MESOSCALE PROCESSES INVOLVED IN FASTEX SECONDARY CYCLONES

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1 INTRODUCTION

The Fronts and Atlantic Storm-Track EXperiment (FASTEX, Joly *et al.* (1997)) took place during January and February 1997. This experiment allows for the first time to document secondary cyclogenesis at several scales thanks to an important experimental design. Indeed several aircraft carrying dual-beam Doppler radars, microphysical in-situ sensors and launching dropsonde were involved. As shown by Bouniol *et al.* (1999) or Lemaître *et al.* (1999) the combination of these measurements allows to document the mesoscale either in precipitating areas or in clear air region, the synoptic scale environment being described thanks to large scale ECMWF analyses.

Thanks to this important data set, two majors ambitions had to be addressed:

- to evaluate hypotheses deduced from the recent theoretical studies of the dynamics of frontal cyclones.
- to document the dynamic of secondary lows in their mature stage at all scales of motions.

In the past ten years numerical studies managed to reproduce the life cycle of secondary cyclones involving different processes, such as:

- upper and low level coupling processes (see for instance Thorncroft and Hoskins (1990)).
- low forcing of the large scale environment (see for instance Bishop and Thorpe (1994a, b)).
- conditional symmetric instability (see for instance Balasubramian and Yau (1994)).
- microphysical processes.

Studies have also concentrated on the derivation of conceptual schemes of secondary cyclones from local observations (see for instance Browning (1997)).

In this context this paper aims at:

- summarizing the three dimensional dynamical and thermodynamical structure of a typical secondary cyclone and comparing the obtained image with the previously mentioned conceptual scheme.
- diagnosing the processes involved in the development of this typical secondary low.
- estimating the degree of generality of the previous results by scrutinizing another FASTEX case which has experienced an explosive deepening.

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2 SELECTED CASES

Investigations are firstly led on the secondary low which was the target of the Intensive Observation Period (IOP) 16 on the 17 February 1997. This secondary low has experienced a deepening of 24 mb in 24 hours.

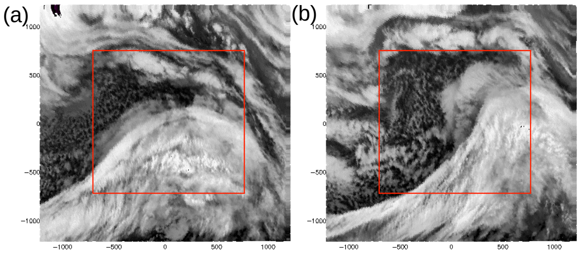

Figure 1 : Infrared METEOSAT images at (a) 06 UTC and (b) 12 UTC 17 February 1997 (FASTEX IOP16). The squares shows the domain used for the analysis conducted in this paper.

Figures 1-a and 1-b show the Meteosat infrared picture at 06 and 12 UTC respectively. These images are centred on 55° North and –16.5° West and set in a cartesian frame. They show the cloud head emerging from the trailing cold front of a primary low which was the target of IOP16 carried out between 06 UTC and 12 UTC. It was sampled by the dual-beam Doppler radar onboard the NOAA-P3 aircraft and by high resolution dropsonding launched from the UK-C130 aircraft. First insights concerning three-dimensional structures of the secondary low deduced from these data are given in Bouniol *et al.* (1999).

Processes involved in the development of the IOP16 case are also investigated on another FASTEX case of explosive cyclogenesis. This IOP12 case has been sampled on the 9 February 1997 between 15 UTC and 21 UTC. The evolution of the cloud pattern associated with this secondary low is shown on Figure 2. This cyclone is qualified as "explosive" following Sanders and Gyakum (1980) since it has known a deepening of more than 54 mb in 24 hours. A mesoscale documentation of this case can be found in Lemaître *et al.* (1999).

