MODELLING OF LONG-TERM AND SHORT-TERM TOTAL OZONE VARIABILITY AT POPRAD-GÁNOVCE, SLOVAKIA

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Abstract: The purpose of this study was construction of daily total ozone model for Poprad-Gánovce (49.03ºN, 20.32ºE, 710 m a.s.l.), Slovakia, utilizing the local upper-air measurements performed there since 1961. The model of daily total ozone was created as a sum of two independent models: (1.) model of the monthly total ozone values, (2.) model of daily total ozone deviations from the monthly average. Long-term variability of the total ozone was modelled using multilinear regression to monthly total ozone data measured with the Dobson spectrophotometer at the closest observatory Hradec Králove (50.18N, 15.83E, 285 m a.s.l.). Differences between the total ozone monthly averages from Hradec Králove and Poprad-Gánovce were negligible (in the range of ±2%) and no systematic bias was detected between both data series during the period of comparison 1994 - 2004. Content of ozone- depleting substances concentration in the stratosphere expressed by equivalent effective stratospheric chlorine (EESC), stratospheric aerosol, index of quasi-biennial oscillations (QBO), index of North Atlantic oscillation (NAO), solar activity expressed by sun spot number (SSN) and upper-air data (height of tropopause for January – February, temperature at 700 hPa level for December and difference between heights of 100 hPa level and 250 hPa izobaric levels for the other months) were the parameters tested before inclusion into the monthly total ozone model. Analysis of the Hradec Králove monthly total ozone shows that concentration ofozone-depleting substances in the stratosphere, NAO-index and upper-air parameter belongs to the best proxies of the total ozone nearly during the whole year. Aerosols play significant role in long-term total ozone variability in December – January. Solar activity variations affect the total ozone values in April - July. QBO index does not affect the total ozone variability significantly during any month, except of February. Comparison of monthly total ozone trends determined from modelled and measured 1970 - 2000 time series shows descending trend of total ozone during all months. The largest total ozone decrease was detected in April and June, but the most significant linear decrease of total ozone was determined in January and in October. Difference between modelled and measured total ozone trend was below 0.3%. Short-term total column ozone variability was modelled using upper-air proxies only. The error of final model of daily total ozone was of 6%. Coefficient of determination between measured and modelled 1993 - 2004 total ozone was of 0.86. The Poprad-Gánovce daily total ozone reconstruction has been performed since 1961, but there were large gaps in the upper-air data and consequently in the modelled daily total ozone in the 60-ties.

1. Introduction

Since the discovery of the polar ozone hole in the 80-ties, the ozone research has been concerned in the study of processes leading to stratospheric ozone depletion. The attention was turned to chemical processes leading to rapid ozone concentration decrease, mainly in the polar region. Relation between the total ozone amount concentration decrease and the increase of the ozone-depleting

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substances concentration was confirmed by several measurement methods (WMO, 2004, 1999). It has been shown that stratospheric ozone chemistry, especially in the upper stratosphere, can also be affected by variability of the solar flux. Extremely low total ozone values measured after the Mt. Pinatubo volcanic eruption (1991) confirm the role of aerosols in the ozone depletion processes (Self et al., 1999). Large differences between polar ozone depletion document importance of atmospheric dynamics in stratospheric ozone depletion in the Northern hemisphere. No significant total ozone depletion has been observed after relatively mild winters when the polar vortex is wake often disturbed by planetary waves, over north polar latitudes. Contrary to relatively warm stratospheric winters, extremely cool winters have been usually connected with strong polar vortex and deep spring ozone holes have been observed in polar area of the North hemisphere (Maney et al., 2005). Variations of the stratospheric ozone concentration related to quasi-biennial oscillations (QBO) were detected not only in tropics, but also over the higher mid-latitudes.

Appenzeller et al. (2000) was first to note, that relatively large decreasing total ozone trends detected at Arosa (Switzerland) can be partly explained by long-term changes of the circulation patterns in the North Atlantic Ocean, expressed by North Atlantic oscillation (NAO) index. It was also detected, that the NAO circulation pattern contributes to total ozone increase and mitigates total ozone negative trends over the higher latitudes (Iceland). Many other studies have analyzed effect of different climate teleconnection patterns on total ozone variability and trends since Appenzeller et al. (2000). Orsoliny et al. (2003) analyzed effect of many teleconnection patterns also with remote centres of action on total ozone measured by satellite system TOMS (total ozone mapping spectrophotometer) in mid-latitudes (30˚N - 70˚N). He showed that there is tight correlation between total ozone values and some quasi-periodic circulation patterns, depending on geographical locality.

