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LONG-TERM CHANGES IN THE STATISTICAL DISTRIBUTION OF DOBSON TOTAL OZONE IN SELECTED NORTHERN HEMISPHERE GEOGRAPHICAL REGIONS

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ABSTRACT

The daily averages of total column amount of ozone taken in the period 1964-1988 at a network of 24 Dobson stations have been analyzed. Year-round data as well as summer data (May-Aug.) and winter data (Dec.-March) have been examined in the following regions: latitude bands (30°N-39°N, 40°N-52°N, 30°N-60°N), North America, Europe, Japan.

To find year-to-year changes in the shape of the annual statistical distribution of total ozone (ASDTO) for these regions, we analyze trends in the following statistic characteristics of ASDTO: mean, standard deviation, median, 10 and 90 percentiles. Time series of the statistical characteristics for the selected regions have been combined by averaging the individual stations values of these characteristics.

The trends have been calculated by the multiple regression model adjusted for: the 11-year solar cycle, the Southern Oscillations effects, and for serial correlations. We have found that:

a) in all regions (excluding Japan, North America), the shape of ASDTO has been drifting towards low ozone values. The drift seems to be not accompanied with a transformation in the shape of ASDTO.

The drift speed (the rate of decrease in the annual means of total ozone) is of order 1-3 % per decade (in the period 1970-1988).

b) the drift speed depends on the regions, the lowest one is in 30°N-39°N band.

b) in Japan, the interannual changes in the shape of ASDTO have not been revealed.

c) in North America, the drift of the year-round ASDTO (the year-round ASDTO comprises all the daily means of total ozone in a given year) has been accompanied with a transformation in the shape. The shape of the year round ASDTO becomes narrower.

d) in all regions, except Japan and the band 30°-39°N, the winter ASDTO (the winter ASDTO comprises the date taken in the period December in a given year through March next year) moves faster towards low ozone values than the summer ASDTO (the summer ASDTO comprises the data taken in the period May through August in a given year).

1. INTRODUCTION

Ozone trend detection has been a subject of interest during the past decade (e.g. Reinsel *et al.*, 1981; Angell *et al.*, 1983; Hill *et al.*, 1986; Oehlert, 1986; IOTP, 1990). Implications for UV radiation changes at the earth's surface have stimulated much of the concern about ozone downward trend.

Almost all studies of the long-term variations in the atmospheric ozone were carried using the monthly (or yearly) averages of ozone. In this paper, we analyze interannual changes in values of a few statistic characteristics of the annual statistical distribution of total ozone (i.e. mean value, standard deviation, median, 10 and 90 percentiles) to disclose the long-term variations in the shape of ASDTO in selected Northern Hemisphere regions

2. DATA

Dobson total ozone data have been analyzed from a network of 24 stations for the period 1964-1988. The names of the stations, locations and the data periods are listed below:

STATION	COUNTRY	LAT.	LON.	PERIOD
1 Lerwick,	U.K.	60°N,	1°W;	1/64-11/88
2 Leningrad,	Russia	60°N,	30°E;	8/68-12/88
3 Churchill,	Canada	59°N,	94°W;	1/65-12/88
4 Edmonton,	Canada	54°N,	114°W;	1/64-12/88
5 Belsk,	Poland	52°N,	21°E;	1/64-12/88
6 Bracknell,	U.K.	51°N,	1°W;	1/69-12/88
7 Uccle,	Belgium	51°N,	4°E;	2/71-12/88
8 Hradec K.,	Czechoslov.	50°N,	16°E;	1/64-12/88
9 Hohenpeiss.,	Germany	48°N,	11°E;	1/67-12/88
10 Caribou,	U.S.A.	47°N,	68°W;	1/64-12/88
11 Arosa,	Switzerland	47°N,	10°E;	1/64-12/88
12 Bismarck,	U.S.A.	47°N,	101°W;	1/64-12/88
13 Toronto,	Canada	44°N,	79°W;	1/64-12/88
14 Sapporo,	Japan	43°N,	141°E;	1/64-12/88
15 Rome,	Italy	42°N,	12°E;	1/64-12/88
16 Boulder,	U.S.A.	40°N,	105°W;	1/64-12/88
17 Cagliari,	Italy	39°N,	9°E;	1/64-12/88
18 Wallops Is.,	U.S.A.	38°N,	76°W;	1/70-12/88
19 Nashville,	U.S.A.	36°N,	87°W;	1/64-12/88
20 Tateno,	Japan	36°N,	140°E;	1/64-12/88
21 Srinagar,	India	34°N,	75°E;	2/64-12/88
22 Kagoshima,	Japan	32°N,	131°E;	1/64-12/88
23 Quetta,	Pakistan	30°N,	67°E;	8/69-12/88
24 Cairo,	Egypt	30°N,	31°E;	11/74-12/88

