Mesoscale Observations of a Cold Front Associated with a Prefrontal Hailstorm

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Abstract

The present paper discusses the analyses of data taken during the passage of a cold front in southern Bavaria. To the east of Munich and in the Salzburg area a prefrontal hailstorm caused heavy damage. The change in temperature and pressure related to the front suggests that there was an intensification of the cold front as it moved towards the east. Also towards the north away from the Alps these changes decrease apparently. Cross-frontal structures are similar to those observed at Australian cold fronts: prefrontal low level jet and postfrontal flow towards the leading edge of the cold air.

1. Introduction

Fronts cross central Europe on about 75 days each year, and they cause approximately 50% of the annual precipitation, which elucidates the strong impact of fronts on the weather and climate of the north Alpine region. Most of these fronts are observed to be deformed or slowed down, as reported by weather forecasters. But some fronts can also be intensified or shifted rapidly along the borders of the Alps as shown for an event associated with heavy precipitacion and snow (Heimann and Volkert, 1988; Volkert et al., 1991). The processes that give rise to these features are not understood in enough detail. The temporal and spatial resolution of conventional meteorological data are not sufficient for detailed analysis. In order to collect high resolution data and to provide more observational evidence of the orographic influence on cold front over Southern Bavaria, several field experiments were conducted during the last five years (Hoinka, 1986; Hoinka and Volkert, 1987). In this paper the analysis of the cold front of 29 July 1986 is presented based on serial radiosonde ascents launched during the event. Conventional surface, radar and satellite data are discussed in order to show the scale-dependent appearance of this cold front.

2. The synoptic environment

During the 29 July 1985 a trough was located over the British Isles leading to southwesterly flow over Central Europe in which a cold front was imbedded. The three-hourly isochrones of the surface front line (Fig.1) reveals that the eastward movement of the front is significantly retarded by the Alps with blocking at its the western edge and slackening along its northern rim. On this day the typical surface pressure structure (Fig.2) can be seen which is characteristic for cross-alpine flow with a mesoscale ridge of high pressure at the windward side of the Alps and a lee side prefrontal trough (Hoinka et al., 1990). An additional low level blocking is apparent in a ridge of high pressure at the rear side of the cold front at the northwestern rim of the Alps. The largescale pressure gradient pointing towards the southeast may cause an acceleration of the front along the northern side of the Alps whereas the mesoscale low level gradient pointing towards the west may force a deceleration.

Fig.1: Three-hourly isochrones of the cold front on 29 July 1985.

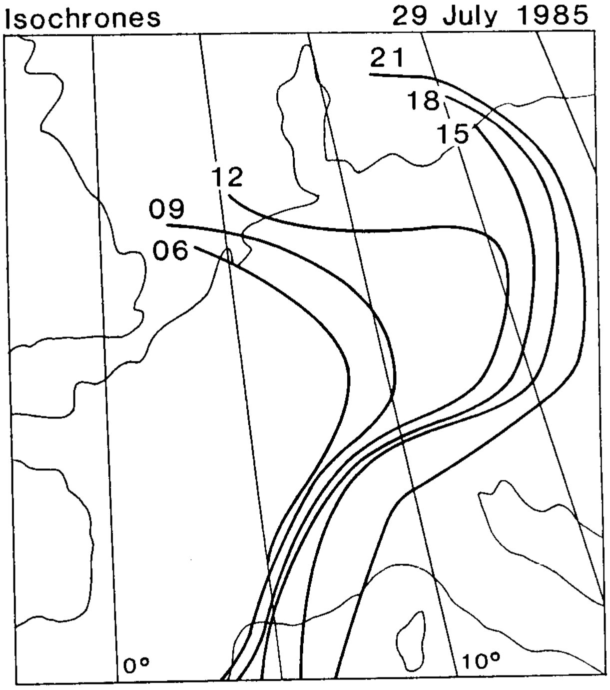


Fig.2: Mesoscale surface analysis of 29 July 1985, 12 UTC (taken from the Berliner Wetterkarte).

