2.3 THE POTENTIAL VORTICITY STRUCTURE OF A SEVERE EXTRA-TROPICAL CYCLONE

Matthias Zillig*, and H. C. Davies
Institute of Atmospheric Science, ETH, Zurich, Switzerland

1. INTRODUCTION

The winter storm 'Lothar'[1] that occurred on 26 December 1999 was one of the most harmful storms in the last decades in Central Europe. It was associated with extremely high surface winds, and in its passage across Europe it caused building and forest damage in France, Southern Germany, Switzerland and Austria. In the Swiss Middleland maximum wind speeds up to 200 km h^{-1} were reached which were the highest velocities ever measured for many stations.

This storm's intensity prompts questions concerning its structure and dynamics: Does the storm possess a distinctively different structure? What features can account for the high surface wind strength, and what is their dynamical origin? To help in addressing these questions we describe dynamical aspects of the storm's structure at the time of lowest surface pressure.

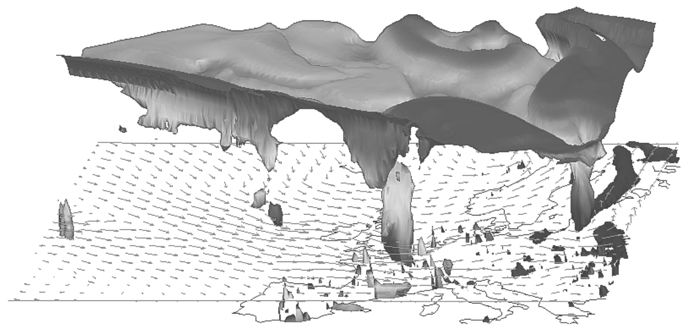

Figure 1: The 2 pvu iso-surface from a HRM simulation at 06 UTC 26 Dec. Shaded with potential temperature values. Also shown are the 850 hPa horizontal wind vectors (the length of the maximum wind vector corresponds to 43.5 m s^{-1}).

2. DEVELOPMENT OF THE STORM

Wernli *et al.* (2001) investigated 'Lothar's' life-cycle with the aid of ECMWF analysis data and mesoscale model simulations (HRM, the 'High Resolution Model' of the German Weather Service). These data sets help to identify a range of dynamical and physical features that characterized the development of the event. 'Lothar' originated in the western Atlantic and travelled eastward as a shallow low-level cyclone with moderate intensity towards Europe. This translation took place below and slightly to the south of a very intense upper-level jet (wind speeds up to 120 m s^{-1}). This phase was accompanied by continuous and intense condensational heating which in turn sustained a pronounced positive low-level PV anomaly (cf. Mallet *et al.* 1999). At tropopause level no significant PV anomalies were identifiable during this early phase of the life cycle.

The surface cyclone intensified rapidly when the shallow cyclone moved underneath the left exit of the jet stream. Rapid surface development was accompanied by the formation of a narrow and deep tropopause fold. This stratospheric PV anomaly almost merged with the diabatically produced low level PV feature to form a vertically aligned tower of positive PV at the time of maximum storm intensity (Fig. 1). This so-called 'PV-tower' is a favourable configuration for strong winds throughout the entire troposphere (Rossa *et al.* 2000).

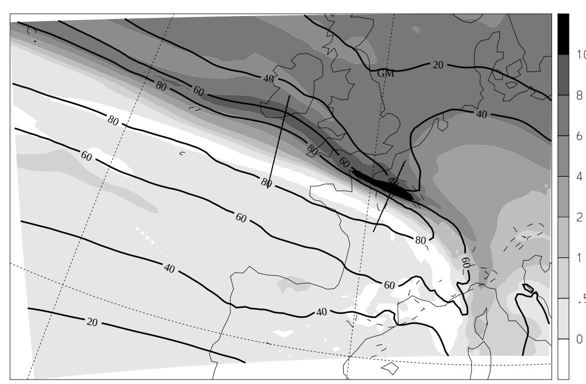

Figure 2: PV (shaded, in pvu) on the 318 K isentropic surface on 06 UTC 26 Dec. The bold contours are isotachs (in m s^{-1}), the dashed line corresponds to the 2 pvu contour on 288 K. The straight lines across the jet mark the locations of the cross-sections of Fig. 3 and Fig. 4 respectively.