In this paper, we analyze the daily mean total ozone record published in "Ozone Data for the World" (ODW) journals. However, International Trend Panel-1988 [IOTP, 1990] found strong incongruities in the published data of many ground-based stations due to instrument calibrations.

For 31 Dobson stations, a provisionally revised data set (1957-1986) was prepared by the Panel, with the corrections being applied to the monthly averages of total ozone.

We examine results of the ozone observations taken at the stations selected by the Panel.

Making use of the Panel's re-evaluated total ozone monthly means we convert daily averages of total ozone (calculated before January 1987) to the provisionally corrected ones in the following way:

$$O_{3\ new}(i,j,k,l)=O_{3\ old}(i,j,k,l)\ \frac{M1(j,k,l)}{M2(j,k,l)}$$

where: $O_{3\ new}(i,j,k,l)$, $O_{3\ old}(i,j,k,l)$ - daily mean of total ozone on i-th day, j-th month, k-th year and at l-th Dobson station, provisionally revised and uncorrected, respectively, $M1(j,k,l)$ - revised monthly mean of total ozone [IOTP, 1990], $M2(j,k,l)$- monthly mean of total ozone derived from ODW data.

Provisionally revised daily averages of total ozone have been transformed to the departures from the long-term monthly means (1964-1988) expressed in percents of the long-term monthly standard deviation.

Using $O_{3\ new}(i,j,k,l)$ and $O_{3\ old}(i,j,k,l)$ (since January 1987) we calculate a few characteristics describing the shape of ASDTO at station l in year k. The following ones have been considered:

mean value (***MEAN***), standard deviation (***SD***), median (***MED***), 90 percentile (***P90***), 10 percentile (***P10***). ***P10*** and ***P90*** estimate locations of the low values tail and the high values tail of ASDTO, respectively.

For selected northern hemisphere regions, the statistic characteristics of ASDTO in a given year have been estimated averaging the individual stations values of the statistic characteristics in that year.

The following regions have been considered: latitude bands (30°N-39°N, 40°N-52°N, 30°N-60°N), North America, Europe, Japan.

The statistic characteristics of ASDTO have been calculated from all daily averages of total ozone values in a given year. To find seasonal differences in the long-term changes of ASDTO, summer (May through Aug.) and winter (Dec. through March) values of the statistic characteristics have been examined also.

3. TREND MODEL

Trends in the statistic characteristics of ASDTO have been found by multiple regression model. The model has been adjusted for: the 11-year solar activity cycle, the long-term stratospheric circulation fluctuations (Southern Oscillations) effects, and the serial correlations.

Variations in total ozone related to the QBO have not been parameterized because the relatively high frequency of the QBO (there are about 12 cycles in the period 1964-1988) makes its inclusion in the ozone trend model (or exclusion) have a negligible effect on the trend estimates (IOTP, 1990).

