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Evaluation of the cold drops based on ERA-Interim reanalysis and ECMWF ensemble model forecasts over Europe

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Abstract—In our work, we planned deeper understanding of cold drops, closed air masses separated from the main western stream, by using ECMWF ERA-Interim reanalysis and ensemble forecasts. Upper level low (ULL) recognition algorithms were used to study 70 independent cold drop occurrences from the last decade in the middle and eastern European region. This led to the ascertainment of the usual location of ULLs in relation to Hungary, their core temperature, axis lean, horizontal temperature change, and identification on „plum" diagrams. Our studies included the usage of the potential temperature of the 2PVU (2 potential vorticity unit) surface, potential vorticity field related to 315 K, and 300 hPa wind speed These recommended new variables are available from operational deterministic and ensemble forecasts, and their usage is highly effective, hence making the identification of cold drops a lot easier than before.

Key-words: cold drops, upper level lows, reanalyses, ensemble model, statistical studies, 2PVU, isentropic potential vorticity, jet stream, visualization, case studies

1. Introduction

Synoptical studies of the cold drops got less attention in the past decades (both in domestic and international literature) than their significance would suggest. Therefore, we have a slice of all the information about their formation points, development conditions, synoptical and dynamical backgrounds. We find that the importance of their study lies in their ability to inflict natural disasters, such as massive thunderstorms that can lead to flooding, or in rare cases, even tornadoes. Furthermore, upper level lows, or ULLs also have a negative impact on human health. At first, the expression of cold drop, ("der Kaltufttropfen") was likely used by *Scherhag* (1948). His article contained case studies, including winter and summer weather situations influenced by cold drops above the territory of Germany.

A cold crop (also called upper level low or ULL) is a closed air mass separated from the main western stream. Isolated from the cooler air of higher latitudes, it carries air substantially colder than its surroundings, to the warm regions of lower latitudes. In practice, its analysis is done at heights of about 5500 m, and a pressure level of 500 hPa, in the middle troposphere. ULLs being elliptically shaped with a diameter of hundreds kilometres, they resemble miniature cyclones on satellite images. A cold drop can determine the weather of the region for a couple of days, often bringing high amounts of intensive rain, especially in summer. They can occur at any time of the year. The unstable nature of ULLs provides perfect conditions for the forming of hails and thunderstorms in summer, and for intensive snowing winter. One of the main characteristics of a cold crop is that the air inside its higher regions is a lot colder than that of the area outside the cold drop. ULLs are sometimes referred to as "eddies", because of their counter-clockwise cyclone-like motion.

Peltonen (1963) investigated an intensive upper air low occurred in late autumn above Northern Europe. He found that the direction of the transition was parallel to surface wind direction, but the typical transition wind speed was only about 60–70% of the surface wind speed.

In Hungary, the first comprehensive study was made by *Bodalainé* (1983). She created subjective classification system based on synoptical patterns caused heavy floods in the Carpathian Basin.

A quite complex study was made by *Kurz* (1990) for the territory of Germany. Kurz investigated the life cycle of the cold drops and studied the relationship between the cold drops and cut off cyclones. He found that this phenomenon mainly occurred in winter the season. He stated that two main mechanisms could cause cold drops. The first one is the consequence of the cut off procedure, and the second one is the consequence of the cyclogenesis in the case when, due to dissipation near to the surface upper level, low becomes dominant.

It is important to note that cold drops could occur in Mediterranean areas too, and they are even mentioned in studies in central and northern Europe. Impacts of the cold drops are important in the Iberian Peninsula, too (*León*, 2003). In the Iberian Peninsula, especially in the southeastern part of Spain it occurs when a large size polar air mass slowly moves to that region in the middle and upper troposhere. It causes high impact weather including heavy rains or snowing (up to 500 mm/day) and extremely strong wind (between 100 and 200 km/h), when cold air mass mixes with warm Mediterranean air mass.

Complex climatological study based on a 41 years long NCEP reanalysis was made by *Nieto et al.* (2005). An objective recognition system using three meteorological variables was applied. The three meteorological variables were the following: cold core at 200 hPa, circulation pattern at 200 hPa, and thermal front parameter field. In contrast to the former studies, it was found that cold drops occurred more often in the winter season than in summer. Authors also found a connection between jet streams and upper level lows.

2. Life cycle of the ULL and relationship between blocking and upper level lows

A classic cold crop has four development phases, starting with the ULL isolating from the main stream and ending with dissolving or fusing with another stream (*Nieto et al*., 2005). The four phases are

- ULL,
- tear-off,
- cut-off, and
- final stage.

2.1. Upper level low phase

In order for a cold drop to form, there have to be unstable waves inside the main stream, where the temperature wave is behind the geopotential wave (*Fig. 1a*). This is the phase where the ULL is still behind the frontal cloud mass, so it shows as a clearly visible cloud trail on satellite images.

2.2. Tear-off phase

The main meteorological process of this phase is the trough tearing off from the main stream (*Fig. 1b*). The waves amplitude gets higher ("the wave gets deeper"), followed by cold air detaching from the stream in its southern regions. The bottom part of the ULL slowly isolates from the main stream, leading to a closed circulation in the upper troposphere.

2.3. Cut-off phase

Contrary to the earlier phases, the isolation is completely finished in this phase, and the ULL is at its prime. The wind field shows the most advanced closed circulation at 500 hPa (*Fig. 1c*).

2.4. *Final phase*

Convection begins to develop in the cold drop (except for its coldest parts). As the air on the surface gets warmer, the eddies' circulations get slowed down by friction. The upper air mass gets warmer by the conviction and friction starts to take effect in this region as well. This causes the ULL to decay slowly (*Fig. 1d*). In most cases, the ULL reattaches to the main western stream before dissolving completely (*ZAMG*, 2007).