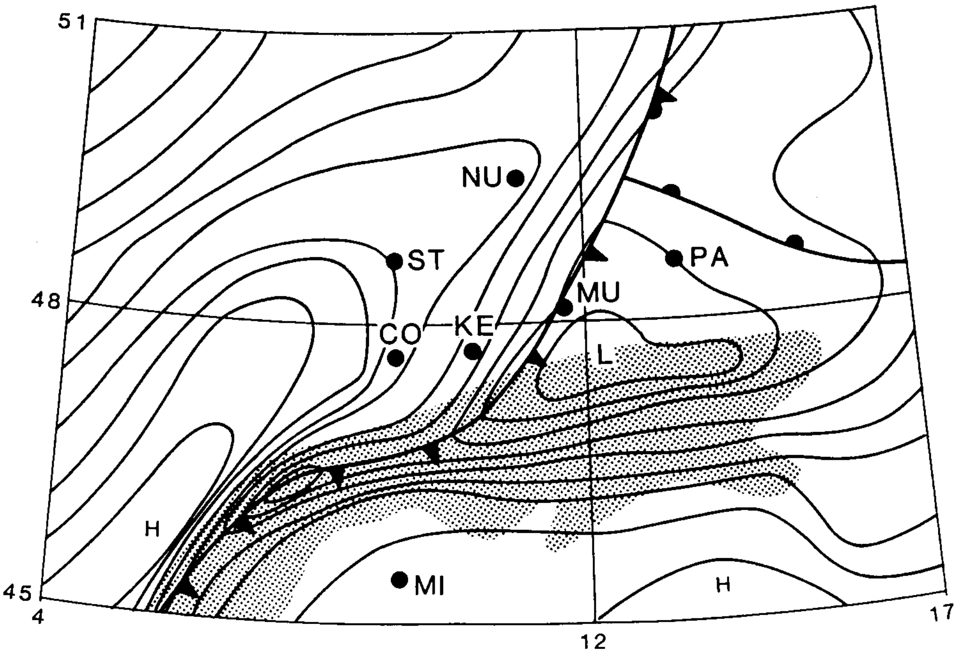


Fig.3 shows the infrared NOAA image of 29 July 1985 with different spatial resolution. The colours indicate four different temperature ranges chosen in order to characterize the ground or areas with weak cloud coveridge (black), low level clouds (green), medium level clouds (red) and high convection (white). The image shows the classical synoptic-scale picture of a cold front with an extended cloud band indicating the frontal transition zone followed by the postfrontal clearing of the sky. At the rear side of the region covered with clouds, a well defined narrow cloud band is apparent. To the east of the narrow cloud band at some distance ahead of the front, several white spots indicate extended deep cumulus clouds. These complexes, to some extent similar to the mesoscale cloud systems occurring east of the Rocky Mountains, grew within three hours approximately trippling its size. Similar convective cells, occurring in the same area, were reported by Setvák and Doswell III (1991).

The surface front line passed Munich (cross) at 1330 UTC which is about 4 hours ahead of the cloud band in the NOAA image. Thus the position of the surface front line in the satellite image is about in the center between the western edge of the main cloud band and the prefrontal mesoscale cloud systems. An intercomparison of the 1800 UTC isochrone (Fig.1) and the NOAA-image at 1738 UTC (Fig.3) shows that the surface front line is well ahead of the narrow cloud band north of the Alps. The cloud band seems to be undisturbed by the western flank of the Alps whereas the surface front line is significantly blocked by the mountains. The intercomparison shows the difficulties in relating the cloud distribution to the surface front line. Various small-scale cloud bands are appear in the postfrontal region, in particular in the enlarged area shown in Fig.3c. Above the Rhine valley, the deepness of the narrow

