3A.5 THE IMPACT OF EXTRATROPICAL TRANSITION ON THE DOWNSTREAM FLOW: IDEALISED MODELLING STUDY

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1. INTRODUCTION

A tropical cyclone undergoing extratropical transition (ET) has a direct influence on the synoptic-scale midlatitude circulation. However, arguably the more significant influence is the excitation of a Rossby wave train on the midlatitude potential vorticity (PV) gradient by a poleward moving tropical cyclone. This wave train then propagates downstream and alters the midlatitude flow pattern. Thus an ET event taking place in the western North Atlantic can initiate explosive cyclogenesis in the eastern Atlantic and western Europe and might trigger severe precipitation events in the Mediterranean. Numerical weather forecasts frequently fail to capture this downstream influence and ensemble prediction systems show enhanced uncertainty in the region downstream of ET events.

The physical processes during an ET event are not yet well understood and their relative importance in affecting the midlatitude circulation is unclear. By conducting numerical experiments with idealised initial conditions we hope to reduce the high complexity of ET into its most relevant players and contribute to identifying and understanding the most important mechanisms.

2. MODEL

We use the PSU/NCAR MM5 modelling system to perform full physics numerical experiments with idealised initial conditions. Periodic boundaries in the zonal direction allow a channel configuration. A vortex-following two-way nesting renders a higher resolution around the modelled tropical cyclone possible. The outer domain has a horizontal resolution of 60 km and a zonal and meridional extent of ~17 000 km and ~9 000 km, respectively. The nest has a 20 km horizontal resolution and a domain size of 1 200 km x 1 200 km. The southern boundary of the domain coincides with the Equator and the Coriolis parameter varies with the earth's geometry. The 41 vertical levels are irregularly spaced, with a higher resolution in the boundary layer and in the tropopause region. Both domains use the Kain-Fritsch-2 scheme to parameterize convection, the Blackadar scheme to represent boundary layer processes, and the Reisner-5 microphysical scheme. In keeping with the philosophy of minimising the complexity, we neglect radiative processes in the current set of experiments. The basic initial conditions consist of a zonally oriented straight jet stream in hydrostatic and thermal wind balance with a baroclinic zone. The jet is centred on 45°N. A tropical cyclone that was spun up in a quiescent environment on an f-plane is inserted into the domain to the south of the jet.

3. NUMERICAL EXPERIMENTS

The simplest representation of the midlatitude flow pattern is the straight jet stream described above. The tropical cyclone approaches the jet from the south and the first clear sign of an interaction between the two systems can be seen in the upper troposphere where the outflow impinges on the jet. The subsequent evolution is depicted for selected time steps in Figure 1. At 120 h into the model run a jet streak has formed due to the interaction of the outflow with the jet stream and a ridge-trough couplet is emerging. 36 h later both features are now well pronounced. Beneath the left exit region of the jet streak a surface cyclone starts to develop. In the next 36 h the surface cyclone intensifies rapidly with a pressure drop of about 20 hPa. A further upper-level ridge-trough pattern develops downstream and initiates another surface cyclone. At the end of the simulation the upper-level wave pattern has extended over most of the domain and initiated the development of 3 surface cyclones.

The development at upper levels can be seen as the excitation of a Rossby wave train (RWT) by the ET event. Its propagation can be conveniently depicted in a Hovmoeller plot of the 200 hPa meridional wind speed (Figure 2). The RWT can be identified after day 4. The ET system itself moves only slowly to the east while the Rossby wave energy propagates with a speed of approx. 2 500 km/day to the east.

