JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. D9, PAGES 18,873–18,885, SEPTEMBER 20, 1995

Diagnosing and forecasting total column ozone by statistical relations

D. Spänkuch and E. Schulz

Meteorologisches Observatorium Potsdam, Deutscher Wetterdienst, Potsdam, Germany

Abstract. The need for forecasting the level of harmful UVB radiation has stimulated the search for strong and reliable relations between total column ozone and suitable meteorological parameters. It is shown that daily total column ozone can be predicted regionally in midlatitudes with an uncertainty of about 15 Dobson units (DU; 1 DU = 2.69×10^{-16} molecules cm^{-2}). Maximum deviations are of the order of ± 20 DU. Deviations of more than about 20 DU between prediction and occurrence are traced back to doubtful measurements, ground-based as well as satellite. The proposed regressions are hence a suitable tool to check the quality of satellite retrievals and of current and historic Dobson series.

1. Introduction

Several factors determine the level of harmful UVB radiation (280–320 nm) at the surface of our planet. The most effective one is cloudiness, which can reduce the UV radiation up to about 10% depending on optical depth [*Chubarova*, 1993]. The maximum available UV radiation is generally given by Sun elevation and total ozone amount Ω. Occasionally, exceptions occur for high- and mid-level clouds [*Chubarova*, 1993] and for broken cloudiness if the cloud array favors reflection to the ground [*McKenzie et al.*, 1991]. The prediction of Ω is therefore a critical issue in assessing the maximum level of harmful UV radiation. The accuracy requirements in predicting Ω are pretty high, since a change in Ω by 1% causes roughly a 2% change in biologically effective radiation [*United Nations Environmental Program*, 1989; *German Bundestag*, 1989]. The precise figure depends on location, season [e.g., *Feister*, 1990], surface albedo, aerosol loading [*Liu et al.*, 1991], and biological process.

The effect of decreasing total ozone on some biological actions as well as on photolysis frequencies for trace gas reactions is studied by *Feister* [1994]. Recent experimental [*Bais et al.*, 1993] and theoretical studies [*Wang and Lenoble*, 1994] give more detailed figures on the spectral dependence of UVB irradiance on Ω and other factors. The most dramatic increase of UVB irradiance with decrease in ozone is in the 290- to 300-nm range with a magnification factor [*Bais et al.*, 1993] of 5 for a 10% decrease (40 Dobson units (DU; 1 DU = 2.69×10^{-16} molecules cm^{-2})) of Ω at medium solar elevations (solar zenith angle 40°–50°) and with clear skies. The decrease of the magnification factor with longer wavelengths is nearly exponential.

The dependence of UV radiation on Ω at the ground is, however, not unambiguous. The vertical distribution of ozone modifies this dependence due to increasing scattering of radiation with increasing air density, resulting in longer optical path through tropospheric than through stratospheric ozone. The effect of stratospheric ozone variations on UV radiation is thus partly compensated or even overcompensated by counterbalanced ozone variations in the troposphere [*Brühl and Crutzen*, 1989]. Short-term variations as discussed in this paper are mainly caused by stratospheric ozone variations. A reliable prediction of potential UV radiation can therefore, as a first step, rely on a reasonable Ω prediction. However, the most difficult task of an actual UV radiation forecast is a reliable and detailed cloudiness forecast.

The gross climatological features of Ω, with less Ω in the equatorial belts and more Ω toward the poles, as well as its seasonal variation with maximum Ω in spring and minimum Ω in autumn and winter, more pronounced in middle and high latitudes, are fairly well known [e.g., *London and Angell*, 1982]. The interdiurnal changes in Ω are shown in Figure 1 for Potsdam derived from a 10-year data set. Although the interquartile range is 30 DU, there are occasions with an interdiurnal change of about 100 DU, or roughly 30%, underlining the necessity of a good Ω forecast.

In principle, Ω can be predicted by physical, statistical, or physical-statistical approaches. The physical approach needs the knowledge of the initial vertical ozone field and the prognosis of air mass trajectories at a number of suitable pressure levels. The vertical ozone field distribution as initial state is at present not known with the precision needed for numerical prediction models, though first attempts to retrieve the vertical ozone structure from TIROS operational vertical sounder (TOVS) data are worth mentioning [*Smith et al.*, 1985]. Significant statistical relations between Ω and a number of meteorological variables have long been known [e.g., *Dobson et al.*, 1929; *Reed*, 1950; *Normand*, 1953; *Vaughan and Price*, 1991] and have recently been used in short-term Ω forecasting in middle and high latitudes [*Burrows et al.*, 1993, 1995; *Poulin and Evans*, 1994; *Austin et al.*, 1994; *Vogel et al.*, 1995]. These significant statistical relations are, however, regionally and seasonally variable in their strengths [e.g., *Ohring and Muench*, 1960; *Schubert and Munteanu*, 1988; *Mote et al.*, 1991; *Petzoldt et al.*, 1994]. Burrows et al. consider this circumstance by taking the climatological total ozone value, derived from TOMS data, as one predictor. Austin et al. used monthly changing regres-