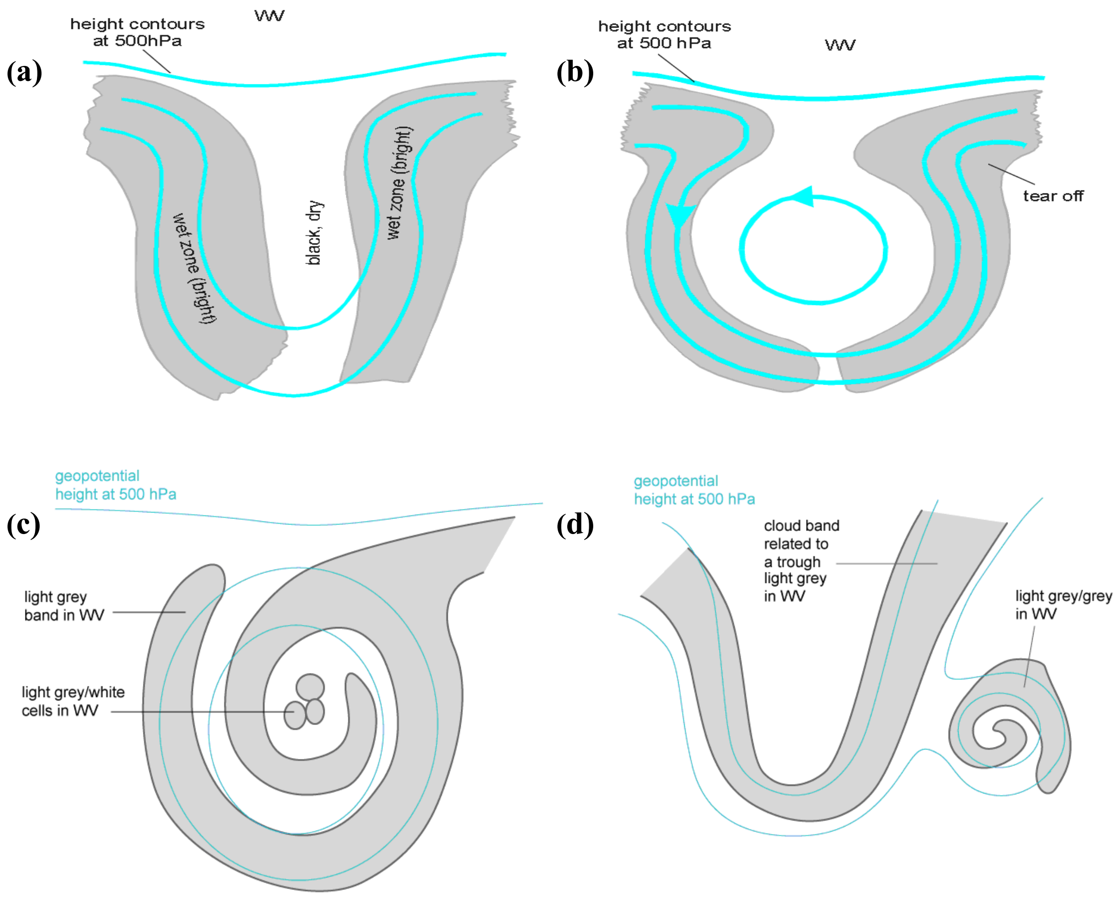

Fig. 1. Phases of the ULL: upper level low phase (a), tear-off phase (b), cut-off phase (c), final phase (d) (*ZAMG*, 2007)

The development of ULL usually takes 3–10 days. There are two kinds of ULLs, based on size and lifetime, "small eddies" which last 2–4 days, and "big eddies" which can last up to 14 days. Larger eddies are usually more common than smaller ones.

When studying cold drops, the phenomenon of blocking has a very high synoptic significance. First comprehensive studies of the blocking were made by *Rex* (1950a, 1950b). At the middle latitudes, two main patterns of the flow are typical: zonal flow and meridional flow (blocking). Life cycle of the blocking can extend from a few days up to two weeks. In the typing of the blocking situations, we can see characteristic flow images that can be analyzed well at 500 hPa pressure level during the occurrence of blocking events. By analyzing the blocking anticyclones at 500 hPa, the following types can be distinguished: Rex-type blocking, Omega-situation, ”fire ring” or detaching anticyclone, detaching low-pressure system, and splitting flow field. For our studies, Omega-type blocking is the one of important, because this event often leads to the detachment of cold drops (*Pelly* and *Hoskins*, 2003).

3. Former studies on cold drops in Hungary

ULLs are mentioned only in a few pieces of Hungarian literature. A synoptic classification system for the Carpathian Basin was invented by *Bodolainé* (1983). This classification system listed situations only that caused floods in the area of the rivers Danube and Tisza. She specified 7 classes: western, ”western boundary disturbance”, zonal, passing Mediterranean, central, cold air drop, and western cyclone-type. *Bodolainé* was a pioneer (both in Hungary and Europe in general) in studying the relation between dangerous weather conditions and cold air drops. She found that cold air drops occur quite rarely and mainly in the summer season.

Their occurrence often forms mezo-scale convective weather-systems (*Horváth*, 2007), and in some cases they have strong effect on the flooding of the river Tisza (*Bodolainé*, 1983; *Bonta et al.*, 1989; *Szépszó*, 2003).

The distinction between upper level lows and upper level cold vortexes is typical. Due to this distinction, the characteristic size of the upper cold drops is up to thousand kilometers, while the characteristic size of the cold vortexes varies between 1000 and 3000 kilometers. Due to the meteorological terminology phrase, “cold drop” is used if around cold core there are isolated isolines in geopotential field in the middle troposhere and the characteristic size is only several hundred kilometers (*Fig. 2*).