Trends in the statistic characteristics of ASDTO have been modelled by means of the ramp trend model, i.e. we assume that the trend in ozone has formed after 1969:

$$y(t) = \alpha+\beta Sun(t)+\gamma Soi(t)+N(t), \qquad t \leqslant 1969$$

$$y(t) = \alpha_1+Tt+\beta Sun(t)+\gamma Soi(t)+N(t), \qquad t > 1969$$

where: α, α_1, β, γ - constants, T - rate of linear changes (trend), $Sun(t)$- annual mean of Zurich sunspot number in year t, $Soi(t)$- Southern Oscillation index (normalized pressure difference between Tahiti and Darwin). The noise term $N(t)$ is modeled as a first order autoregressive process, i.e. $N(t) = \delta N(t-1) + e(t)$, where $e(t)$ is a noise with normal distribution and zero mean.

In our model, we assume that declining tendency in total ozone has begun around 1970. This hypothesis was widely used in the trend modeling in the past decade (e.g. Reinsel *et al.*, 1981; IOTP, 1990).

We run the trend model using as $y(t)$ the composite time series of: ***MEAN***, ***SD***, ***MED***, ***P90***, and ***P10***, combined from individual station values of these characteristics. Constants α, α_1, β, γ, δ, T are derived by the least square fit.

For example, the comparison between observed and modeled time series of ***MEAN*** for 10 European Dobson station (see section 2 for the names of these stations) is presented in Fig. 1. The correspondence between the long-term variations in the observed and modeled time series allows to state that the model reproduces adequately the long-term variations in total ozone.

Fig. 1 Observed and modelled departures of annual total ozone means from its long-term (1964-1988) mean (expressed in percent of the long-term mean) in the period 1964-1988 for European Dobson stations (see section 2 for the names of stations)

4. RESULTS

In Fig. 2 we present an example of analyzed time series set. The annual values of the statistic characteristics have been combined from ten European Dobson stations. It is seen that the pattern of ***SD*** time series is almost constant during observation's period (1964-1988), but other time series (***MEAN***, ***P90***, ***P10***) show similar decreasing tendency. Moreover, variations in time series of ***MEAN***, ***P90*** and ***P10*** seem to be highly correlated. The correlation coefficients between: ***MEAN*** and ***P90***, ***MEAN*** and ***P10***, ***P90*** and ***P10*** are equal 0.93, 0.93, 0.75, respectively.

These high correlations, similar negative trends in *MEAN, P10, P90,* and no trend in *SD* let us suggest that year-to-year variations in the shape of ASDTO are caused by a drift of the shape (towards low ozone values) rather than by a transformation of the shape (for example a change of the distribution type).

For the European stations, we have found that ASDTO is well approximated by the log-normal distribution. The long-term changes in the shape of ASDTO can be mathematically described as a translation of the distribution towards low ozone values because almost similar negative trends have been found in time series of *MEAN, P10* and *P90,* while no trend in *SD.*

For all analyzed northern hemisphere regions, the high correlations between *MEAN, P10* and *P90* have been detected. Then, the long-term changes in the shape of ASDTO have been deduced from the trend analyses of the following composite time series: *MEAN, SD, MEDIAN, P10, P90.* The results are presented in Tab. 1.

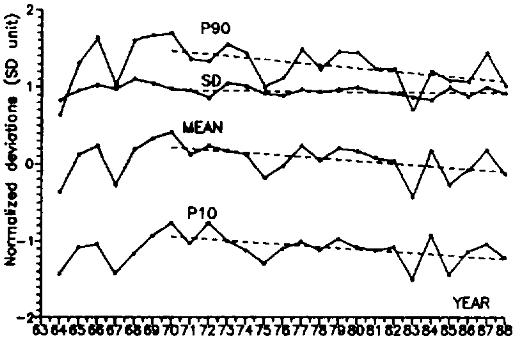

Fig. 2. Time series (1964-1988) of statistic characteristics (annual mean - **MEAN***, standard deviation-* **SD***, 90 percentile-* **P90***, 10 percentile -***P10***) of the distribution of total ozone combined from the individual station values of these characteristics. The analyzed time series have been obtained from the data taken at 10 European Dobson stations. Values of the characteristics are expressed in standard deviation unit. Dashed lines represent linear regression lines.*

