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The unexpected snowstorm of 13–14 January 2002 in Zagreb

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The purpose of this paper is to present the causes of an unusual event of local snowstorm which lasted continuously for 28 hours resulting in 23 cm of snow. It was poorly forecasted since it occurred under a steady surface anticyclone in south-eastern Europe, east of the Alps. In the troposphere the most noteworthy feature was the middle-upper tropospheric front in an environment marked by sinking motion presented by the Q vectors field. It formed upstream from an intensifying cold trough in less than half a day. Another extraordinary feature was a low tropopause with a breaking region exchanging tropospheric and stratospheric air just above the area of Zagreb. The processes which mainly characterised this event in synoptic scale were advections of potential vorticity in the stratosphere and troposphere along the tropospheric cold trough.

The interactions of orographically induced polar air upsloping clouds by synoptic scale in westerlies and the low level mesoscale saturated air, influenced by the terrain in the area of Zagreb by easterly flow, were considered the causes of the snowfall. Such an event leads to the "feeder-seeder" process in which large scale ascent generating higher level seeder clouds containing ice droplets large enough to efficiently washout precipitation to interact with the lower level (feeder) moisture area and cause precipitation. This is considered one of the few significant mesoscale precipitation processes that is essentially entirely microphysical in nature.

Keywords: middle-upper tropospheric front, potential vorticity, tropopause break, "feeder-seeder" washout process

1. Introduction

It is known that snowfall usually occurs under the influence of surface fronts and cyclones. This paper presents an interesting and unusual snowstorm event in Zagreb (Croatia) without fronts and cyclones at the surface. Instead there is a broad and steady anticyclone occupying the south-easterly part of Europe to the east of the Alpine area.

The extraordinary feature found in the troposphere was the middle-upper tropospheric front, also called a hyperbaroclinic zone, a zone of strong quasi-horizontal temperature gradient, which does not necessarily extend to the surface (Bluestein, 1993). Unlike surface fronts, upper-level fronts are not described as warm and cold, since they behave like segments of quasi-stationary fronts that move parallel to themselves.

Supposing that the temperature on a constant pressure surface decreases to the north (y) according to the quasi-geostrophic theory, the frontogenetical function for these fronts is

$$F = \frac{\partial v_g}{\partial y}\frac{\partial \theta}{\partial y} + \frac{\partial \omega}{\partial y}\frac{\partial \theta}{\partial p} \tag{1}$$

where v_g is the meridian wind component, θ is the potential temperature, ω is the vertical velocity.

Subsidence ($\partial\omega/\partial y < 0$) superimposed upon a temperature gradient ($\partial\theta/\partial y < 0$) in a statically stable atmosphere ($\partial\theta/\partial p < 0$) can initiate upper-tropospheric frontogenesis. If the static stability and quasi-horizontal variation in subsidence remain constant, the frontogenesis occurs at a relatively slow rate which is according to (1)

$$\frac{d}{dt}\left(-\frac{\partial \theta}{\partial y}\right) = \frac{\partial \omega}{\partial y}\frac{\partial \theta}{\partial p} \tag{2}$$

For typical values of ω and static stability $\partial\theta/\partial p$ the temperature gradient only doubles in approximately one day. Therefore this simple and physically clear version of (2) can explain only a part of the process, and through this mechanism the observed rates of frontogenesis would be too slow.

However, the influence of the geostrophic circulation in the time scale for frontogenesis can be illustrated by comparing the process included in the quasi-geostrophic and semi-geostrophic processes. The semi-geostrophic model (subject to the geostrophic momentum approximation) can produce an infinite temperature gradient at the surface in less than half a day (e.g. Holton, 2004).

For locating the middle-upper tropospheric front one needs to identify an area of vertical motions. In order to do this properly, the studies of vertical motions in the traditional way are criticized by many authors (Trenberth, 1978; Hoskins and Pedder, 1980; Durran and Snellman, 1987; and others). The authors who provide a convenient way to a quick and qualitative assessment of this problem are Hoskins et al. (1978). They have shown that a drawback of the usual ω equation is that there can be large cancellation between two terms in ω equation, the vertical derivative of vorticity advection and the horizontal Laplacian of thermal advection; each term in isolation can be misleading since they are not independent. Each term contains a common cancelling component, particularly for the middle troposphere, where both terms contribute nearly equally to vertical motions, and part of each term cancels.

Hoskins et al. (1978) introduced the Q-vector forced by the divergence of this vector defined by the relation

$$\left(\sigma\nabla^2 + f^2 \frac{\partial^2}{\partial p^2}\right)\omega = -2\nabla \cdot \boldsymbol{Q} \tag{3}$$

where ∇ is the static stability, and f the Coriolis parameter.

This shows that the vertical motion will be upward when the Q-vector field is convergent and downward if this field is divergent. Q-vector is estimated best between 600–400 hPa when the vertical motion is least influenced by the forcing at other levels. This is important for the present study since it concerns mostly the middle tropospheric condition.

Evidently there are still other physical factors that are relevant for explaining the structure and fast development of the middle-upper tropospheric front, such as potential vorticity. The creation of potential vorticity by the stretching of vortex tubes and the horizontal advection of absolute vorticity gives the simplest version of the modern concept of potential vorticity which we shall indicate as PV for short.

Hoskins et al. (1985) indicate that a definition of tropopause in terms of PV would be more useful than a lapse rate. Keyser and Shapiro (1986) noted that some models considered that tropospheric frontal systems result from a process of tropopause breaking influenced by PV which transports lower stratospheric air downward into the troposphere, occasionally reaching 700–800 hPa in particularly intense cases. This was based on the relation

$$PV = -(\xi_\theta + f)\frac{\partial\theta}{\partial p} \tag{4}$$

where the isentropic absolute vorticity $(\xi_\theta + f)$ is a dynamical tracer for distinguishing between stratospheric and tropospheric air along parcel trajectory. The decrease of PV with decreasing altitude is suggestive of turbulent mixing in stratospheric and tropospheric air across the frontal boundaries.

The major importance of snowfall in this event is the interaction of two orographically induced clouds. One is the polar air cloud over mountains in synoptic scale, and another is the mesoscale moisture area in the plains at low levels close to Zagreb.

The upper level cloud is sufficiently cold to generate ice crystals, supplying them to the moisture area below, and washout its water to produce precipitation. This represents the illustration of the "feeder-seeder" process by which the lower feeder cloud is microphysically simulated to receive the ice particles from the seeder cloud above it. The super cooled layer of cloud may form well above the upslope clouds in the counter-current that brings its moisture from a totally different source (Reinking and Boatman, 1986).