Appenzeller et al. (2000), analyzing Arosa and Reykjavik total ozone data, and Steibrecht et al. (2001) analyzing February Hohenpeissenberg total ozone concluded that quasi-periodic circulation patterns can affect trends in total ozone time series, while Hansen and Svenøe (2005), analyzing 65-year long Tromsø (Norway) total ozone measurements, did not confirm effect of investigated circulation patterns on total ozone trends. Metelka et al. (2005) did not used linear regression models but neural networks, to analyse total ozone changes in Europe during period 1957 – 1999. Chemical depletion effect on total ozone was expressed by time-dependent variable entering the model. Heights and temperatures of selected isobaric levels , NAO –index, aerosol optical depth, variability of solar activity expressed as radio flux at wavelength 10.7 cm were next proxies. The model results indicated that main part of systematic changes of total ozone is connected to evolution of ozone-depleting substances in the stratosphere.

All investigated models of monthly total ozone, including different circulation patterns as proxies, manifest high correlation between measured and modelled data and can be used not to analyze of existing total ozone time series only but also for validation, homogenization and regional reconstruction of total ozone.

The main purpose of this study is creation of the total ozone daily average reconstruction model reliable for Poprad-Gánovce where the total ozone measurements have been performed only since 1993, but upper-air measurements (important proxies of the total ozone) have been available here since 1961.

As the Poprad-Gánovce total ozone time series has not been long enough to create regression model reflecting long-term variability of the total ozone, regression model of monthly total ozone was built using total ozone measurements from the close observatory Hradec Králove located also in Central Europe, nearly at the same latitude as Poprad-Gánovce.

The first step to modelling of long-term total ozone variability was analysis of phenomena affecting long-term variability of total ozone measured by the Dobson spectrophotometer at Hradec Králove (Vaníček et al., 2003).

2. Material and methods

The multilinear regression analysis was applied to create reconstruction model of daily total ozone at Poprad-Gánovce. The model contains two independent parts: (1.) model of the monthly total ozone values, (2.) model of the daily deviations from the monthly average. Important input parameters entering both parts of the reconstruction model were upper-air data measured at Poprad-Gánovce. Homogeneity of upper-air measurements since 1961 has been checked and considered suitable for climatological analyzes (Chmelik, 2000). However, the sounding systems operating in 60-ties did not often reach levels of the middle and upper stratosphere.

The inputs into the second part of reconstruction model were only the upper-air data (height of selected isobaric levels, differences between selected isobaric levels heights, temperature at chosen isobaric levels) form the day of total ozone measurement and also from the day before it. The problem of short-term total ozone changes modelling is high degree of autocorrelation of modelled data and also correlation between input upper-air data (Pribullová and Chmelík, 2000). Individual regression equations were constructed for every month.

Only one upper-air parameter (marked as parameter DYN), manifesting the best correlation with total ozone entered model of the monthly total ozone. Temperature of the lower troposphere (at 700 hPa isobaric level), height of the tropopause and temperature at the lower stratosphere characterized by the difference between the 100 hPa and 250 hPa isobaric level heights were the tested aerologic parameters. Except the winter months, temperature of the lower stratosphere has been the best correlating upper-air parameter.

Longer time series than 11-year long total ozone measurements performed at Poprad-Gánovce was needed for building of the monthly total ozone model involving effect of phenomena with longer periodicity (e.g., variability of solar activity, variability related to teleconnection patterns). Total ozone measurements performed at observatory Hradec Králove were used for monthly total ozone model construction. The 1970 – 2000 data set was employed for the monthly model construction due to availability of continuous and homogeneous time series of upper-air proxies at Poprad-Gánovce and total ozone data at Hradec Králove.

The total ozone has been measured at Hradec Králove with the Dobson spectrophotometer since 1962. Poprad-Gánovce total ozone time series is shorter; the measurements have been performed there since August 1993 with the Brewer spectrophotometer MKIV. Both instruments have been regularly calibrated. Total ozone data obtained at both observatories were compared during 1994 - 2003 time period, when Poprad-Gánovce measurements were available. Differences between daily total ozone measured at Hradec Králove and at Poprad-Gánovce were the largest during January – March, when the relative difference between both data sets was of 5%. Frequency of relative differences less than 5% was in the range of 62 – 72% during all investigated years. Comparison of monthly total ozone data confirms good agreement between both time series. Relative differences between monthly total ozone values do not exceed 2%. The total ozone measured at Poprad-Gánovce fits well also the TOMS satellite measurement (version 8.0 of TOMS data). Relative differences between monthly averages do not exceed 3% during 1997 – 2004 periods, when the satellite data was available. The largest discrepancy between daily total ozone values was determined in period October - December (9%). Frequency of low relative differences between ground and satellite data (less than 5%) was in the range of 70 – 85% at Poprad-Gánovce.

The other input parameters used in the monthly total ozone modelling were similar to those usually applied in multilinear regression analysis of total ozone time series (WMO, 2003).

The ozone depletion was involved into the model through equivalent effective stratospheric chlorine concentration (EESC) in ppbv, calculated for area of Central and Western Europe using Baseline scenario A1 (WMO, 1998). EESC data extended from 1900 to 2005 can be found in the internet site http://dataservice.eea.eu.int. The concentration of EESC was expressed as a nearly constant until the year 1960. A linear function represents the increase of EESC since 60-ties until the years 1997 – 1998, when the maximal content of ozone-depleting substances in the stratosphere was supposed. Descending trend of EESC has been assumed since peak of the EESC concentration until the present.