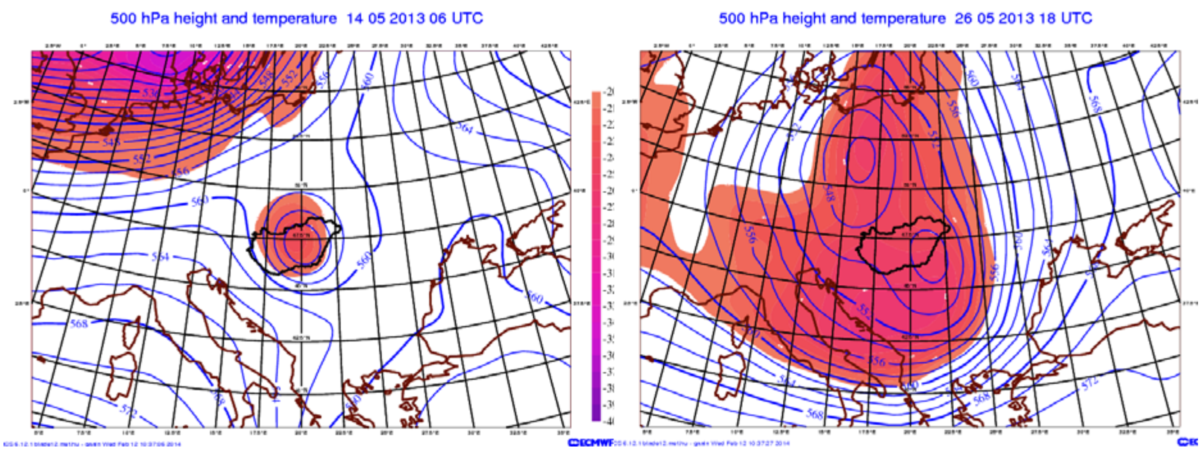

Fig. 2. Cold drop: May 14, 2013, 06 UTC (left), upper level cold vortex: May 26, 2013, 18 UTC (right).

4. ERA-Interim reanalysis of the European Centre for Medium-range Weather Forecasts

Due to the fact that there is a continuous development in the numerical weather prediction models, the use of operational models is not the most straightforward way to go if we would like to intend to study climatological characteristics of any atmospheric phenomena. To solve this problem, several reanalysis projects started applying a frozen version of the model to provide homogeneous quality of the analysis and forecasts.

The European Centre for Medium-Range Weather Forecast (ECMWF) was established in 1975, with the collaboration of 18 European countries (*Woods*, 2006). The ECMWF was among the first centers which create reanalysis database of a longer time period (from 1979 to 1993), it was ERA-15 project in the mid ’90s (*Gibson et al*., 1997). In 2003, ECMWF produced a new longer reanalysis, ERA-40 for the period between 1958 and 2002, with improved spatial resolution and state-of-the-art 3D data-assimilation (*Uppala et al.*, 2005).

The ERA-Interim reanalysis project started in the middle of the first decade of the 21st century. At first, the starting year of this reanalysis was 1989, but it was extended to 1979 (*Dee et al.*, 2011). The ERA-Interim database gets updated each month, with a 2 months delay. Using even more advanced spatial resolution (0.75*0.75 degrees) and the newest 4D-var dataassimilation techniques (as opposed to ERA-40s 3D-var technology) led to a significant increase in the quality of ERA-Interim.

As it was shortly summarized above, the currently available datasets provide state-of-the-art tools for studying cold drops in our region. In addition to model and pressure level fields, several selected predefined isentropic fields are also available from ERA-Interim. It widely supports to extend the potential tools and methods for recognition and investigation of the cold drops.

Beside the importance of the reanalysis datasets, we have to shortly summarize the main characteristics of the current operational models, too. Since June 25, 2013, the deterministic model has contained 137 levels in the vertical and its horizontal resolution is 16×16 kms. Ensemble model contains 62 levels in the vertical and its horizontal resolution is 32×32 kms. In the autumn 2013 vertical resolution of the ensemble model will be increased to 91 levels. The above-mentioned developments have positive impacts on forecasting of the ULLs too. Forecasted meteorological fields are available at standard pressure levels, all model levels, and selected isentropic levels from deterministic and ensemble models.

5. Developments of new methods for statistical and meteorological studies of cold drops

5.1. The horizontal and vertical structure of cold drops

Due to the fact that cold drops relatively rarely occur at any geographical locations, it is not an easy task to get a quite large sample if we plan to study and summarize the typical characteristics of cold drops. For solving the above mentioned problem, we planned to collect cold drops from a larger area, so we needed to develop an objective method for recognition of cold drops. Firstly, several occurrences were collected when cold drops was determined by forecasters in the last ten years. Secondly, the general characteristics of cold drops were determined by applying our newly developed methods. Finally, we plan to extend the sample to investigate cold crops by applying objective recognition algorithm for a 30-year period.

At first, we gathered 70 cases from those submitted by synoptical meteorologists as ULL situations between 2002 and 2011 (*Gaál*, 2012a). These 70 cases were studied daily in 6-hour intervals, so this led us to have 280 different states. At first, a few meteorological parameters as temperature, geopotential, relative humidity, and winds were commonly used at standard pressure levels (850, 700, 500, and 400 hPa), so this approach supported our examination of 3D structure in the atmosphere. Since cold crops have characteristically small horizontal extension, and they rarely occur at each geographical location, we had to choose an area which is large enough for our examinations. The northwestern counterpoint of the area was at latitude N 60º and longitude E 10º, while its southeastern counterpoint was at latitude N 40º and longitude E 40º (*Fig. 3*). *Fig. 3* shows the core positions of the 280 ULLs studied between 2002 and 2011. As we can see, the minimum temperature spots of the cold drops are located mostly west, northwest, and north from Hungary. The purple spots mark the center of the ULLs, and they mostly appear west, north, and northeast from Hungary. All the data used came from the ECMWF MARS database (*Raoult*, 2001).