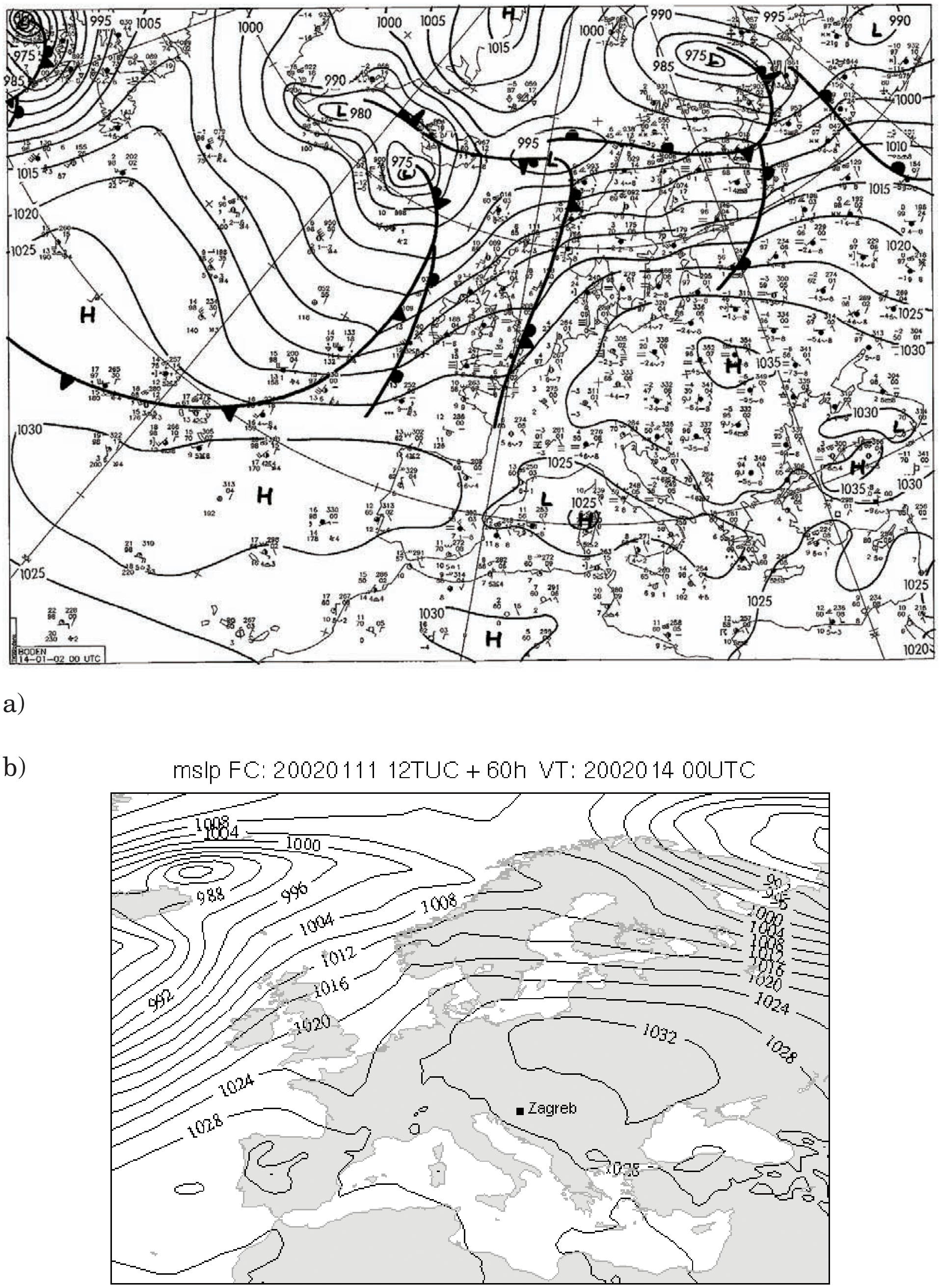


Figure 1. a) Surface analysis 14 January 2002 00 UTC. (Deutscher Wetterdienst) b) Prognostic surface map 14 January 2002 00 UTC, run model 11 January 2002 12 UTC (ECMWF).

The low upslope lifting alone does not influence the precipitation although its moisture is ready for such a condition. It is the seeder cloud above which supplies the feeder area resulting in snow. According to Bluestein (1993) the generation cells are often located in layers of contributive instability and the precipitation may form in the cloud below. The "feeder-seeder" process is thus hybrid in that both a layer of convective instability and stability are present. It is one of the few significant mesoscale precipitation events that are essentially entirely microphysical in nature.

2. Synoptic overview

The snowstorm considered in this paper occurred locally in the city of Zagreb lasting continually from 14 UTC on 13 January to 18 UTC on 14 January 2002 resulting in 23 cm of snow depth (Jurčec and Dragojlović, 2003). It was not predicted by local forecasters. Such an anticyclonic area could have showers but mainly in summer due to large convection with high temperature at the surface and cold core in the high troposphere. This was not the case, and in this event it was cold in the troposphere, and cold at the surface. Both the surface map (Figure 1a) and prediction (Figure 1b) were very similar during the snowstorm in Zagreb, with an anticyclonic centre in Eastern Europe.

The condition in the lower troposphere is best pronounced by the RT 500/1000 thickness map on 13 January at 12 UTC; with a cold centre to the north of Zagreb, which follows the cold tropospheric frontal zone. This is shown in Figure 2a for 13 January 2002 at 12 UTC just before the snow began falling. The corresponding prognostic map RT 500/1000 at this time shows in Figure 2b with stronger thickness gradient on W-SW part of this centre.

The precipitation prediction for each 12 hours in the considered period is given by ECMWF (Figure 3a) showing this distribution of precipitation for two 12h periods: on 13 January from 18 UTC to 14 January at 06 UTC, when the precipitation started, and continued until 14 January at 18 UTC, when it already started weakening in the area of Zagreb. Only a very small part of the left figure shows some stronger precipitation in the middle which could be in the area of Zagreb. However, all this predicted amount of precipitation is weak, contributing less then 10mm. On the other hand, even such a small amount could be sufficient for this process, since a number of authors (e.g. Raddatz and Khandekar, 1979) consider that to be the main contribution toward the upslope precipitation rates coming from a low level amount of water.

Figure 3c shows, for the same 12h periods, the amount of snow which, according to this prediction, is not more than 5cm in the area of Zagreb. Thus, when these amounts of precipitation and snow were available to the parameters at that time, they could not help to give a correct prediction for the snow that led to chaos in Zagreb transportation.

