidence from observations and simulations suggest that the rapid intensification of Hurricane Opal occurred during the group propagation of Rossby waves at upper levels. Rapid intensification occurred as a large-amplitude, long wave developed in the vicinity of the storm, with the trough to the west and the ridge over the top of the storms. This large-scale structure thus resembles the "favorable distant trough" category described in Hanley et al. (2001). Analysis of the structure of the waves and observed and theoretical group and phase speeds suggest that a combination of large-amplitude, long waves and the associated jet structure can establish a favorable environment for intensification. Under these conditions it can be shown theoretically that it is possible to have large group propagation to rapidly change the environment of storms (including the wind shear), and small phase propagation so that the encounter with the high wind shear zones of eastward-propagating troughs is delayed. We suggest that the presence or absence of DD may be a distinguishing feature between the FDI and UDI composites of HMK01. We are currently exploring this aspect in more detail

Numerical simulations are used to diagnose the environmental flow changes in the vicinity of the storm during the downstream event and to explore how these changes influence the behavior of the vortex and its rapid intensification. The main conclusions are: 1. Regions of anticyclogenesis within the downstream events provide a low vertical wind shear environment for intensification. 2. The downstream events are mostly defined by dry dynamics and independent of the presence of the storm. 3. During rapid intensification, the storms move into diagnosed environments characterized by: (a) an overlaying upper level negative potential vorticity anomaly, (b) regions of enhanced low to midlevel cyclonic vorticity, and (c) regions of both ascent and *descent.* 4. There is no evidence from the simulations of enhanced environmental upper divergence in the vicinity of the storms during rapid intensification.

The authors hypothesize that short-term partial suppression of ascent within the storm by the environment during the passage of the Rossby wave allows the storm's boundary layer to moisten via sustained surface fluxes. Once the period of external inhibition to ascent passes, deeper, more active convection develops, with rapid intensification in the low wind-shear, increasingly-cyclonic, low-level environment.

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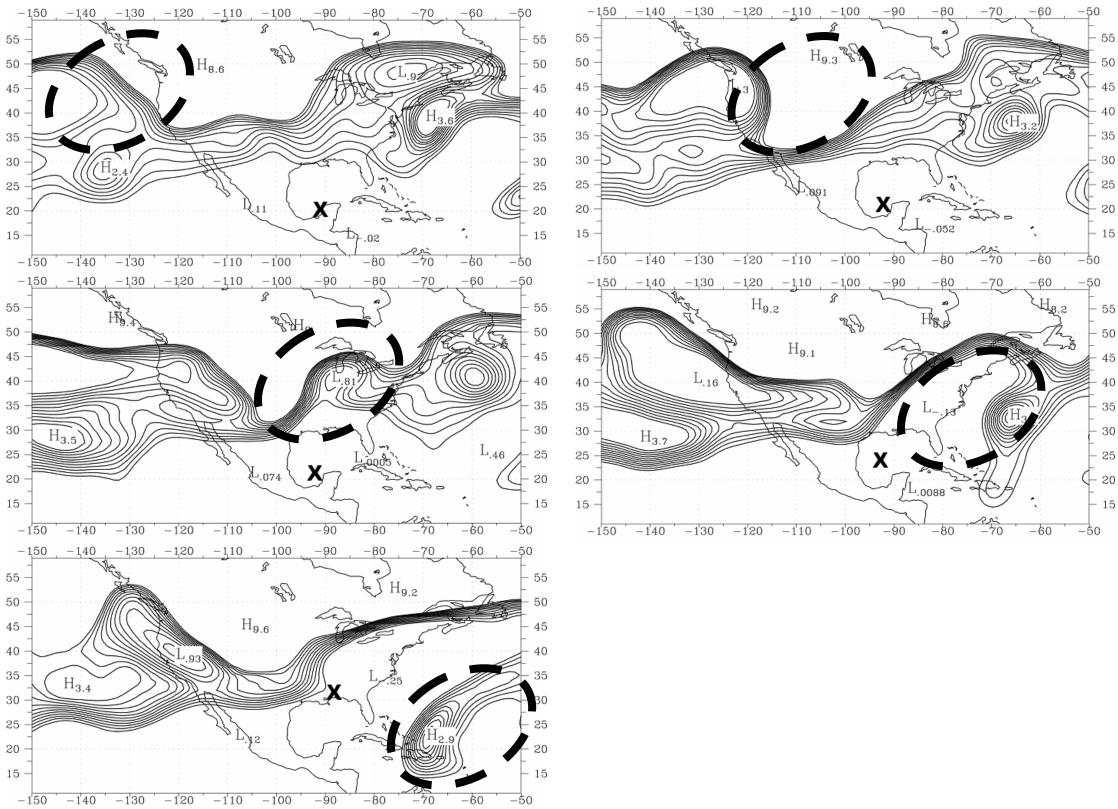

