Evaluation of total ozone extremes at Poprad-Gánovce

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A b s t r a c t : The aim of this paper is the selection of appropriate criteria for extreme total ozone (TO3) events detection, evaluation of frequency and annual distribution of TO3 extremes and comparison of the frequency of extremely low and extremely high TO3 events observed at Poprad - Gánovce (49°03′N, 20°32′E, 710 m a.s.l.) during the 1994-2004 period and at the closest TO3 observatory Hradec Králové (50°18′N, 13°83′E, 235 m a.s.l.) during the 1962-1990 period. The results of statistical analysis enabled the usage of long-term TO3 average from Hradec Králové as a climatological "normal" for the observatory at Poprad-Gánovce.

The occurrence of below- and above-normal TO3 at Poprad-Gánovce was evaluated with respect to both the 1994-2004 Poprad-Gánovce data and the 1962-1990 Hradec Králové data. Three methods were used for the selection of extreme TO3 events. Firstly, daily TO3 was considered to be below-normal (above-normal), when it was below (up to) the 80% (120%) of daily mean value $\bar{O}_3$ calculated by the robust locally weighted regression method. Then, the smoothed daily mean of TO3 $\bar{O}_3$ and its standard deviation σ were used for selection of below- or above-normal TO3 values. The third method coupled both the mentioned methods.

The number of cases with below-normal TO3 was nearly the same, if an extreme occurrence was determined by both methods with respect to the Poprad-Gánovce average TO3. As soon as the Hradec Králové 1962-1990 average TO3 values were applied to the extreme total ozone values separation, the number of extremely low TO3 values rapidly increased.

The relationship between TO3 extremes and extremes in tropopause and in standard pressure level, characteristics was studied, too.

Key words: total ozone, extreme total ozone, mini-hole, synoptic situation, tropopause, standard pressure levels

1. Introduction

Occurrence of extreme TO3 values at the midlatitudes relates more to atmospheric dynamics, than to chemical processes *(Koch et al., 2002; Semane et al., 2002)*. Events with extremely low TO3 values (ELO3 or ozone

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mini-hole) are of special interests due to possible huge increase of the solar ultraviolet radiation raised by low amount of ozone, especially in urbanized midlatitudes of the North hemisphere. It is not clear, how the frequency of the ELO3 will change in the future in connection with the change of circulation patterns raised by global climate change *(James, 1998)*.

There are differences between criteria for separation of ELO3 events. According to *Bojkov and Balis (2001)*, a situation is classified as TO3 mini-hole if the decrease of TO3 below 220 DU is observed for 2 to 3 days in the northern mid- and polar latitudes in autumn. Such episodes represent situations with TO3 lower than one third of the pre- 1976 monthly mean values October – December period. Similarly *Brönnimann and Hood (2004)* considered the TO3 decrease below 225 DU as an ozone mini-hole. *James and Peters (2002)* defined an ozone mini-hole as synoptic-scale ozone minima at least 70 DU below climate mean level with respect to location and season over the midlatitudes. *Koch et al. (2004)* considered the TO3 decrease of 100 DU from the long-term mean as a mini-hole. On the contrary, *Gil et al. (2004)* have chosen the level of the TO3 decrease to be 40 DU as ELO3 detection criterium. According to *Krzyścin et al. (1998)*, periods with TO3 less than the long-term daily mean minus 1 sigma range for the investigated period persisting for at least three days were defined as TO3 mini-holes. A mini-hole can be defined also by the 20% ozone decrease from the long-term daily mean *(Krzyścin, 2002)*.

The occurrence of extreme TO3 events depends on synoptic situation in the troposphere and in the stratosphere.

Situations with extremely low TO3 develop when ozone poor, relatively warm air masses from the subtropics are moved polewards along areas of anticyclonic ridging. This horizontal advection in combination with forced vertical air motions at the ridge leads to an increasing amount of ozone poor air masses in the total air column in mid- and high latitudes *(Rood et al., 1992)*. Several studies confirm also the importance of stratospheric conditions to ELO3 formation. Events with extremely low TO3 values are accompanied by advection of cold air masses in the middle stratosphere. Deformation of the polar jet stream by planetary waves also contributes to ELO3 formation. Disappearance of tropopause at its former position and its rebuilding at higher position (tropopause uplift) was observed in the area of anticyclonic flow produced by wave at the polar jet stream *(Orsolini et*

al., 1995; Hood, 1999).