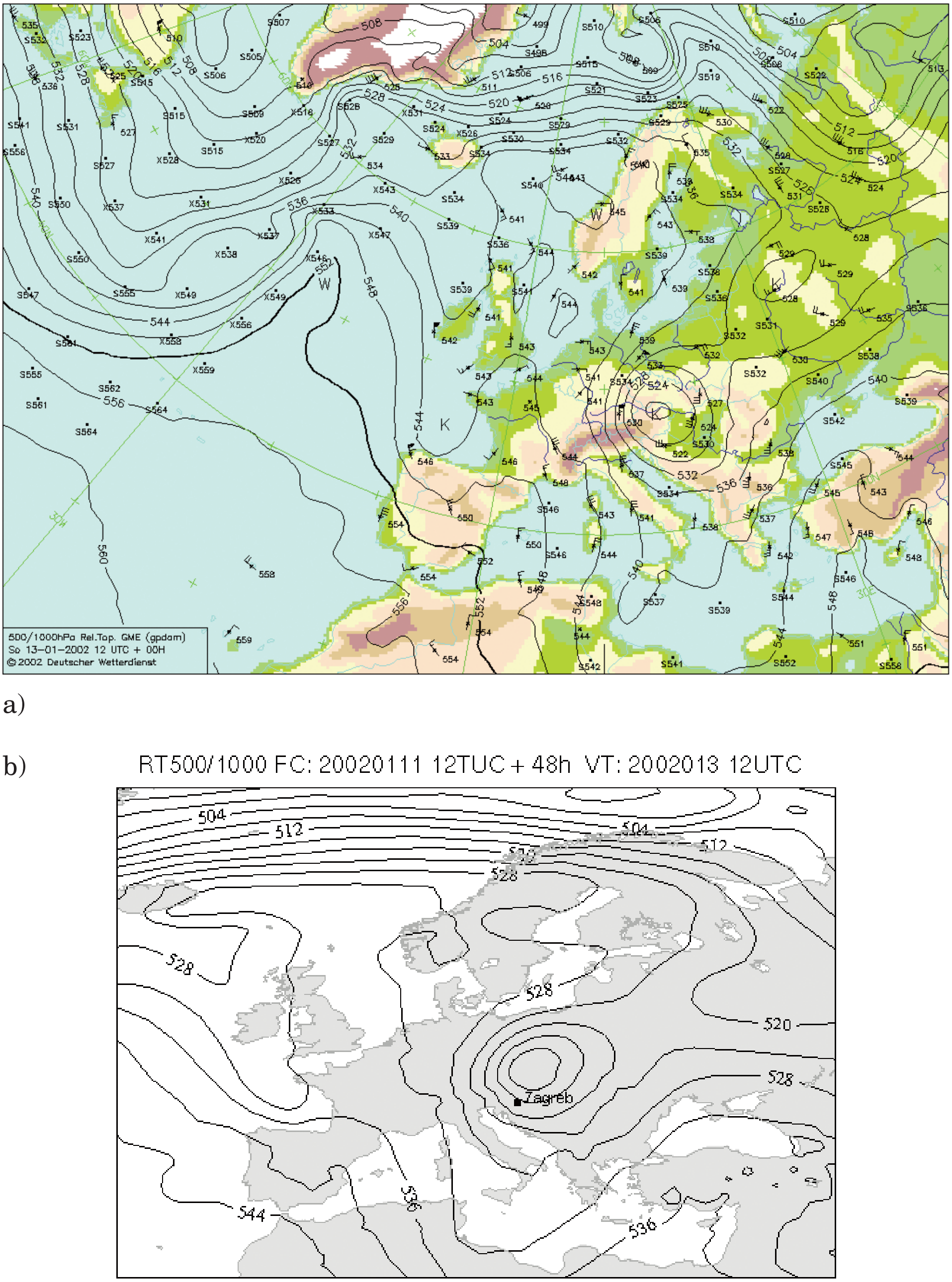


Figure 2. a) 500/1000 hPa thickness, 13 January 2002 12 UTC. (Deutscher Wetterdienst) b) Prognostic thickness 500/1000 hPa 13 January 2002 12 UTC, run model 11 January 2002 12 UTC (ECMWF).

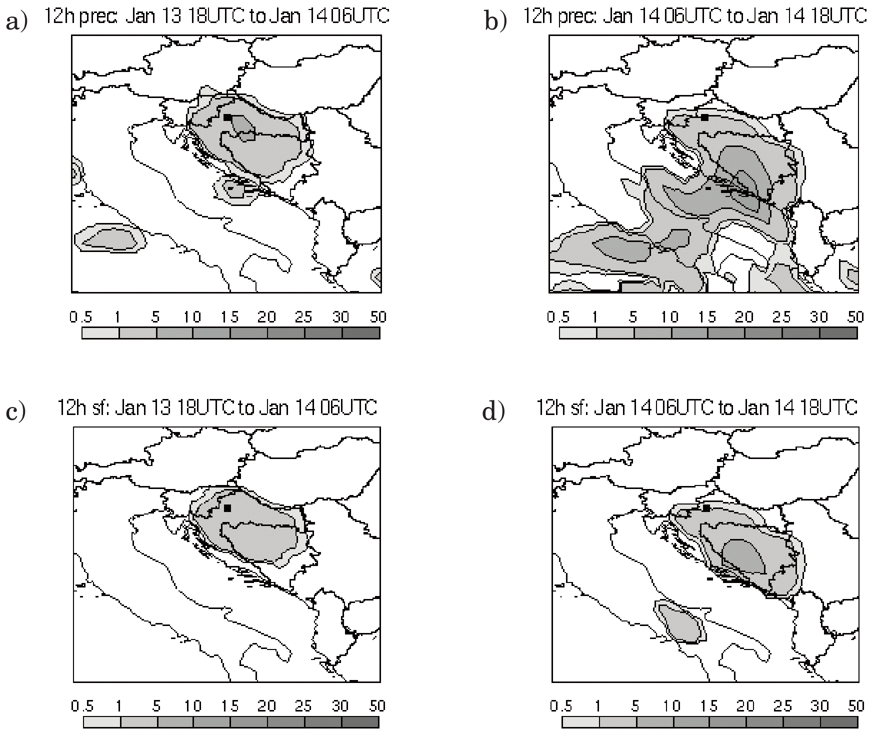


Figure 3. Prognostic chart, run model 11 January 2002 12 UTC (ECMWF):
a) 12 h percipitation 13 January 2002 18 UTC – 14 January 2002 06 UTC,
b) 12 h percipitation 14 January 2002 06 UTC – 14 January 2002 18 UTC,
c) 12 h snow 13 January 2002 18 UTC – 14 January 2002 06 UTC,
d) 12 h snow14 January 2002 06 UTC – 14 January 2002 18 UTC.

The satellite picture (Figure 4a) dated 13 January 2002 shows clouds over western Croatia related to the middle-upper tropospheric front. Figure 4b, dated 14 January 2002, shows weak strengthening and moving toward the south-east.

3. Middle-upper tropospheric front and Q-vector forcing

The most characteristic feature on 500 hPa (Figure 5) is a frontal zone with a large temperature gradient associated with strong geostrophic winds close to the western side of the cyclone. This is the middle-upper tropospheric front described earlier. On 13 January at 12 UTC this front formed in north-eastern Germany, and by the next day it was moving to the south, toward the north Adriatic Sea. This front was developing very fast and it was frontogenetical with the strong subsidence in the cold advection area.