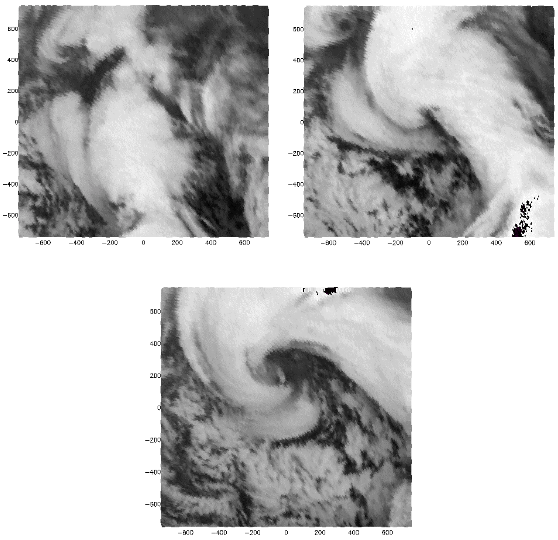

Figure 2: Infrared METEOSAT images at (a) 12 UTC and (b) 18 UTC on 9 February 1997 and (c) 00 UTC on 10 February 1997 (FASTEX IOP12).

3 DYNAMIC STRUCTURE OF THE IOP16 SECONDARY LOW: ROLE OF COUPLING PROCESS

As previously mentioned the three dimensional structure at mesoscale has been described in Bouniol *et al.* (1999). Air particle trajectories have been computed from the observational data showing strong similarities with the conceptual scheme of Browning (1997) validating this scheme in this case.

The dynamical and thermodynamical structures at synoptic scale at 06 UTC and 12 UTC are also described in Bouniol *et al.* (2001) but are reminded here for 12 UTC (figure 3) i.e time when the cloud head is fully developed, as shown on figure 1-b.

The figure 3-a shows the kinematic situation at 9 km altitude. It evidences a cloud head (located by the cross on figure 3 and in the following) emerging above the exit of a strong jet streak. In the low levels a strong baroclinic region (figure 3-c) corresponding to the frontal surface is shown with a wavy pattern north of the cloud head. The figure 3-b reveals a low level jet decelerating in the warm side and a second minimum associated with the cloud head in accordance with the cyclonic circulation observed in Bouniol *et al*. (1999).

As explained in Bouniol *et al.* (2001) the cloud head is fed by an ascending rotating flux called in the conceptual scheme of Browning (1997) the “cold conveyor belt”. But as explained in the same paper the exit of the jet-streak does not correspond to the indirect ageostrophic diagnosed by the work of Uccellini and Johnson (1979). Indeed the subsiding branch of the ageostrophic circulation is removed due to the curvature effect. As shown by Shapiro and Kennedy (1981) variations in curvature of the upper level jet produce divergence and convergence cores superimposed on the jet axis. These cores can then amplify or remove the convergence or divergence pattern due to a deceleration of the upper level jet.

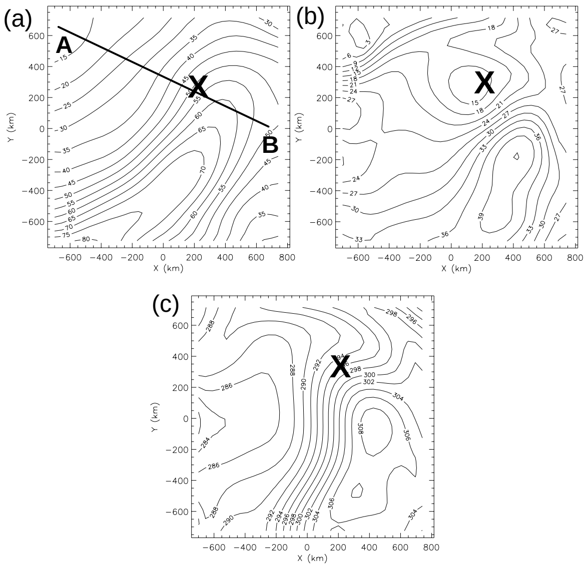

Figure 3 : (a), (b) Isotachs at 9 km and 1.5 km altitude respectively (per contours of 5 and 3 m.s^{-1} respectively) and (c) equivalent potential temperature at 1.5 km altitude for IOP16 at 12 UTC.