Paper number 95JD01639.
0148-0227/95/95JD-01639$05.00

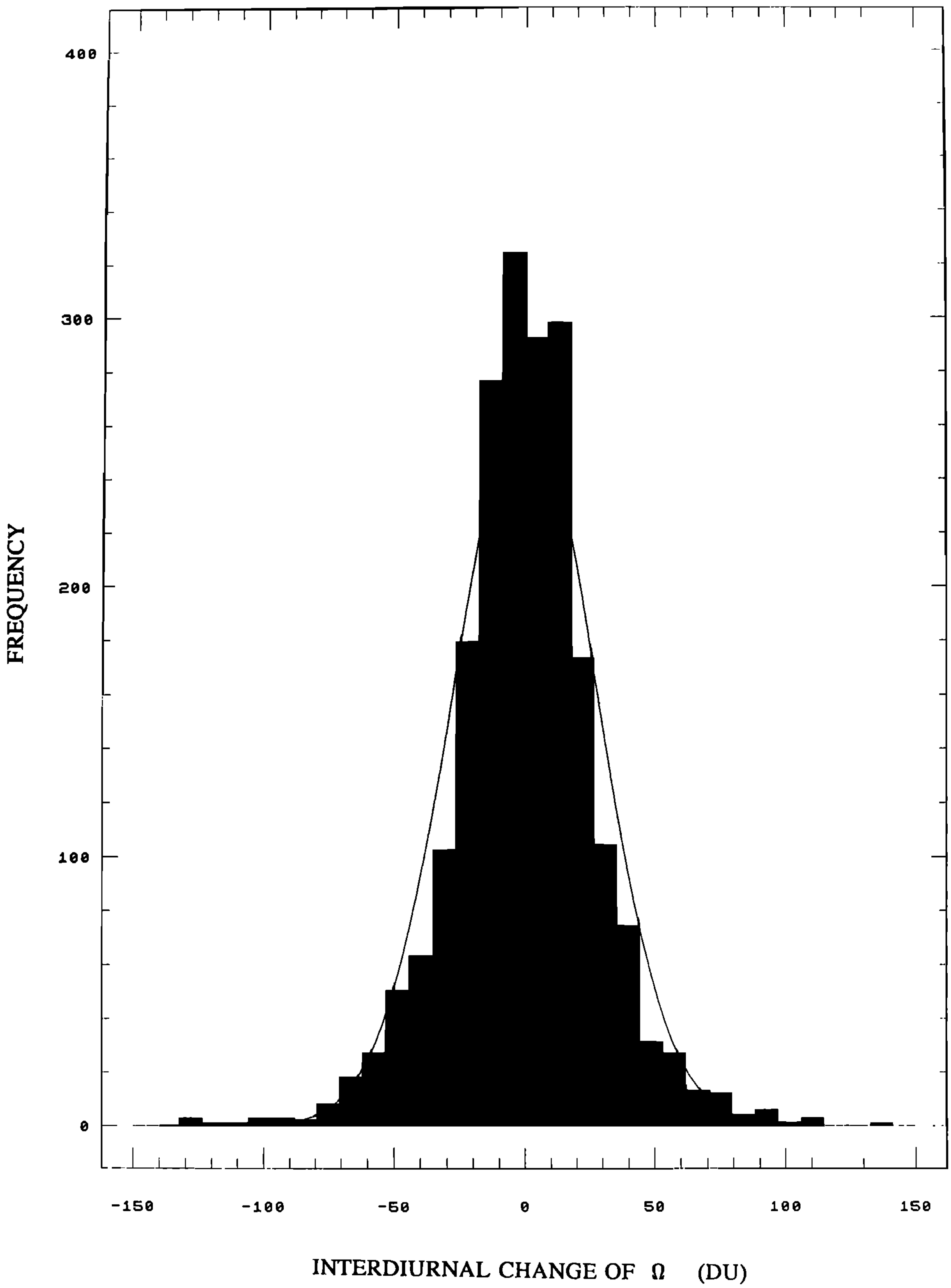


Figure 1. Histogram of interdiurnal changes of total column ozone at Potsdam, derived from TOMS data, version 6.0, for the 10-year period 1981–1990.

sion coefficients but the same predictors for the whole year. Vogel et al., focusing their study on regional forecasts for Germany, used multiple regressions on a monthly basis, too, but with partly changing predictors. They demonstrated the quality of their results on a limited time interval in January with high interdiurnal changes in Ω. The present paper describes in more detail the results of Ω diagnosis and forecasts throughout the year.

Table 1. Monthly Multiple Regressions for Total Column Ozone $\Omega(i)$

Month	Regression Equations	σ_{re}	σ_{cl}
January	$\Omega(i) = 756.7 + 0.449\Omega(i-1) + 0.1860\phi_{50}(i) - 0.4115\phi_{100}(i) + 0.1394\phi_{100}(i-1)$	18.8	40.8
February	$\Omega(i) = 1018.6 + 0.363\Omega(i-1) + 0.1119\phi_{30}(i) - 0.1684g_{17}(i) - 0.1970\phi_{300}(i) + 0.060\phi_{300}(i-1)$	23.8	46.9
March	$\Omega(i) = 1444.0 + 0.554\Omega(i-1) - 0.3498\phi_{300}(i) + 0.2009\phi_{500}(i) + 0.0852\phi_{300}(i-1)$	26.5	45.1
April	$\Omega(i) = 2266.3 + 0.509\Omega(i-1) - 0.1803\phi_{300}(i) - 0.2093g_{15}(i-1) + 0.0744\phi_{30}(i)$	22.4	37.4
May	$\Omega(i) = 405.0 + 0.679\Omega(i-1) + 0.3229\phi_{250}(i) - 0.4830\phi_{300}(i) + 0.1433\phi_{500}(i-1)$	13.4	29.2
June	$\Omega(i) = 1101.6 + 0.499\Omega(i-1) - 0.1880\phi_{300}(i) + 0.0892\phi_{300}(i-1)$	12.9	25.9
July	$\Omega(i) = -325.8 + 0.338\Omega(i-1) + 0.1314\phi_{30}(i) - 0.2144\phi_{300}(i) - 0.1169g_{15}(i) + 0.0669\phi_{300}(i-1)$	11.8	21.7
August	$\Omega(i) = -1774.5 + 0.561\Omega(i-1) + 0.1431\phi_{30}(i) - 0.1327\phi_{300}(i) - 0.0712g_{15}(i-1) + 0.0483\phi_{300}(i-1)$	10.1	20.1
September	$\Omega(i) = 46.49 + 0.510\Omega(i-1) - 0.1748g_{17}(i) + 0.1584g_{55}(i) - 0.0644\phi_{300}(i) + 0.0674\phi_{300}(i-1)$	9.8	20.7
October	$\Omega(i) = -771.5 + 0.500\Omega(i-1) + 0.1658\phi_{30}(i) - 0.1890\phi_{100}(i) - 0.2404\phi_{500}(i) + 0.2583\phi_{700}(i) + 0.1894\phi_{500}(i-1) - 0.1530\phi_{700}(i-1)$	11.2	23.8
November	$\Omega(i) = -110.3 + 0.625\Omega(i-1) - 0.1381g_{17}(i) + 0.1281g_{55}(i) - 0.0638\phi_{500}(i) + 0.086\phi_{500}(i-1)$	17.6	28.2
December	$\Omega(i) = 670.3 + 0.3659\Omega(i-1) + 0.1527\phi_{30}(i) - 0.0393\phi_{300}(i) - 0.2032\phi_{70}(i)$	19.2	37.4

Predictors are $\Omega(i-1)$ total column ozone of the preceding day, $\phi_k(i)$ or $(i-1)$ geopotential height of day (i) or $(i-1)$ at the pressure level k (hPa), g_{17}, g_{15}, g_{55} thickness at 100–700 hPa, 100–500 hPa, 50–500 hPa; ϕ and g are in geopotential meters (1 gpm = 0.98 m), and σ_{re} and σ_{cl} are residual and climatological standard deviation in Dobson units (DU).

2. Estimation of Daily Total Ozone Amount: Linear Multiple Regressions

The multiple regression approach is a purely pragmatic solution of the problem and is only justified by the quality of its results. Although the selection of potential predictors is somewhat arbitrary, their choice is guided by the quoted previous studies. Table 1 lists the monthly regression equations together with the climatological standard deviation, σ_{cl}, and the rms of the difference between the estimated and the measured Ω, σ_{re}. The predictors examined were the column ozone amount of the preceding day, $\Omega(i-1)$, and geopotential heights ϕ_t and thicknesses g_t at standard pressure levels of the day considered and the preceding day. An analogous approach was made with corresponding temperatures and temperature differences of the pressure levels at standard pressure levels instead of ϕ_t and g_t with nearly the same quality of results (see Table 3). The approach of using parameters of preceding days as predictors is motivated by the fact that these parameters are analyzed or, in case of local studies, directly measured quantities, whereas the parameters of the ith day have to be predicted, too, and are hence less accurate. For this reason, Vogel et al. needed one additional regression between analyzed and predicted temperatures to reduce the influence of the temperature error of the forecast. All other cited studies related analyzed parameters directly to Ω. Absolute or isentropic potential vorticity is a predictor of significant contribution, as shown by *Vaughan and Begum* [1989], *Allaart et al.* [1993], and *Burrows et al.* [1993], but was deliberately omitted in our study, because prediction of either of these factors is less accurate than thickness or temperature fields. The reduction of variance, RV $= 1 - (\sigma_{re}^2/\sigma_{cl}^2)$, was in fact better when analyzed vorticities were used as predictors instead of geopotential heights or temperatures (see Table 3), but this benefit could not be saved with predicted vorticities. Parameters at higher stratospheric levels than 30 hPa were also omitted due to increasing forecast errors with height; $\Omega(i-1)$ takes the atmosphere's memory into account.