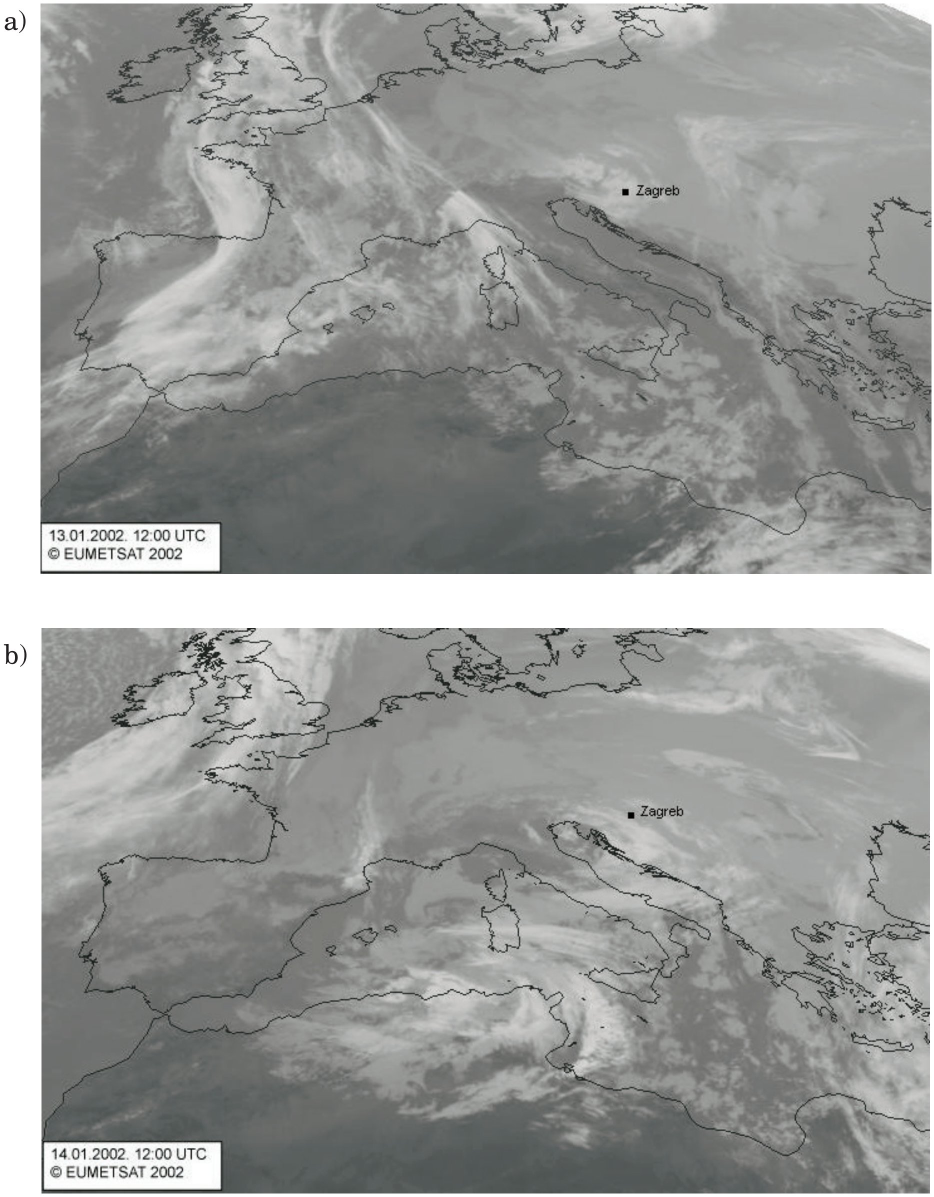


Figure 4. a) Meteosat 7, IR 10.8 satellite image from 13 January 2002, 12 UTC b) Meteosat 7, IR 10.8 satellite image from 14 January 2002, 12 UTC.

It is frontogenetical not only in the sense that it generates frontal properties along parcel trajectory, but also in that it transports these properties downward as they are generated (Keyser and Shapiro, 1986). Figure 5 indi-

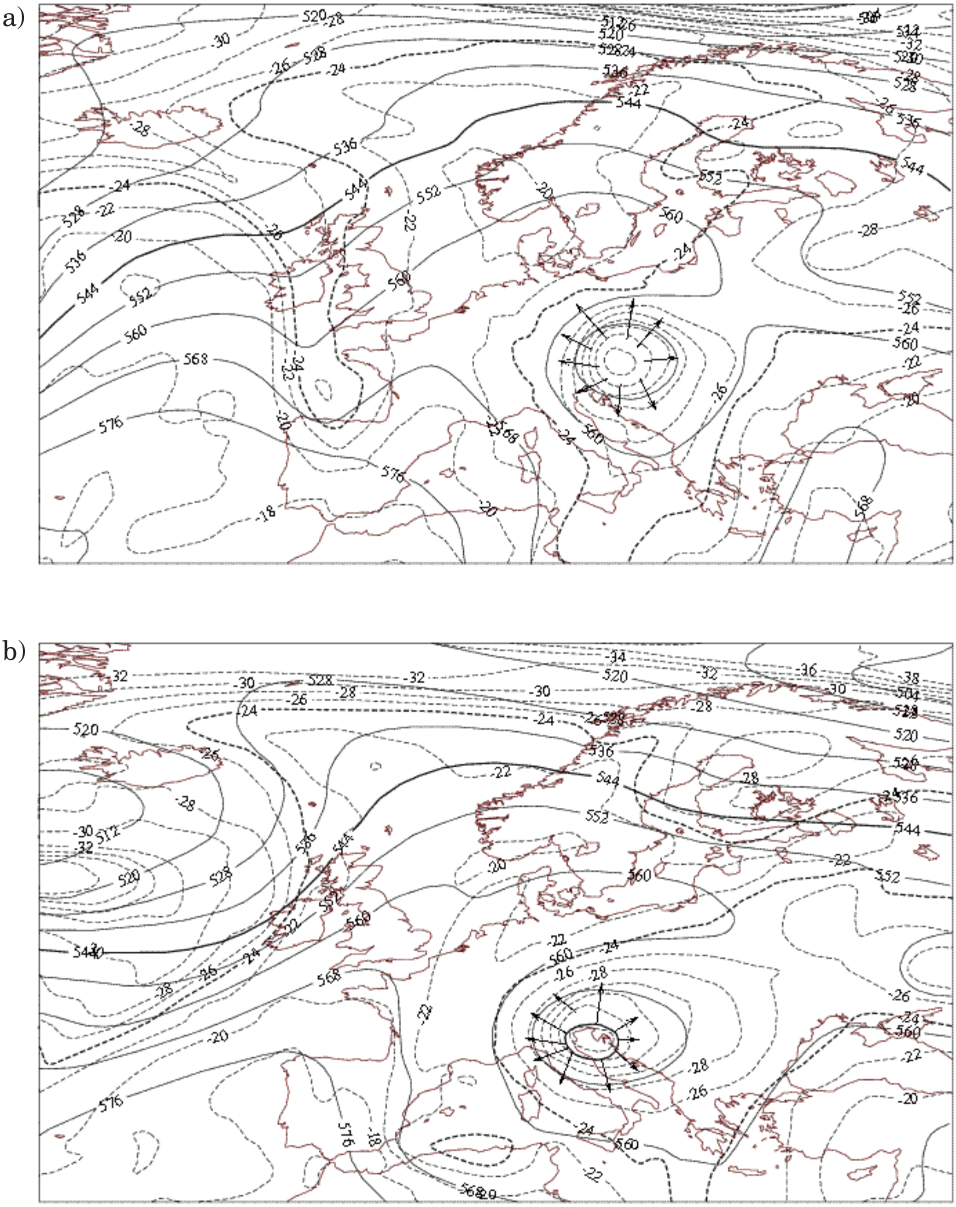
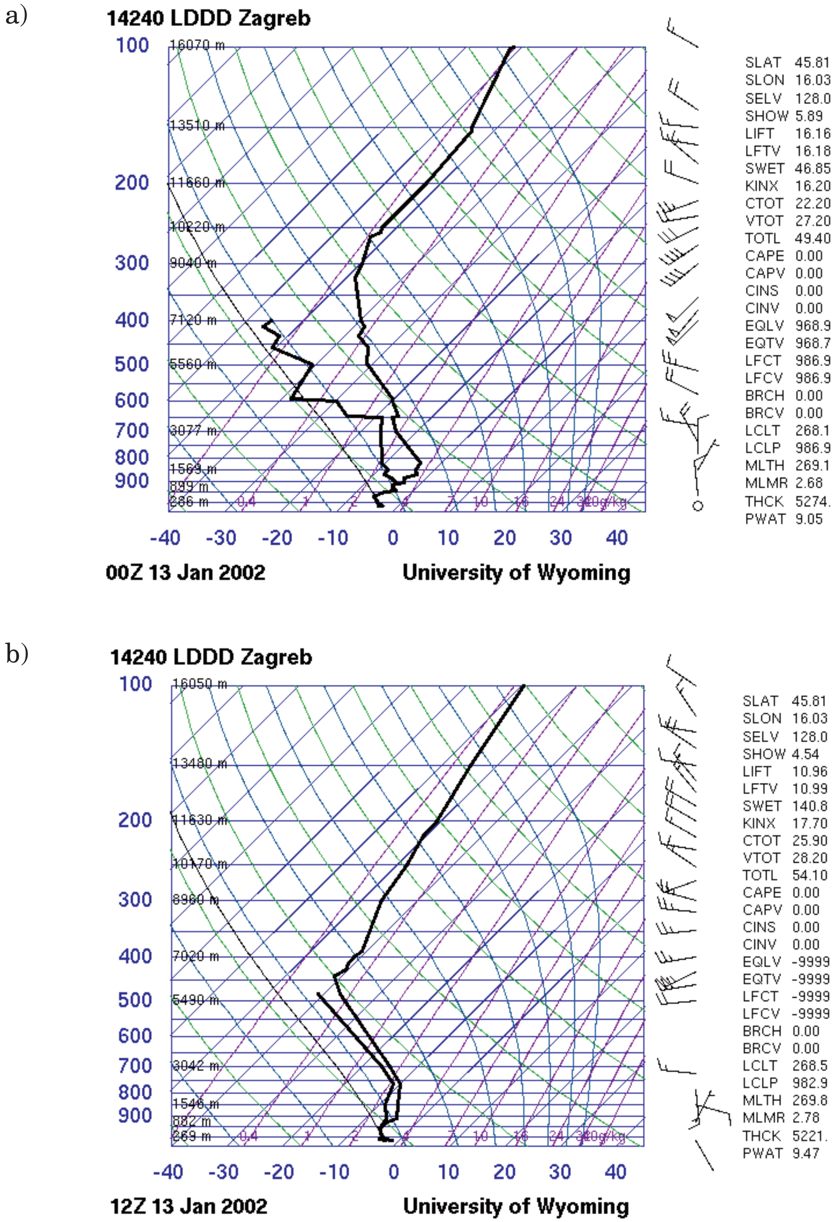