The main finding from Tab.1 is a drift of the shape of ASDTO towards low ozone values (only the results for Japan show that the shape remains constant in the period 1970-1988). We have found that the annual rates of the changes in selected statistical characteristics (*MEAN, MEDIAN, P90, P10*) of ASDTO are almost the same (within 2σ band) and the trends in *SD* are not statistically significant (except North America where the trend is negative). Therefore, it seems that the long-term changes in the shape of ASDTO in all the analyzed regions (except Japan, North America) are expressed simply as a translation of the shape towards low ozone values. The speed of this translation (the rate of decrease in the annual means of total ozone) depends on latitude (the lowest is found in the latitude band 30°N-39°N) The speed varies with season also. For the winter ASDTO, which is built from the all daily means of total ozone in the period December-March, the speed is greater than the speed for the summer ASDTO (May through August daily means of total ozone have been used to prepare the summer ASDTO).

In North America, for the year round data, statistically significant trend in SD time series has been revealed. Therefore, the drift of the shape of the year-round ASDTO (the year-round ASDTO comprises all the daily means of total ozone in a given year) seems to be accompanied with a transformation of the shape. The shape of the year round ASDTO becomes narrower. There is a likelihood that the negative tendency in the annual standard deviations over North America, calculated from all the daily total ozone means in a given year, is forced by the large decline in the high value tail of ASDTO (see Table 1, section for North America, where a large difference between the trends in *P90* and *P10* can be seen).

Tab.1. Long-term trends (year-round, winter and summer trends in the period 1970-1988) in the characteristics of the annual statistical distribution of total ozone (in % per decade) for selected northern hemisphere regions: latitude bands (30°N-39°N, 40°N-52°N, 30°N-60°N), North America, Europe, Japan.
For the period 1964-1986 provisionally revised daily averages of total ozone and for the period 1987-1988 the data published in Ozone Data for the World journals have been used. Errors (on 2σ level) are shown in parentheses. Statistical significant results are underlined

E U R O P E

Trends

	Year-round	_Winter_	_Summer_
MEAN	-2.10 (1.80)	-2.50 (2.89)	-1.11 (1.83)
SD	-1.64 (5.66)	2.54 (7.13)	-3.10 (7.20)
MED	-1.98 (1.82)	-1.96 (2.99)	-1.20 (1.79)
P90	-2.45 (2.32)	-2.17 (3.65)	-1.63 (2.29)
P10	-1.99 (1.60)	-3.33 (2.37)	-0.70 (1.72)

N O R T H   A M E R I C A

Trends

	Year-round	_Winter_	_Summer_
MEAN	-2.60 (1.62)	-3.83 (2.14)	-2.03 (1.47)
SD	-4.91 (3.38)	-1.44 (6.12)	-5.29 (5.87)
MED	-2.70 (1.59)	-3.65 (2.12)	-2.17 (1.46)
P90	-3.26 (1.98)	-4.31 (2.80)	-2.50 (1.98)
P10	-1.95 (1.40)	-3.70 (2.16)	-1.37 (1.37)

J A P A N

Trends

	Year-round	_Winter_	_Summer_
MEAN	-0.70 (1.19)	-0.73 (2.01)	0.05 (1.68)
SD	0.59 (4.30)	-2.67 (9.14)	0.16 (4.61)
MED	0.16 (1.25)	-0.88 (2.12)	0.33 (1.78)
P90	0.06 (1.29)	-0.44 (2.80)	0.33 (2.10)
P10	0.14 (1.15)	-0.11 (1.89)	-0.07 (1.33)

BAND: 40°N - 52°N

	Trends		
	Year-round	Winter	Summer
MEAN	-1.90 (1.35)	-2.33 (2.06)	-1.34 (1.23)
SD	-2.83 (5.12)	-3.18 (7.43)	-3.53 (6.24)
MED	-1.82 (1.34)	-2.11 (2.11)	-1.44 (1.20)
P90	-2.27 (1.77)	-2.21 (2.79)	-1.50 (1.65)
P10	-1.64 (1.12)	-3.01 (1.71)	-0.90 (1.23)