Variability of solar activity was parameterized by the sun spot number (SSN). The data source was on the web site of the Solar influences data centre of the Royal Observatory of Belgium. Not smoothed monthly values of SSN-index have been available since 1750.

Tab. 1 **the lag of QBO- and NAO-indices time series in months, what the highest absolute values of coefficient of determination between monthly total ozone and QBO-index and between monthly total ozone and NAO- index was calculated for. 1970 – 2000 data were elaborated.**

Month	1	2	3	4	5	6	7	8	9	10	11	12
QBO	-8	-10	-2	-15	-13	-13	-13	0	-6	-16	-20	-20
NAO	-8	-12	-12	-10	-3	-4	-9	-6	-5	-9	-9	-9

Atmospheric oscillations were represented by two atmospheric oscillation patterns: quasi biennial oscillation and North Atlantic oscillation. As soon as investigated circulation patterns can affect the local values of total ozone with any lag, time series of QBO and NAO were lagged in the aspect of total ozone data. The time lag manifesting the best correlation between investigated circulation pattern and total ozone was applied on the data.

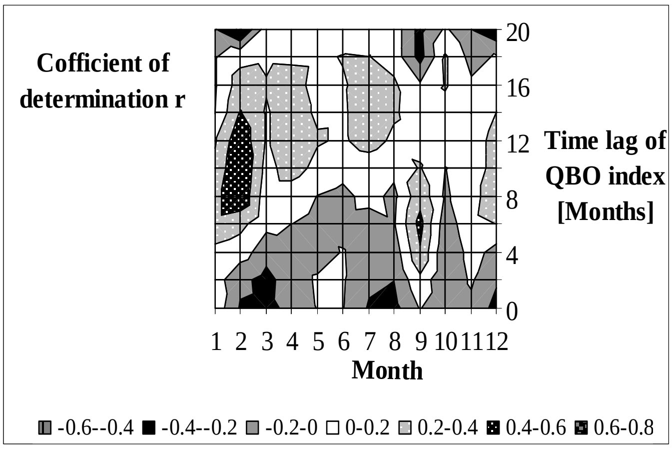

Fig. 1 **Coefficient of determination between monthly total ozone at Hradec Králove and QBO-index. The QBO-index was lagged in the aspect of total ozone from 0 to 20 months.**

The QBO was characterized by average velocity of zonal wind at the 30 hPa level at the tropics (Naukojat, 1986). The data source was on the web page of the University Washington http:/tao.atmos.washington.edu/data/qbo/. The QBO-index was lagged to total ozone time series from 0 to 20 months. Lagged QBO-index time series best correlated with the total ozone were used in monthly total ozone model (Tab. 1). The QBO-oscillation affects the total ozone values at Hradec Kralove by positive correlation and also by anticorrelation (Fig. 1). The best positive correlation between monthly total ozone and QBO-index was detected in February, when the QBO-index was between the first three best proxies of monthly total ozone.

The NAO-index represents monthly average of differences between sea level air pressure at Stykkisholmur in Iceland and in Lisbon, normalised to December-March average values and recalculated with respect to 1864 - 1983 data (Hurrel, 1995). The monthly NAO-index data presented at the web page of Climate Prediction Centre of the National Oceanic and Atmospheric Administration (NOAA) pc.ncep.noaa.gov/products/precipp/CWlink/pna/nao.shtml were involved into the model. Similarly to QBO-index, also NAO-index data was lagged with the aspect of total ozone time series (the tested NAO-index lag was of 0 – 11 months). Differently lagged NAO-index time series entered the total ozone monthly model equations (Tab. 1). The highest positive coefficient of determination between the monthly total ozone and NAO-index was detected in July with NAO-index lagged 9 months in the aspect of total ozone time series. The largest negative coefficient of determination (best anticorrelation) between the monthly total ozone and NAO-index was found during all months, except of July, with the time lag of the NAO-index ranging from 4 to 12 months (Fig. 2).

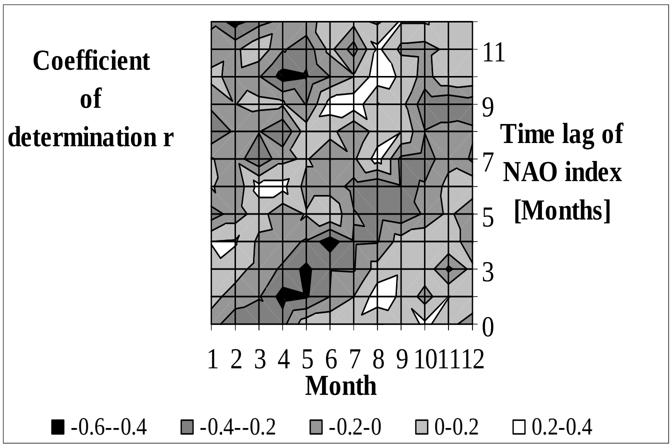

Fig. 2 **Coefficient of determination between monthly total ozone at Hradec Králove and NAO-index. The NAO-index was lagged in the aspect of total ozone from 0 to 11 months.**

The content of stratospheric aerosol (model parameter AER) was characterized by an aerosol optical depth for radiation with wavelength 340 nm. The average values calculated for area in range 40º - 50º N were found at internet page of the Surface radiation research branch of NOAA http:/www.srb.noaa.gov/research/aerosol.html. Increased values of the aerosol optical depth were recorded after huge volcanic eruptions e.g., Mt. El Chic on (1982), Mt. Pinatubo (1991).