Figure 5. The tropospheric cyclone at 500 hPa, with the Q vector field indicating a sinking motion particularly strong on the western side of the cyclone, with strong geopotential (solid lines) and temperature (dashed lines) gradient. The middle-tropospheric frontal zone is indicated where gradient sinking motions are strongest.

a) 500 hPa 13 January 2002 12 UTC (ECMWF),
b) 500 hPa 14 January 2002 12 UTC (ECMWF).



a)

SLAT	45.81
SLON	16.03
SELV	128.0
SHOW	5.89
LIFT	16.16
LFTV	16.18
SWET	46.85
KINX	16.20
CTOT	22.20
VTOT	27.20
TOTL	49.40
CAPE	0.00
CAPV	0.00
CINS	0.00
CINV	0.00
EQLV	968.9
EQTV	968.7
LFCT	986.9
LFCV	986.9
BRCH	0.00
BRCV	0.00
LCLT	268.1
LCLP	986.9
MLTH	269.1
MLMR	2.68
THCK	5274.
PWAT	9.05

b)

SLAT	45.81
SLON	16.03
SELV	128.0
SHOW	4.54
LIFT	10.96
LFTV	10.99
SWET	140.8
KINX	17.70
CTOT	25.90
VTOT	28.20
TOTL	54.10
CAPE	0.00
CAPV	0.00
CINS	0.00
CINV	0.00
EQLV	-9999
EQTV	-9999
LFCT	-9999
LFCV	-9999
BRCH	0.00
BRCV	0.00
LCLT	268.5
LCLP	982.9
MLTH	269.8
MLMR	2.78
THCK	5221.
PWAT	9.47

Figure 6. The skew-T log p diagrams:
a) Zagreb 13 January 2002 00 UTC,
b) Zagreb 13 January 2002 12 UTC,
c) Udine 13 January 2002 12 UTC,
d) Vienna 13 January 2002 12 UTC.

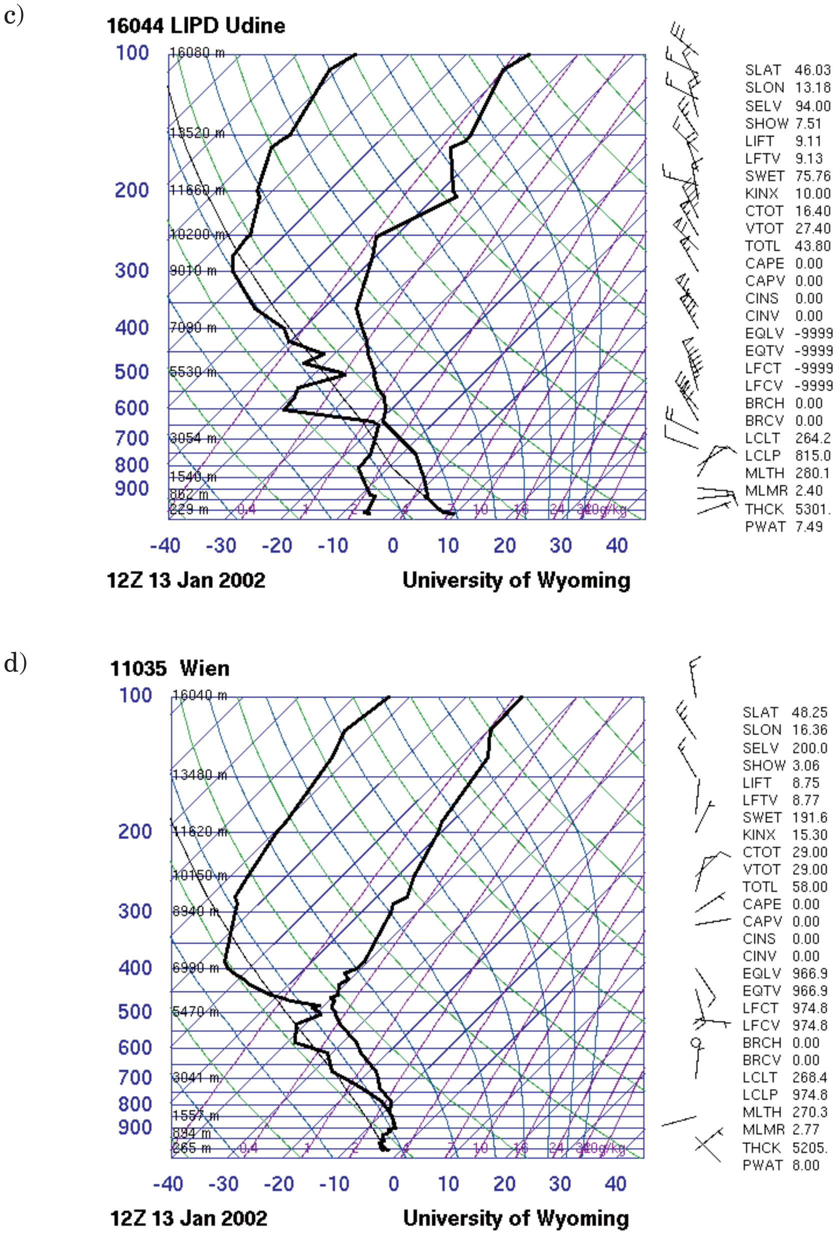


Figure 6. Continued.

cates the estimation of Q-vector field on 13 and 14 January on 500 hPa level. They are obtained by the following procedure (Sanders and Hoskins, 1990):

the direction of Q-vector is determined by the change of geostrophic wind vector along the isotherms with cold air to the left of the direction of isotherms. The direction of Q is 90° to the right from the wind vector change. The intensity of Q is proportional to the temperature gradient values (we are not estimating the precise value of Q). These values indicate the subsidence over the front due to the divergent field.