The sensitivity of the evolution with respect to the structure of the jet stream and the tropical

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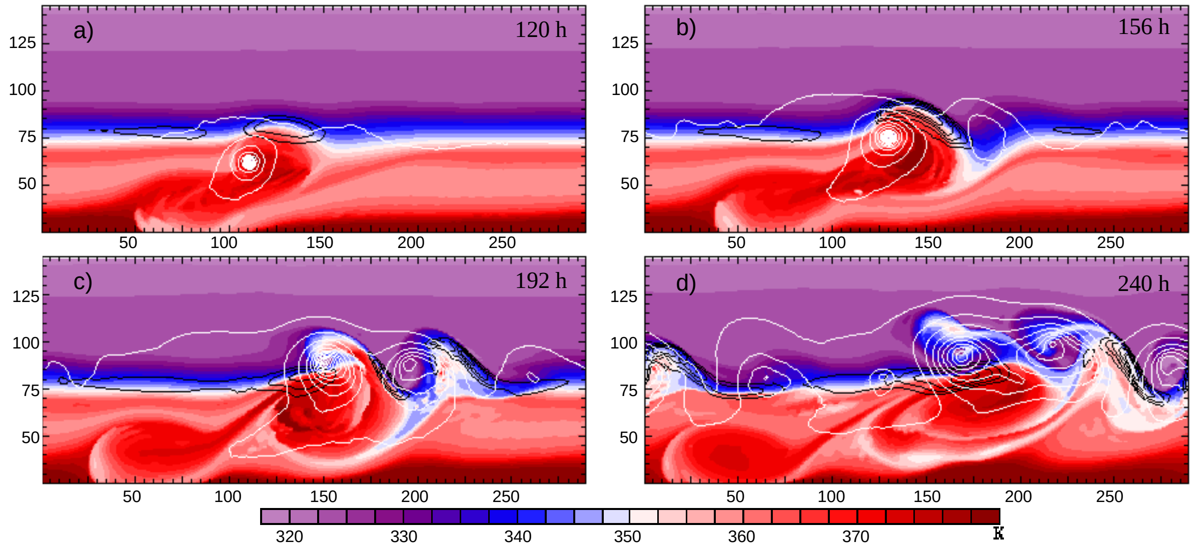

Figure 1: Potential temperature on the dynamic tropopause (PVU=2, colour shaded), surface pressure (white contours, every 5 hPa) and wind speed on 200 hPa exceeding 40 m/s (black contours, every 5 m/s) for times 120 h (a), 156 h (b), 192 h (c), and 240 h (d) into the integration of the straight jet experiment. The scale of the axes is in grid points.

cyclone was investigated by performing a set of numerical experiments with variations in the strength of the jet stream and the intensity and size of the tropical cyclone (not shown). In these experiments the interaction of bigger and stronger tropical cyclones led to an earlier interaction with the midlatitude jet and the formation of stronger jet streaks. The experiments also indicated an impact on the structure of the low pressure system directly downstream of the ET event. With stronger, bigger tropical cyclones the midlatitude system tends to show more anticyclonic life-cycle behaviour with a more meridional orientation and less cyclonic wrap up of the upper level PV trough. The propagation of the RWT does not seem to be affected. Variations in the strength of the wind maximum in the jet stream showed a strong influence on the development. With a stronger jet the midlatitude cyclones develop more rapidly and the RWT is amplified and propagates faster.

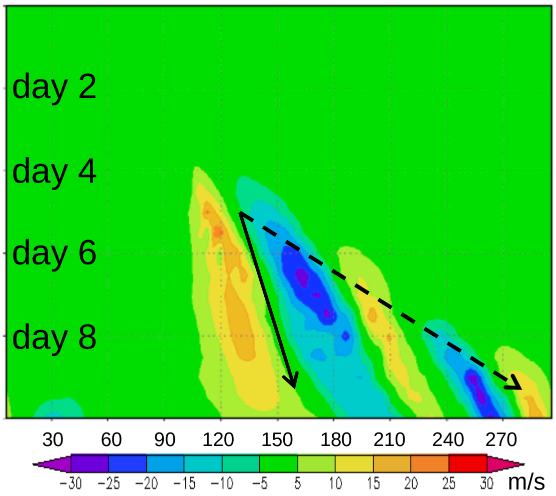

Figure 2: Hovmoeller plot of the 200 hPa meridional wind speed of the experiment depicted in Figure 1 (meridionall average from grid point 60 to 120). The solid arrow denotes the movement of the ET system, the stippled arrow the propagation of the RWT. The scale of the x-axis is in grid points.