**Corresponding author address*: Matthias Zillig, Swiss Federal Institute of Technology, Institute for Atmospheric Science, ETH Hönggerberg, CH-8093 Zurich, Switzerland, e-mail: zillig@atmos.umnw.ethz.ch

[1] Also referred to as the 'French storm' or the '1999 Boxing Day low'.

3. STRUCTURE AT TIME OF MAXIMUM INTENSITY

In terms of surface wind speed and core pressure 'Lothar' attained its maximum intensity at about 06 UTC 26 Dec. when the cyclone's centre was over north-western France. Here a digest is presented of the storm's structure at this stage.

Fig. 2 shows the potential vorticity and wind speed on the 318 K isentropic surface. The surface cyclone (denoted by the dashed contour line) is located below a narrow filament of high PV extending from England to France at the left exit of the very strong Atlantic jet. Southwest of, and co-aligned with, this filament, there is a region with relatively low PV. This 'PV-dipole' and the resulting very large PV gradient delineate the location of the jet, and are integral to the troposphere-spanning exceptionally strong winds.

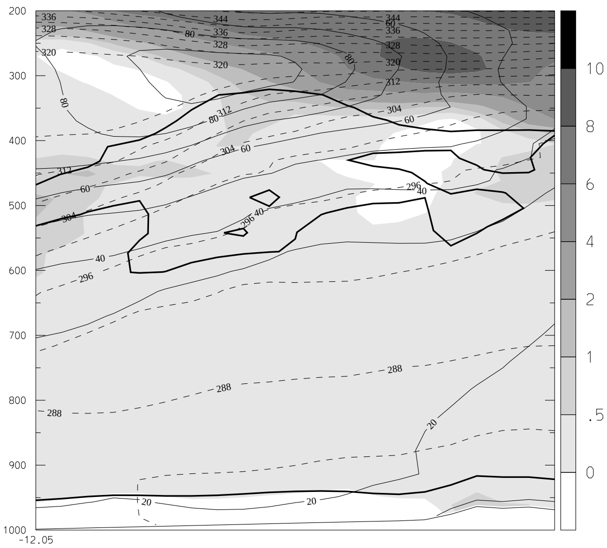

Figure 3: PV (shaded, in pvu) on a vertical cross-section at 8 degrees west (marked in Fig. 2) on 06 UTC 26 Dec. Also shown are the isotachs (solid lines, contour spacing 10 ms^{-1}) of the wind component perpendicular to the cross-section and the isentropes (dashed, contour spacing 4 K). The thick solid line near the tropopause surrounds the area where the model's Richardson Number is less than unity.

Figs. 3 and 4 are vertical cross-sections, aligned approximately perpendicular to the jet axis at the locations marked in Fig. 2. The upstream section (Fig. 3) shows a compact and intense ($\sim$90 m s^{-1}) jet located at the tropopause break. Beneath it in the mid-to-lower troposphere there is a deep layer with wind speeds in access of 20 m s^{-1}. The section in Fig. 4 is through the forementioned PV filament and the centre of the low level system. The prominent PV-dipole is evident as well as the accompanying intense jet (>90 m s^{-1}) in the region of the largest PV gradient. The diabatic low level PV almost merges and is vertically aligned with a very