The subsidence is stronger on 13 January when the temperature gradient is strongest in the frontal zone. On 14 January this front is still sufficiently strong on the western side of the cyclone.

4. Vertical atmospheric structure

In this section we first present the skew-T log p diagrams for Zagreb on 13 January at 00 UTC and at 12 UTC in comparison to those of Vienna and Udine on 13 January at 12 UTC (Figure 6). The skew-T log p diagram for Zagreb on 13 January at 00 UTC (Figure 6a) shows that at this time, at 650 hPa the temperature and dew-point temperature indicate a possible appearance of the middle-upper tropospheric front according to its description by Bluestein (1993). Observations at this time indicate that relative humidity above 500 hPa is mainly below 20 % obviously due to subsidence. The vertical structure of the Zagreb diagram after 12 hours (Figure 6b) is dramatically changed. The most noteworthy feature at this time is the low tropopause at 440 hPa above Zagreb.

The skew-T log p diagram of Udine (Figure 6c) at the same time indicates a dry low troposphere in comparison to Zagreb and Vienna, which means that there could be no humidity advection to Zagreb from the southwest, which is frequently the case during precipitation.

The skew-T log p diagram of Vienna on 13 January at 12 UTC (Figure 6d) indicates in the low troposphere a saturation layer from the surface to 840 hPa, which also influenced large humidity in Zagreb.

Vertical motions are suppressed at the tropopause in part because the static stability is large and because the thermal wind reverses direction. The tropopause acts this way like an upper boundary to the tropospheric frontogenesis, and plays a role that is similar to the role the ground plays to surface frontogenesis (Bosart, 1981).

Figure 7 presents an idealized vertical cross section by Shapiro (1983) who used the Sawer-Eliassen equation to diagnose the circulation in the middle-upper tropospheric frontogenesis. Upstream from a trough with a warm anticyclonic shear side to the left, and the cold cyclonic shear side to the right. Cold advection is occurring upstream from the trough. Shapiro considered frontogenetically acting meridional gradient of vertical motions shifted toward the warm side of this system. The reason for this shift is that geostrophic shear acts frontolitically on the cold side and frontogenetically on the warm side.

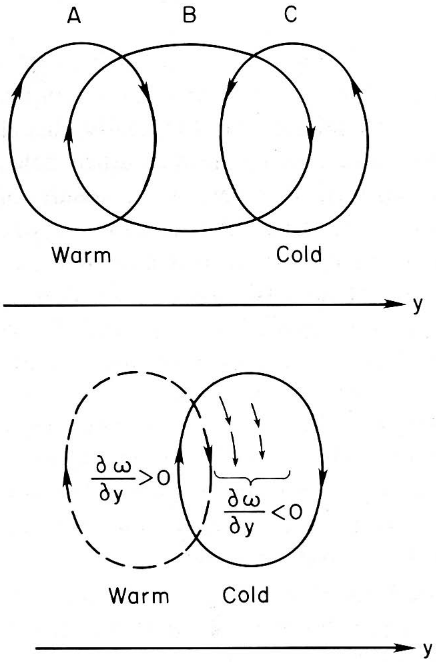


Figure 7. Idealized vertical cross sections through a developing middle-upper tropospheric front: (top) Thermally direct circulation (B) forced by confluence tightening up the cross-stream temperature gradient; thermally direct circulation (A) forced by anticyclonic shear increasing the cross-stream temperature gradient; thermally indirect circulation (C) forced by cyclonic shear decreasing the cross-stream temperature gradient. (bottom) The vertical circulation for confluence only, as B at the top (solid streamline); the vertical circulation for the combined effects of confluence and shear, as A+B+C (dashed streamline). (Shapiro, M.A., 1983)

Hence the strength of the thermally direct circulation is weakened on the cold side and strengthened on the warm side. This analysis shows that a feedback mechanism leading to an increase in horizontal gradient of upward motion is not present and the effects of tilting, which are important in the cold advection, are not important in the warm advection case.

Nevertheless, we consider such an approach interesting but with several remarks. This theory is based on quasi-geostrophic frontogenesis of equation (1), which we have indicated as too slow. However, for semigeostrophic advection there is positive feedback that greatly reduces the time scale of frontogenesis. As temperature contrast increases the ageostrophic circulation must increase so that the amplification rate also increases rather than remaining constant as in the quasi-geostrophic case. Because of this feedback the semi-geostrophic model can produce an infinite gradient at the surface in a very short period of time. In such a fast development the effects of other processes could influence the state at the surface and thus also increase the upward part of ageostrophic circulation in the warmer air which could be essential for the state of precipitation.