Upper cyclones are formed in the region of the tropospheric jet stream to the meridionally elongated low-pressure trough. If such a low-pressure area cuts off, the ozone rich polar air moves to lower latitudes. The occurrence of cut-off cyclones manifests the predominance of ozone rich stratospheric air in total column, so the increase of TO3 is observed. Relatively higher TO3 values are also connected with tropopause fold events *(Ravetta and Ancellet, 2000).*

It is still a topic of many discussions, whether the ELO3 events relate only to dynamical uplift in the area of tropopause *(Teitelbaum et al., 2003)*, or the enormous regional decreases of TO3 relate more the to transport processes *(Koch et al., 2002).*

2. Methods

2.1. Total ozone at Poprad - Gánovce

The daily TO3 has been measured at Poprad-Gánovce (49°03′N, 20°32′E, 710 m a.s.l.) by the Brewer spectrophotometer MKIV since 1993. The measurements have been provided daily, except of short-term gaps due to the instrument calibration. Daily mean of the TO3 is calculated from measurements in DS (direct Sun) mode. If the weather does not enable DS measurements, the ZS (zenith sky) mode is used. The instrument has been regularly calibrated with the Brewer spectrophotometer world standard device.

The annual course of TO3 at Poprad - Gánovce was expressed including monthly means, maxima, minima and standard deviations. The TO3 interdiurnal variability at Poprad - Gánovce was also calculated to analyze its change during the year. The length of increase/decrease of TO3 was also determined.

At the closest TO3 observatory Hradec Králové (50°18′N, 13°83′E, 235 m a.s.l.), TO3 has been measured by the Dobson spectrophotometer since 1962. Hradec Králové 1962-1990 ozone data are considered to be a climatic normal for estimation of long-term variability of TO3 extreme occurrence at Poprad - Gánovce.

2.2. Total ozone extremes

The TO3 average was calculated for every day in the year. Because annual course of daily TO3 obtained by this way was ridged, there was a need to smooth it. The method of robust locally weighted regression (RLWR) *(Kalvová and Dubrovský, 1995)* was applied to the daily average ozone data. A 50-day long period was used as half-window width and the polynomial function of 2^{nd} order was selected as a regression smoothing function (`http://www.st-andrews.ac.uk/~wjh/robustfit/`).

Three methods were used for the selection of extreme TO3 events:

1. Method of percent: Daily TO3 was considered to be below-normal (above-normal), when it was below (up to) the 80% (120%) of daily mean value $\bar{O}_3$ calculated by the RLWR method [criterion used by *Krzyścin (2002)* for TO3 extremes selection].

2. Method of $\bar{O}_3 \pm 2\sigma$: The smoothed daily mean of TO3 $\bar{O}_3$ and its standard deviation σ were used for the selection of below- or above-normal TO3 values. Daily TO3 was considered to be below-normal (above-normal), when it was below (up to) the value of $\bar{O}_3 + 2\sigma(\bar{O}_3 - 2\sigma)$.

3. Coupled method: This method uses both of the mentioned methods, the method of percent and the method of $\bar{O}_3 \pm 2\sigma$. In the period, when $\bar{O}_3 + 20\%(\bar{O}_3 - 20\%)$ is higher (lower) than $\bar{O}_3 + 2\sigma(\bar{O}_3 - 2\sigma)$, $\bar{O}_3 + 20\%(\bar{O}_3 - 20\%)$ is selected as the criterion for above-normal (below-normal) TO3 selection. Similarly, in the period, when $\bar{O}_3 + 2\sigma(\bar{O}_3 - 2\sigma)$ is higher (lower) than $\bar{O}_3 + 20\%(\bar{O}_3 - 20\%)$, $\bar{O}_3 + 2\sigma(\bar{O}_3 - 2\sigma)$ is selected as the criterion for above-normal (below-normal) TO3 selection.