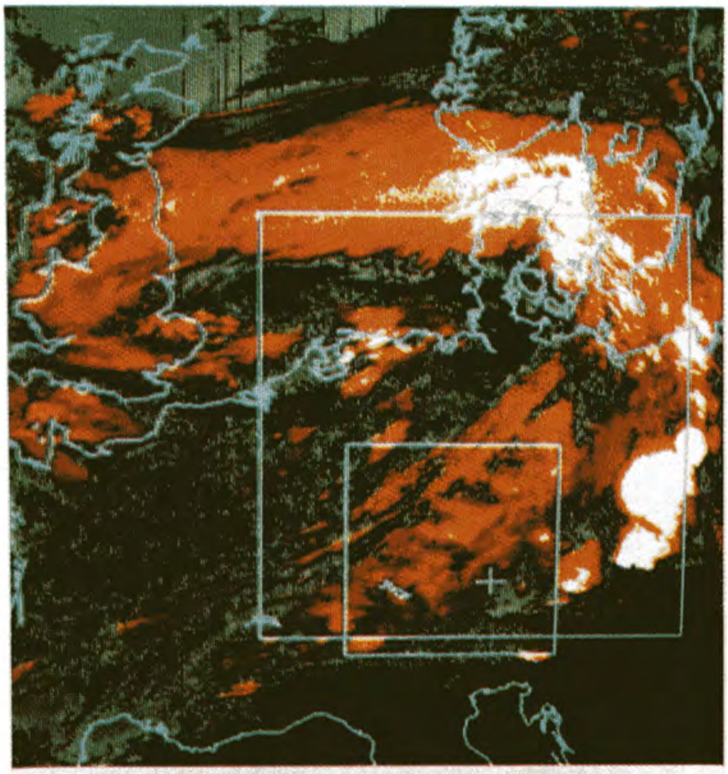
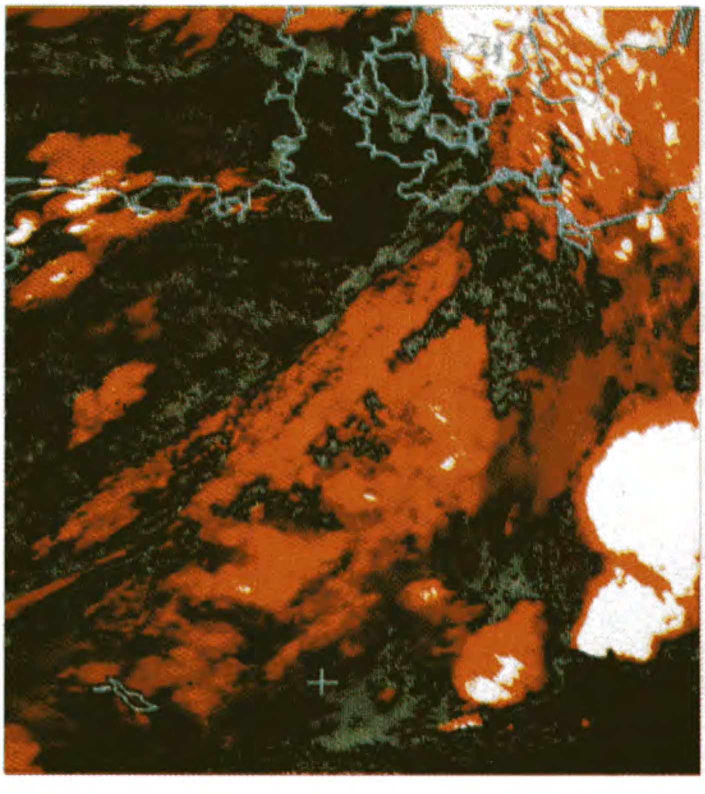
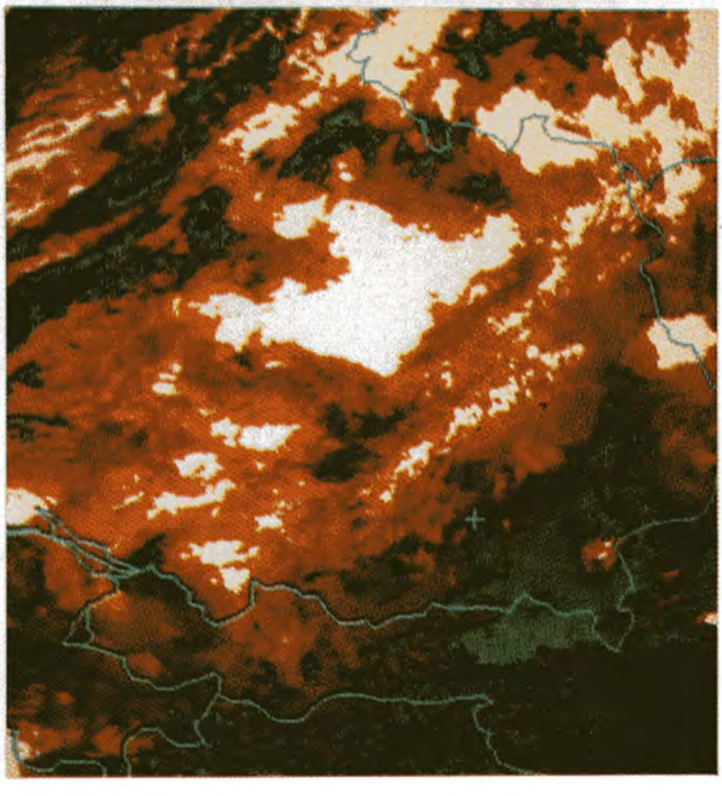
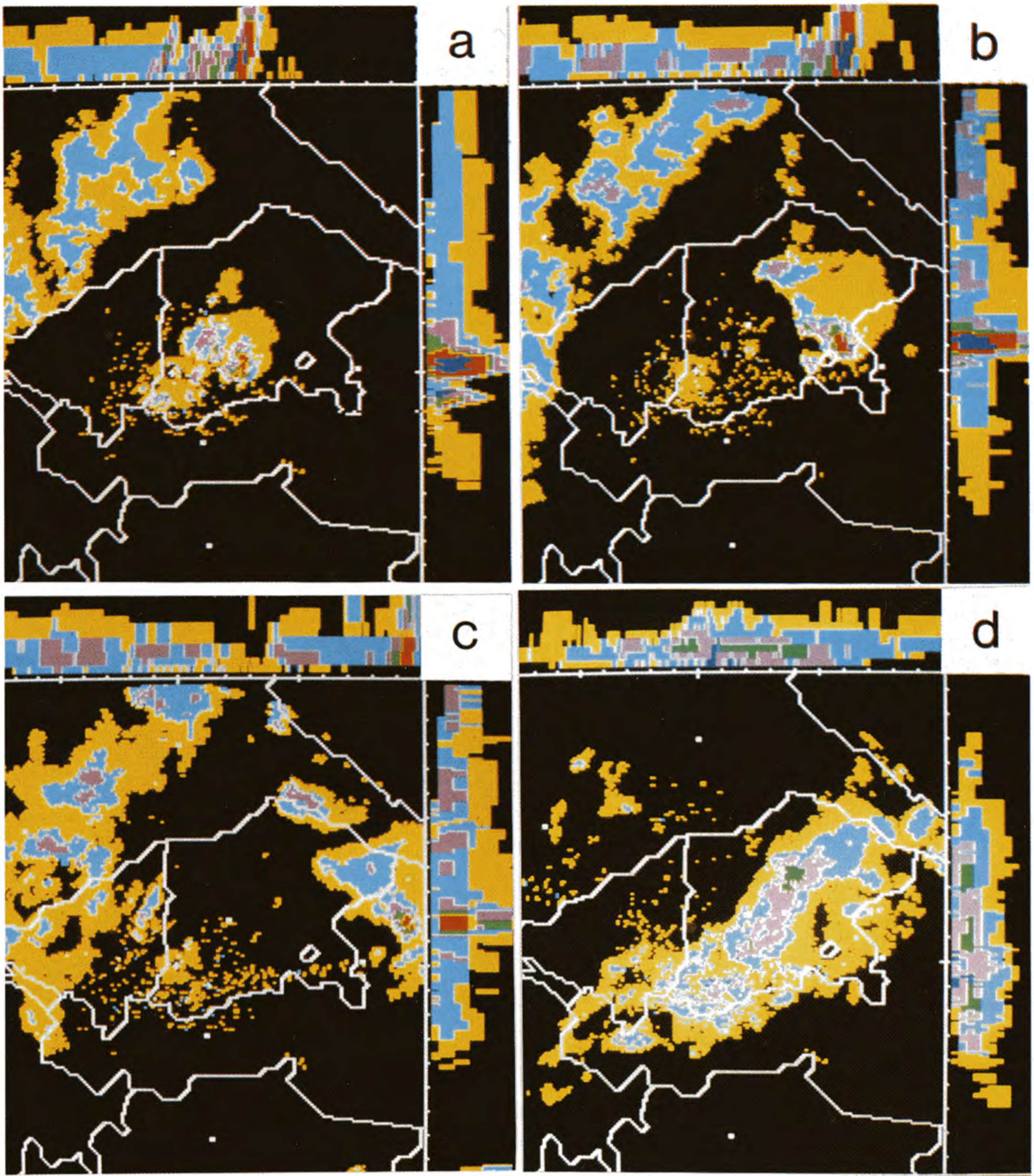