In the next set of experiments we add some complexity but gain a more realistic representation of the midlatitudes and investigate the interaction of the tropical cyclone with developing baroclinic waves. The waves can be excited by localised as well as periodic perturbations at different vertical levels. The resulting life-cycles constitute a variety of synoptic patterns for the tropical cyclone to interact with and for the downstream development to take place.

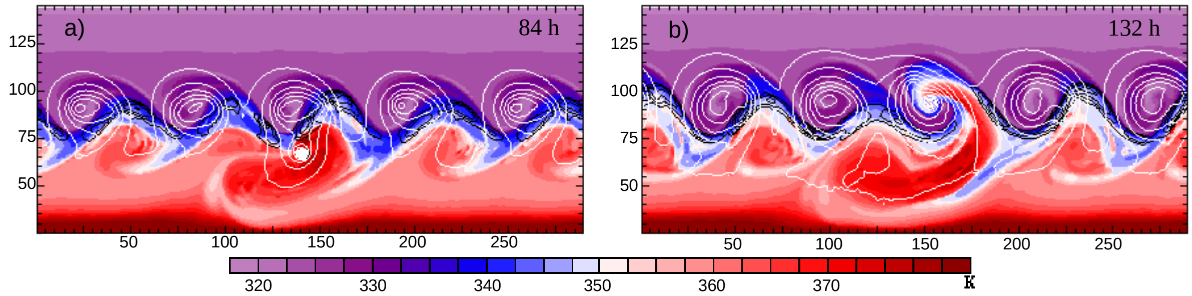

Figure 3: same as Figure 1 but for an ET experiment with periodic initial perturbations in the midlatitude jet stream. Times 84 h (a) and 132 h (b) are depicted.

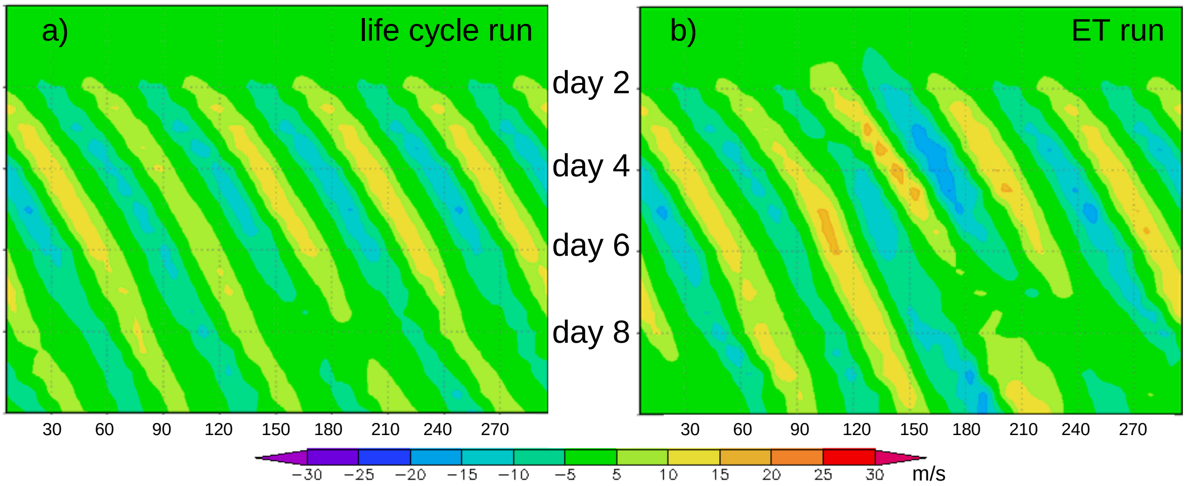

Figure 4: same as in Figure 2 but for the experiment with a periodic initial perturbation and without (a) and with (b) a tropical cyclone.