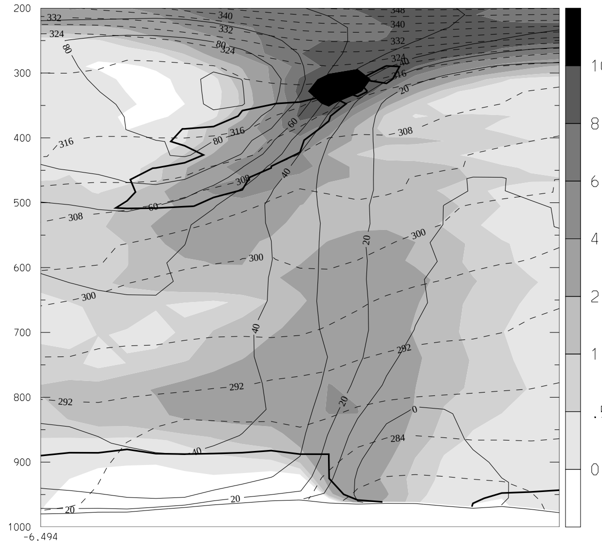

Figure 4: Same quantities as in Fig. 3 on a vertical cross-section (marked in Fig. 2) through the core of 'Lothar' on 06 UTC 26 Dec.

deep and narrow stratospheric intrusion. Comparison of the two sections suggests that the tropospheric part of the PV-tower adds (and subtracts) $\sim$20 m s^{-1} of the wind strength to the south (north) of the storm. This confirms the importance of the presence of both features (jet and tower).

In the south-west, behind the low level system, dry stratospheric air extends downward to tropo-

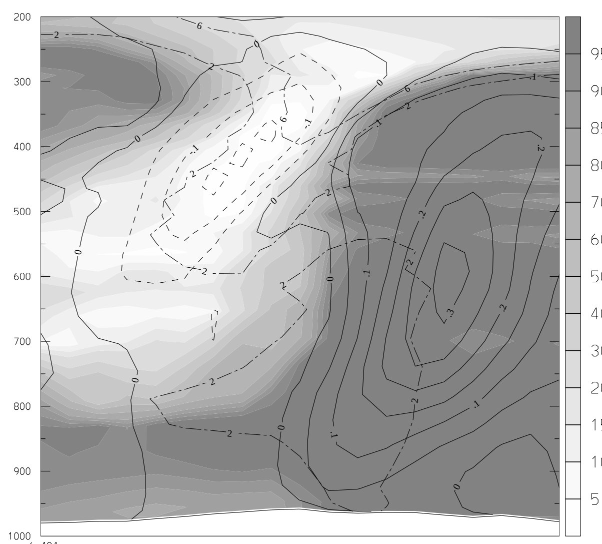

Figure 5: Same cross-section as in Fig. 4. Relative humidity (shaded, in %) and vertical wind. Solid contours for positive, dashed lines for negative values (contour spacing 0.05 ms^{-1}). The 2 pvu and the 6 pvu PV-isolines are plotted as dash-dotted lines.

sphere levels (Fig. 5). Ascent is strongest slightly to the north and downstream of the region of maximum latent heat release and is linked to low PV values at high altitudes (Fig. 2).

4. ANALYSIS OF BACKWARD TRAJECTORIES

Insight into the origin of the key features can be gained by computing backward trajectories. The low PV band south of the jet (Fig. 2) is the outflow region of moist ascending trajectories. Backward trajectories from the region of maximum PV (Figs. 2 and 4 where PV$>$10 pvu) show a significant increase of PV in the last few hours before the storm reached maximum intensity. On the average PV increased by $\sim$2.8 pvu in the last 4 hours along the trajectories. As for potential temperature θ and pressure p the lower trajectories (315 K$\leqslant \theta_{end} \leqslant$321 K) behaved differently from the higher (323 K$\leqslant \theta_{end} \leqslant$328 K) ones. Table 1 summarizes their properties.

Variable	lower trajectories	higher trajectories
PV	$\nearrow$ (3.0 pvu/4 h)	$\nearrow$ (2.3 pvu/4 h)
θ	$\longrightarrow$	$\searrow$ (-1.2 K/4 h)
p	$\nearrow$ (16 hPa/4 h)	$\searrow$ (-13 hPa/4 h)

Table 1: Tendencies of some key variables in the last four hours before the storm's maximum intensity on 06 UTC 26 Dec. See text for details.