Fig.3: Infrared NOAA-9 image of 29 July 1985, 1738 UTC. The approximate borders of figures (b) and (c) are indicated in (a). In (c) Southern Germany is enlarged showing with blue lines the boundaries of western Austria. The cross indicates the location of Munich. The colours limit the following temperatures, T, in (a) and (b), the values for (c) are given in brackets:
white $T \leq -60\ (-45)\ C^0$,
red $T \leq -40\ (-25)\ C^0$,
green $T \leq 0\ (5)\ C^0$ and
black $T \leq 15\ (15)\ C^0$.







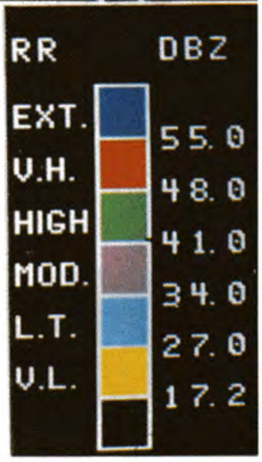


Fig.4: Range height intensities (RHI) of radar reflectivity taken by the weather radar at Hohenpeissenberg on 29 July 1985, at 1506 UTC (a), 1606 (b), 1706 UTC (c) and on 30 July, at 0106 UTC (d). The RHI angle is 0.5° (by courtesy of DWD Hohenpeissenberg). At the top and right hand side rims of the figures the vertical distribution of the reflectivity along the corresponding zonal or meridional band is shown. The lower figure to the right shows the colour scale of the rain rate (RR) and of the reflectivity in dbz.

cloud band is about 12 km derived from the temperature of the cloud tops. The cross-banded scale is about 30 km. Additionally, the banded structure of the embedded convection can be seen clearly. The cloud distribution shown in the satellite images suggests that the frontal structure was three-dimensional, in particular for scales smaller than the mesoscale.

Heavy hail was associated with the embedded convective complexes above south-eastern Germany and at the border to Austria in the Salzburg area during the late afternoon on 29 July 1985. This hail caused heavy damage in housing, forests and high tension cables. The storm gusting up to 50 m s^{-1} took about 40 min and produced hail stones of up to 20 cm. A weather radar at the observatory Hohenpeissenberg, located about 50 km to the south of Munich, took hourly observation. The radar images (Fig.4) depict clearly the development of the isolated area of strong cummulus convection to the east of Munich with very strong radar signal indicating heavy precipitation between 1506 UTC (Fig.4a) and 1706 UTC (4c). Even in the satellite image (Fig.3c) the starting phase of the isolated hailstorm in south-eastern Germany is notable by an isolated red-white spot to the east of Munich.

The vertical distribution of reflectivity (top and right hand side rims) indicates that the strong convective elements grew up to a height of more than 8000 m. The radar images indicate also that a broad band of postfrontal precipitation crossed the Danube river to the west of Munich around 1500 UTC; this shows that the strong postfrontal rain started about 70 km (or 1.5 hrs) behind the leading edge of the front. The orientation of the precipitation area was south-west to north-east. The structure became convex with decreasing propagation at the northern rim of the Alps during the night (Fig.4d).