The frequency distribution of local interdiurnal changes of Ω at Potsdam, derived from 10 years of grid point TOMS data (2096 days) and shown in Figure 1, is a normal distribution with 0.05 level of significance, median 0.0 DU, standard deviation of 27.5 DU, and interquartile range of 30 DU. A persistence forecast is therefore often a very good first guess in forecasting Ω, as shown by *Vogel et al.* [1995]. There is, however, another reason for using $\Omega(i-1)$ as one of the predictors. All satellite charts of the daily Ω distribution indicate considerable mesoscale structure of total column ozone, which is not reflected in corresponding stratospheric analyses [*Spänkuch*, 1994]. Regressions without $\Omega(i-1)$ as predictor, which have been used in the earlier quoted studies of *Burrows et al.* [1993, 1994], *Poulin and Evans* [1994], and *Austin et al.* [1994], give up this mesoscale information and contain mainly gross geographical features. Another difference between our regression and the others is the monthly change of our predictors in a somewhat obscure manner, whereas Austin et al., for example, used the simple form $\Omega(i) = ag_{250}(i) + bT_{150}(i) + cT_{30}(i) + d$ with monthly changing coefficients a–d and g_{250} the 1000- to 250-hPa thickness and T_{150} and T_{30} the temperatures at 150 and 30 hPa, respectively. The meteorological background for the regressions is the same, the positive correlation between local ozone concentration and temperature in the lower stratosphere as well as the known anticorrelation between tropospheric temperatures and lower stratospheric temperatures [e.g., *Reed*, 1950; *Normand*, 1953; *Spänkuch et al.*, 1973; *Spänkuch and Döhler* 1975; *Rood and Douglass*, 1985; *Tung and Yang*, 1988] and the anticorrelation between tropopause height and Ω. The aim of the previous studies was the interpretation and forecasting of large-scale Ω patterns with reasonable accuracy. Their advantage is the simplicity of the approach, probably at the expense of some loss in accuracy.

All regressions of this study were derived from data of the years 1979–1992, but of every third day to reduce the degree of interdependence of the data. For Ω, the grid point column ozone amounts at Potsdam, derived from the total ozone mapping spectrometer (TOMS), version 6.0, were used. TOMS data are preferable to ground-based Dobson spectrometer measurements because they are available daily and are more homogeneous. Grid point TOMS data represent an area of approximately 110 km × 120 km and are reported to be accurate within ±2% [*Fleig et al.*, 1990; *Herman et al.*, 1991]. The intercomparison with careful Dobson measurements gives deviations less than 5% [*Lefèvre et al.*, 1991; *Heese et al.*, 1992] with a bias of about 2% due to the use of the climatological tropospheric ozone content [*Heese et al.*, 1992], if the same ozone absorption coefficients are used. Geopotential height data were taken from the 1200 UTC ascents at Berlin-Tempelhof.

The regressions of Table 1 contain diagnostic variables from the preceding day, $(i - 1)$, and prognostic variables from the ith day. The only predictor present every month in the regression is $\Omega(i - 1)$, or $\Omega(i - 1)$ and $T_{55}(i)$, the difference of the temperatures at 50 hPa and 500 hPa, when temperatures instead of geopotential heights were used as predictors. It is interesting to note that the tropopause height/Ω relationship, reflected in the occurrence of ϕ_{300} or ϕ_{250} in the regressions, gives with the present combination of predictors no additional significant information in January, October, and November, though high individual correlations between Ω and tropopause pressure with correlation coefficients greater than 0.6–0.7 are frequently found in January in the geographic area considered [e.g., *Dameris et al.*, 1995]. In most months the meteorological state and recent past (preceding day) of the troposphere and stratosphere are considered, but there are three months, March, May, and June, when only the tropospheric and tropopause states seem to contribute significantly to the interdiurnal Ω change. The simplest regression was found for June with the tropopause height (by $\phi_{300}(i)$) and its change (by the difference of the terms $\phi_{300}(i)$ and $\phi_{300}(i - 1)$) as additional predictors to the past $\Omega(i - 1)$. The number of predictors was determined by 0.95 significance level. The use of that single predictor, which contributes the informative part to the regression, reduces the variance up to about 0.4–0.5, as discussed in section 3.

The quality of the regressions found is demonstrated in Figures 2 and 3. Figure 2 shows TOMS grid point and estimated Ω values at Potsdam for every day of the years 1979–1992. For the first 4 years, 1979–1982, equations with $\Omega(i - 1)$ and temperatures at standard levels as predictors were used to demonstrate the equivalence of temperatures and corresponding geopotentials as predictors. For the rest of the years the regressions of Table 1 were taken. The lack of discontinuity between both time intervals is evidence for nearly the same quality of both approaches. The general course of Ω variations with high and low total column ozone episodes is well described by the regressions. Table 2 compiles the corresponding systematic and random deviations for the three ozone seasons [*Bojkov*, 1965] and the whole year. Years with higher Ω than normal, as in the beginning of TOMS measurements (1979, 1980), or with anomalous low Ω values, as in 1992 [*Bojkov et al.*, 1993; *Gleason et al.*, 1993; *Herman and Larko*, 1994; *Komhyr et al.*, 1994; *Planet et al.*, 1994] are indicated by only a small bias of the corresponding sign during those years (±6 DU for the yearly averages, ±10–11 DU for autumn and winter) but without any increase in standard deviation. The standard deviations of estimated Ω against TOMS data are 20–28 DU in winter, when the Ω variability is highest, 11–16 DU in summer, and 14–22 DU in autumn. These figures may be too large, as discussed in section 5 and Table 5.

In Figure 3 the frequency distribution of estimated Ω against TOMS data is given. The hypothesis of a normal distribution is not rejected at a level of significance 0.05 with mode −1.0 DU, median 0 DU, standard deviation 18.5 DU, and interquartile range 21 DU. Large interdiurnal changes of Ω, which are not reflected by the regression, have to be taken with caution, as discussed in section 5.

3. Intercomparison of Regression Relations

Table 3 compares the reduction of variance, RV, for the estimated column total ozone for some linear regressions with one predictor only (columns 2 and 3) as well as for some stepwise multiple linear regressions. Together with the results of some of our approaches (columns 6–8) we list results from *Austin et al.*'s [1994] equation with their original coefficients, derived from data of the year 1993, and with modified coefficients, derived from our 10-year local data set (columns 4 and 5). Austin et al. did not publish coefficients from February until May. The lower RV values for regressions with one predictor only when compared with multiple regressions are not surprising. Nevertheless, considerable RV values, about 0.5 in average, can be achieved with the temperature difference between stratospheric and tropospheric temperatures, $T_{50} = T_{50} - T_{500}$, as the single predictor. The seasonal variation is remarkable, however, with maximum RV of 0.65 in September and minimum RV of 0.27 in December. The value of $\Omega(i - 1)$ reaches similar RV (0.4–0.5) as $T_{55}(i)$ from February through May but has small RV values of less than 0.2 in June and July. Austin et al.'s approach declared as representative for Europe is not superior to the single correlation with T_{55} from September to November. The improvements for the other months are about 0.08–0.1 but significantly larger in December. Austin et al. found RV values between 0.64 and 0.88, obviously in disagreement with our values in column 4. This discrepancy is explained by the fact that these authors used only data of the year 1993 to calculate the coefficients. Austin et al's results can be improved further, up to about 0.1, by locally adapted coefficients. There remains, however, a substantial change in the magnitude of RV from month to month. The relative low RV in spring and early summer (April to June) with no improvement of RV upon the single regression with T_{55} is particularly critical, because during these months, people are generally less adapted to UV radiation.

The highest RV values, explaining nearly 90% and partly more of the variance from August to January, are found with $\Omega(i - 1)$ and relative vorticity as a predictor. Only February with 0.5 and July with 0.57 have low RV values. We mentioned already that we did not use this regression due to lower forecast accuracy of vorticity than of temperature or geopotential. The regressions preferred in our study give RV between 0.7 and 0.8. The discussion of the following two sections indicates, however, that the explainable variance should be substantially higher, since outliers are identified as doubtful TOMS retrievals or Dobson measurements.

