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TREND
ANALYSIS OF THE LONG-TERM SWISS OZONE MEASUREMENTS

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ABSTRACT

Trend analyses, assuming a linear trend which started at 1970, were performed from total ozone measurements from Arosa (Switzerland, 1926-1991). Decreases in monthly mean values were statistically significant for October through April showing decreases of about 2.0-4% per decade. For the period 1947-91, total ozone trends were further investigated using a multiple regression model. Temperature of a mountain peak in Switzerland (Mt. Säntis), the F10.7 solar flux series, the QBO series (Quasi Biennial Oscillation) and the southern oscillation index (SOI) were included as explanatory variables. Trends in the monthly mean values were statistically significant for December through April.

The same multiple regression model was applied to investigate the ozone trends at various altitudes using the ozone balloon soundings from Payerne (1967-1989) and the Umkehr measurements from Arosa (1947-1989). The results show four different vertical trend regimes: On a relative scale changes were largest in the troposphere (increase of about 10% per decade). On an absolute scale the largest trends were obtained in the lower stratosphere (decrease of approximately 6% per decade at an altitude of about 18 to 22 km). No significant trends were observed at approximately 30 km, whereas stratospheric ozone decreased in the upper stratosphere.

1. INTRODUCTION

A multiple regression model, similar to a previously used model by Bojkov *et al.*, 1990 and the OTP, 1989, was applied to calculate ozone trends from the long term Swiss ozone measurements. They include the world's longest total ozone series (Arosa), ozone balloon soundings (Payerne) and one of the most extensive data sets of Umkehr measurements (Arosa).

2. MEASUREMENTS

The total ozone series from Arosa (monthly mean values) adjusted to the Dobson world standard instrument (Hoegger *et al.*, 1992) was used.

The Umkehr measurements (wavelength pair C) have been processed using the program of Mateer (Mateer, 1965) and the aerosol correction of J. DeLuisi (pers. commun.).

The ozone balloon sondes (Brewer mast sondes) were launched from Thalwil (near Zürich) during the first 2 years (1967-1969) and thereafter from Payerne, which is about 200 km to the west of Arosa. Three ascents per week were planned from the beginning, the number of the successful ascents and their data quality is described in Staehelin and Schmid, 1991.

3. TREND ANALYSES OF TOTAL OZONE

We first present the results of a trend model which only includes total ozone (monthly means) using a linear trend which started at 1970.

$$Y_t = \mu + \sum_{i=1}^{i=12} \mu_i I_{it} + \sum_{i=1}^{i=12} \beta_i I_{it} R_t + N_t \qquad (1)$$

Y_t : Ozone monthly mean at the month t

μ: overall mean of ozone

μ_i: deviation of ozone of the i-th month of the year from the overall mean; $\Sigma_i \mu_i = 0$

I_{it}: 1 if month t corresponds to i-th month of the year, otherwise 0

β_i: trend for the i-th month of the year

R_t: linear ramp function: $R_t = (t-t_0)/12$ if $t > t_0$ (t_0: Dec. 1969) and 0 = if $t < t_0$

Summation goes over i=1 to 12.

The month to month correlation in ozone, which is present after the elimination of seasonal and other effects, was modelled by an autoregressive series of second order (AR(2)):

$$N_t = \phi_1 N_{t-1} + \phi_2 N_{t-2} + \varepsilon_t \qquad (2)$$

We first included in eq.(2) the values back to the sixth month, but the results showed that an AR(2)-model is appropriate to treat the data. We used maximum likelihood fitting of model (1) assuming Gaussian errors ε_t. The variances for each month were estimated, then model (1) was calculated again using weighted least squares. This procedure did not yield new results and was therefore not applied in the further calculations.