Here we present two examples of such interactions. In Figure 3 the interaction of a tropical cyclone with a baroclinic life-cycle initiated by periodic perturbations is shown. At the time of the ET event the midlatitude system is already in a mature stage of development (Figure 3a). The remnants of the tropical cyclone are then absorbed into the midlatitude system and at upper levels tropical air intrudes northwards whereas on the eastern side of the positive tropopause anomaly formed by the outflow a streamer of high PV from the midlatitudes is advected far to the south (Figure 3b).

Comparing the Hovmoeller plot of this ET event (Figure 4a) with the run without a tropical cyclone (Figure 4b) it can be seen that the impact of the ET is localised and there is little influence on the upper level flow pattern downstream.

Figure 5 shows the interaction of a tropical cyclone with a developing baroclinic wave that was excited by a trough-like perturbation at upper levels. The tropical cyclone moves in front of the trough and as the outflow impinges on the jet stream again a distinct jet streak develops.

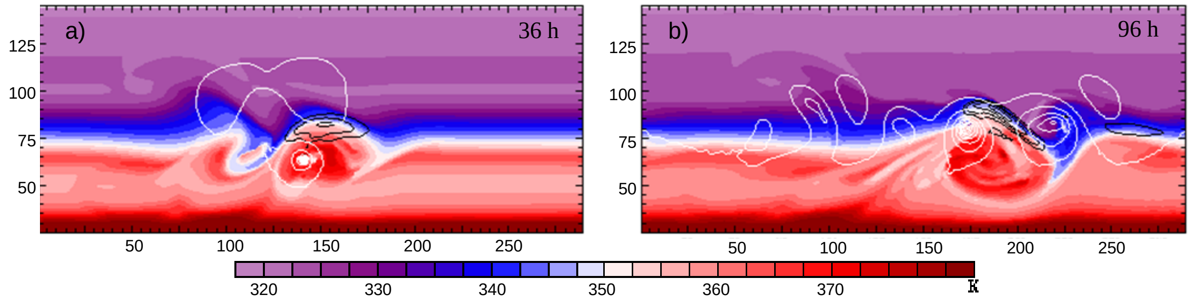

Figure 5: same as Figure 1 but for an ET experiment with an upper-level initial perturbation in the midlatitude jet stream. Times 36 h (a) and 96 h (b) are depicted.

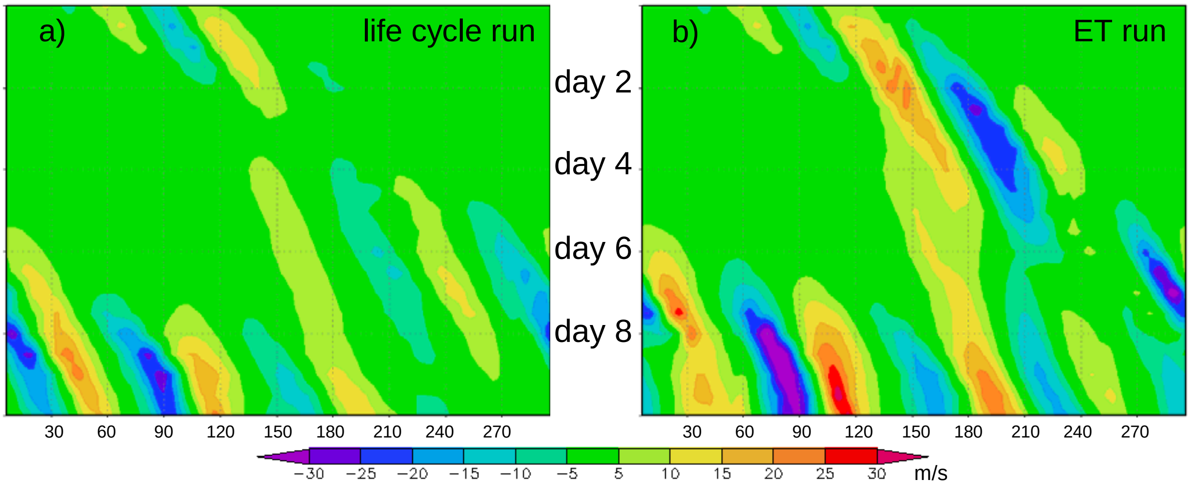

Figure 6: same as in Figure 2 but for the experiment with an upper-level initial perturbation and without (a) and with (b) a tropical cyclone.