In the period between 1979 and 2008, we calculated the monthly average temperatures at 500 hPa. We looked at the 30-year average, the minimum and maximum monthly-mean temperatures for each month (*Fig. 4*). Based on the timeline of these 30 years, the amplitude is smaller at 500 hPa (15 ºC) than at the surface (22–25 ºC). The annual thermal values of the mid-troposphere follow those of the surface with about a month delay. This is in accordance with the fact that the atmosphere gets heated mainly from the direction of the ground, and the effects of the minimum and maximum levels of irradiation show up with an offset in the mid-troposphere. The temperature is clearly lower on days with cold drops than the monthly averages of the 30 years. *Fig. 4* shows the monthly average temperatures (at 500 hPa) from the last 30 years (1979–2008). This is marked by the brown line on the picture, and it stands out quite well that the temperature of the cold drops (marked in purple) resides below the average monthly data in every case. We can also see that ULLs do not have an absolute temperature threshold.

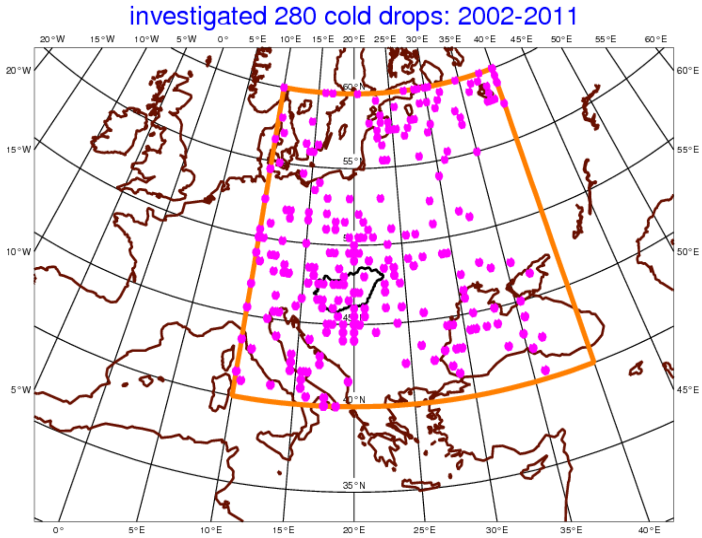

Fig. 3. Centers (local minimums) of the investigated 280 cold drops between 2002 and 2011.

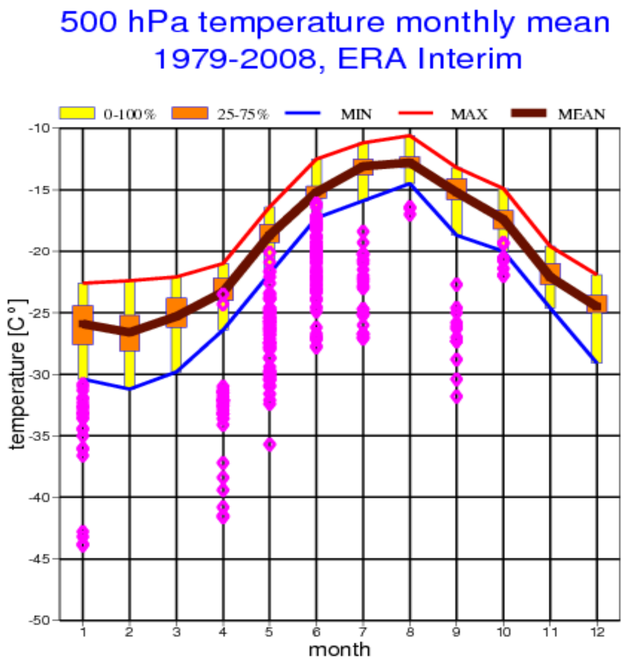

Fig. 4. Monthly means of the 500 hPa temperature (brown line), the coldest monthly means (blue lines), and the warmest monthly means (red lines) in the last 30 years. Purple dots show the investigated minimums of 280 cold drops.

As it has been mentioned, in order to have enough samples for statistical analysis, we have set a goal of generating an algorithm that recognizes ULLs (*Gaál*, 2012a, *Gaál*, 2012b). Firstly, local minima of the temperature fields are determined at 400, 500, 700, and 850 hPa standard pressure levels. Secondly, we calculated horizontal gradients with several radius around the minima. Lastly, we calculated the axis inclination of cold drops at a few layers in the vertical. In the next few paragraphs, the results are briefly summarized.

Around the local minima, horizontal gradients were calculated within a circle determined by radius, which was changed between 100 and 750 km. Histograms were made from the 280 elements sample for each selected radius and pressure. Typical characteristics of the horizontal structure of ULLs were studied by the investigation of these histograms.

Our results match up with the anticipated structure, which means that gradients are getting lower as we get further away from the core. The unique horizontal temperature structure of cold drops gives us a good way of distinction from the cyclones of temperate zones, which are characterized by a much larger extension and thermal dissymmetry (except for their occluded phase). Another unique trait of cold drops is that their inner core is only clear in the upper troposphere, while in the lower troposphere, it is barely visible (as opposed to those of temperate cyclones). The horizontal thermal gradients are calculated around the core at 100, 250, 500, and 700 km. We also made a histogram of the aforementioned 400, 500, 700, and 850 hPa pressure levels with a gradient frequency of 0.5 ºC/100 km (*Fig. 5*).

