Abstract. Extra tropical cyclones evolution depends a lot on the dynamically and thermodynamically interactions between the lower and the upper troposphere. The aim of this paper is to demonstrate the importance of dynamic tropopause fold in the development of a cyclone which affected Romania in 12th and 13th of November, 2016. The coupling between a positive potential vorticity anomaly and the jet stream has caused the fall of dynamic tropopause, which has a great influence in the cyclone deepening. This synoptic situation has resulted in a big amount of precipitation and strong wind gusts. For the study, ALARO limited area spectral model analyzes (e.g., 300 hPa Potential Vorticity, 1.5 PVU field height, 300 hPa winds, mean sea level pressure), data from the Romanian National Meteorological Administration meteorological stations, cross-sections and satellite images (water vapor and RGB) were used. Accordingly, the results of this study will be used in operational forecast, for similar situations which would appear in the future, and can improve it.

Key words: potential vorticity, tropopause fold, cyclone.

1. INTRODUCTION

Dynamic tropopause is the 1.5 or 2 PVU (potential vorticity units) surface that separates the dry, stable, stratospheric air from the humid, unstable, tropospheric air [1]. The dynamic tropopause fold corresponds to a positive potential vorticity anomaly, with high amplitude in the upper troposphere [2,3], which induces a cyclonic circulation that propagates to the surface and reduces, under it, static stability. The gradient of potential vorticity is maximal at the dynamic tropopause level.

Dynamic tropopause folds are characteristic of a non-linear evolution of the baroclinic waves [4, 5]. Its can contribute to the joining of the low and high levels of the troposphere and determine the cyclogenesis, especially explosive cyclogenesis [6, 7] and jet amplification (eg. [1, 8, 9, 10]). Its may also
activate mesoscale severe weather phenomena, including deep convection (eg. [2], [3], [11], [12], [13]).

In order to outline a climatology of dynamic tropopause folds, studies of its geographic and seasonal distribution were carried out. Among the areas in Europe targeted by such studies are: Turkey [14], France [15], the Alps [16]. More recent studies have been made by Skerlak, [17] (over the entire Earth) and even more recently by Akritidis, [18]. The later focuses on the tropopause folds in the eastern Mediterranean, the Middle East, and the Balkan Peninsula, including Romania (Fig. 1). The model used therein was ECAM (ECHAM5/MESSy Atmospheric Chemistry). The results showed that the occurrence of the tropopause folds is higher in southern Turkey due to the dynamic interaction between the subtropical jet and the Asiatic Anticyclone [18], [19].

In Romania, the occurrence frequency of tropopause folds is less than 2 - 3%, but the severity of the phenomena induced by them can be so great that they cannot be neglected.

Fig. 1 (color online) - Tropopause folds average occurrence frequency (%), between 1979 and 2013, during summer. EMAC simulations. In the box is the studied area [18].

The concept of Potential Vorticity (PV) has been used for many scientific studies describing the dynamic and thermodynamic behavior of the atmosphere. This paper aims to describe the processes that cause the folding of dynamic tropopause and some of the effects induced by it, such as cyclogenesis, jet streaks, and low-level jet. A better understanding of these phenomena will be useful for meteorological forecast.

Section 2 will detail the dynamic and thermodynamic processes induced by a positive potential vorticity anomaly which can determine: cyclogenesis, jet streaks, and low-level jets (LLJ). Section 3 presents the data and methods used for this study and the results are presented in Section 4. The conclusions end the paper.
2. THEORETICAL CONSIDERATIONS

In the atmosphere, if an air parcel has an adiabatic and frictionless movement the PV is conserved:

\[-g(\zeta + f) \frac{\partial \theta}{\partial p} = c_t\]

where \( g \) is gravitational acceleration, \((\zeta + f)\) is the absolute vorticity, and \(\frac{\partial \theta}{\partial p}\) is potential temperature vertical variation (static stability) [20].

From the PV conservation equation (1), the structure of the high positive PV anomaly can be deduced. It is associated with a large absolute cyclonic vorticity and an increase in the static stability \(\frac{\partial \theta}{\partial p} \gg 0\) (Fig. 2). Under the anomaly, the potential temperature gradient will decrease and will induce an decrease in static stability.