Fig. 1a shows the seasonal variation of total ozone at Arosa. The total ozone decrease is much stronger during winter time (see Fig. 1b). The results are consistent with results from more sophisticated models in which shorter time periods have been used (OTP, 1990, Bojkov *et al.*, 1990, Stolarski *et al.*, 1992).
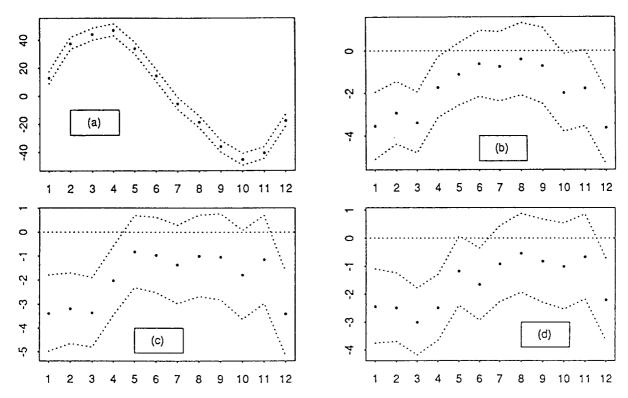
Figure 1: Total ozone series of Arosa. Labels of the abscissa: number of the calendar month. (a): Deviation of the monthly mean values (in D.U.) from the long-term annual mean value (332 D.U). The dashed lines include the 95% confidence intervals of the monthly deviations. (b)-(d): Trends in the monthly mean values (in % per decade). The dashed lines include the 95% confidence intervals for the calculated trends which were assumed to start in Jan. 1970. (b): Model of eq. (1), ozone series 1926-91. (c): Model of eq. (1), ozone series 1947-91. (d): Model of eq. (3), ozone series 1947-91, including temperature of Mt. Säntis and the F10.7 solar flux as explanatory variables.

4. INFLUENCE OF EXPLANATORY VARIABLES

The following multiple regression model is an extension of the model described in Bojkov *et al.*, 1990. We added the SOI (Southern Oscillation Index, used e.g. by Zerefos *et al.*, 1992) and the temperature from a mountain peak in Switzerland representing the temperature in the free troposphere as potential explanatory variables. Because some variables were not available before 1957 the model was applied for the later measurements.

$$Y_t = \alpha + \sum_{i=1}^{i=12}\mu_i I_{it} + \sum_{i=1}^{i=12}\beta_i I_{it}R_t + \sum_{i\epsilon K_1}\gamma_k \log(F10.7)_{t-k}$$
$$+ \sum_{i\epsilon K_2}\delta_k T_{t-k} + \sum_{i\epsilon K_3}\eta_k QBO_{t-k} + \sum_{i\epsilon K_4}\xi_k SOI_{t-k} + N_t \quad (3)$$

Where:

Summation: i: 1...12 and k: kϵk$_n$

α: Intercept

$F10.7_{t-k}$: solar 10.7-cm flux series with time lag k and associated coefficient γ_k

T_{t-k}: deseasonalized temperature at Mt. Säntis with time lag k and associated coefficient δ_k

QBO_{t-k}: QBO time series with time lag k and associated coefficient η_k

SOI_{t-k}: Southern Oscillation Index series with time lag k and associated coefficients ξ_k

N_t: noise series, AR(2)

K_i (i = 1.... 4): Sets of time lags at which the different variables influence total ozone at Arosa

We tried to evaluate the appropriate time lags using the lagged regression model of Shumway (Shumway, 1988). Temperature influences ozone strongly with a time lag of zero. The calculations of the other variables did not indicate any clearly evident pattern of time lags. Some sensitivity runs, including different time lags of the explanatory variables, indicated that the QBO- and ENSO series did not significantly influence the results of the trend calculations. However, the F10.7 significantly influences total ozone at Arosa (time lag of 0 month). We therefore included in the calculations of total ozone trends temperature of Mt. Säntis and F10.7. The calculated trends of the period 1947-91 are stronger in May and June using model of eq (3) than model of eq (1), otherwise the results of the two models are very similar (see Fig. 1c and 1d).

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Dütsch and Staehelin,1989, have shown that the negative correlation between total ozone at Arosa and the temperature record of Mt. Säntis can be interpreted by the transport of ozone rich air masses from the polar region to midlatitudes by polar cyclones, i.e. regional weather influences. Dütsch *et al.*, 1992, have used a similar model inluding the total ozone from 1926 to 1989, the temperature of Mt. Säntis, and the solar cycle which was described by the sunspot number. In this study, the influence of the solar cycle on total ozone was statistically significant (at 5%) only if the temperature of Mt. Säntis was included in the analysis (1.26% or 4.4D from minimum to maximum of the solar cycle, in good agreement with previous studies of the worldwide Dobson network (WMO, 1989)).