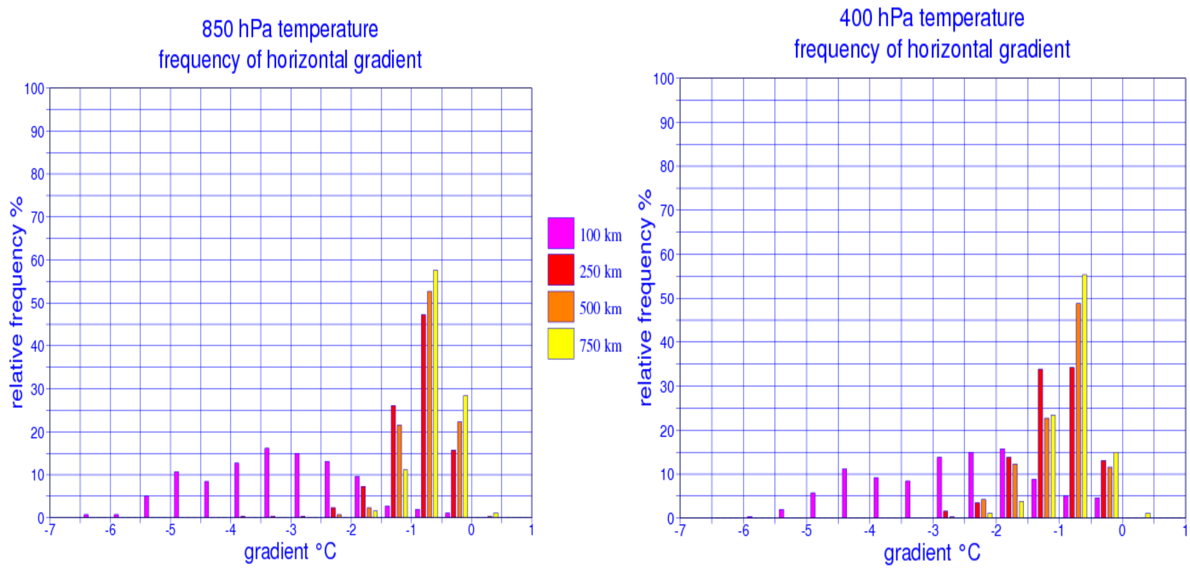

Fig. 5. Histograms of the gradient around the center of cold drops from 100 to 750 km circles at 850 hPa (up) and 400 hPa (down).

Gradients studied at 100 km are usually much larger than those studied at larger areas, and the values of the gradients get lower as the studied area gets larger, since ULLs have a characteristically small horizontal extension. We also made a cross chart showing the gradients calculated at the main isobaric-pairs.

Our calculation of the gradient pairs of 750/100 km, 500/100 km, and 250/100 km allowed us to establish that the gradients calculated on a larger area are always lower than those calculated on a smaller area (*Fig. 6*).

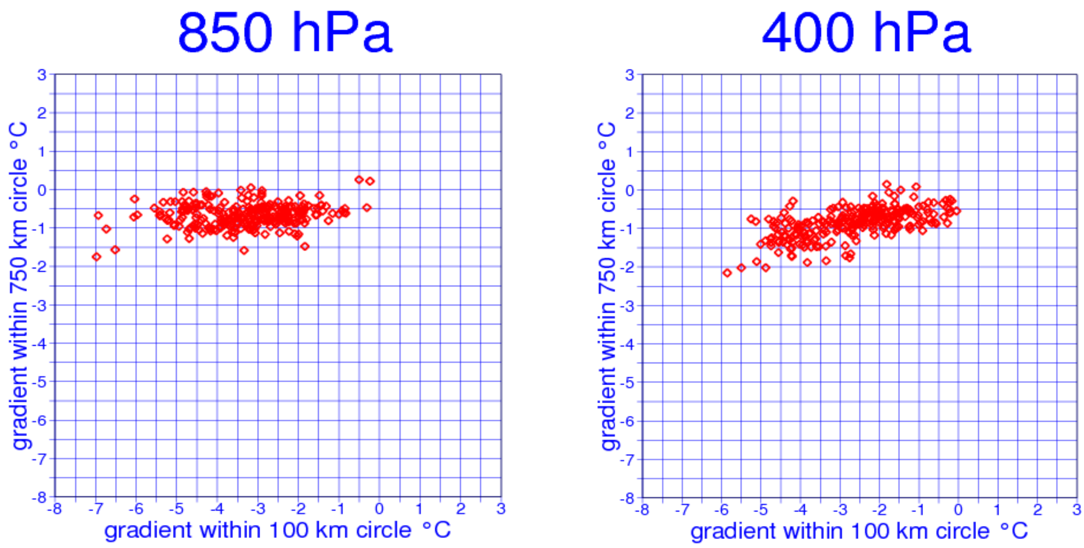

Fig.6. 750/100 km gradient pairs at 850 hPa (left) and 400 hPa (right) pressure levels

We also studied the relative spatial displacement of the cold drops on the mentioned pressure levels, or in other words, the axis inclination of the ULLs. *Fig. 7* shows the axis inclinations at the 400/500 hPa and 400/850 hPa layers. As we can see, the inclination is much lower at 400/500 hPa than at the higher-difference layers, with the axis usually being straight, or leaning towards the east of southeast (which also allows a clear study of the orientations towards different directions).

5.2. Relationship between meteorological fields in cold drops

In this part of the work, we aimed to extensively extend the number of the applied meteorological variables for studying cold drops. Additional variables are 300 hPa wind speed, potential temperature of the 2 potential vorticity unit (2PVU), isentropic potential vorticity at 315 K, horizontal temperature advection at 500 hPa, and wind shear between 850 and 300 hPa. In this paragraph, considering the technical limitations of this paper, only two new meteorological variables are briefly mentioned below.