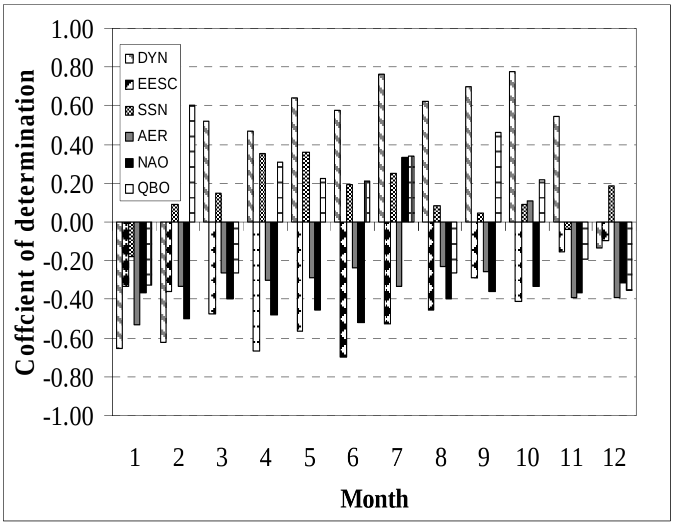

Fig. 3 **Coefficient of determination between monthly total ozone at Hradec Králove and its proxy parameters used in monthly total ozone model determined from 1970 - 2000 data. Explanation of legend can be found in text.**

Correlation analysis of the data shows, that relation between monthly total ozone and its proxies has seasonal course (Fig. 3). It was necessary to select the parameters determining total ozone in every month. In the first step all available proxies of monthly total ozone were ordered descending according to individual correlation coefficient. The significance of every proxy parameter contribution to quality of linear regression was tested using the partial F-test. The input parameters were once again sorted in descending order in accordance with the F-test values. The proxies were one after other added into the multilinear model. Change of the reduced correlation coefficient after addition of the next parameter was a criterion for intrusion of the parameter into the model. If the reduced correlation coefficient increased after addition of the proxy parameter, the parameter was involved into the model, if do not, the investigated parameter and all following parameters were not used in the model. The parameters selected as inputs into the model of monthly total ozone are summarized in Tab. 2.

Tab. 2 the proxy parameters selected for monthly total ozone multilinear model. The parameters are in descending order in accordance with significance of their contribution to monthly model improvement characterized by partial F-test method. 1970 – 2000 Hradec Králove total ozone data was elaborated. Legend to model parameters is explained in text.

Input parameter order	1	2	3	4	5	6
Month						
1	AER	NAO	EESC	QBO	DYN	SSN
2	NAO	DYN	QBO	AER	EESC	SSN
3	DYN	EESC	NAO	SSN		
4	EESC	NAO	SSN	QBO	AER	DYN
5	DYN	SSN	EESC	NAO	QBO	AER
6	EESC	SSN	DYN	NAO	QBO	AER
7	DYN	NAO	EESC	QBO	SSN	
8	DYN	EESC	NAO	QBO	AER	SSN
9	DYN	NAO	EESC			
10	DYN	EESC	NAO	AER	QBO	SSN
11	DYN	AER	NAO	QBO	EESC	
12	AER	NAO	DYN	QBO	SSN	

The order of input data reflects the contribution of every input parameter to total correlation between modelled and measured data. The statistical analysis shows, that the model entered also parameters manifesting low significance of their contribution to linear model quality determined by the F-test values. The reduced correlation coefficient however slightly increased after inclusion of these parameters into the model. It is probably more due to dependence of the reduced correlation coefficient on the number of model parameters, than due to real contribution of the noted input parameters to the model improvement.

The reconstruction of the Poprad-Gánovce daily total ozone time series has been performed since 1961.