4. Forecast of Total Column Ozone

The main aim of our study is the prediction of Ω for Germany. Hence better results are expected when locally derived coefficients are used than when hemispherically or globally more representative regressions are used. Since the beginning of 1994 the regressions of Table 1 have been used for daily Ω forecasts for Germany as part of the daily UV index prognosis. Figure 4 shows the results of this forecast compared with ground-based Dobson spectrometer measurements. Because

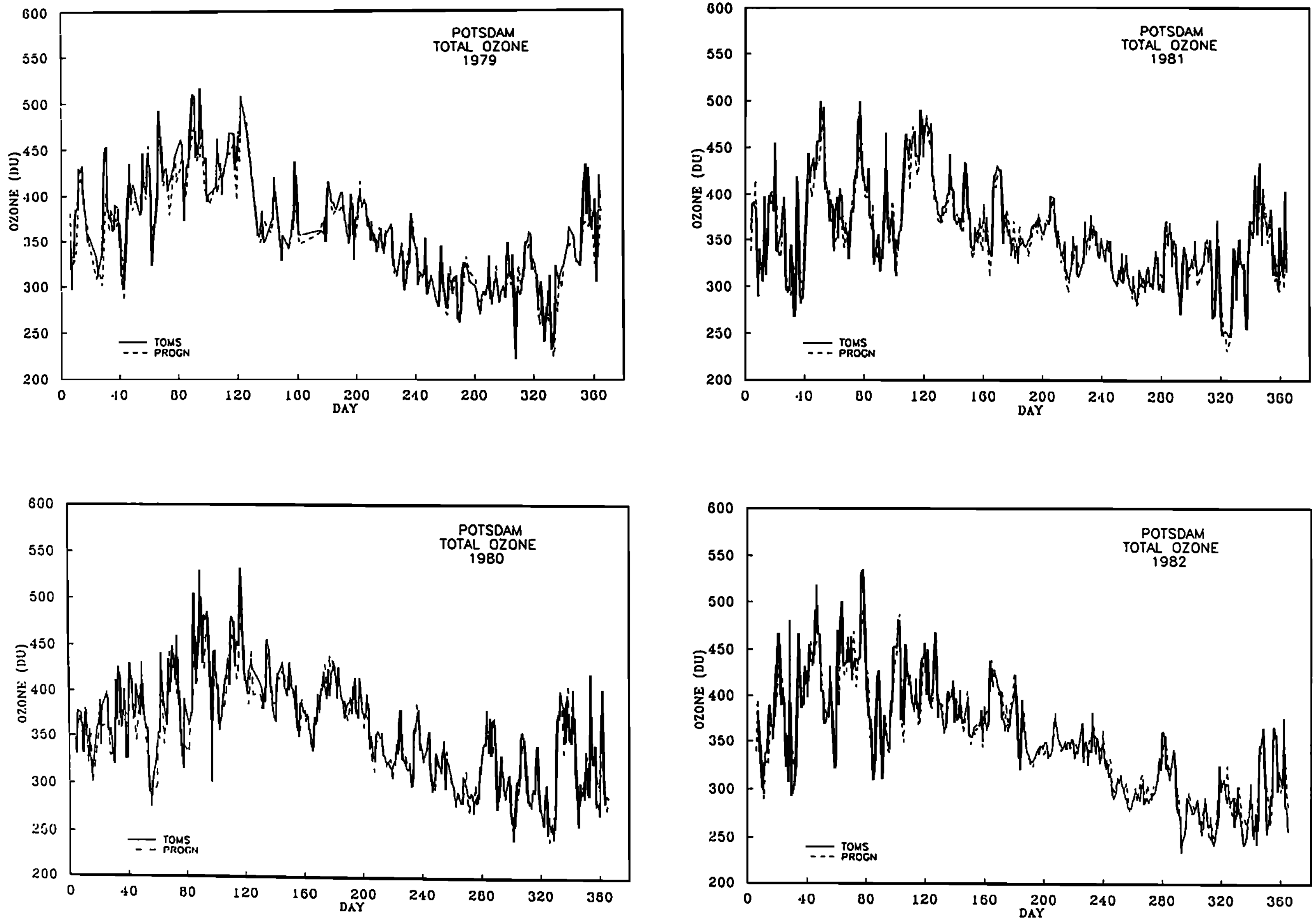


Figure 2. Comparison of TOMS grid point and estimated total column ozone, the latter based on using linear multiple regressions. For the first 4 years, 1979–1982, regressions with $\Omega(i - 1)$ and temperatures at some standard pressure levels as predictors were used. For the other years the regressions of Table 1 were taken.

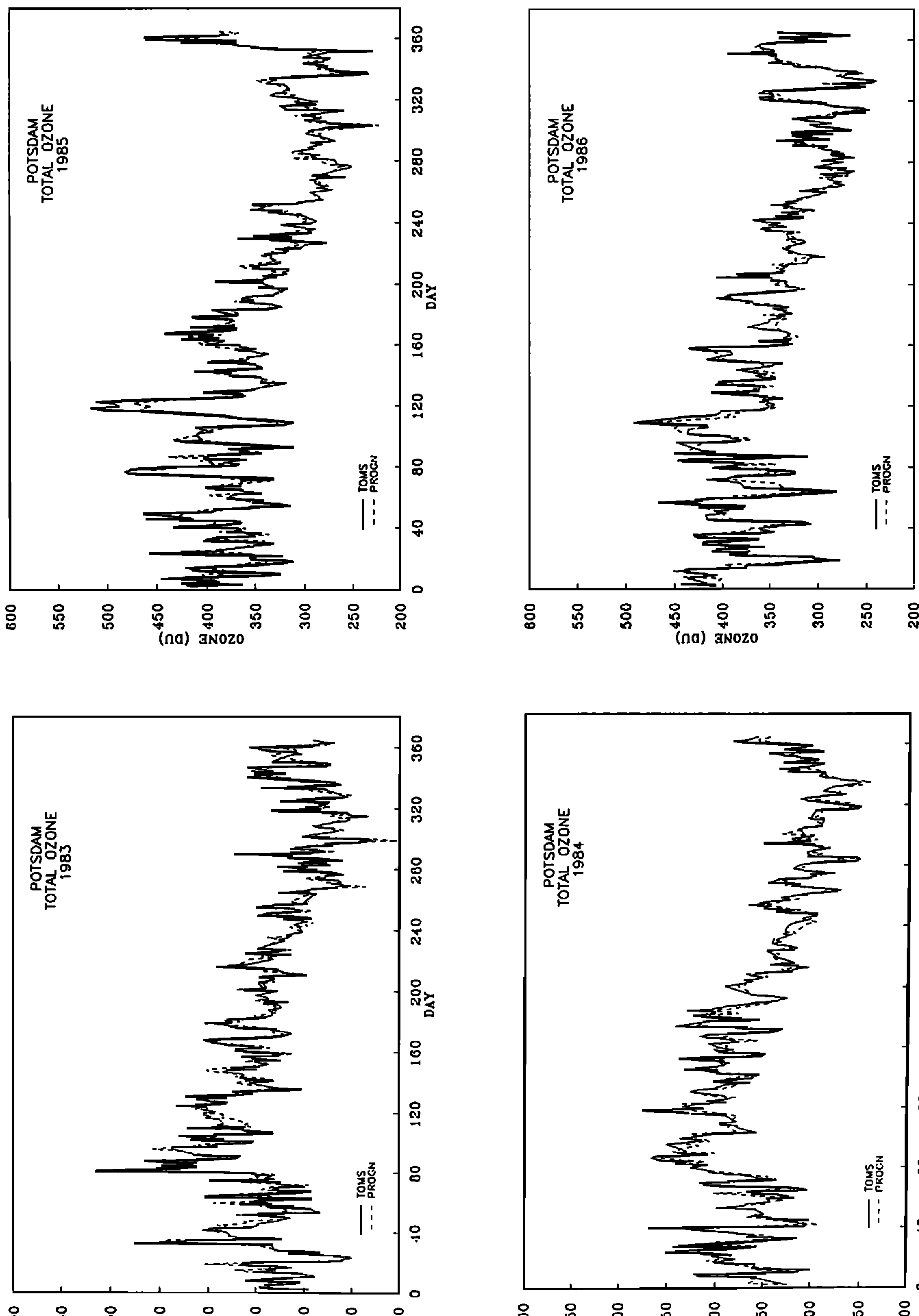


Figure 2. (continued)