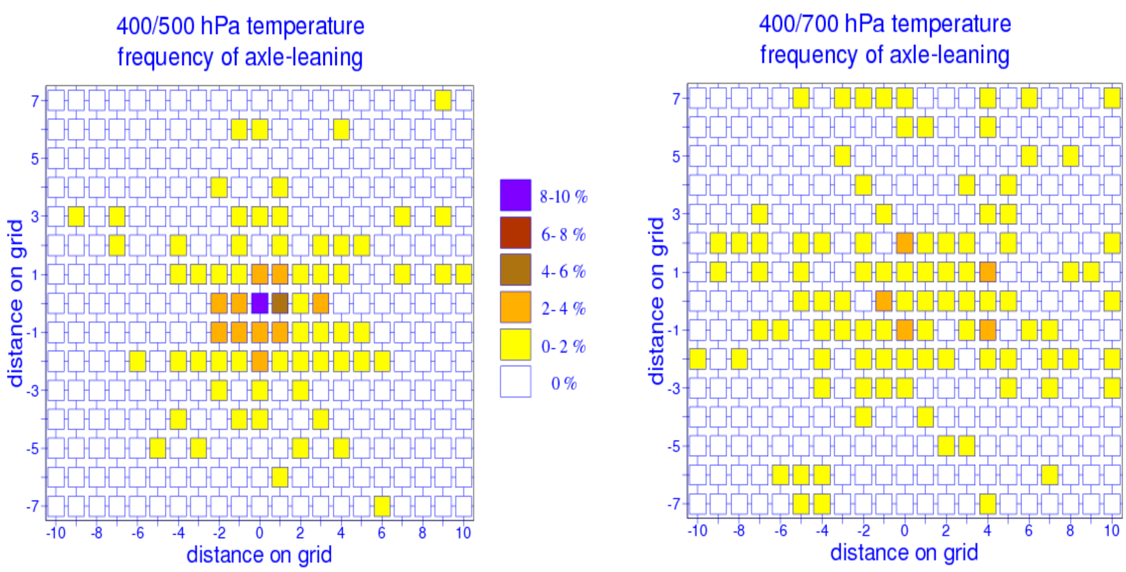

Fig. 7. Frequency of axis leaning at the 400/500 hPa layer (left) and 400/700 hPa layer (right).

Studying connection between cold drops and jet streams we found, that there is a very strong relationship between the position of the cold core and the structure of the jet stream (*Fig. 8*). Before the tear-off phase, the area of the most intensive part of the jet stream quickly moves to south at most part of the wave. At the next step it moves toward to northeast, this change causes a tearing of the drop. In most cases due to further rotation of the cold drop, two intensive parts of the wind shear are visible. One of them appears to the left and the other one appears to the right of the core. In cases of larger cold vortexes, 3 or 4 separated intensive parts of the jet streams can be found quite often. At the final stage of the lifecycle, when the cold drop joins to the main stream, an intensive part of the jet is always found at the eastern part. When the cold drop does not join the main stream it becomes stationary, increased warming at the core is typical, and the intensity of the jet stream decreases.

Besides studying cold drops on standard pressure levels, the investigation could benefit by applying ”pv-thinking”. The potential vorticity (pv) was introduced by *Ertel* (1942), it was not commonly used until the middle 1980s (*Hoskins et al.*, 1985; *Hoskins*, 1991; *Hoskins*, 1997). The potential vorticity theory is based on the structure of the potential vorticity field. Potential vorticity is the absolute circulation of the air mass between two isentropic surfaces. In the troposphere, its value is usually low. Approaching the tropopause, it sharply rises in the vertical (from 1 PVU to 4 PVU, 1 PVU=10^{-6} $m^2s^{-1}Kkg^{-1}$) with 2PVU being the dynamic tropopause, the subject of our studies.