BAND: 30°N - 39°N

	Trends		
	Year-round	Winter	Summer
MEAN	-1.34 (1.13)	-1.52 (2.14)	-1.50 (1.50)
SD	-1.68 (4.36)	2.00 (5.93)	0.96 (5.62)
MED	-1.34 (1.19)	-1.51 (2.23)	-1.52 (1.52)
P90	-1.29 (1.27)	-0.84 (1.99)	-1.51 (1.66)
P10	-1.44 (1.00)	-1.45 (2.40)	-1.46 (1.30)

BAND: 30°N - 60°N

	Trends		
	Year-round	Winter	Summer
MEAN	-1.66 (1.18)	-2.30 (1.54)	-1.23 (1.21)
SD	-1.62 (3.25)	-0.45 (4.66)	-2.24 (3.25)
MED	-1.65 (1.18)	-2.14 (1.62)	-1.26 (1.24)
P90	-1.87 (1.44)	-2.16 (1.84)	-1.39 (1.44)
P10	-1.52 (0.96)	-2.46 (1.34)	-0.98 (1.01)

5. Discussion and Conclusion

We have found that the long-term changes in the shape of ASDTO, calculated for selected northern hemisphere geographical regions, have been expressed as a drift of the shape towards low ozone values. Some regional and seasonal peculiarities in the drift speed (the rate of decrease in annual means of total ozone) have been revealed.

The errors of the trend estimates in the statistical characteristics of ASDTO have been calculated too large to make conclusive statement about details of a transformation of ASDTO in the period 1964-1988. However, in all the analyzed regions (excluding Japan, North America), the high correlations between time series of ***MEAN***, ***P90*** and ***P10*** and almost similar trends in these characteristics (while no trends in ***SD***) let us suggest that the shape of ASDTO has been drifting towards low values without a transformation of the shape. Results for the North America stations show that the drift of the shape has been accompanied with a transformation of the shape. The rate of ozone loss found in the high values tail of ASDTO (***P90***) is greater than ozone loss in ***MEAN***, and ozone loss in the low values tail of PDFTO (***P10***) is lower than the trend in ***MEAN***. As the result of these changes, ***SD*** should show decreasing tendency. The trend analysis of ***SD*** time series reveals this tendency. It means that the shape of ASDTO becomes narrower during its drifting towards low ozone values.

The long-term trends (in the period 1970-1990) calculated from the monthly averages of Dobson total ozone values (Stolarski *et al.*, 1992) are broadly consistent with the trends in ***MEAN*** derived from the interannual variations of ASDTO, i.e. there is a significant winter loss and a smaller summer loss in total ozone over the Northern Hemisphere, this difference is more pronounced at high and mid latitudes than at low latitudes.

The results of our trend model (for the variable ***MEAN***) and the newest trend estimates in monthly means of Dobson total ozone by Stolarski *et al.* [1992] are almost the same. The differences between the ozone trends are lower than 0.6 % per decade for North America, Europe, and the northern temperate regions. For example, Stolarski *et al.* [1992] found the following trends over 26°N-64°N band in the period 1970-1990: year-round -1.8% per decade, winter - 2.7% per decade, summer -1.3% per decade.

The errors in our trend estimates are larger, because relatively small number of data points (annual means) has been used in the trend detection.

In the last decade, the rate of ozone loss seems to be greater than that in the period 1970-1990, Stolarski *et al.* [1992]. We have tried to prove this hypothesis comparing the trends in the periods 1970-1986 and 1978-1988. The differences between the trends in the statistical characteristics of ASDTO calculated for these periods have been found statistically insignificant (limited number of the data points has been used to estimate trends, especially in the period 1978-1988). Then, the analysis of the interannual variations in ASDTO for the detection short-term trends (in the period of one decade) is not able to provide a support for the hypothesis probably due to large errors of the trend estimates.

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