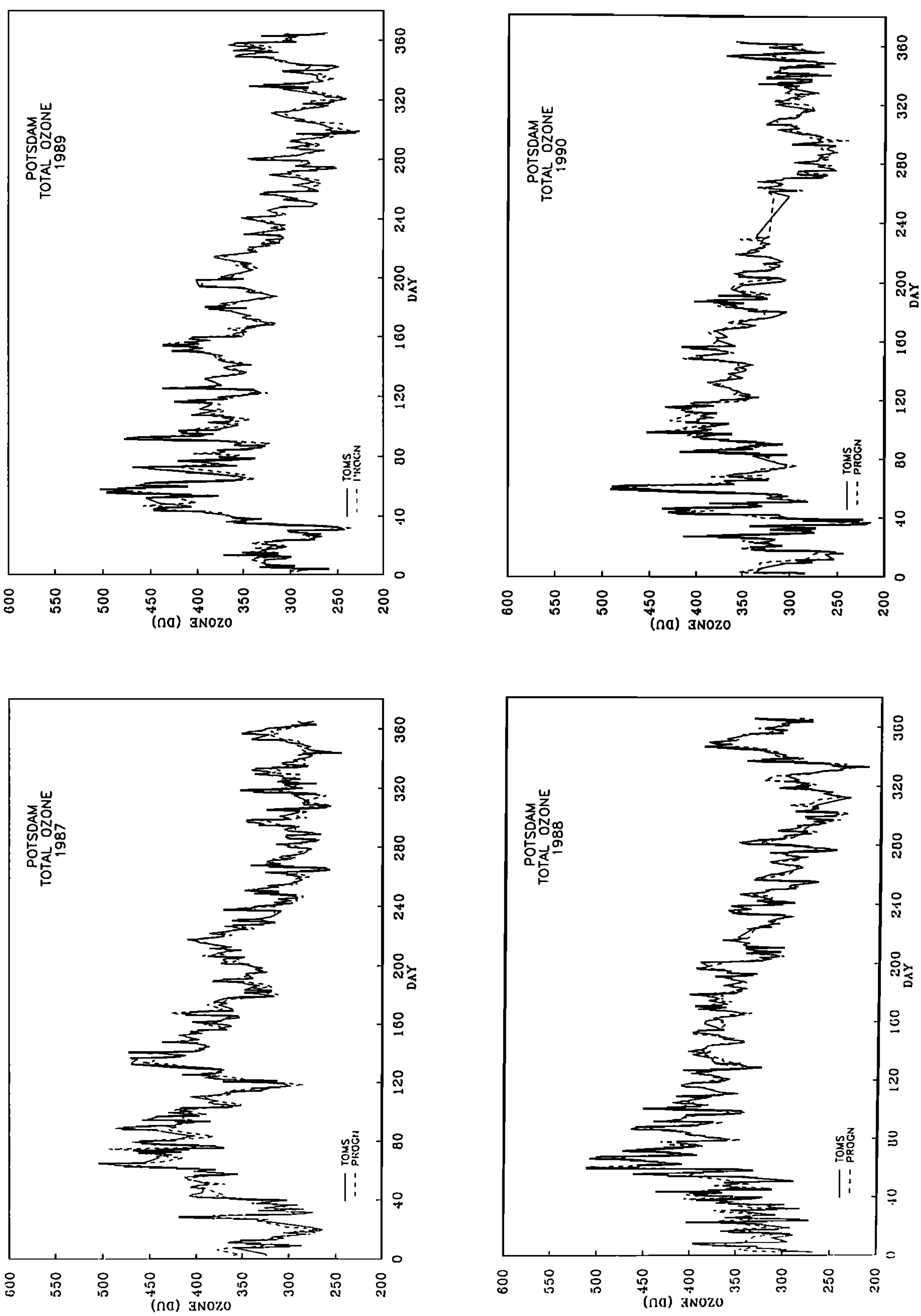
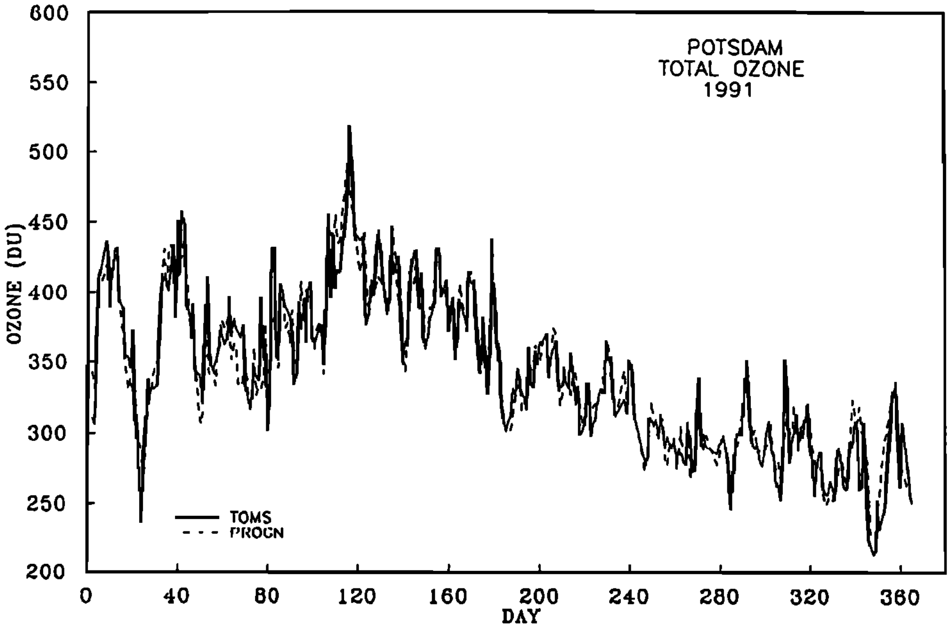


Figure 2. (continued)



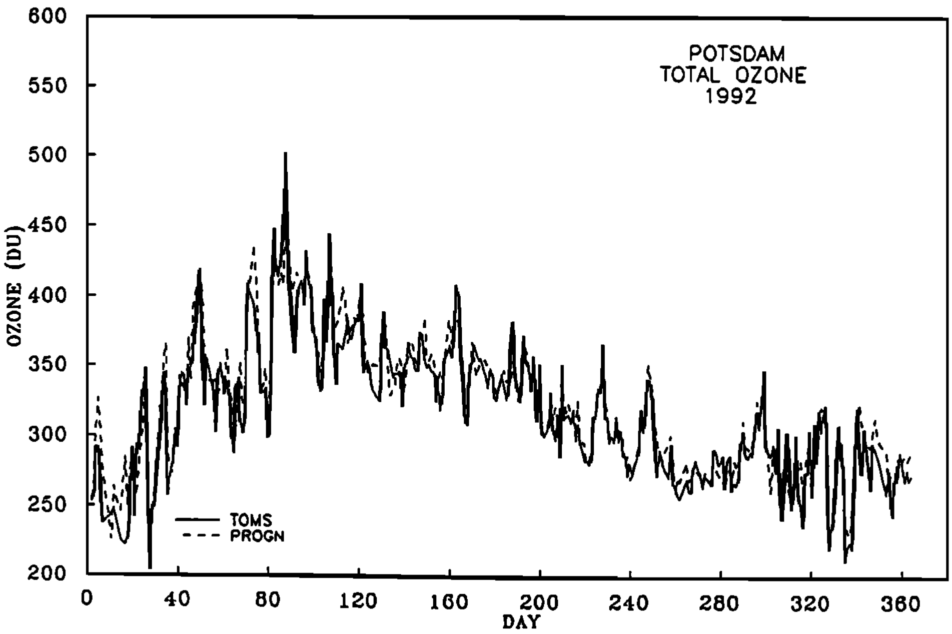


Figure. 2. (continued)

the regression coefficients were derived from TOMS instead of Dobson data, some bias of about 6 DU (Dobson-TOMS) is introduced. The Ω forecasts were made with measured as well as with predicted temperatures or geopotential heights. The forecast is of the same quality as the diagnosis shown in Figure 2. Bias and standard deviation are of the same order (Table 2) with -6.8 ± 19.8 DU and 0.3 ± 22.2 DU in the case of forecast and measured parameters as predictors.