Figure 1: 200hPa potential vorticity for Opal at one day intervals commencing 0000 UTC 30 September 1995. Units are PV Units. Contour interval is 0.2 PVU. Only contours between 1 and 3 PVU are plotted. The ellipses mark the location of the leading synoptic-scale amplification at each time. ‘X’ marks Opal’s location at analysis time. RI occurred during the time between the right center and bottom left panels (3 - 4 October)

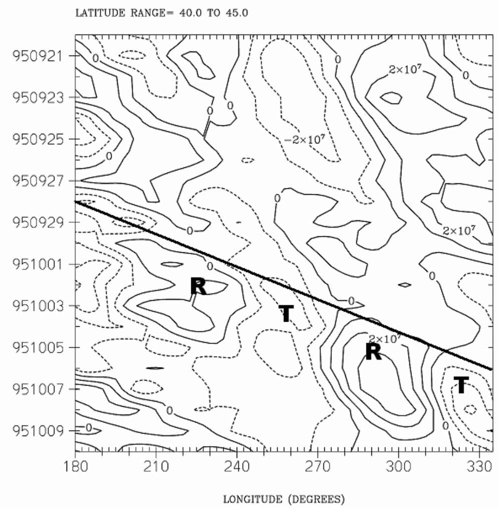

Figure 2: Time-longitude section for the 40^0 – 45^0N band of 200 hPa stream function anomaly for the period 20 September to 10 October 1995. The longitudinal span is 180^0 – 330^0 E. Contour interval is$1.0X10^6$ m^2s^{-1}. The ‘T’s and ‘R’s indicate where the troughs and ridges are amplifying.