The occurrence of below- and above-normal TO3 at Poprad - Gánovce was evaluated with respect to both the 1994-2004 Poprad - Gánovce data and 1962-1990 Hradec Králové data. Then, the number of TO3 extremes at Poprad - Gánovce selected by all criterions with respect to Poprad - Gánovce 1994-2004 TO3 data was compared to the number of TO3 extremes detected at Hradec Králové by all methods with respect to Hradec Králové 1994-2004 TO3.

The dependence of extreme TO3 events on synoptic situation was evaluated. Synoptic situation calendar published at the SHMI web page:

(www.shmu.sk) was used for characterization of the daily synoptic condition. The coupled method of TO3 extreme selection was used for this intention.

2.3. The influence of tropopause and standard pressure levels on TO3 extremes

The correlation between daily TO3 and temperature, pressure and height in the tropopause level during the whole year and the correlation between TO3 and standard pressure levels' temperature and height (at 925 hPa, 850, 700, 500, 400, 300, 150, 100, 70, 50, and 30 hPa level) was studied. The examined seasons were months October-April of the years 1994-2004, when the TO3 mini-holes were detected. The coincidence between the occurrence of TO3 extrema and extrema in characteristics of tropopause and of standard pressure levels was also tested. Values of characteristics of tropopause and standard pressure levels were considered as extreme when they exceeded the interval p $\pm 2\sigma$, where p and σ are smoothed (RLWR method) daily values of average and standard deviation of the characteristics of the tropopause and standard pressure levels, respectively.

3. Results

3.1. Annual course of total ozone at Poprad - Gánovce

The annual course of TO3 at Poprad - Gánovce during the 1994-2004 period was well expressed. The annual mean value was 325.6 DU. The highest monthly mean was observed in April (366.3 DU), the lowest in October (281.7 DU).

Variability characterized by standard deviation from monthly average and by variational range is the highest in February (11.9% for standard deviation and 165.0 DU, 46.3% for variational range) and lowest in August (4.5% for standard deviation and 56.1 DU, 18.2 % for variational range).

The average interdiurnal change of TO3 is 17.3 DU (5.3%). The highest interdiurnal change was detected between January and March (27.5 DU, 7.9%). The lowest interdiurnal change of the TO3 was detected between October and December (10.6 DU, 3.4%, Table 1).

Table 1. Absolute value of interdiurnal change, mean values of positive and negative interdiurnal change and the duration of increase and decrease of TO3 in separate quarters at Poprad - Gánovce in 1994-2004 period

	I		II		III		IV	
	[DU]	[%]	[DU]	[%]	[DU]	[%]	[DU]	[%]
Value of interdiurnal change	27.5	7.9	14.8	4.2	10.6	3.4	17.3	5.9
Mean increase of TO3	26.7	7.6	14.8	4.2	11.2	3.6	17.9	6.1
Mean decrease of TO3	28.0	8.0	14.8	4.3	10.3	3.3	16.7	5.7
Duration of increase [day]	1.9		1.8		1.7		1.9	
Duration of decrease [day]	1.8		1.8		2.1		1.9	

An average duration of TO3 decrease or increase is similar. In average, it does not exceed 2 days (Table 1).