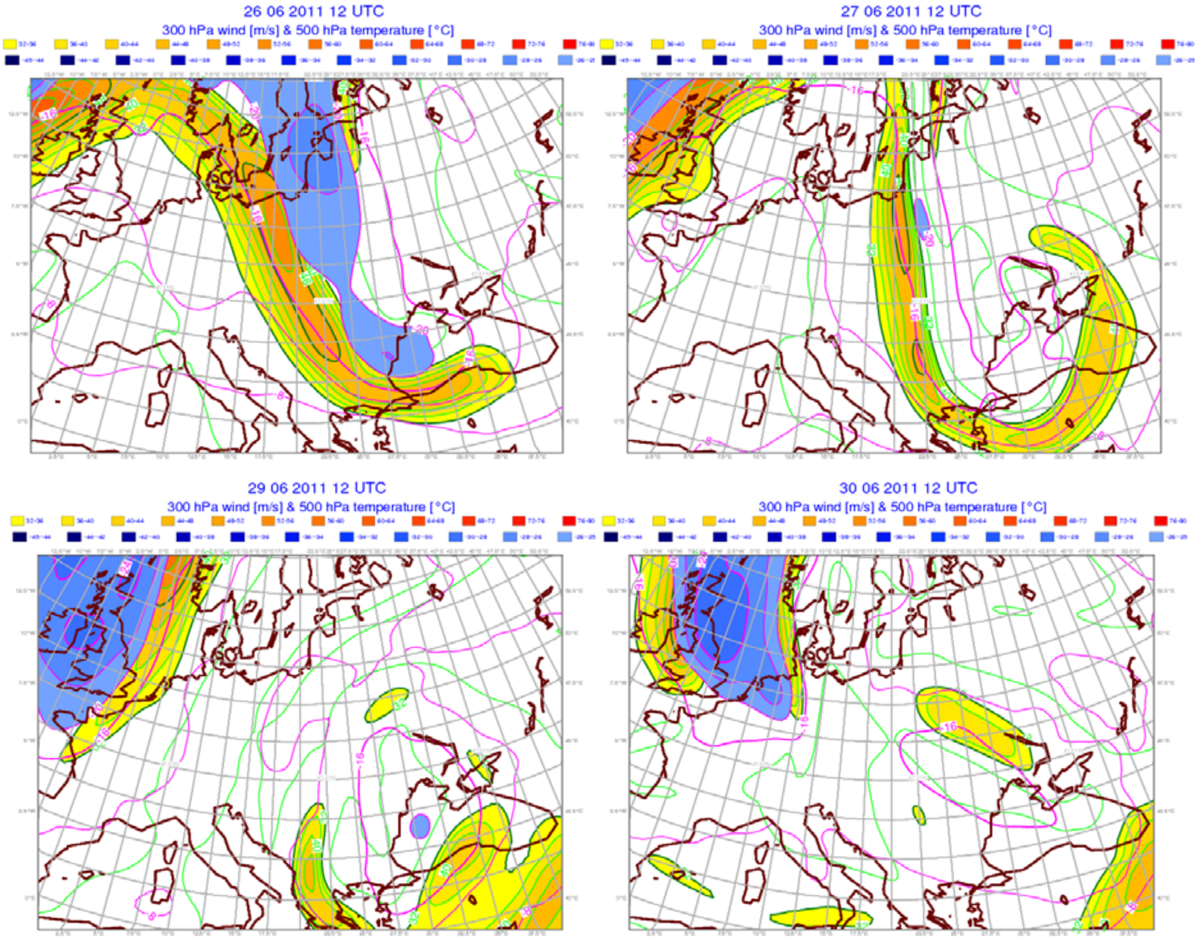

Fig. 8. 300 hPa wind stream and 500 hPa temperature at 12 UTC, June 26, 27, 29, and 30, 2011.

Studying the relationship between the local minimum of the isentropic level of the 2PVU and the position of the cold drops at 500 hPa we found, that these two minimums are typically very close to each other (*Fig. 9*). If there are more than one cold cores, there are consequently more minimums on the 2PVU fields too. We found that in tearing phase there was always a short delay (6–18 h) of the 2PVU field with tailing shape comparing to cold core at 500 hPa.

5.3. New ensemble based graphical products for supporting the recognition of cold drops

Predictability of cold drops of the numerical weather prediction models is not an easy task. It is highly recommended to use ensemble forecasts besides deterministic forecasts. At the Hungarian Meteorological Service, wide range of the ensemble based graphical products, among them EPS plumes, meteograms, spagetthy and probability maps are available in the operational forecasting practice. As a result of our former investigation of the cold drops, it would have been useful to develop new tools for supporting better recognition and forecast of the cold drops. As in Section 4.1 it was clearly stated, additional meteorological fields besides the 500 hPa temperature can provide very valuable information as far as cold drops are concerned. We developed two new types of ensemble plume diagrams. First one contains three variables: 500 hPa temperature, isentropic potential vorticity at 315 K isentropic level, and potential temperature of the 2PVU surface. The second one contains four variables: in addition to previous three variables, 300 hPa wind speed is also part of the graph.