3. Results and Discussion

Reconstruction model of daily total ozone at Poprad-Gánovce O_{3DAY} was created as a sum of monthly average of total ozone O_{3AVG} model and model of deviations of daily total ozone from monthly average ΔO_3. The modelled daily total ozone was calculated using following formula:

$$O_{3DAY} = O_{3AVG} + \Delta O_3 \qquad (1).$$

3.1. Model of monthly total ozone

The number, sort and order of input parameters entering the model of monthly total ozone differ from month to month. The coefficient of determination between measured and modelled monthly total ozone ranged from 0.63 to 0.86 (Tab. 3) at Hradec Králove. The December and March were months with the lowest coefficient of determination ($r_{total} < 0.70$). Decrease of correlation during the winter months probably relates to selection of the upper-air parameters. It is known, that during winter months the total ozone correlates better with higher standard pressure level characteristics (10 hPa – 30 hPa) (Pribullová and Chmelík, 2000), than those involved into the model. Decrease of correlation between measured and modelled monthly total ozone during winter months can also relate to selection of monthly total ozone proxies – probably also other teleconnection patterns can affect variability of total ozone during this months. The root mean square (RMS) error of the monthly total ozone model was below 3% from May to November, what is comparable with differences between Poprad-Gánovce ground and TOMS satellite data. Increase of RMS error was detected during December – April, when the RMS error increased to values of 3.1% – 4.8% (Tab. 3). The coefficient of determination between the measured and modelled monthly total ozone r was of 0.96 and RMS error of 2.9% at Hradec

Králove for the period 1970 – 2000 (Fig. 4A). The coefficient of determination between the measured and modelled monthly total ozone *r* was of 0.93 and RMS error of 3.4% at Poprad-Gánovce for the period 1993 – 2004 (Fig. 4B).

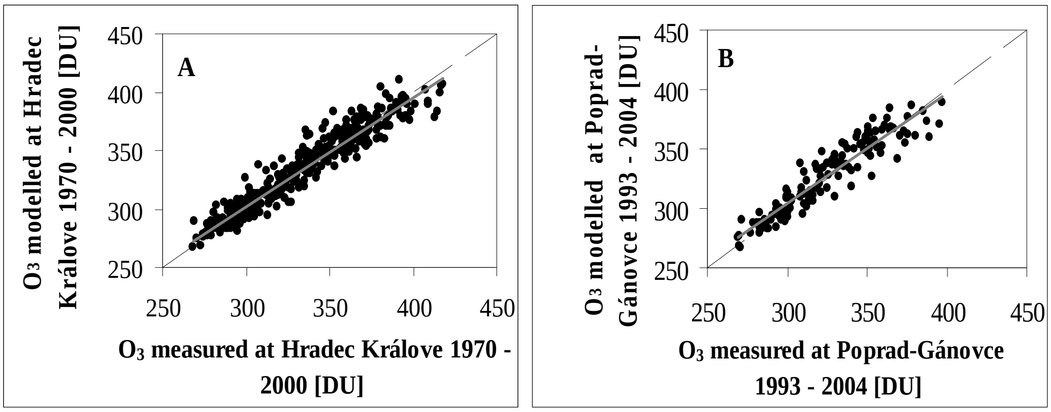

Figure 4 A-B Measured monthly total ozone as a function of modelled monthly total ozone at Hradec Králove during period 1970 – 2004 (4A) and at Poprad-Gánovce during period 1993 - 2004 (4B) expressed by linear functions.

Analysis of the Hradec Králove monthly total ozone shows, that concentration of ozone-depleting substances in the stratosphere affects the total ozone not only in April and June, when the largest total ozone decrease was detected. The EESC parameter was between the first three best correlated parameters determining the monthly total ozone during the whole year except November, December and February. Except January and April, the upper-air parameters belong to the best total ozone proxies. Inclusion of the NAO index into the model improves its quality during the whole year, except April and May. The monthly total ozone is determined mainly by the atmospheric oscillations (NAO, QBO) and also by ozone-depleting substances concentration in stratosphere in February. The solar activity variations were between the three best proxies of monthly total ozone in period April - June. Aerosols determine the long-term total ozone variability in December and in January. The QBO effect on the total ozone was found to be more significant during February only.

To detect possible differences in long-term variability of measured and modelled monthly total ozone, both 1970 – 2000 data series dependence on the time was expressed by liner function. For all months and both modelled and measured data, descending lines fitted the total ozone data. The trends of monthly total ozone were calculated using 30-years long time period 1971- 2000 (Tab. 3). The steepest decreasing trend of total ozone of -2.5 %/decade and -2.6%/decade was detected analysing measured data in April and June respectively. During these months, the the parameter EESC determined the total ozone values. The trend of modelled total ozone was of -2.8%/decade in April. The differences between linear trends calculated from modelled and measured data were of range 0.0 – 0.3%/decade. The largest difference of 0.3%/decade was detected in December and September. Statistical significance of trends was tested using method of variance analysis. The hypothesis of nonzero slope of linear function expressing the monthly total ozone dependence on time was tested.

Tab. 3 The coefficient of determination *r* between measured and modelled monthly total ozone at Hradec Králove, *RMS* error of the model, linear trends of modelled O_{3mod} and measured O_{3meas} monthly total ozone in %/decade and differences between linear trends of modelled and measured monthly total ozone. Statistically significant trends of total ozone calculated at significance level $\alpha = 0.25$ are marked by gray bold letters, statistically significant trends of total ozone calculated at significance level $\alpha = 0.05$ are marked by black bold letters. The first three best monthly total ozone proxies are for each month in the last three rows. If their linear trends are statistically significant at the significance level $\alpha = 0.05$, parameters are marked by bold letters and the linear trend calculated in %/decade is shown in brackets.