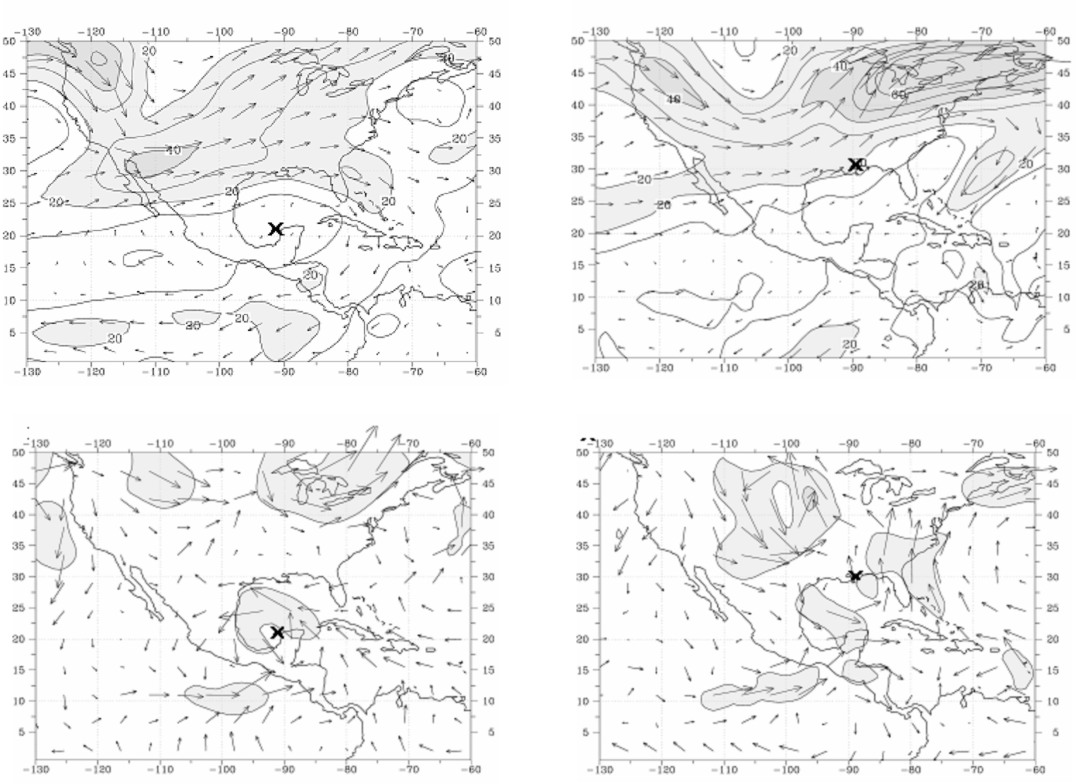

Figure 3: initial conditions (left panels) and 72 hour simulations (right panels) of 850 hPa wind (lower panels) and 200 hPa wind (upper panels). Contour interval for winds is 10 ms^{-1} and winds greater than 10 ms^{-1} at 850 hPa and 20 ms^{-1} at 200 hPa are shaded.