Dobson spectrometer measurements are, however, of different quality, depending on the state of cloudiness. Measurements using direct sunlight (DS measurements) are most accurate, followed by zenith blue measurements (ZB) in the case of cloudless zenith. The least accurate measurements are against the cloudy zenith (ZC) and are only made when clouds prevent DS and ZB measurements. In Figure 5 the difference between Dobson Ω and forecasted Ω is shown for 1994. It is evident at first glance that the extreme outliers are ZB measurements, causing question of the accuracy of the ground-based Dobson spectrometer measurements. The thorough analysis of the prevailing weather on these days confirms this question (Table 4). The outliers are either Dobson measurements made during unfavorable weather conditions as, for example, during precipitation breaks, or the result of erroneous values on $\Omega(i - 1)$ on the following day. Even the DS

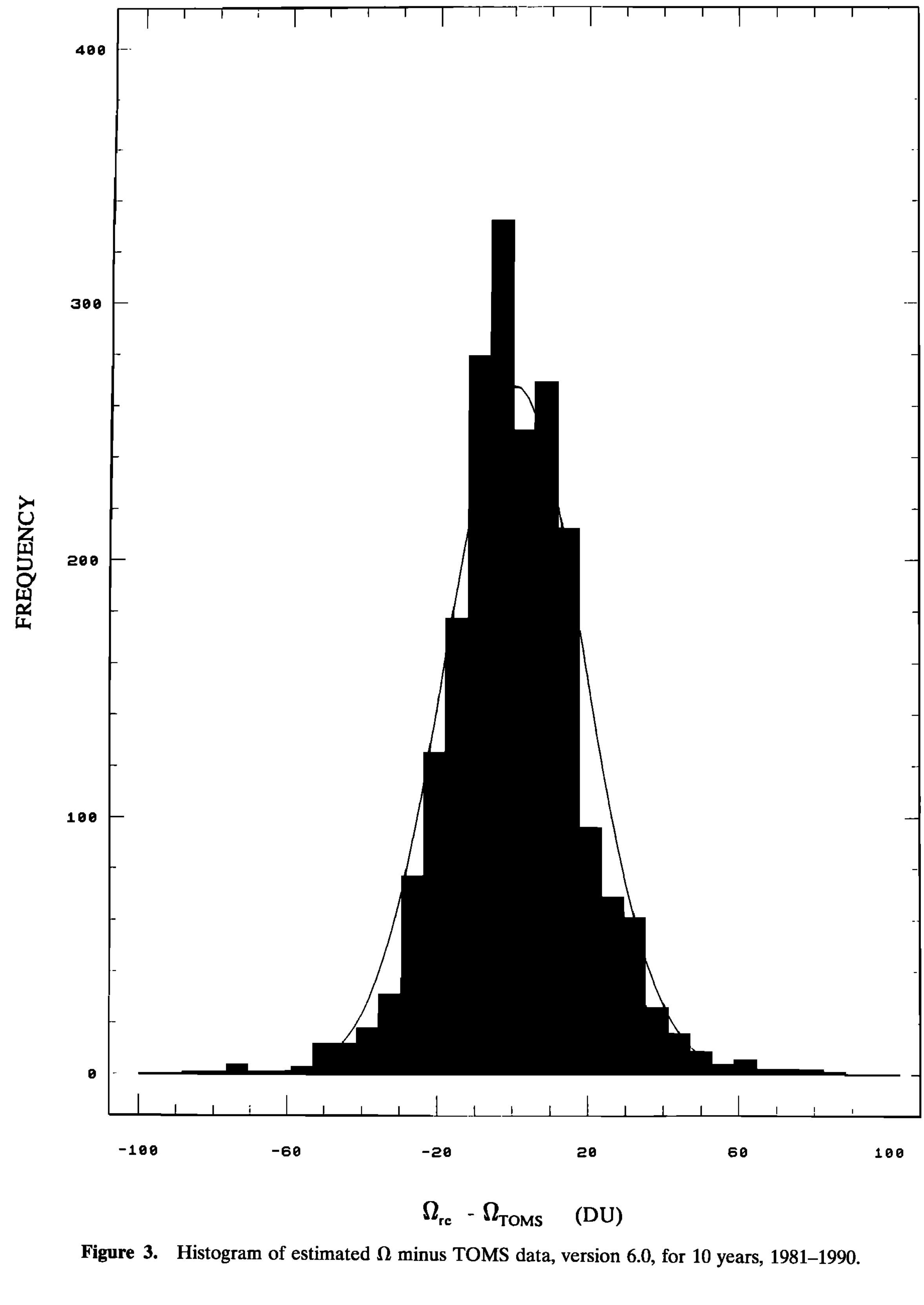


Figure 3. Histogram of estimated Ω minus TOMS data, version 6.0, for 10 years, 1981–1990.

measurement (Number 10 in Figure 5 and Table 4) could be in error, since during that day, permanently strong winds of 20 m s^{-1} were reported. Taking these dubious values away reduces the rms deviation between measurement and forecast to 12 DU, equivalent to about 3%.

5. Regression as Check on Satellite and Ground-Based Measurements

The regressions are a suitable means to check doubtful measurements, satellite or ground-based, as demonstrated in the