Month	1	2	3	4	5	6	7	8	9	10	11	12
r	0.85	0.81	0.66	0.83	0.81	0.84	0.86	0.73	0.80	0.86	0.70	0.63
RMS [%]	4.2	4.8	4.8	3.1	2.7	2.3	1.6	2.3	2.4	2.4	2.6	4.0
Trend O_{3meas} [%/decade]	**-2.2**	**-1.6**	**-2.1**	**-2.6**	**-1.9**	**-2.5**	**-1.4**	-1.2	-0.4	**-1.5**	-0.3	-0.4
Trend O_{3mod} [%/decade]	**-2.2**	**-1.7**	**-2.3**	**-2.8**	**-1.9**	**-2.4**	-1.3	-1.1	-0.7	**-1.6**	-0.5	-0.1
Trend difference O_{3meas} - O_{3mod} [%/decade]	0	0.1	0.2	0.2	0	-0.1	-0.1	-0.1	0.3	0.1	0.2	-0.3
Parameter 1 (trend [%/decade])	AER	**NAO (64)**	DYN	**EESC (91)**	**DYN (-2.0)**	**EESC (91)**	**DYN (-0.4)**	DYN	DYN	DYN	DYN	AER
Parameter 2 (trend [%/decade])	NAO	DYN	**EESC (91)**	**NAO (111)**	SSN	SSN	NAO	**EESC (91)**	NAO	**EESC (91)**	AER	**NAO (161)**
Parameter 3 (trend [%/decade])	**EESC (91)**	QBO	NAO	SSN	**EESC (91)**	DYN	**EESC (91)**	**NAO (169)**	**EESC (91)**	**NAO (103)**	**NAO (169)**	DYN

The values of linear trend obtained from statistically significant regressions at the significance level α = 0.25 are depicted by bold gray letters in Tab. 3. Trends calculated at the significance level α = 0.05 were detected for modelled total ozone in two months only – January and October (bold black letters in Tab.3). Except of the total ozone trends, also linear trends of its first three best proxies were calculated and analyzed with respect to their statistical significance (Tab. 3). Monthly total ozone proxies manifesting statistically significant linear dependence on the time are marked by thick letters, trends determined at significance level α = 0.05 are in brackets in the Tab. 3. Increasing statistically significant linear trend of EESC (91%/decade) was equal for all months. Trend analysis of other monthly ozone proxies shows, that statistically significant linear increasing trend of NAO-index can affect the totals ozone trend in period February – April and also form August to December. Anticorrelation between monthly total ozone and NAO-index was detected during these months. This indicates an idea, that prevailing positive phase of the NAO-index observed during the 90-ties (IPCC, 2001) can relate to enlargement of the total ozone decrease in Central Europe. But on the other hand, no significant negative trend of the total ozone was detected in August and November, when the largest ascending trend of the NAO-index was detected. Statistically significant decrease of lower stratospheric temperature (expressed via upper-air parameter DYN) was determined in May and July. It is not clear, how ozone concentration decrease in the lower stratosphere contributes to negative temperature trends observed there, and how long-term changes of climate (green-house effect) affect radiation balance and consequently temperatures in the lower stratosphere. Neither aerosol content in the stratosphere (in spite of increasing trend detected in winter months), nor solar activity variations manifest statistically significant linear trend during investigated period at Hradec Králove.

3.2 Model of daily total ozone deviations from the monthly average

Assumption that short-term changes of the total ozone relate to variability of atmospheric dynamics only was used by modelling of daily total ozone deviations from monthly average. Four upper-air characteristics (temperature at 700 hPa isobaric level, height of 250 hPa isobaric level, differences between the 100 and 200 hPa isobaric level heights and temperature difference between 100 and 250 hPa isobaric levels) determining temperature of lower stratosphere and troposphere entered the model. As daily total ozone manifests strong autocorrelation, the same upper-air data obtained on day of total ozone measurement and also on day before it were used as model input parameters. Finally eight upper-air parameters were involved into the model. Model equations were created separately for every month, but equal number and sort of input parameters were used for every month. Linear relation between upper-air data and deviation of daily total ozone from its monthly average was assumed. Model was constructed applying 1993 – 2000 upper-air and total ozone data measured at Poprad-Gánovce.

Tab. 4 **The coefficient of determination *r* between modelled and measured deviations of daily total ozone from monthly average and *RMS* error of model of daily total ozone deviations from monthly average in Dobson units (DU) calculated from 1993 – 2000 Poprad-Gánovce data.**

Month	1	2	3	4	5	6	7	8	9	10	11	12
r	0.73	0.83	0.82	0.74	0.76	0.79	0.82	0.73	0.81	0.69	0.71	0.69
RMS [DU]	28	23	21	21	13	12	10	10	11	11	20	23

The model RMS error ranged from 10 DU in August to 28 DU in January (Tab. 4). The coefficient of determination between measured and modelled values of modelled parameter ranged from 0.69 to 0.83 (Tab. 4). It confirms good agreement between the signs of modelled and observed deviations of daily total ozone from monthly average.