5. RESULTS OF THE TREND ANALYSES CONSIDERING THE VERTICAL DISTRIBUTION OF OZONE

A similar type of multiple regression model (eq. (3)) was used to elucidate the vertical distribution of the trends. In a pre run the autocorrelations were calculated. Based on the results of the calculations of total ozone (see 4) we included the time lags of zero in this model. A strong dependency between the temperature at Mt. Säntis and ozone was found for most altitudes (see Fig. 2). The strongest signal of QBO was found for an altitude of approximately 22.5 km, which is about the altitude of the ozone maximum layer, where ozone concentration is most strongly influenced by the transport from the tropics. The influence of SOI on ozone concentration is generally weak, but noticeable at the altitude of about 19km. Similarly, the influence of the solar cycle is weak for most altitudes and only weakly statistically significant at an altitude of about 30km, which already has been described in Dütsch *et al.*, 1992.

Four different regimes of trends can be distinguished in the vertical (see Fig. 3a-3d):

- On a relative scale, changes are strongest in the troposphere showing strongly increasing ozone concentrations especially during the eighties (Staehelin and Schmid, 1991). This is most probably attributable to the tropospheric air pollution by nitrogen oxides, hydrocarbons and carbon monoxide.
- On an absolute scale trends are strongest in the lower stratosphere. In this region, ozone decrease was faster in winter (about 10% per decade), than in summer and in autumn (approximately 5% per decade). The altitude where the ozone decrease was strongest was at approximately 16 km in winter and at approximately 20 km during summer and autumn.
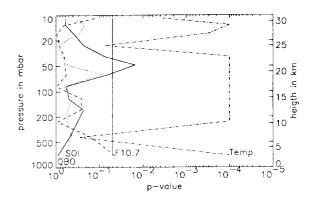- No trends were observed at an altitude region of 30 km.
- The Umkehr measurements indicate decreasing trends of ozone in the upper stratosphere.

The trends in the upper stratosphere can be explained by the gas phase ozone destruction. However, at the altitude of the strongest stratospheric trends heterogeneous processes destroying stratospheric ozone are probably important.

ACKNOWLEDGEMENTS

Figure 2: Significance, given as error probabilities (p-values), of the dependence of the ozone concentration on the used explanatory variables as function of the altitude. The p-value in this case is the probability that the standardized regression coefficient is smaller than the estimated value.

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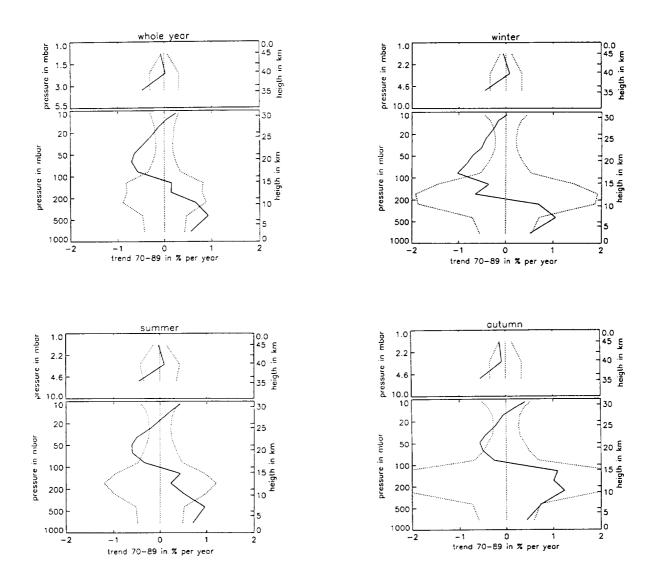
Figure 3: Trends for different altitudes deduced from the ozone balloon soundings from Payerne (1967-89) and the Umkehr-measurements from Arosa (1956-89), calculated using model of eq. (3). Trends are assumed to start on Jan., 1970. The dashed lines describe o±2s (s is the standard deviation of the trends). Thus points outside the dashed line indicate trends, which are statistically significant according the t-test for regression coefficients approximately at the 5% level. a: Year around trends; b: Trends for winter (Dec. to March); c: Trends for summer (May to Aug.); d: Trends for fall (Sept. to Nov.).