3. The mesoscale frontal structure

Between 0800 and 1400 UTC a prefrontal convergence line crossed southern Bavaria followed by the cold front by about 5 hrs (Tab.1). Associated with the convergence line was a pressure jump, weakly increasing along the borderline of the Alps towards the east; a similar increase is apparent in the temperature drop. In contrary the temperature drops associated with the following cold front decrease towards the east; the pressure drop remains about constant. The readings of the pressure drop at Mühldorf show, however, a very strong drop which is due to the isolated hailstorm which developed at the same time in this area. The character of the prefrontal convergence line can be seen also in the data taken at a tower north of Munich (Fig.5). The change in wind direction and wind speed at 1030 UTC, when the convergence line (A) passed the tower, is significant whereas the temperature drops are moderate for both surface lines. With the passage of the convergence line the wind is veering from the east towards the northwest. With the front itself no change in direction occurs and the velocities drop apparently about one hour later. One feature worth noting is that the temperature drop at 50 m occurred about 12 min in advance of the temperature drop at the surface. This time difference relates to about 4 km horizontal distance based on a frontal propagation of about 6 m s^{-1}. This forward sloping of the frontal surface might be due to boundary layer effects. The pressure begins steadily to rise behind the convergence line since the front itself is associated with a weak pressure drop.

Location	$t(\Delta p)$	$\Delta p/\Delta t$	$t(\Delta T)$	$\Delta T/\Delta t$
Prefrontal convergence line (A)				
Kempten	0800	1 hPa/30min	0800	-1 K/h
Augsburg	0830	1 hPa/h	0830	$\approx$0 K/h
Garching	1030	1 hPa/h	1030	-3 K/h
München-Riem	1030	very weak	1030	-2 K/h
Oberpfaffenhofen	1045	1 hPa/h	1200	-3 K/h -1 K/5 min
Mühldorf	1300	1 hPa/h	1330	-3 K/h
Passau	1400	2 hPa/h	1400	-4 K/h
Cold front (B)				
Kempten	-	no	-	no
Augsburg	1230	1 hPa/h	1300	-4 K/h
Garching	1400	1 hPa/h	1400	-2 K/30min
München-Riem	1300	1 hPa/h	1500	-3 K/h
Oberpfaffenhofen	1535	0.8 hPa/5min	1535	-4 K/h -1.9 K/5 min
Mühldorf	1600	2 hPa/30min	1700	-2 K/h
Passau	-	no	1800	-2 K/h

Tab.1: Pressure jumps and temperature drops observed at various stations in Bavaria associated with the prefrontal convergence line (A) and the cold front (B) of 29 July 1985.

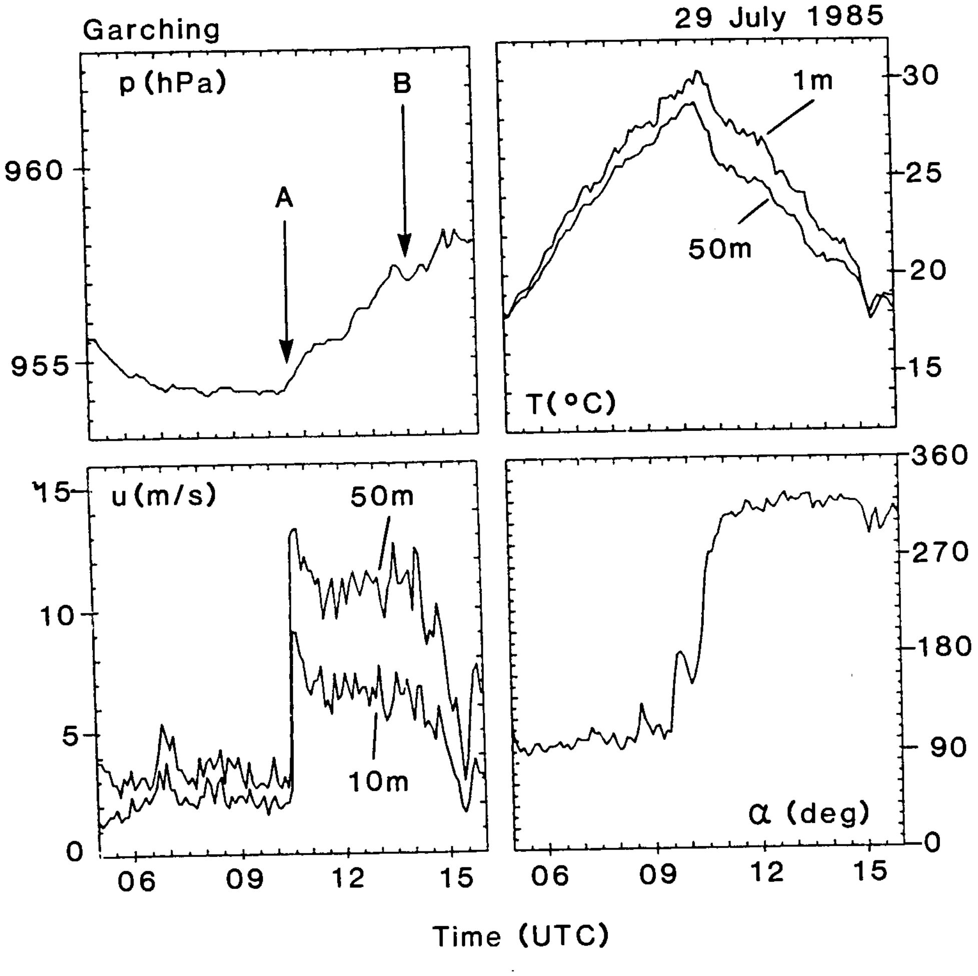


Fig.5: Time series of wind velocity, wind direction, pressure and temperature on 29 July 1985 taken by a tower at Garching which is about 25 km north of Munich. The arrow (A) indicates the prefrontal convergence line and (B) the cold front.