![Fig. 2 - Positive PV anomaly cross section. Blue line is dynamical tropopause, red lines are isotachs, and gray lines are isentropes (adaptation after Comet Program).](image)

According to the thermal wind equation near the positive PV anomaly have to be the strongest winds and higher values of the absolute vorticity (Fig. 2). A positive potential vorticity anomaly determines a cyclonic movement which weakens as it spreads towards the ground. The positive PV anomaly induced circulation will penetrate the atmosphere vertically, on a distance \(H\) that is called the Rossby penetration depth and is given by the equation:

\[ H = \frac{f L}{N} \]

where \(f\) is the Coriolis parameter, \(L\) is the horizontal scale, and \(N\) is Brunt–Väisälä frequency [21]. If it overlaps over a ground baroclinic area, a warm advection will be to the east of the ground disturbance, and a cold advection to the west of it (Fig. 3). The warm advection will determine a positive temperature anomaly (equivalent
to the PV anomaly) and a cyclonic circulation to the ground, which, in turn, will
propagate upward to the level of the upper positive PV anomaly. The effect of
coupling the two structures is the amplification of the upper positive PV anomaly
and increasing of the amplitude of the baroclinic wave. If the environment is
favorable, eventually, a mutual amplification of the two structures will be achieved.
This situation induces cyclogenesis, sometimes even an explosive one (Fig. 3).

One way to identify the dynamic influence of the upper layers of the
atmosphere on cyclogenesis is to monitor dry air intrusions using water vapor and
RGB 18 satellite images. Cyclogenesis is associated with the appearance of a
pronounced dry band in satellite imagery (dark gray to black in water vapor images
(Fig. 4a) and brick color in the RGB 18 Air Mases images (Fig. 4b)). Those dry
bands can indicate the tropopause fold and the position of the cyclone.

A positive potential vorticity anomaly can interact with jets. As a result of
this interaction, an energy exchange occurs between the two structures that
intensify each other. On the one hand the horizontal wind in the jet grows, and areas with large modifications are called jet streaks. There is a link between vertical movement and strong variation of horizontal winds in the confluence or divergence zones associated with the entry or exit areas of the jet. The right entrance and the left exit are associated with a pronounced divergence in the upper layers of the atmosphere that produce tropospheric ascending motion, which is an important factor in the development of severe weather systems. Thus jet streaks are considered tracers of synoptic disturbances at mid-latitudes.

On the other hand, when a positive PV anomaly interacts with a jet stream there is a tropopause fold that induces important changes in the surrounding atmospheric structure (wind field, geopotential field, temperature field, etc). As such, the study of the dynamic tropopause high and the areas characterized by a strong 1.5 PVU surface horizontal gradient along with the evolution of a jet stream provides suggestive information on the synoptic dynamics. That’s why „PV thinking” is a very good approach in operational forecasting [22].

3. DATA AND METHODS

Synoptic conditions between 12 November 2016, 12 UTC and 13 November 2016, 12 UTC reflect the theory of coupling between a positive PV anomaly and a jet stream. Accordingly, this study was made with the purpose of using the results in operational forecast, for similar situations which would appear in the future. To achieve this, observational data recorded to the meteorological stations validated and managed by the Romanian National Meteorological Administration (NMA), satellite images from Meteorsat 9 – WV (water vapor) and RGB 18 (Air Masses), and ALARO limited area spectral model reanalises (horizontal resolution is 6.5 km and has 60 vertical levels), were used (Fig. 5).

Initial and limited conditions were provided by the global model ARPEGE (Action de Recherche Petite Echelle Grande Echelle) with a frequency of 3 hours (operational at Meteo-France); this model is also a spectral one, with a Gaussian grid having an average resolution of 16 km and 105 vertical levels. The horizontal resolution of the global model over Romania is 9 km.

Fig. 5 (color online) - Model integration domain ALARO – Romania.
4. RESULTS AND DISCUSSIONS

The chosen case aims to highlight the importance of tropopause folding in meteorological forecast, especially in the evolution of cyclones. Between 12th of November, 12 UTC and 13th of November, 12 UTC, Romania was crossed by a developing cyclone, from south-west to north-east (Fig. 6).

On 12th of November, 12 UTC (Fig. 9, a) the pressure at the center of the cyclone, located above Serbia, was 1010 hPa. After 12 hours it was located above Transylvania and dropped 6 hPa (Fig. 9, b); then, gradually, it moved to the north-east, so that after 13th of November, 12 UTC, it exited Romania, and also weakened.