3.2. Extremes of TO3 at Poprad - Gánovce

The number of cases with below-normal TO3 was nearly the same if an extreme occurrence was determined by both methods with respect to the Poprad - Gánovce average TO3. There were 7.5 days/year found by the method of percent and 8.8 days/year by the method $\bar{O}_3 \pm 2\sigma$. However, there was a difference between the seasons of occurrence of the extreme ozone events detected by both methods. As the method $\bar{O}_3 \pm 2\sigma$ takes into account the annual course of TO3 variability and the method of percent does not, the separated extreme situations were differently distributed in the annual course (Fig. 1, left). Therefore, in the period with large variability of TO3 (December – March), the method $\bar{O}_3 \pm 2\sigma$ was a stricter criterion for extreme TO3 selection compared with the method of percent. The method of percent detected more below-normal TO3 days in years 1994, 1995, 1996, 2001 and 2003. For example, in 2001 there were 16 days with below-normal TO3 detected by the method of percent and 12 days detected by the method $\bar{O}_3 \pm 2\sigma$. On the contrary, in the period with relatively small natural variability of TO3 the criterion of percent detected less extreme ozone events than $\bar{O}_3 \pm 2\sigma$. More days with below-normal TO3 were found by the method of $\bar{O}_3 \pm 2\sigma$ in years 1997, 1998, 2000 and 2004. In 2004, there were 8 days with below-normal TO3 found out by the method $\bar{O}_3 \pm 2\sigma$, but only 2 by the method of percent.

Generally, the method $\bar{O}_3 \pm 2\sigma$ found out more extreme high TO3 events than the method of percent (14.8 days/year with $\bar{O}_3 \pm 2\sigma$ method and 8.5

days/year with the method of percent, Table 2). There is also an annual distribution of TO3 extremes found by both methods.

As soon as the Hradec Králové 1962-1990 average TO3 values were applied for extreme TO3 values separation, the number of extremely low TO3 values rapidly increased, mainly by the method $\bar{O}_3 \pm 2\sigma$ (Fig. 1, right). The method $\bar{O}_3 \pm 2\sigma$ found low TO3 events bulked mainly to June and July. The increase of extremely low TO3 situations relates the ozone depletion developed in the period 1994-2004 to the 1962-1990 normal period. Noteworth is significant increase of extremely low TO3 events in June, when the largest linear decrease of TO3 was detected at Hradec Králové, analysing the 1971-2000 monthly ozone dataset *(Pribullová et al., 2006)*. On the contrary, extremely low ozone values were found by the method of percent primarily in the winter months.

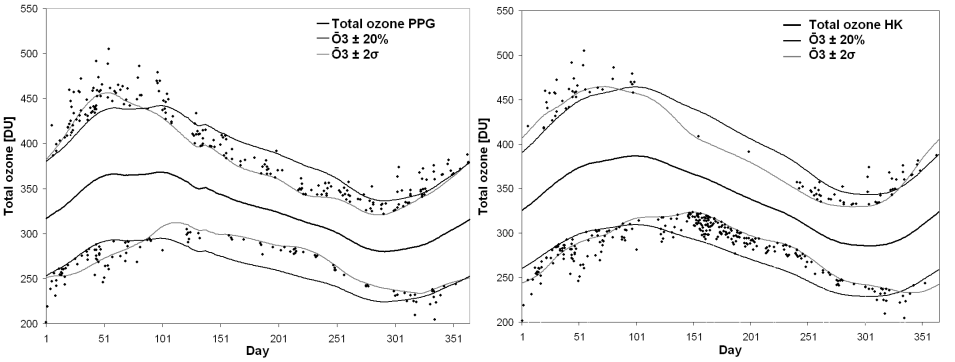

Fig. 1. Smoothed annual course of daily TO3 $\bar{O}_3$ at Poprad - Gánovce (PPG) for period 1994-2004 (left) and at Hradec Králové (HK) 1962-1990 (right) depicted by thick black lines with intervals of $\bar{O}_3 \pm 20\%$ from average daily value depicted by thin black lines and intervals of $\bar{O}_3 \pm 2\sigma$ depicted by gray lines together with extreme TO3 events detected by both methods.

If the TO3 long-term average from Hradec Králové was used for extreme TO3 event selection, the detected extremely low TO3 events involved, except of low ozone events caused by the sudden atmospheric dynamics change, also many cases raised by long-term chemical depletion. For the detection of TO3 mini-holes, the criteria for the extreme ozone selection related to Poprad - Gánovce average TO3 have been considered more reliable.

The disadvantages of both methods (overestimation of extreme TO3 events by the method of percent during a period with high natural TO3 variability and by the method of $\bar{O}_3 \pm 2\sigma$ during a period of lower TO3 variability) can be eliminated by contemporary usage of both criteria for extreme ozone selection.