Prefrontal convergence lines are characteristic features of the prefrontal atmosphere north of the Alps. These convergence lines may be transformed into a new front lines, which seems to be the more typical process than a strengthening of the primary front close to the Alps. Usually the pressure rise starts with the passage of the leading line whereas the air mass change is associated usually with the second line which passed Oberpfaffenhofen at 1535 UTC in the present case.

Tab.2 shows the temperature drops followed by the cold front at various stations in Southern Germany along lines parallel to the baseline of the Alps. In general these drops are larger in magnitude than those associated with the prefrontal convergence line. At all distances from the Alps the temperature drops increase towards the east. These values indicate also that the closer the front is to the orography the stronger are the temperature drops. A similar behaviour is reported from Volkert et al. (1991) for the "Papal Front" of 3 May 1987. By aid of a numerical model and observations, Hartjenstein and Egger (1990) showed also that during a strong frontal event the temperature drop increase along the Alps and decrease away from the Alps. These variations in the temperature drops in combination with an increase in speed of frontal propagation suggest that the Alps may have influenced these cold fronts.

≈200 km:	Mannheim -1.0	Würzburg -1.4		Nuremberg -5.6	Weiden -4.6
≈150 km:	Karlsruhe ≈0.0	Stuttgart -2.9	Stötten -3.6	Regensburg -4.0	Gr. Arber -5.6
≈50 km:	Freiburg -0.6	Constance -3.8	Kempten -7.0	Munich -7.4	Passau -9.3

Tab.2: Three-hourly temperature drops associated with the cold front of 29 July 1985 towards the east along three lines north of the Alps; the values in km are the corresponding distances to the north from the baseline of the Alps.

The mesoscale velocity of the front is evaluated by tracing the temperature and pressure signals along several synoptic stations north of the Alps. It was determined subjectively on the assumption that the front was locally straight and moved with uniform speed and orientation. The arrival times were based on the time where the pressure starts steadily to rise; the frontal speed resulted to $c = 6.1$ m s^{-1} from 315^0. This speed is smaller than the value observed from a synoptic scale objective analysis (10.7 m s^{-1}) based on a line parallel to the baseline of the Alps from west to the east.

During the passage of the cold front on 29 July 1985 seventeen radiosondes were launched from the Oberpfaffenhofen airport located about 25 km to the southwest of Munich. Fig.6 presents a cross-sectional analysis of potential temperatures (top) and equivalent potential temperatures (bottom) derived from these data. The veering of the wind vector with height can be seen clearly. The south-westerly flow above the frontal surface and the westerly to north-westerly flow within the cold air can be seen clearly by the veering of the wind vector with height after the passage of the convergence line around 1100 UTC. Usually, the equivalent potential temperature (θ_e) is an excellent measure of an air mass. In the present situation, however, there was no strong change in air mass which results in no strong differences between the potential and the equivalent potential temperature. This is also confirmed by the moderate temperature drop at the tower of Garching (Fig.5). In the low level prefrontal area the potential temperatures are up to 310 K indicating the warming due to a weak prefrontal foehn which occurred at that day. The steep sloping of the isentropes indicates that the head of the frontal surface is characterized by a steep inclination within the lowest 1500 m.

The cross-frontal temperature differences were not very strong for the present front resulting in about 0.34 K km^{-1}. Further cross-frontal changes are: $d\theta/dx = 0.36$ K km^{-1}, and $d\theta_e/dx = 0.61$ K km^{-1}. These values are based on a frontal propagation speed of 6.1 m s^{-1}. For an orographically forced cold front in Australia (southerly buster), values of up to 0.5 K km^{-1} in the cross-frontal difference in the virtual potential temperatures were reported (Coulman et al., 1985). These temperature gradients are not comparable in magnitude to those found in frontal zones observed above the ocean, 0.8 K per 100 m (Bond and Fleagle, 1985), in the vicinity of the Rocky Mountains, 3 K per 100 m (Shapiro, 1984), and in southern Germany, 1 K per 100 m (Hoinka, 1987). The value for the last case was obtained by analysing aircraft data; this and the other mentioned values represent small-scale cross-frontal differences. The weak gradients observed at the front of 29 July 1986 are mainly due to the observing system of radiosonde recording half-hourly the data; thus, strong gradients cannot be obtained. Of strong importance is the flow relative to the front. Time-height cross sections of the cross-front and along-front components of the wind, in a frame of reference moving with the front, are shown in Fig.7 which reveals a number of significant features of the low level wind structure. The prefrontal southwesterly 'jet' (only 5 m s^{-1}) is characteristic for prefrontal southerly flows in the Alps, mostly associated with foehn. Consequently, in the cold air there is the postfrontal northerly 'jet' with maximum wind of up to 10 m s^{-1} (Fig.7, bottom). The physical basis for both, the pre- and the postfrontal jet involves the opposition of surface geostrophic wind and thermal wind, and the influence of friction near the ground. The cross-frontal winds show the typical flow towards the frontal zone in both, the pre- and the postfrontal area. Similar features were reported for Australian cold fronts by Garratt et al. (1985; see their Fig.12).