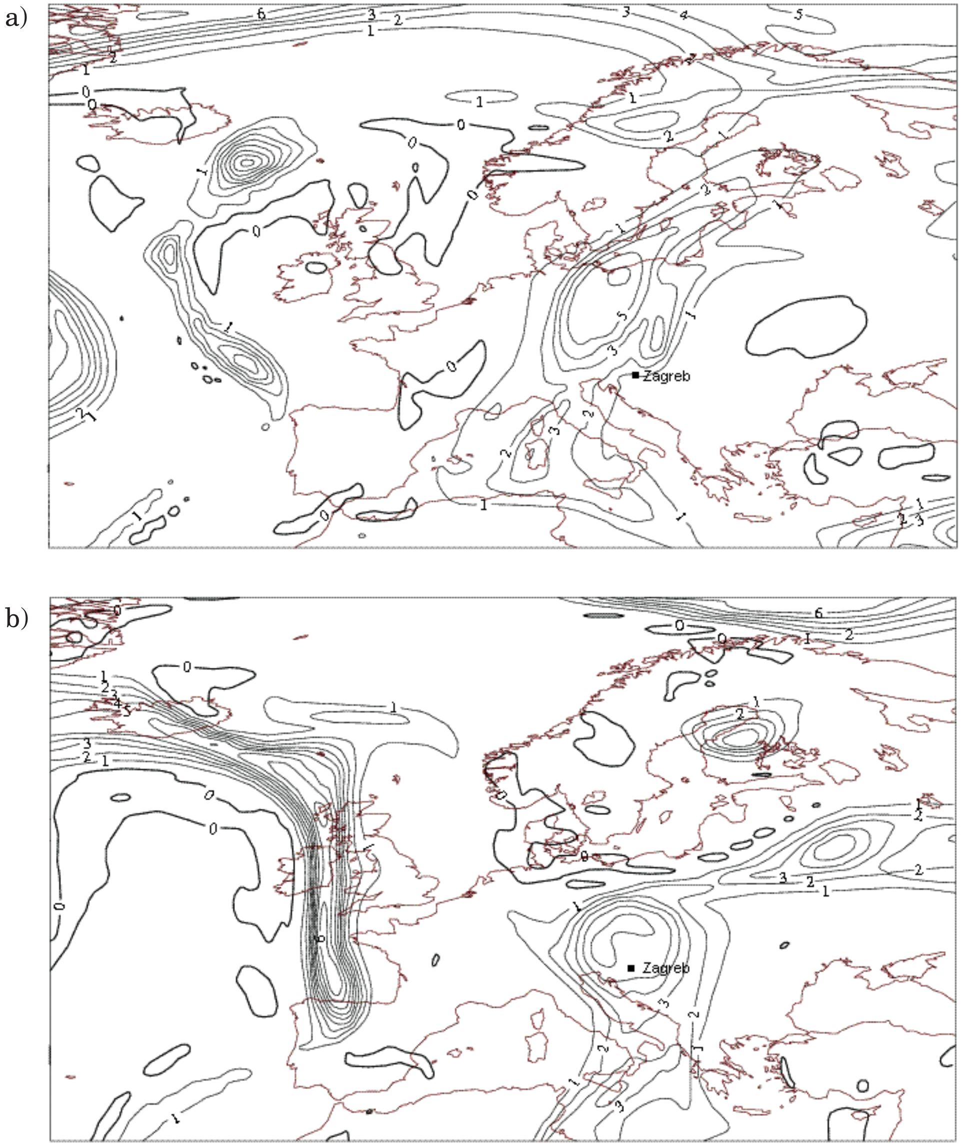


Figure 8. 300 hPa PV
a) 12 January 2002 12 UTC,
b) 13 January 2002 12 UTC,
c) 14 January 2002 12 UTC (ECMWF).

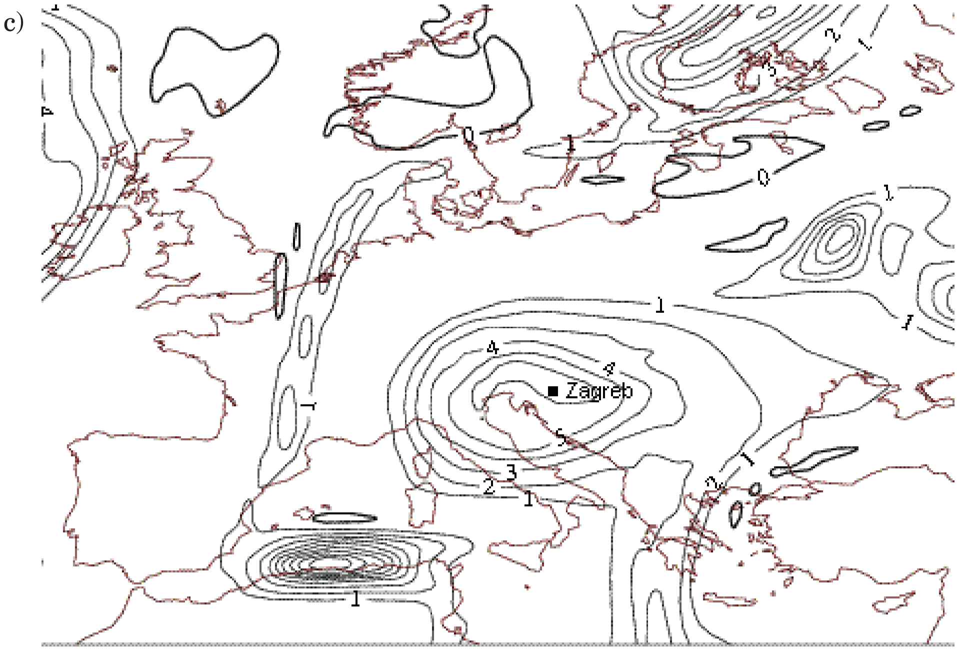


Figure 8. Continued.

5. Potential vorticity

Potential vorticity is the essential feature in this event. Figure 8 shows the PV values at 500 and 300 hPa levels. It is often presented as potential vorticity units (PVU). 1 PVU is 10^{-6} K kg m^2 s^{-1}. In the troposphere PVU is around 2 units, whereas in the stratosphere it is much higher. The maximum of PV at 500 hPa on 12 January at 12 UTC was in northern Germany (not shown), where the middle-upper tropospheric front was also initially found.

On 13 January at 12 UTC the PV centre at 500 hPa is already stronger with a centre in Austria extending toward the north Adriatic. On 14 January at 12 UTC the centre of PV at 500 hPa is in the north Adriatic.

At 300 hPa on 12 January at 12 UTC PV extends from the Baltic Sea toward the Mediterranean along the cold tropospheric trough, and on 13 January at 12 UTC it is in Austria. The horizontal area is larger and close to 6 units in the centre, but it is the largest on 14 January at 12 UTC with the centre in Zagreb.

Similar distribution is seen in the middle and lower troposphere for presentation of PVU for 2 units on isobaric surfaces (Figure 9). On 13 January PVU are extending in the meridional direction. The largest horizontal area of these surfaces is on 14 January.

Upper level PV advection with disturbances of large horizontal scale, such as seen on 14 January in comparison with those on 13 January, will produce