The coupling between 300 hPa positive PV anomaly (6 - 8 PVU values in Romania) (Fig. 7) and jet stream (Fig. 8) determined the tropopause fold (Fig. 9), which favored the rapid increase of the cyclone (Fig. 6).
As the positive PV anomaly moved to the north-east, the dynamical tropopause has descended more and more (Fig. 9), so the 1.5 PVU surface high reached 5...6 km/pg on 13\textsuperscript{th} of November, 2016, 12 UTC (Fig. 9, c) The cyclone deepened rapidly while the dynamic tropopause fold (Fig. 6).

In Fig. 8, a jet streak can be seen in southern Bulgaria, at the junction of the jet stream and the positive potential vorticity anomaly (where the wind speed exceeded 60 m/s) (Fig. 9b).
Fig. 9 (color online) - The high of the 1.5 PVU surface, a) 12.11.2016, 12 UTC, b) 13.11.2016, 00 UTC, c) 12 UTC.

At the intensification of this cyclone a significant contribution was also that of its location to the left jet exit, where strong upward movements and the development of depressions are favored. Developing cyclone and jet stream also led to the low level jet (LLJ) which has increased between 25 and 30 m/s, at 850 hPa level, on the morning of November 13th (Fig. 10).

Fig. 10 (color online) - 850 hPa wind (colored arrows), 13.11.2016, 06 UTC.

Air circulation was particularly active at ground level too, with the wind gust at 25 ... 26 m/s, especially in eastern and south-eastern Romania. The precipitations fell on large areas, locally exceeded 30...40 l/mp occasionally 60 l/mp. An important contribution had the LLJ, which determined the intensification of the advection of warm and humid air to Romania (Fig. 11).
In order to better highlight the processes that competed to the severe weather event occurrence, vertical sections were made in the direction of the green arrow in the RGB 18 satellite image of METOSAT 9 (Fig. 12 a) for 13.06.2016, 00 UTC.

In Fig. 12 b) it can be observed the descent of the dynamic tropopause to the middle of the troposphere, the generation of potential vorticity in the lower troposphere, inside the occluded front area, and the deformation of the potential equivalent temperature field towards the positive PV anomaly. In Fig. 12 c) are being presented both the stratospheric dry air intrusion associated with tropopause fold (orange lines) and the high humidity ahead of the positive PV anomaly (green lines), extended up to about 400 hPa, due to strong ascending (Fig 9 b). Fig. 12 d) shows the jet stream around 300 hPa level, and the low level jet (LLJ).
In this context, large amounts of water have accumulated as a result of intense precipitation (on extended areas over 25...30 mm, and in Caras-Severin, Hunedoara and Botosani counties, occasionally, over 50...60 mm (Fig. 13)). The wind was very intense, and the gusts exceeded 20 m/s (up to 25...26 m/s) in southern, eastern and central part of Romania.
Satellite images are very useful in identifying dynamic tropopause fold, both WV, especially WV 6.2 µm (Fig. 14 a) and RGB 18 (Fig. 14, b). The WV 6.2 µm gray and dark gray areas shows the stratospheric dry air intrusion and downward movements, and light gray and white, upward tropospheric movements (above 600 hPa). In RGB 18, the air masses and the potential vorticity field can be identified. Brick tones highlight air that is warmer, more stable and with a high potential vorticity.

![Image of satellite image](image)

**Fig. 14 (color online) - Meteosat 09 satellite image. 13.11.2016, 06 UTC - a) WV 6.2 µm, and b) RGB 18- Air Masses.**

5. CONCLUSIONS

This work revealed the influence of dynamic tropopause folding on cyclogenesis, jet streak and low-level jet formation. The coupling between a positive high PV anomaly, jet stream and a low level baroclinic zone leads to a particular development of cyclones. In the example case it has been revealed that in the case of a tight, long-lasting coupling the jet stream takes energy from the PV anomaly, a jet streak forms, then the cyclone intensifies considerably which leads to heavy rain and an intense wind in the lower layers of the atmosphere. Understanding the dynamic and thermodynamic processes involved in tropopause folding, along with knowing how numerical models are capable of reproducing
certain processes in the atmosphere, would help to improve the forecasting techniques.

Not any anomaly of potential vorticity gets to determine extreme phenomena. Complex processes need to occur simultaneously, so that upper and lower levels of the atmosphere connect, and even more a mutual amplification between them is detected - like the one between the dynamic tropopause and ground cyclones. However, any disturbance in the high troposphere must alert the meteorologists to pay special attention to processes in the lower troposphere which might be coupled with a dynamic tropopause fold and eventually might produce severe phenomena.

In conclusion, the depth of a positive PV wave in the troposphere helps to anticipate the possibility of interaction with the low and medium layers of the atmosphere.

REFERENCES