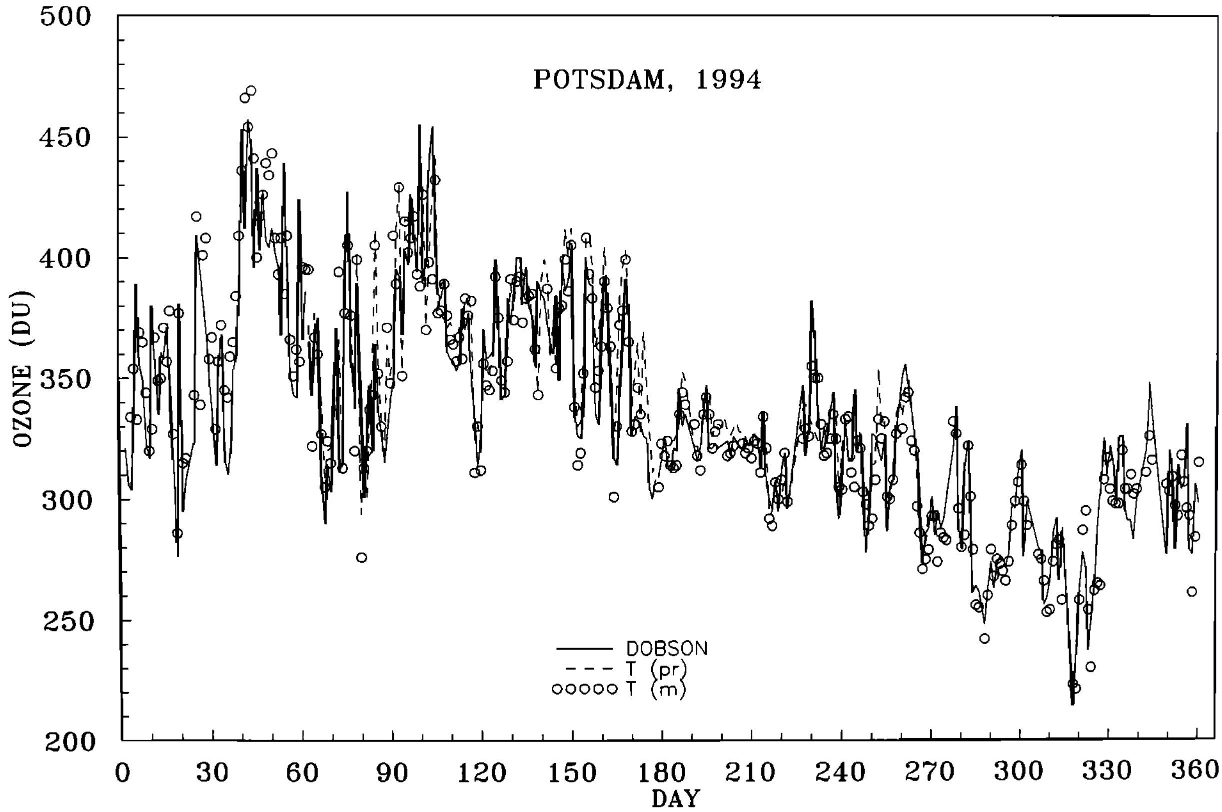


Figure 4. Comparison of predicted total column ozone, using measured (circles) and predicted (dashed line) predictors, with measured Ω, made with a Dobson spectrometer at Potsdam.

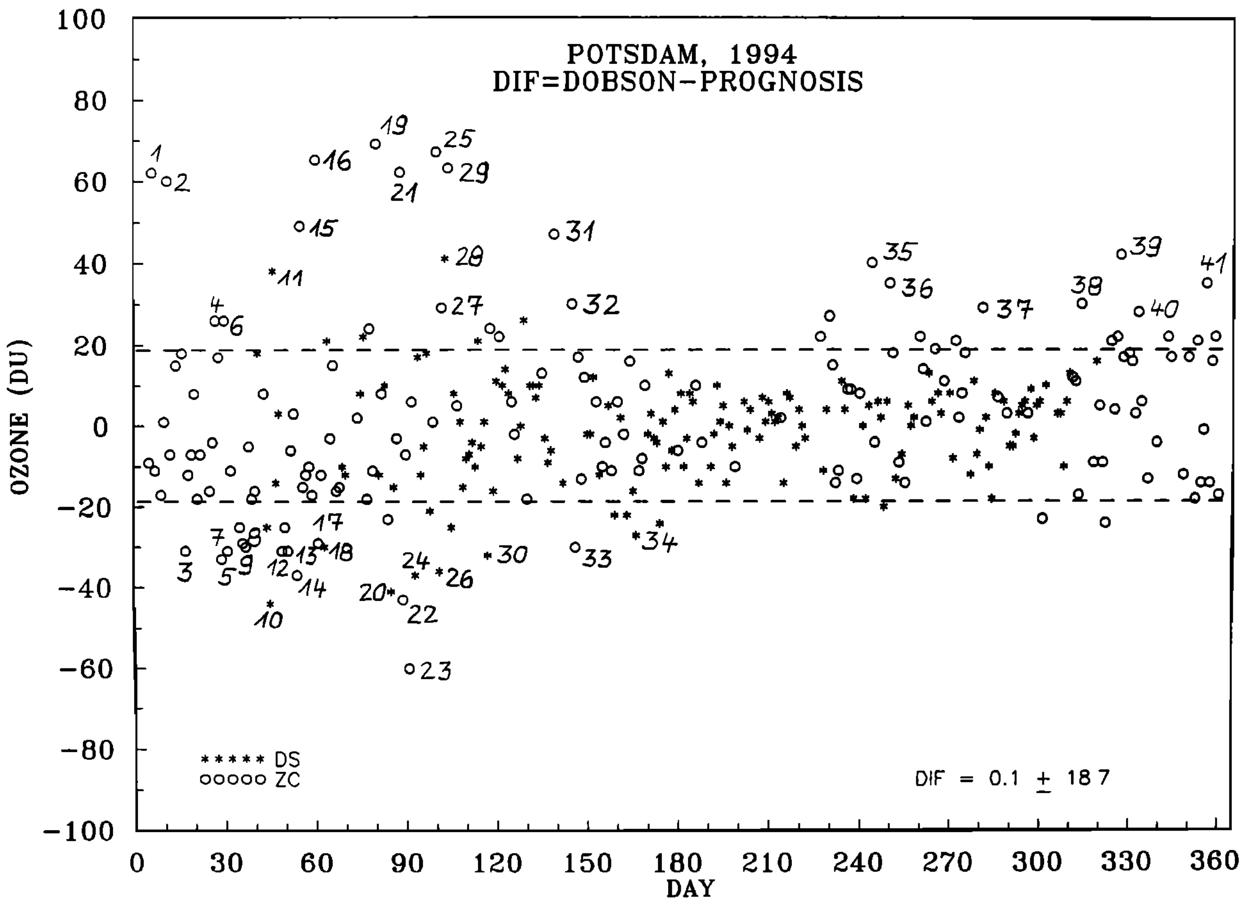


Figure 5. Difference between measured and predicted total column ozone during 1994 at Potsdam using measured predictors. Distinction is made between direct sun (DS) and less accurate zenith blue and zenith cloudy (ZC) measurements. For explanation of serial numbers, see Table 4 and text.

Table 2. Comparison Between TOMS Grid Point and Calculated Column Ozone Amount Using Linear Multiple Regressions for the Ozone Seasons January–April, May–September, October–December, and Yearly Average

	Jan.–April		May–Sept.		Oct.–Dec.		Year	
Year	Bias	s.d	Bias	s.d.	Bias	s.d.	Bias	s.d.
1979	11.4	22.9	1.0	13.1	7.6	21.4	6.1	19.5
1980	11.1	26.8	2.4	13.0	1.5	20.1	4.9	20.4
1981	5.4	24.0	2.6	12.5	3.1	19.1	3.6	18.5
1982	3.9	24.2	−2.8	11.8	−3.8	17.3	−0.9	18.3
1983	−3.8	25.4	−2.1	13.1	−1.2	20.8	−2.4	19.8
1984	−1.3	22.4	3.4	11.3	2.8	14.1	1.8	16.3
1985	2.7	26.8	−0.6	14.4	−1.7	19.5	0.0	19.9
1986	2.8	22.3	0.9	12.4	0.1	14.3	1.3	16.6
1987	3.2	22.0	5.6	14.2	2.6	17.3	4.1	17.8
1988	−1.8	27.9	2.6	11.7	−2.0	16.9	0.1	19.6
1989	−3.9	20.5	3.0	13.4	0.1	17.9	0.0	17.3
1990	−5.6	27.5	−1.8	12.7	−3.3	16.6	−3.4	19.7
1991	0.2	22.0	1.0	15.8	−9.1	18.7	−1.7	19.1
1992	−7.3	21.8	−4.4	11.7	−8.1	17.6	−6.2	16.9

Bias and s.d. are in Dobson units.

preceding section for Dobson spectrometer measurements, compared to Ω forecasts. Here we add a similar analysis concerning TOMS data. Table 5 compiles days with large differences between TOMS data and Ω, estimated by the regressions for the year 1979. Analogous results were also received for all the other years. All days listed except December 27 were rainy days, either overcast the whole day or with only a few hours of sunshine. The weather information suggests multilayer or compact cloudiness, difficult to take into account properly in a routine retrieval scheme. The estimated Ω seems to be nearer the true value in these cases than the TOMS guess.