4. Conclusions

In the present study data taken at a cold front associated with a prefrontal convergence line and a prefrontal hailstorm were analyzed. These lines are frequently observed at the northern side of the Alps and it is assumed that they are sometimes generated by the influence of the mountains. It is under discussion which role these lines play in generating prefrontal hailstorms and squall lines. Meischner et al. (1991) analyzed recently the development of a prefrontal squall line in Southern Germany and suggested that the squall line was associated with prefrontal convergence lines. They emphazise that favorable synoptic conditions for the occurrence of hailstorms and squall lines in Bavaria are a southwesterly flow towards the Alps in the leading branch of a trough with an imbedded cold front and prefrontal convergence lines. Between fall and springtime this synoptic environment is favorable for foehn at the north side of the Alps whereas during the summer foehn is very rare. During this time of the year the increased surface heating associated with deep-layered instability generate strong convection; so, hailstorms and squall lines are usually observed during the summer.

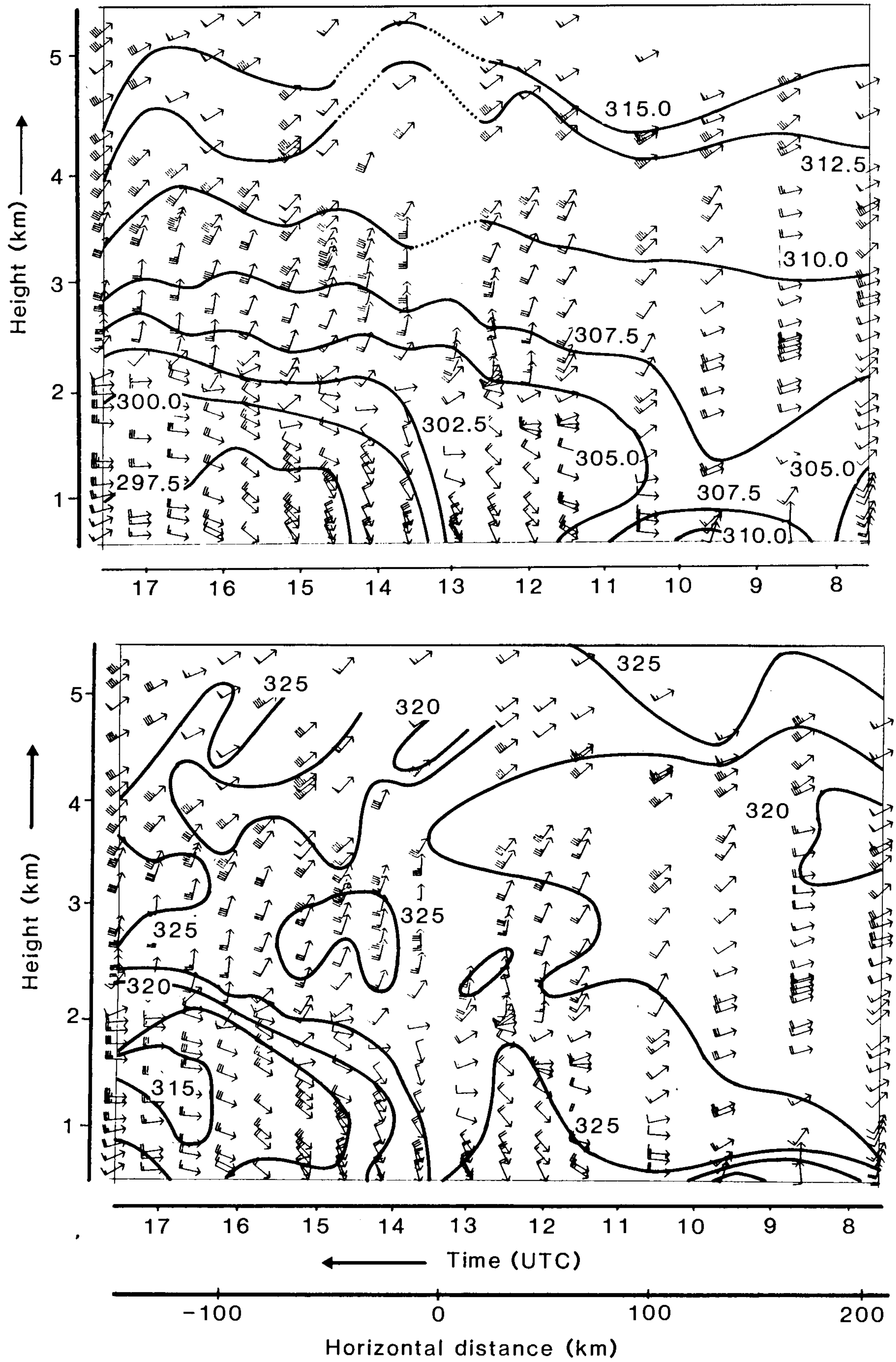


Fig.6: Time-height cross sections of horizontal wind vector, potential temperature (top) and equivalent potential temperature, both in K, on 29 July 1985 based on radiosonde data. The temperatures are given in K. The horizontal wind vector is shown with 4 m s^{-1} equivalent to one barb and the triangle stands for 20 m s^{-1}.