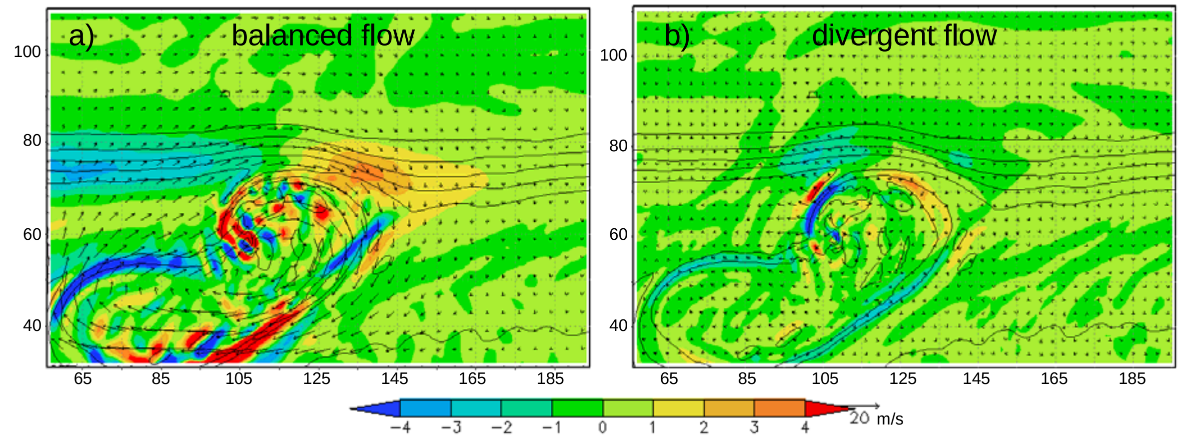

Figure 7: PV (contours), wind barbs (arrows) and PV advection (colour shaded) in 120 hPa due to the balanced flow associated with the ET system (a) and due to the divergent flow (b) at time 108 h of the numerical experiment depicted in Figure 1. Values of PV advection are in 10^{-5} PVU/s.

60 h later directly downstream of the ET event the extratropical low pressure systems is deeper (~ 15 hPa) than in the run without the tropical cyclone (not shown). A comparison of the Hovmoeller plots (Figure 6) shows that in this case the RWT is considerably enhanced.

4. PV INVERSION DIAGNOSTIC

Piecewise inversion of Ertel's potential vorticity using non-linear balance is performed to assess quantitatively the influence of the tropical cyclone on the building of the ridge associated with ET and the formation of the trough directly downstream. The formation of this ridge-trough pattern constitutes the excitation of the RWT. All PV features that are attributable to the ET system define the PV anomaly for which the balanced flow is deduced by PV inversion. The definition of the PV anomaly is straightforward at the beginning of the interaction, as the tropical cyclone and the midlatitude flow environment are well separated. At later times during the ET the definition becomes increasingly complicated. Using the diagnostic non-linear balance equation the balanced flow associated with a PV anomaly is non-divergent. So we complement the PV inversion by using Helmholtz' theorem to partition the flow into its rotational and divergent parts. A shortcoming of this approach is that it cannot be inferred whether parts of the divergent flow are attributable to the tropical cyclone outflow or are inherent to the midlatitude circulation.