Applying the coupled method for the TO3 extremes selection, the extreme TO3 events were detected only in a period of the highest natural stratospheric ozone variability from November to March. 6.2 days with extremely high TO3 were found with respect to 1994-2004 Poprad - Gánovce data and 3.7 with respect to 1962-1990 Hradec Králové data (Table 2).

Table 2. Average number of days/year with extremely low and extremely high TO3 found by methods related to Poprad - Gánovce 1994-2004 data (PPG) and to Hradec Králové 1962-1990 average (HK)

	Low TO3 PPG	Low TO3 HK	High TO3 PPG	High TO3 HK
Method $\bar{O}_3 \pm 20\%$	7.5	11.5	8.5	4.5
Method $\bar{O}_3 \pm 2\sigma$	8.8	24.7	14.8	6.9
Coupled method	4.9	8.5	6.2	3.7

The most of the below-normal TO3 situations detected using the coupled method occurred during the Southwestern anticyclonic situation (SWa, 5.2%), Anticyclone (A, 3.4%), Southern anticyclonic situation (Sa, 2.4%) and Western cyclonic situation (Wc, in 2.2% of all cases, Fig. 2, left).

The most above-normal TO3 events were detected by Cyclone (C, 8.7%), Migratory anticyclone of the 4^{th} type (Ap4, 7.7%), Northeastern cyclonic situation (NEc, 7.6%) and by Northern cyclonic situation (Nc, 6.6%, Fig. 2, right).

3.3. Comparison of total ozone extremes at Poprad - Gánovce and at Hradec Králové

Generally, more cases with below-normal TO3 were detected at Poprad - Gánovce by all three methods with respect to TO3 at Poprad - Gánovce than at Hradec Králové by all three methods with respect to Hradec Králové TO3 in the years 1994-2004 (Table 3). On the other side, more cases of above-normal TO3 were detected at Hradec Králové by all three methods with respect to TO3 at Hradec Králové in the period 1994-2004 than at Poprad - Gánovce by all three methods with respect to Poprad - Gánovce TO3 in

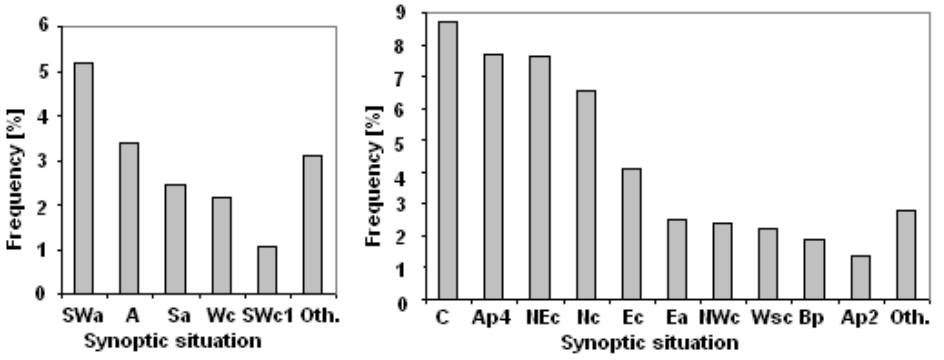

Fig. 2. Frequency of extremely low (left) and high (right) TO3 events (according to the method using both criterions with respect to Poprad - Gánovce 1994-2004 average TO3) observed during different synoptic situations. The category "others" involves synoptic situations with frequency below 1%. Legend to synoptic situation categorization can be found at the web page of the SHMI (www.shmu.sk).

the years 1994-2004.

The coupled method was used for selection of days with extreme TO3 at both observatories to evaluate their coincidence in occurrence.

There were on average 4.9 days/year with below-normal TO3 at Poprad - Gánovce and 1.9 days with below-normal TO3 at Hradec Králové. The time coincidence in the occurrence of below-normal TO3 at both observatories is 34.8% in reference to low TO3 at Poprad - Gánovce.