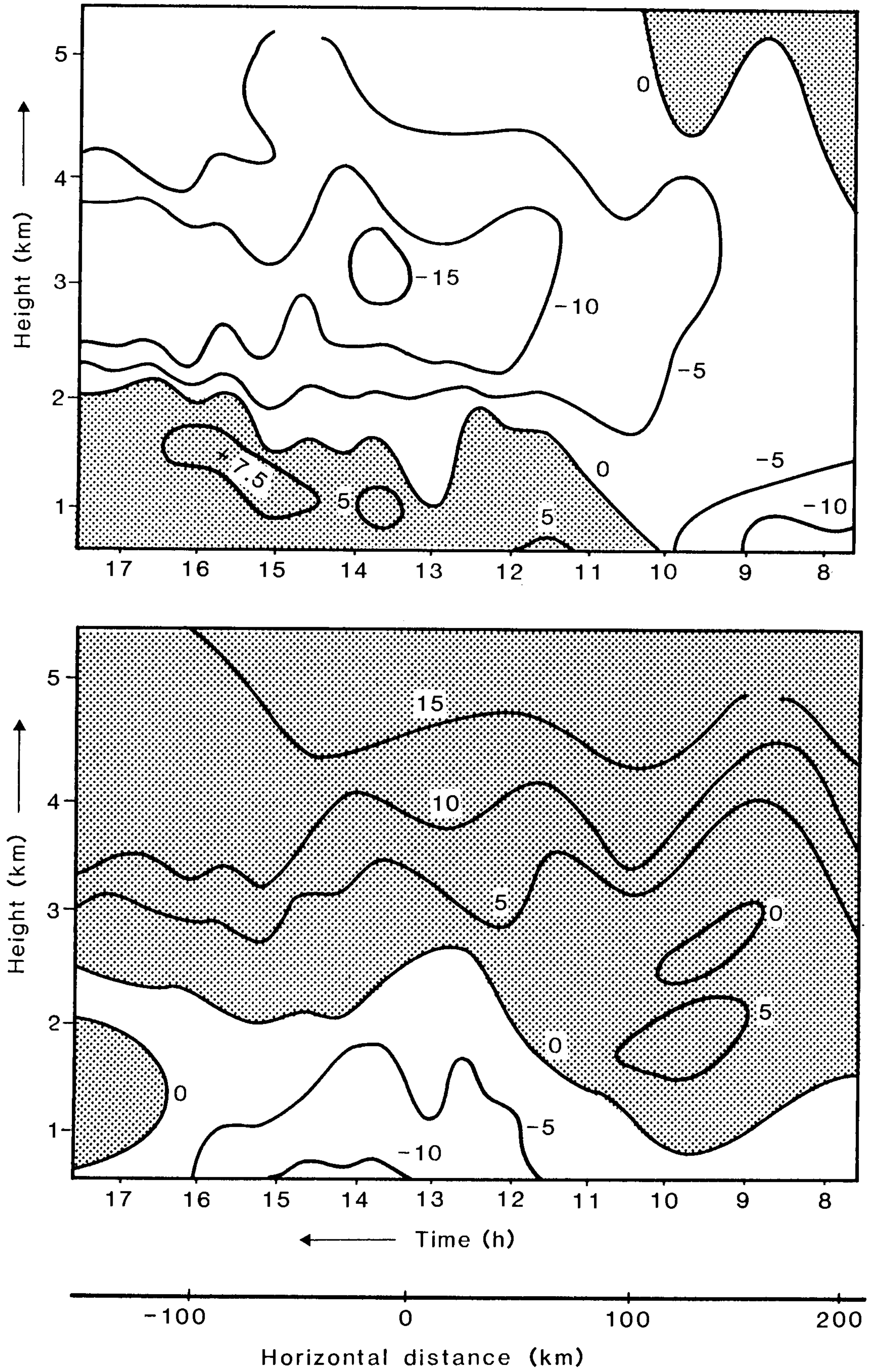


Fig.7: Same as Fig.6, but for the cross-frontal wind u-c (top) and for the along-front wind v (bottom), both in $m\,s^{-1}$. Positive cross-frontal velocities signify flow from the left. Positive values in the along-front flow means flow into the plane of the cross-section. The hatched areas indicate negative flow values. The sections are oriented from the north-west (to the left) to the south-east (to the right).

In general it is not clear, whether these convergence lines force convection or whether the developing convection generates the line-structured convergence. Additionally the orographic impact on these interactive processes are in question.

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