The size of the region with PV$>$10 pvu is almost at the limit of the model's spatial resolution and hence the tabulated tendencies are influenced both by explicitly evaluated flow dynamical effects and by parameterized processes. The latter can relate to asymmetric (Richardson Number$<$1/4) turbulent processes and cloud diabatic, radiative effects. Fig. 4 shows a closed contour wherein the model's Richardson Number is very small. The second process under consideration is diabatic heating due to radiation. If we consider the deep tropopause fold as a PV (Fig. 4) and a dry (Fig. 5) anomaly embedded in a tropospheric environment, Forster and Wirth (2000) predict a $\dot{\theta}$-distribution which leads to $\dot{PV} >$0. The θ-evolution mentioned in Table 1 is not fully compatible with this argument, but as the θ-gradients in the corresponding region are large and the data time interval for the trajectory calculation is one hour, a small error in the parcel position leads to significantly different θ values. The tracking of θ along the trajectories might therefore not be very reliable in such cases.

Fig. 6 indicates that the flow field around the mesoscale system 'Lothar' has significant cross-isobar-angles in the area of maximum wind. Note the almost calm conditions in the north of the system's centre.

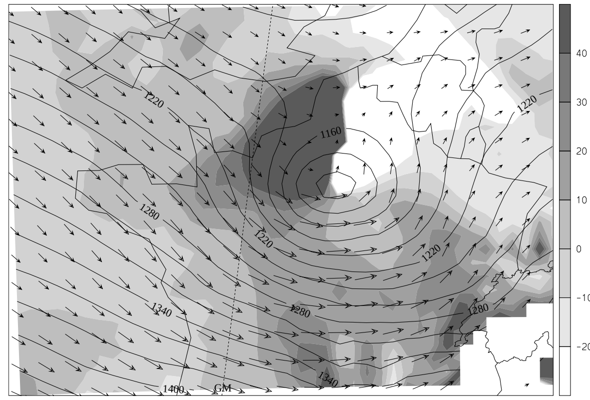

Figure 6: Geopotential field and wind vectors on 850 hPa. The maximum wind vector length corresponds to 47.5 m s^{-1}. Shaded are the values of the cross-isobar-angles (in degrees, positive sign for wind vectors deviating anticlockwise from the geostrophic wind).

5. SUMMARY AND FURTHER REMARKS

The surface winds of 'Lothar' were anomalously strong. The system was charakterised by a low level PV anomaly (generated by cloud diabatic processes) moving below the tropopause fold of an extraordinarily strong zonal jet.
Additional information and all figures of this paper in colour are available on http://www.lapeth.ethz.ch/$\sim$mzillig/cyclone/

ACKNOWLEDGMENTS

Thanks to Heini Wernli, Sébastien Dirren and Mark Liniger for the collaboration and fruitful discussions.

REFERENCES

Forster, C., and V. Wirth, 2000: Radiative decay of idealized stratospheric filaments in the troposphere. *J. Geophys. Res.*, **105**, 10169-10184

Mallet, I., J.-P. Cammas, P. Mascart, and P. Bechtold, 1999: Effects of cloud diabatic heating on the early development of the FASTEX IOP17 cyclone. *Quart. J. Roy. Meteor. Soc.*, **125**, 3439-3467

Rossa, A. M., H. Wernli, and H. C. Davies. 2000: Growth and decay of an extra-tropical cyclone's PV-tower. *Meteorol. Atmos. Phys.*, **73,** 139-156

Wernli, H., and H. C. Davies,1997: A Lagrangian-based analysis of extratropical cyclones. I: The method and some applications. *Q. J. R. Meteorol. Soc.* **123,** 467-489

Wernli, H., S. Dirren, M. Liniger, and M. Zillig, 2001: Dynamical aspects of the life-cycle of the winter storm 'Lothar' (24-26 December 1999). *Quart. J. Roy. Meteor. Soc.*, submitted.