In the same period, there were on average 6.2 days/year with above-normal TO3 at Poprad - Gánovce and 8.1 days with above-normal TO3 at Hradec Králové. The time coincidence in the occurrence of above-normal TO3 is 43.3% in reference to high TO3 at Poprad - Gánovce (Table 3).

Table 3. Average number of days/year with extremely low and extremely high TO3 found by methods related to Poprad - Gánovce 1994-2004 data (PPG) and to Hradec Králové 1994-2004 average (HK)

1994-2004	Low TO3 PPG	Low TO3 HK	High TO3 PPG	High TO3 HK
Method $\bar{O}_3 \pm 20\%$	7.5	5.7	8.5	11.5
Method $\bar{O}_3 \pm 2\sigma$	8.8	4.9	14.8	15.9
Coupled method	4.9	1.9	6.2	8.1

3.4. The relationship between tropopause and standard pressure levels' characteristics and TO3 extremes

The correlation between TO3 daily means and temperature, pressure and height of tropopause at 12 h in the period 1994-2004 were examined to describe the relationship between TO3 and tropopause extremes. The TO3 amount correlated weakly with the temperature in tropopause (R= 0.30). The correlation between TO3 and pressure in tropopause (R= 0.53) and the anticorrelation between TO3 and the tropopause height (R= −0.55) was medium.

These results were also manifested in the coincidence of the tropopause characteristics' extremes with TO3 extremes. The coincidence in the occurrence of below-normal TO3 during below-normal temperature, pressure and above-normal height period in the tropopause level was generally small (less than 10%) for all studied tropopause characteristics. The accordance between above-normal TO3 and above-normal temperature was 22.1%. Stronger coincidence was detected between the above-normal TO3 and below-normal tropopause height (41.0% in reference to TO3 extremes) and above-normal tropopause pressure (42.9%).

On the other hand, the below-normal TO3 appeared on average only in less than 6% of all cases of extreme tropopause characteristics and the above-normal TO3 appeared only in less than 13% of all cases of extreme temperature, pressure and height in the tropopause level.

The correlation between TO3 and temperature and height of standard pressure levels was also tested. TO3 correlated best with temperature at 100 hPa level (R= 0.60, Table 4), then temperature in 70 hPa and 50 hPa level (0.54). The best anticorrelation was detected between ozone and temperature of 500 hPa and 400 hPa level (−0.61).

In 36.3% of all events, above-normal ozone occurred during a period of below-normal temperature in 700 hPa level and in 34.9% during a period of

Table 4. Average correlation coefficient between TO3 and temperature at standard pressure levels and between TO3 and height of standard pressure levels in the months October – April of the period 1994-2004

Press.level (hPa)	925	850	700	500	400	300	250	200	150	100	70	50	30
Ozone-Temp.	-0.26	-0.44	-0.58	-0.61	-0.61	-0.49	-0.01	0.42	0.52	0.60	0.54	0.54	0.48
Ozone-Height	-0.19	-0.29	-0.20	-0.55	-0.43	-0.52	-0.17	-0.53	-0.48	-0.32	-0.17	-0.04	0.08

below-normal temperature in 400 hPa level with respect to all above-normal TO3 cases.

The best coincidence between below-normal TO3 and extremes of standard pressure level characteristics was found for below-normal temperature in 70 hPa (52.0%) and in 50 hPa (50.6%) level with respect to ozone data.

These results confirm the results of *Petzoldt et al. (1994)* that regions with very low TO3 in the Northern midlatitudes were frequently accompanied by abnormal high and cold tropopause and cold mid-stratosphere. Events with extremely low TO3 values are accompanied with advection of cold air masses in the middle stratosphere. The stratospheric condition is important to ELO3 formation.