In the present case the effect of curvature is to reinforce the ascending motions ahead of the cloud head and to remove the subsiding branch of the upper level ageostrophic circulation. This is clearly illustrated by the ageostrophic circulation in the vertical cross section given Figure 4. This cross section evidences then a coupling of the vertical motions associated on one part to the low level ageostrophic circulation and on the other side to the upper level ageostrophic circulation. The vertical motions are then extended from the ground throughout the troposphere as symbolized by the black arrow on Figure 4.

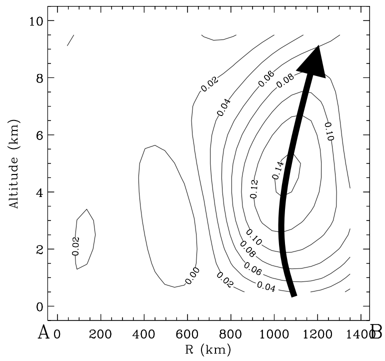

Figure 4 : Vertical cross section along the line AB shown on Figure 3-a of the vertical wind (per contours of 0.02 m.s^{-1}).

As recalled in the introduction, this coupling process is in accordance with the development hypothesis proposed by Thorncroft and Hoskins (1990). But in order to determine if this process is the one explaining the development of the cyclone, the other processes encountered in the literature have to be investigated and in particular instability processes which are discussed in the next section.

4 ROLE OF INSTABILITY PROCESSES

These processes are investigated using the ECMWF analysis and focusing on the time (12 UTC) were the coupling is acting. Two main instabilitiy processes can play a role at mesoscale: the upright and slantwise convection. Several tools allow to diagnose these processes such as the Brünt-Väisälä frequency for upright convection and the equivalent potential vorticity for slantwise convection. These two parameters are shown for the low, middle and high troposphere level on Figure 5.

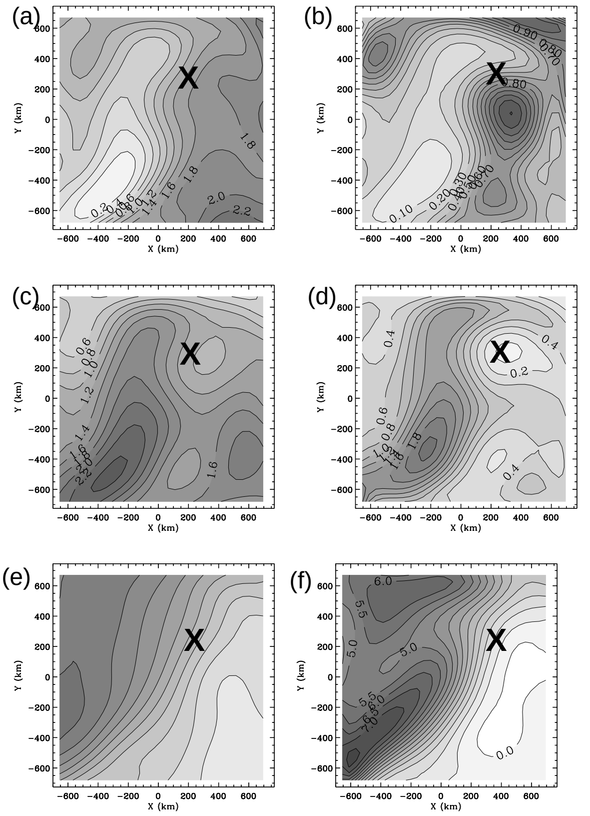

Figure 5 : (a), (c), (e) Brünt-Väisälä frequency at 1.5, 5 and 8 km respectively (per contours of $0.2.10^{-4}$ s^{-1} for a and b and $0.5.10^{-4}$ s^{-1} for c). (b), (d), (f) Equivalent potential vorticity at 1.5, 5 and 8 km respectively (per contours of 0.1 PVU, 0.2 PVU and 0.5 PVU respectively) at 12 UTC.