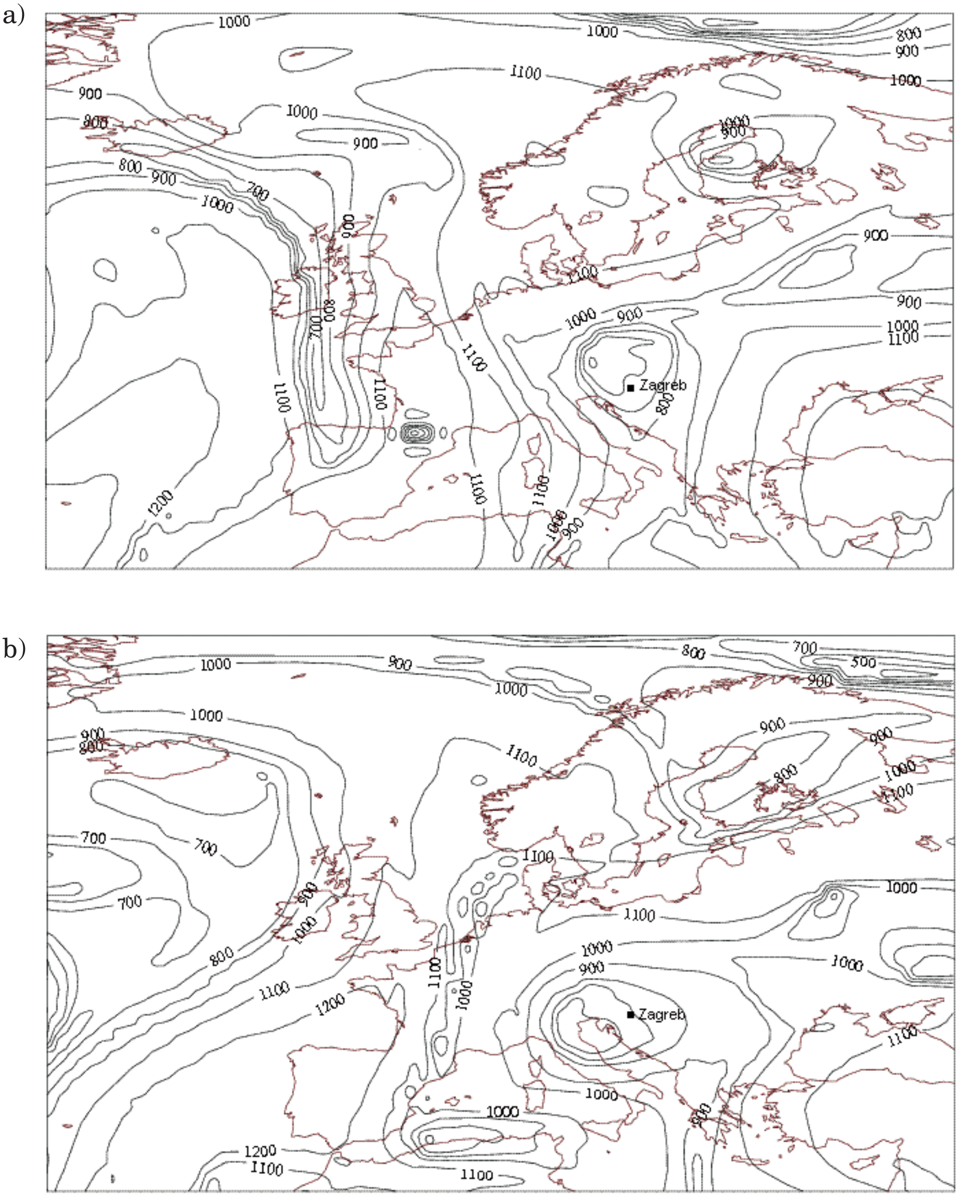


Figure 9. 2PVU Geopotential a) 13 January 2002 12 UTC b) 14 January 2002 12 UTC (ECMWF).

geopotential tendencies that extend down to the surface with little loss of amplitude, whereas for disturbances of small horizontal scale, as on 13 January, the response is confined close to the level of forcing. This is consistent with the view that upper air PV advection plays a key role in the smallest scale of frontogenetical processes (Hoskins et al. 1985).

6. Upslope induced snowfall and "feeder-seeder" process

Plains in the lee of mountains receive their winter precipitation from circulation that is in the opposite direction in respect to the climatologically prevailing westerlies (Reinking and Boatman, 1986). For upslope storms it is considered that advection over generally rising terrain induces lifting and precipitation. This is inexact since the lifting from low to higher plains is not the same as lifting by mountain ranges.

We consider here the upper level synoptic scale storm and low level mesoscale storm. The upper level storms are characterized by seeder clouds, and the low level storms below are the feeder area, indicating the "feeder-seeder" process. The synoptic scale clouds in our case come from the continental polar area and are directed southward toward the Alpine mountains. Here this cold polar air follows the circulation system, turns eastwards and reaches the lee side of the Alps in the area of Zagreb.

Zagreb area is close to Medvednica Mountain, rising to 1035 m. The mesoscale upslope currents influenced by this orography are associated with easterly flow caused by the horizontal pressure gradient within the anticyclone (Boatman and Rainking, 1984). Raddatz and Khandekar (1979) conclude from the results of their mesoscale model that the main contribution toward the upslope precipitation rate comes from feeder area at low levels. They are influenced by seeder clouds containing cold droplets but large enough to efficiently washout the precipitation. The snowfall intensity from upslope systems increases with cloud thickness of water.

The inversions in low level clouds are not uncommon. The skew-T log p diagram of Zagreb shows that such an inversion occurred here a day before the snowfall began. The moisture increased by evaporation and snow melting in this low layer, and contributed to precipitation water in the feeder area. If synoptic distribution indicates a closed-off system in the vertical circulation and the system slowed down for some time, this contributed to heavy snowfall.

7. Conclusion

This study investigates the synoptic situation that lead to complete traffic chaos in Zagreb after an intense snowfall ending in 23 cm of snow. Such high snowfall occurring only in the area of the city of Zagreb was not predicted by other forecasting centres in Europe. The mid-tropospheric cyclone associated with the tropopause break, middle upper tropospheric front, strong advection of potential vorticity and the tropopause break were very special and interesting features in this fast developing case. However it was not possible to attach them to a reasonable explanation for the reason of local snowfall in Zagreb contributing to a total of 23cm of snow in only 28 hours without rain.

This study explains such behaviour of the snowstorm by the extraordinary process of "feeder-seeder", apparently rarely occurring in Europe, and not often described in literature. It includes two special features:

1. The upslope current in the Medvednica plain close to the northern side of Zagreb, caused by the easterly surface winds from Eastern Europe, end accumulating the saturated water in the Medvednica feeder cold area.

2. The larger scale cold clouds moving upslope from the polar area over the Alps turned toward the east, reaching Zagreb on the Alpine lee side over the feeder area. Here the cold droplets from the upper clouds seeded the cold feeder area in the Medvednica plain and washed out its cold water causing the snowstorm in Zagreb.

The reason for this unexpected high snowfall in Zagreb was the "feeder-seeder" phenomenon, which is one of the few significant precipitation mechanisms that is entirely microphysical in nature.

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Neočekivana snježna oluja 13–14. siječnja 2002. u Zagrebu

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Cilj je ovog rada da prikaže pojave koje prate snježnu oluju u Zagrebu i kaos u prometu grada s kontinuiranim oborinom od 28 sati i 23 cm debljine snijega. Oluja nije dobro prognozirana jer je bila pod utjecajem dugotrajne prizemne anticiklone u jugoistočnoj Europi istočno od Alpa. U troposferi je najizrazitija bila visinska fronta srednje troposfere, karakterizirana silaznim gibanjima prikazanim poljem Q-vektora. Ova se fronta formirala uzlazno od hladne doline u troposferi, i ojačala u razdoblju manjem od pola dana. Druga izvanredna pojava je bio lom tropopauze iznad Zagreba, označen razmjenom troposferskog i stratosferskog zraka na tom području. Pojava koja je najviše utjecala na razvoj ove situacije je bila advekcija potencijalne vrtložnosti duž troposferske hladne doline.

Ovakav intenzivni razvoj sinoptičke situacije već ukazuje i na mogućnost obilnijih snježnih oborina. Pokazano je da je tu bitnu ulogu imala uzlazna komponenta gibanja uz obronke planina, kako u makro tako i u mezorazmjerima. Stvaranje oblaka u makrorazmjerima u navjetrini Alpa i njihovo gibanje u zapadnoj struji do zavjetrine, dovelo ih je iznad niskog vlažnog područja nastalog na obroncima gorja (gore Medvednice) na području Zagreba. Ovdje nastaje međudjelovanje visokih i niskih oblaka do nastalih oborina, a očituje se u procesu opisanom koncepcijskim modelom ispiranja. Visoki hladni oblaci sadrže ledene čestice koje zasiju nisko područje velike vlage i time uzrokuju oborinu. To je fenomen »sijač-primač«, što je jedan od malobrojnih značajnih mezoskalnih procesa koji su u biti potpuno mikrofizikalni.

Ključne riječi: visinska fronta srednje troposfere, potencijalna vrtložnost, lom tropopauze, »sijač-primač« proces ispiranja

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