3.4 Model of daily total ozone

Modelled daily total ozone was obtained as a sum of monthly total ozone and deviation of daily total ozone from its monthly average. Finally 14 input parameters were required for daily total ozone modelling. While model of total ozone deviations from its monthly average was based on local upper-air data only, the model of total ozone monthly averages was constructed using Hradec Králove total ozone, global characteristics of solar activity and ozone depleting substances content in the stratosphere, regional teleconnection pattern indices and stratospheric aerosol characteristic, and local upper-air data. The final model of daily total ozone was tested on 1993 – 2004 Poprad-Gánovce data.

Tab. 5 ***RMS*** **error of daily total ozone model in % calculated from 1993 – 2004 Poprad-Gánovce data.**

Month	1	2	3	4	5	6	7	8	9	10	11	12
RMS [%]	9.8	8.7	7.3	6.7	4.1	4.9	4.7	4.2	4.6	5.5	7.6	8.0

The differences between measured an modelled daily total ozone were determined for daily ozone modelled using both measured and modelled monthly total ozone, separately. The RMS error of daily total ozone model was of 5.4% (17 DU) and coefficient of determination *r* was 0.90 when measured monthly total ozone entered the model. But the model of daily total ozone was not significantly deteriorated after using of modelled monthly total ozone (RMS = 20 DU or 6.1%, r = 0.86). Modelled daily total ozone using measured and modelled average monthly total ozone as a function of measured daily total ozone is in the Fig. 5.

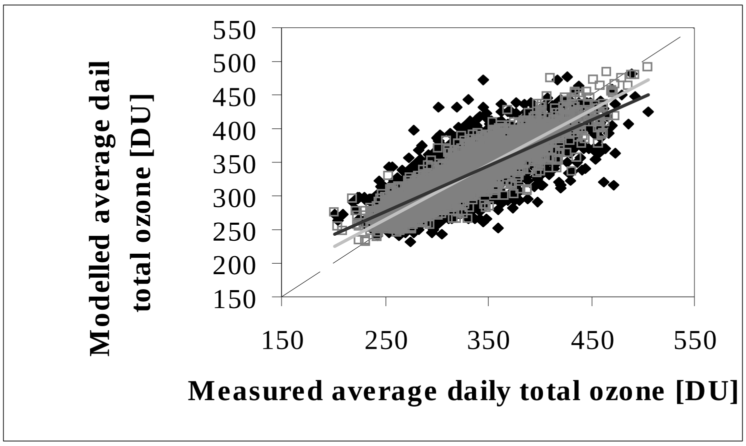

Fig. 5 **Measured daily total ozone as a function of modelled total ozone for model with usage of monthly total ozone measured at Hradec Králove (gray symbols) and for modelled monthly total ozone (black symbols) at Poprad-Gánovce in period 1993 - 2004 together with linear fits of both data groups.**

Linear regression lines of these scatter-plots are also depicted in this Fig. Lower scattering of data and regression line closer to ideal case, when modelled daily total ozone is equal to measured values, can be seen on scatter-plot of daily total ozone modelled using measured monthly total ozone as an input. Underestimation of the highest values of daily total ozone and overestimation of extremely low daily total ozone is more significant for daily total ozone calculated using modelled monthly total ozone data. The model error varies in annual course. Tab. 5 shows RMS errors of daily total ozone for every month. Deterioration of the model can be seen during the winter months (Fig. 6), when RMS error of the model increased to values of 7.6 - 9.8 %. The RMS error values are below 5% from May to October.

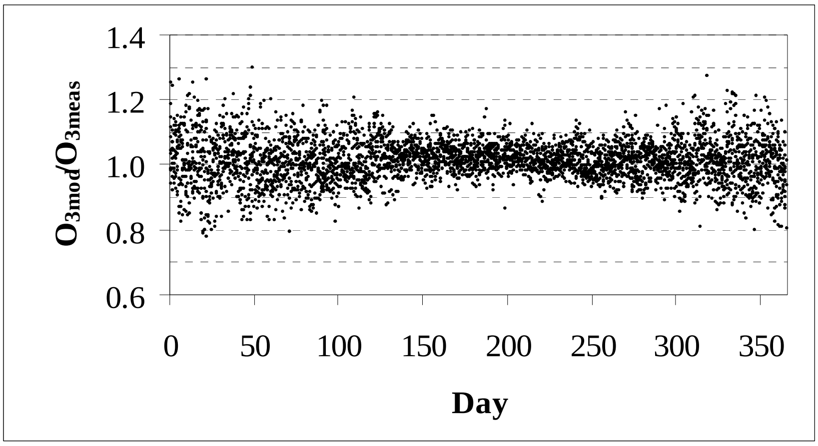

Fig. 6 Annual course of a ratio between modelled and measured daily total ozone at Poprad-Gánovce in period 1993 - 2004.