The impact of the balanced flow associated with the tropical cyclone on the midlatitude upper level PV gradient in an early stage of the interaction for the numerical experiment shown in Figure 1 is depicted in Figure 7a. There is positive PV advection on the eastern side of the ridge and negative PV advection on the western side thus reinforcing the ridge's self-propagation to the west. This might help to promote phase-locking of the building ridge and the ET system. There is also positive PV advection in the base of the digging trough downstream of the ET so the balanced flow associated with the ET system directly contributes to the intensification of this

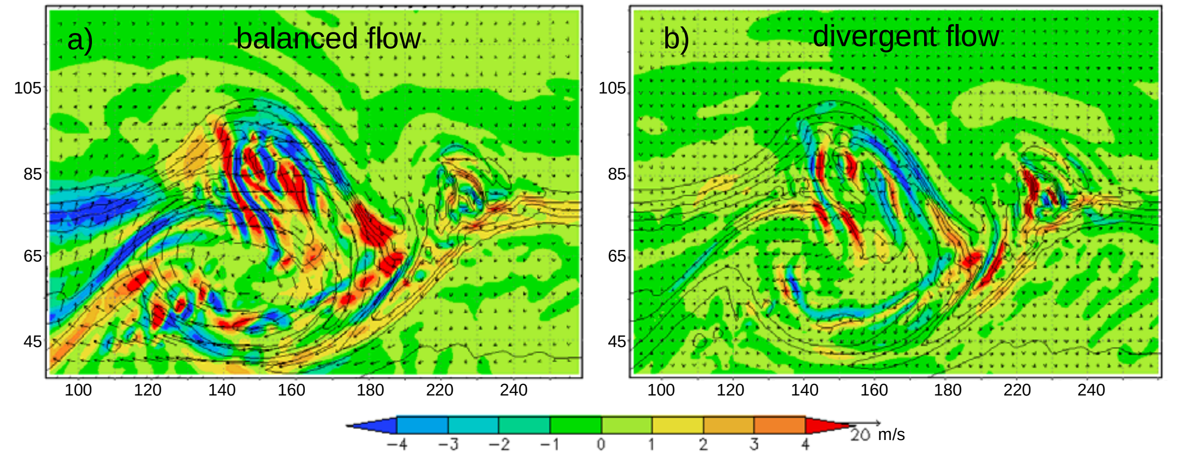

Figure 8: same as Figure 7, but at time 180 h.

feature. The impact of the divergent part of the flow on the upper-level PV gradient in this early stage of the interaction is low (Figure 7b). It is limited to the western side of the ridge and contributes to its propagation to the west.

Later the PV advection field is more complicated (Figure 8). A main feature is that the balanced flow now accelerates the ridge to the east and continues to amplify the trough by advecting high PV values into its base (Figure 8a). It promotes also the anticyclonic breaking of the wave as the axis of the trough is further tilted to the west. The advection of the midlatitude PV gradient by the divergent flow (Figure 8b) is now comparable to the advection by the balanced flow, in particular on the eastern side of the ridge and in the base of the trough. It contributes to the advection in the same manner as the balanced flow but is more localised.

5. SUMMARY

Idealised numerical experiments of ET events show that a tropical cyclone excites a Rossby wave train on a straight midlatitude jet stream and initiates rapid surface cyclogenesis directly downstream of ET. The response of the midlatitudes depends strongly on the midlatitude flow pattern itself, in particular whether the tropical cyclone interacts with mature or developing extratropical systems. A systematic investigation of the sensitivity of the evolution to the phasing between the tropical cyclone and midlatitude flow pattern is one of the foci of future work.

The advective impact of the ET system on the upper-level midlatitude PV gradient was assessed using piecewise PV inversion. In the early stage of the interaction the balanced flow associated with the ET system slows down the eastward motion of the ridge, making phase-locking more likely. There is positive PV advection into the trough downstream at early and later stages of the ET indicating that the ET system has a direct influence on the formation of this trough. An extension of this analysis to consider the advection of the low-level temperature gradient by the balanced flow is in progress. Furthermore, the PV inversion will be extended to quantify the importance of the flow associated with the developing midlatitude wave pattern.

6. ACKNOWLEDGEMENT

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