3.5. Analysis of ELO3 from December 29th 1997 to January 2nd 1998

On the January 1st 1998, the daily TO3 at Poprad - Gánovce attained its lowest value of 201.3 DU (61.8% of the 1962-1990 Hradec Králové normal) in the history of TO3 measurements at this observatory. Extremely low TO3 values are also confirmed by the satellite measurements. The situation of the period around January 1st 1998 can be evaluated as a deep ozone mini-hole. Low TO3 persisted over Poprad - Gánovce for 4 days: from the December 31st 1997 to January 3rd 1998. This ELO3 was detected also in other countries – e.g. at Hradec Králové this ELO3 persisted for 5 days (from December 30th to January 3rd), at Belsk (Poland), this situation lasted 4 days (from December 30th to January 2nd). At all the mentioned observatories, the minimum value of TO3 mean was reached on 1st January 1998. It has been the lowest TO3 daily mean since the beginning of the measurements in eastern Europe (since 1994 at Poprad - Gánovce, since 1962 at Hradec Králové and since 1963 at Belsk). The observatory Belsk recorded the lowest value of TO3 (163 DU, 49.1% of long-term daily mean). The TO3 value at Poprad - Gánovce and at Hradec Králové was comparable (201.3 DU, 61.8% to the daily mean at Poprad - Gánovce, 198.4 DU, 60.9% of the daily mean at Hradec Králové).

Fig. 3 documents the passage of the TO3 mini-hole over Europe in the period December 30th, 1997 – January 3rd, 1998 obtained from the Total Ozone Mapping Spectrophotometer measurements (`http://www.toms.gsfc.nasa.gov`). On the December 30th 1997, the centre of the mini-hole was situated

over Ireland, on December 31st over Denmark. On the January 1st, 1998, when the extreme TO3 values were reached in Slovakia, Czech Republic and Poland, the centre of ELO3 was situated over Poland. On January 2nd, the mini-hole moved towards Ukraine and disappeared. The dynamical origin of this ozone loss is suggested *(Krzyścin et al., 1998)*, because the chemical processes cannot deepen the ozone mini-hole in such a range.

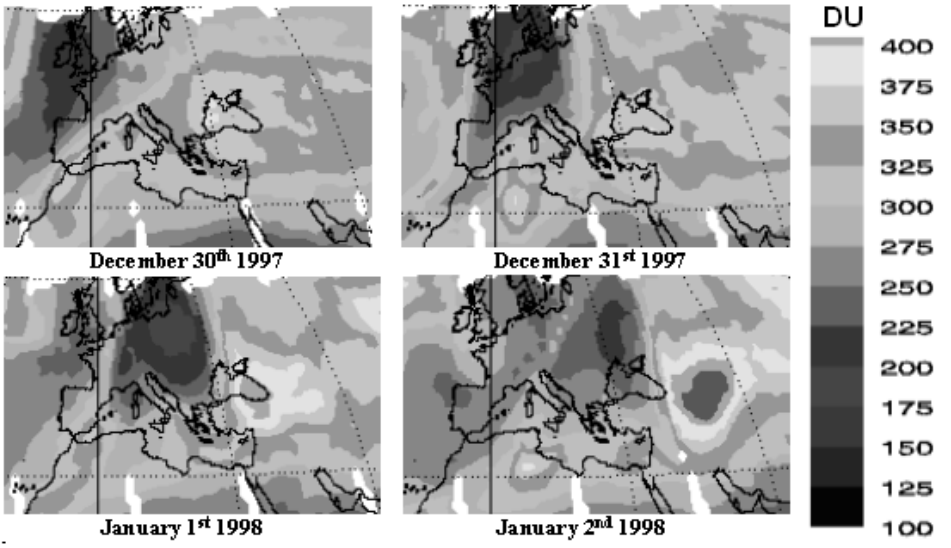

Fig. 3. Situation of ozone mini-hole over Europe in December 30th 1997 – January 3rd 1998.

On the January 1st 1998, the Southwest anticyclonic situation dominated over the territory of Slovakia. The low pressure trough in the higher troposphere (500 hPa) was situated over the east Atlantic. The isolated centre of low pressure was situated near Iceland. On the east of the low pressure trough in the upper troposphere, there was a ridge of high pressure stretched from Spain to Central Europe. Through the anticyclone, warm, originally subtropic air mass penetrated the area of Central Europe and caused the deficit of ozone in the upper troposphere.