The Brünt-Väisälä frequency shown on Figure 5-a, c and f is everywhere positive which means that the atmosphere is stable with respect to upright convection. The equivalent potential vorticity for the low levels (Figure 5-b) also shows an atmosphere stable for slantwise convection. The middle levels (Figure 5-d) evidences a negative region co-located with the area where emerges the cloud head. If we scrutinize the upper level, this region of negative values extends all along the right hand flank of the upper level jet. These negative values identified then a potential for slantwise convection in the middle troposphere (where the coupling is acting) and in the upper troposphere.

The relevant question is then: are these instabilities relaxed? This aspect can be investigated by computing the lagrangian evolution of the Brünt-Väisälä frequency and of the equivalent potential vorticity. This is done on Figs. 6a and 6b. The diagnosed tendency is to reinforce the stability with respect to upright convection (which means that the Brünt-Väisäla frequency is increasing) in the region where emerges the cloud head (see Figure 6-a). It is also to increase the equivalent potential vorticity. The negative region of equivalent potential vorticity becomes positive which means that the slantwise instability is relaxed. Following the work of Emanuel *et al.* (1987) this relaxation intensifies the ascending motions and thus reinforces the coupling process.

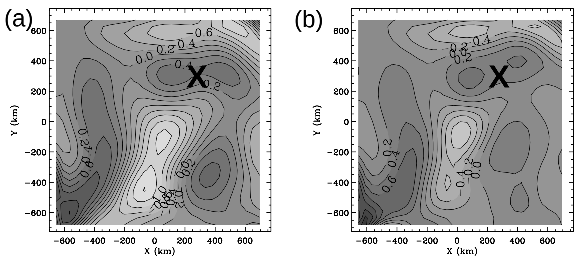

Figure 6 : Lagrangian evolution of the (a) Brünt-Väisälä frequency (per contours of $0.2.10^{-8}$ s^{-2}) and (b) equivalent potential vorticity (per contours of $0.2.10^{-4}$ $PVU.s^{-1}$) at 5 km altitude for 12 UTC.

As a conclusion, in accordance with the work of Balasubramanian and Yau (1994) slantwise convection appears involved in the development of the secondary cyclone. The diagnostics of the main contributing process (coupling or instability) can be performed by using modelling tools. These tools allow also to investigate the impact of microphysics processes on the development. These aspects are presently under investigation. The degree of generality of these results is presently investigated by comparing this typical case to an explosive case sampled during the IOP12.

5 COUPLING PROCESS FOR IOP12 CASE

The processes involved in the IOP16 development has been investigated at a stage where the cloud head is fully formed (12 UTC). We choose here to investigate the IOP12 at the same stage of its life cycle : 18 UTC on the 9 February 1997. The cloud cover corresponding to this time is shown in Figure 2-b.

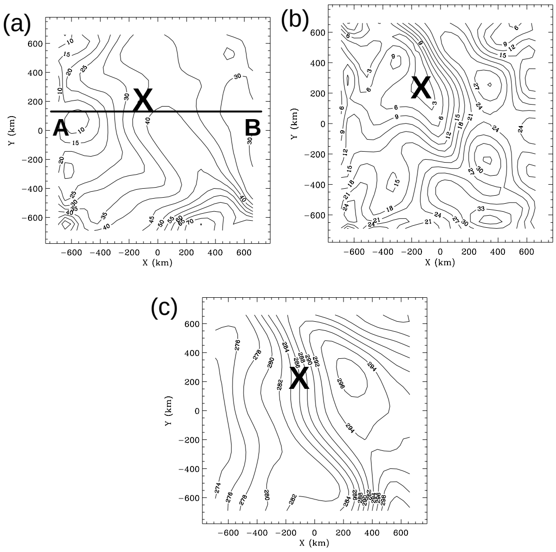

Figure 7 : (a), (b) Isotachs at 9 km and 1.5 km altitude respectively (per contours of 5 and 3 $m.s^{-1}$ respectively) and (c) equivalent potential temperature at 1.5 km altitude for IOP12 at 18 UTC.