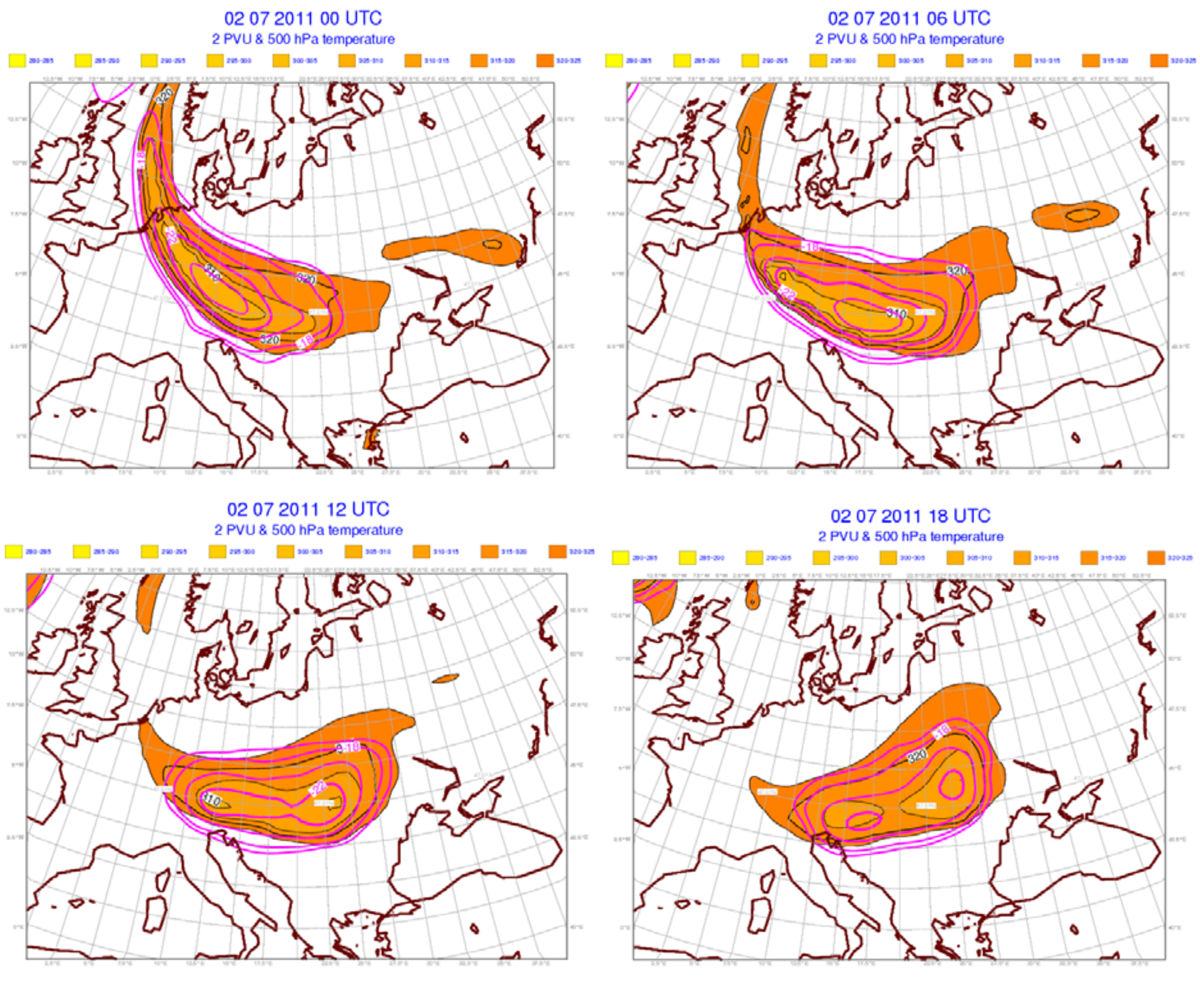

Fig. 9. Potential temperature of the 2PVU surface and the 500 hPa temperature between 00 and 18 UTC, July 2, 2011.

Usefulness of these new tools is demonstrated in a case study. On June 30, 2011, a cold drop pathed across Hungary. *Fig. 10* shows new ensemble plume diagram, ULL occurred on June 30, 2011. We can see the strong U-shape on the second forecast day at 500 hPa, showing a high chance of about 8 degrees drop in temperature in 24 hours and the same amount of rising temperature after the cold drops passing. *Fig. 10* displays the uncertainty of ULL core forecasting and intensity perfectly.

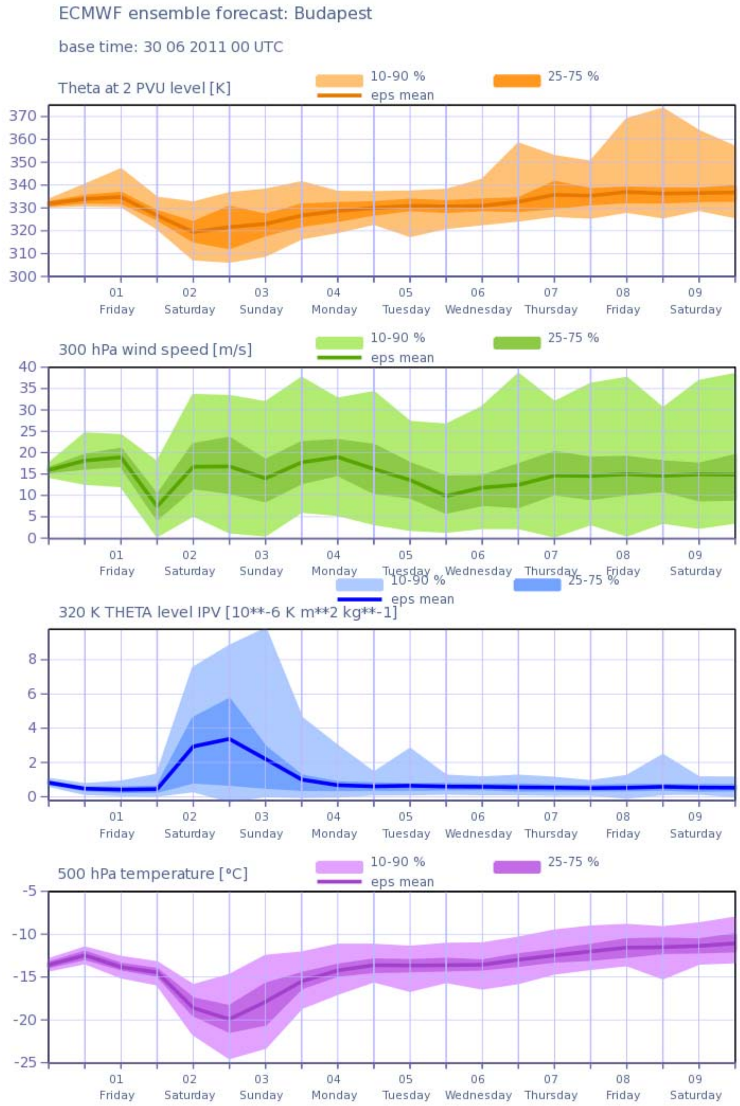

Fig. 10. New ensemble plume diagram, containing potential temperature of the 2PVU surface, isentropic potential vorticity at 315 K isentropic level, wind speed at 300 hPa, and temperature at 500 hPa, for Budapest, model started at 00 UTC, June 30, 2011.

6. Summary, conclusions

Due to the fact that cold drops relatively rarely occur at any geographical locations, it is not an easy task to get quite a large sample if we plan to study and summarize the typical characteristics of cold drops. For solving the above-mentioned problem, we collected cold drops from a larger area and developed an objective method for recognizing cold drops. Firstly, several situations were collected when cold drops were determined by forecasters in the last ten years. Secondly, the general characteristics of the cold drops were determined by applying our newly developed methods.

Besides determining the general characteristics of the horizontal and vertical structure of cold drops, several new methods were developed for studying and providing guidance for forecasting cold drops. The two most important aspects are the usage of the ensemble forecasts and model forecasts on isentropic levels. At the operational practice, using ensemble forecasts besides the deterministic model can provide very valuable additional information due to the fact that the intensity and position of the cold drops are quite often uncertain. In addition to applying standard pressure level fields, potential temperature of the 2PVU and isentropic vorticity fields are also useful, they could provide more realistic features of the cold drops than we can see from pressure levels. The objective ULL-recognition is required to be able to reliably distinguish cold drops from cyclones. Our results so far make this a very real and reachable goal. One of our plans is to designate the areas with a potential for the formation of cold drops based on ensemble forecasts. In the future, we would like to run further tests with our ULL-recognition algorithm to study the last 30 years of cold drops, and we would also like to experiment more with ULL forecasting.

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