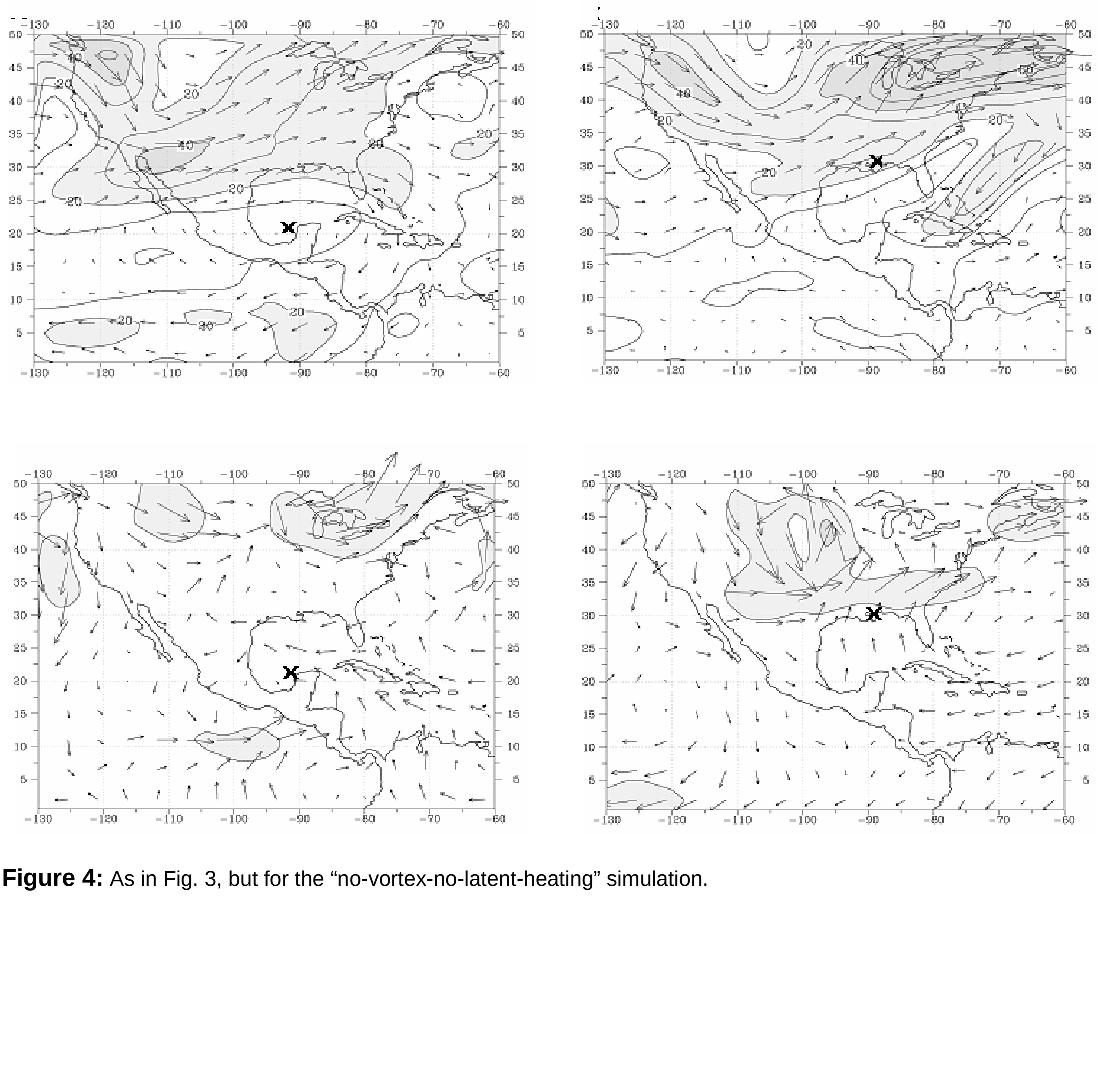

Figure 4: As in Fig. 3, but for the "no-vortex-no-latent-heating" simulation.

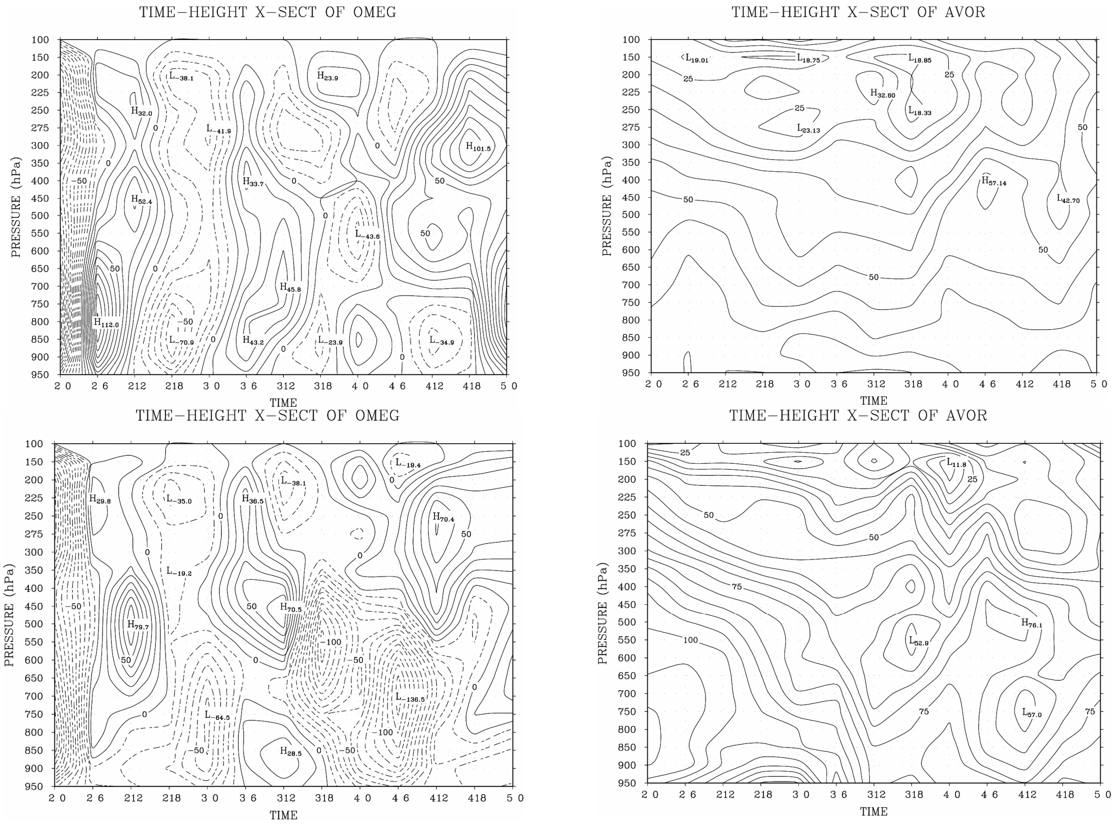

Figure 5: Time-height series of vertical motion (left panels) and absolute vorticity (right panels) from the "no-vortex-no-latent-heating" simulation (top panels) and full physics simulation (lower panels). Contour interval for vertical motion is 10 hPa/day. Ascent is negative and indicated with dashed lines. Contour interval for absolute vorticity is 5 x 10^{-6} s^{-1}. RI commenced at approximately 1800UTC 3 October.