Figure 7 shows the dynamical and thermodynamical structure for IOP12 case at the same levels as the IOP16 case (the location of the cloud head is still symbolized by a black cross). As for IOP16, the equivalent potential temperature (Figure 7-c) evidences a strong gradient (of same magnitude in both case) and also a wavy pattern. The kinematics situation appear very different. The cloud head emerges in a region where the wind is relatively weak 35 $m.s^{-1}$ and does not correspond to an exit of a jet-streak. The structure in the low level is also very different. The warm sector corresponds also to strong wind values (greater than 21 $m.s^{-1}$) with local reinforcements (that reach magnitudes greater than 30 $m.s^{-1}$). On the contrary, as the IOP16 case, the cloud head emerges in a region with a minimum of wind magnitude in accordance with an intense cyclonic circulation.

As it has been observed on Figure 7 the structure of IOP12 is strongly different from the IOP16 one. This reveals that processes involved in the development of these cyclones are likely to be different. Numerical simulations validated through comparisons with airborne observations have shown that the significant deepening of the IOP12 case can be explained by the effect of latent heat release (Lagouvardos *et al.* 1999). When ice phase microphysics is removed in the simulations, the deepening of this cyclone decreases.

Another interesting aspect evidenced on Figure 8 is the discoupling of vertical motions relevant to the upper and low level dynamics (see upward motions symbolized by black arrows).

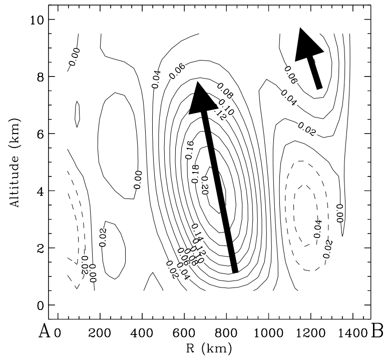

Figure 8 : Vertical cross section along the line AB shown on Figure 7-a of the vertical wind (per contours of 0.02 $m.s^{-1}$).

At this time (18 UTC) the vertical motions are not extended throughout the troposphere since the coupling between upper and low level ageostrophic circulations is not present. It must be noticed the strong intensity of vertical motions in the middle troposphere. The relevant question is then: are these strong vertical motions due to microphysical processes (as suggested by Lagouvardos et al. (1999)) or are they due to the relaxation of instabilities (through slantwise or upright convection)? Investigations are presently carried out on this aspect.

6 CONCLUSION

This paper gives an overview of two secondary cyclones sampled during the FASTEX experiment at the same stage of their life cycle. The first one is a classical case (IOP16) and the other one appears as a very intense deepening (IOP12). If the thermodynamical structure in the low levels show similarities between these two cases, the dynamical structure appears very different. Indeed the IOP16 cyclone is developing below the exit region of a jet-streak whereas the IOP12 cyclone is located in a region with very weak upper level wind.

Investigations are lead in order to determine the processes involved in the typical secondary cyclone development. Two of them are diagnosed and illustrated here. The first one is a coupling process between upper and lower ageostrophic circulation. On the other side implication of instability process and in particular slantwise convection is demonstrated. For IOP12, the vertical motion associated with upper and lower pattern are found to be disconnected which indicates that the coupling process is not acting at this stage of the life cycle of this cyclone. The illustration of all these results will be the object of the presentation.

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