Lower differences were found between modelled and measured daily total ozone than between satellite and ground-based measurements of daily total ozone at Poprad-Gánovce from October to December. Error of the daily total ozone model is 2% larger than differences between Poprad-Gánovce and Hradec Królove daily ozone and also larger than differences between ground-based and satellite total ozone measurements at Poprad-Gánovce.

4. Conclusions

The purpose of this study was construction of daily total ozone model for Poprad-Gánovce utilizing the local upper-air measurements performed there since 1961. The model of daily total ozone was created as a sum of two independent models: (1.) model of the monthly total ozone values, (2.) model of the daily total ozone deviations from the monthly average. Long-term variability of the total ozone was modelled using multilinear regression analyze of monthly total ozone data measured by the Dobson spectrophotometer at the closest observatory Hradec Królove. Differences between the total ozone monthly averages from Hradec Królove and Poprad-Gánovce were negligible (in the range of ±2%) and no systematic bias was detected between both data series during the period of comparison 1994 - 2004. The 1970 – 2004 total ozone data from Hradec Królove were utilized for a monthly total ozone modelling. Linear increase of ozone-depleting substances concentration in the stratosphere, stratospheric aerosol content, index of quasi-biennial oscillations, index of North Atlantic oscillation, solar activity expressed via sun spot number and Poprad-Gánovce upper-air parameters (height of tropopause for January – February, temperature at 700 hPa level for December and difference between heights of 100 hPa level and 250 hPa level for the other months) were the parameters tested before inclusion into the monthly total ozone model. Correlation analysis and partial F-test were applied to select the parameters significantly affected the model quality. Analysis of the 1970 - 2000 Hradec Królove monthly total ozone shows, that in spite of usage of upper-air proxies measured at Poprad-Gánovce, upper-air parameter affects the monthly total ozone at Hradec Królove significantly during all months, except January and April. Ozone depletion term was between the three best proxies of monthly total ozone, except November, December and February. The NAO-index also frequently belongs to the best monthly total ozone proxies. Exceptions are months April and June, when the largest total ozone depletion was detected. Variability of solar activity affects monthly total ozone more significantly during summer months April - June and does not play important role in monthly total ozone variability during the rest of year. Aerosols affect total monthly total ozone variability significantly in winter. The QBO-index was found between first three best significant proxies only in February.

Analysis of linear trends of both measured and modelled monthly total ozone shows that there are not large differences between trends determined from measured and modelled data. The largest differences between trends do not exceed 0.3%/decade. Both modelled and measured total ozone decreasing trend was detected during all months. The linear regressions of total ozone as function of time were significant at significance level $\alpha = 0.25$ from January to July and during October. Trends and their statistical significance were determined also for the first three best monthly total ozone proxies. Statistically significant linear increase of NAO-index (at the significance level $\alpha = 0.05$) with time was determined in February, April, and August and from October to December. As monthly total ozone anticorrelates with NAO-index lagged in the aspect of total ozone by different number of months, there is possible effect of NAO circulation pattern on long-term changes of total ozone. Upper air parameters expressed as difference between height of 100 hPa and 250 hPa isobaric levels (proportional to lower stratosphere temperature) also significantly decreased during investigated 1970 – 2000 period. It is not clear from this study how this trend relates to total ozone depletion and how effect of tropospheric green-house phenomena contributes to lower stratospheric temperature decrease. Interesting is very significant (at significance level $\alpha = 0.05$) descending trend of total ozone detected in October which can relate to NAO-index long-term variability and also to zone-depleting substances concentration increase in the stratosphere. It is also worth to note, that decreasing trend of monthly total ozone was determined more by the NAO and QBO teleconnection patterns and aerosols in February, than by long-term variability of ozone-depleting substances.

Short-term total column ozone variability was modelled using aerologic proxies only. High degree of correlation was reached between modelled and observed deviations of daily total ozone from monthly average. The error of final model of daily total ozone was of 6.1%. Coefficient of determination between measured and modelled 1993 - 2004 total ozone was of 0.86. Usage of measured monthly total ozone instead of modelled one improves the daily model RMS error to value of 5.4% ($r = 0.90$). During summer months, the model error is comparable to differences between daily total ozone at Hradec Králove and at Poprad-Gánovce. From October to December the model error is less than differences between satellite and ground-based measurements at Poprad-Gánovce. The largest discrepancy between measured and modelled daily total ozone was in winter. During winter months, selection of different upper-air proxy parameter (higher standard pressure level heights) can probably improve the model quality, or the next proxies (other teleconnection patterns) are needed for daily total ozone modelling. Probably also usage of regional, not local, indices of NAO teleconnection pattern can contribute to model improvement. The daily total ozone reconstruction has been performed since 1961, but there are large gaps in the aerologic data and also in the modelled daily total ozone in the 60-ties. The series of reconstructed daily total ozone is available at authors of this publication. The analysis of total ozone at Poprad-Gánovce using reanalysed homogeneous and continuous upper-air data will be done in future.

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