The relatively highest value of TO3 in PPG in the period 1994-2004 was measured on February 24th 1999, when the TO3 value reached 134.2% of the normal value for the day. The low pressure trough moved through

the territory of Slovakia. The centre of the cyclone was situated over the Northern Sea and a low pressure trough hit also Slovakia. The centre of anticyclone was situated in the west of the Iberian Peninsula and the Bay of Biscay. The ridge of high pressure hit the area of the Northern Atlantic.

During the period of the TO3 mini-hole, below-normal temperature in the 30, 50, 70, 100, and 150 hPa levels was observed.

4. Conclusions

The TO3 amount and variability at Poprad - Gánovce had a well expressed annual course with the mean monthly value of 325.6 DU. The highest mean monthly value was achieved in April (366.3 DU) and the lowest in October (281.7 DU). The variability characterized by standard deviation, variational span, and interdiurnal change is generally highest in the period January - April, what can be related to the disturbation of the dynamical balance in lower stratosphere at the end of the polar night on the Northern hemisphere. The great variability of TO3 at the end of winter and in the spring months can be also influenced by the large synoptic variability in the midlatitudes of the Northern hemisphere. The lowest TO3 variability was detected in August.

The number of cases with below-normal TO3 was nearly the same if an extreme occurrence was determined by the method of percent and the method of $\bar{O}_3 \pm 2\sigma$ with respect to the Poprad - Gánovce average TO3 (there were 7.5 days/year found by the method of percent and 8.8 days/year by the method $\bar{O}_3 \pm 2\sigma$). However, there was a difference between the time-period of occurrence of the extreme ozone events detected by both methods. As the method $\bar{O}_3 \pm 2\sigma$ takes into account the annual course of TO3 variability and the method of percent does not, the extreme situations found-out by both investigated methods were differently distributed in the annual course.

As soon as the Hradec Králové 1962-1990 average TO3 values were applied to extreme TO3 values separation, the number of extremely low TO3 values rapidly increased, especially by the method $\bar{O}_3 \pm 2\sigma$. The increase of extremely low TO3 situations relates probably to the chemical ozone depletion developed in the period 1994-2004 in comparison with the 1962-1990 normal period. The Hradec Králové long-term TO3 average is therefore not

suitable for the detection of ELO3 cases at Poprad - Gánovce in the period 1994-2004.

The disadvantages of both methods (overestimation of extreme TO3 events by the method of percent during a period with high natural TO3 variability, and by the method of $\bar{O}_3 \pm 2\sigma$ during a period of lower TO3 variability) could be eliminated by contemporary usage of both criteria for extreme ozone selection (coupled method). In my opinion, the coupled method is more suitable for extreme TO3 separation than the method of $\bar{O}_3 \pm 2\sigma$ or the method of percent, because it detects the most extreme TO3 cases in every period.

The most of the below-normal TO3 situations detected using both criterions occurred during the following situations: SWa, A, Sa, and Wc. The most above-normal TO3 events were detected by C, Ap4, NEc, and by Nc.

The obtained results showed that the coincidence in the occurrence of below-normal TO3 during below-normal temperature, pressure and above-normal height period in the tropopause level at 12 h was generally small (less than 10%) for all the studied tropopause characteristics. The accordance between above-normal TO3 and above-normal temperature is 22.1%. Stronger coincidence was detected between the above-normal TO3 and below-normal tropopause height (41.0% in reference to TO3 extremes) and above-normal tropopause pressure (42.9%).

The relationship between TO3 and temperature and height of standard pressure levels was also tested. In 36.3%, above-normal ozone occurred during a period of below-normal temperature in 700 hPa level and in 34.9% during a period of below-normal temperature in 400 hPa level with respect to all above-normal TO3 cases. The best coincidence between below-normal TO3 and extremes of standard pressure level characteristics was found for below-normal temperature in 70 hPa (52.0%) and in 50 hPa (50.6%) level with respect to ozone data. These results confirm the results of *Petzoldt et al. (1994)* that regions with very low TO3 in the Northern midlatitudes were frequently accompanied by abnormal high and cold tropopause and cold mid-stratosphere.

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