Thompson et al. [1993] detected a positive bias in TOMS total column ozone of more than 20 DU in regions of persistent subtropical marine stratocumulus due to lower cloud tops of these clouds than the climatological cloud top height, which is used in the current TOMS retrieval algorithm. A positive bias in TOMS column ozone of up to 20 DU also was detected by *Seftor et al.* [1994] in the presence of partial cloud cover. This bias is most pronounced at lower latitudes and in the case of small-scale cloud structure. Our finding also suggests incorrect TOMS data at cloud patterns similar to those of Seftor et al., which should be investigated by further studies. Often, questionable TOMS retrievals were reported by a large change in Ω from day to day not simultaneously confirmed by the regressions. This jump in TOMS Ω was often accompanied by a passage of a cold front with scattered cloudiness behind. Such cloud patterns produce randomly distributed albedo patterns and are hence particularly difficult to handle properly in an operational retrieval scheme. When these doubtful TOMS data are taken away, the rms of the estimated Ω is reduced to the same order as the forecast error, namely, to about 3%.

6. Conclusions

1. The mid-European, local interdiurnal change of total column ozone is well approximated by linear multiple regressions. Predictors are total column ozone of the preceding day and some thermodynamic parameters of the stratosphere and troposphere (temperature gradient or geopotential height) of the day considered. The mean deviations of regressed ozone amount against daily TOMS, version 6.0, data for the 10-year period 1978–1988 were 3.2 ± 25.2 DU, 1.3 ± 13.0 DU, and 0.8 ± 18.4 DU for the spring (January–April), summer (May–September) and autumn (October–December) ozone seasons, respectively. The bias is caused by long-term ozone variations and possible drifts in the TOMS spectrometer calibration. The accuracy quoted is on the pessemistic side, as thorough analysis reveals substantial doubt about the accuracy of the measurements during unfavorable weather.

2. The linear multiple regressions found are a suitable means for quality check of satellite as well as ground-based

Table 3. Reduction of Variance RV in Estimating Column Ozone Amount $\Omega(i)$ for the ith date in Potsdam Using Different Linear Regressions

	Type of Regression						
	Single Linear		*Austin et al.* [1994]		Stepwise Multiple Linear		
Month	$\Omega(i-1)$	$T_{55}(i)$	Unmodified	Modified	$\Omega(i-1)$/ Vorticity	$\Omega(i-1)/T$	Table 1
January	0.26	0.53	0.65	0.72	0.87	0.66	0.83
February	0.46	0.49		0.69	0.50	0.69	0.70
March	0.37	0.54		0.70	0.68	0.78	0.78
April	0.41	0.42		0.41	0.70	0.70	0.70
May	0.48	0.51		0.55	0.81	0.76	0.76
June	0.19	0.60	0.68	0.68	0.77	0.77	0.74
July	0.14	0.49	0.59	0.71	0.57	0.68	0.74
August	0.29	0.38	0.44	0.62	0.87	0.76	0.76
September	0.30	0.65	0.60	0.63	0.93	0.77	0.77
October	0.24	0.53	0.56	0.69	0.89	0.71	0.76
November	0.32	0.39	0.44	0.52	0.94	0.75	0.68
December	0.30	0.27	0.52	0.70	0.89	0.77	0.74

Time period is 1983–1992. Column 2: The single predictor is total column ozone of the preceding day, $\Omega(i-1)$. Column 3: The single predictor is $T_{55}(i) = T_{50} - T_{500}$, where T_{50} is temperature at 50 hPa and T_{500} is temperature at 500 hPa. Column 4: *Austin et al.*'s [1994] regression $\Omega(i) = ag_{250}(i) + bT_{150}(i) + cT_{30}(i) + d$ with their original coefficients. Column 5: The same equation as in column 4 but with locally adapted coefficients. Column 6: Predictors are $\Omega(i-1)$ and relative vorticity at some standard pressure levels. Column 7: Predictors are $\Omega(i-1)$ and temperature at some standard pressure levels. Column 8: Regressions of Table 1.

Table 4. Weather Information for Days With Large Deviations Between Measured and Predicted Column Ozone Amount

Serial Number	Julian Day	$\Omega_D - \Omega_r$	Weather Information or Comments
1	6	62	rain with some breaks, cloud base varying from 300 m to 4000 m
2	11	60	rain with some breaks, occasionally fog, cloud base 70–130 m
3	17	−31	snow showers, cloudy 5/8 to 7/8
4	27	26	rain, overcast sky
5	29	−33	graupel showers, cloudy, strong winds (17 m s^{-1})
6	30	26	erroneous prediction due to erroneous $\Omega(i-1)$
7	31	−31	rain showers from time to time, strong winds up to 21 m s^{-1}, cloudy 6/8
8	36	−29	cloudy 7/8 to 8/8, strong winds (15 m s^{-1})
9	37	−30	erroneous prediction due to erroneous $\Omega(i-1)$, overcast sky, hazy
10	45	−44	cloudless, but strong winds (20 m s^{-1})
11	46	38	erroneous prediction due to erroneous $\Omega(i-1)$, strong winds (17 m s^{-1})
12	49	−31	snow in the morning
13	51	−31	snow in the morning, cloudy 5/8 to 8/8
14	54	−37	snowfall from 0.00 to 1.00 UTC, cloud base 80–500 m
15	55	49	erroneous prediction due to erroneous $\Omega(i-1)$
16	60	65	rain in the morning, cloudy before noon, strong winds (20 m s^{-1}), cloud base 360–1800 m
17	61	−29	erroneous prediction due to erroneous $\Omega(i-1)$
18	63	−30	rain in the morning, cloudy 2/8 to 8/8, strong winds (16 m s^{-1})
19	80	69	snow and rain, cloud base 140–460 m
20	85	−41	rain showers from time to time, cloudy (4/8 to 7/8), cloud base 200–500 m, strong winds (18 m s^{-1})
21	88	62	cloudy 7/8 to 8/8, cloud base 240–300 m
22	89	−43	erroneous prediction due to erroneous $\Omega(i-1)$
23	91	−60	rain showers the whole day, cloud base 400–1500 m
24	93	−37	cloudy (4/8 to 6/8), cloud base 400–1200 m
25	100	67	rainy, 8/8 cloud amount, cloud base 170–3000 m
26	101	−36	erroneous prediction due to erroneous $\Omega(i-1)$, cloudy (6/8 to 8/8), cloud base 100–2000 m
27	102	29	hazy, overcast sky, rain in the afternoon, erroneous $\Omega(i-1)$
28	103	41	cloudy (2/8 to 7/8), cloud base 200–1000 m
29	104	63	rainy and stormy (15 m s^{-1}), cloud base 430–1500 m
30	117	−32	cloudy (3/8 to 7/8), cloud base 500–1200 m
31	139	47	rainy, cloud base 100–180 m
32	145	30	rainy
33	146	−30	erroneous prediction due to erroneous $\Omega(i-1)$
34	166	−27	cloudy 6/8
35	244	40	rain in the morning, overcast sky
36	250	35	rain in the morning, overcast sky
37	281	29	rain in the morning, overcast sky
38	314	30	cloudy 7/8
39	327	42	fog with visibility of 200 m the whole day
40	333	28	drizzle in the morning, overcast sky, strong winds (15 m s^{-1})
41	356	35	overcast sky

See Figure 5 for identification of serial numbers. Here, Ω_D and Ω_r are ozone column amount from Dobson measurements and regression, respectively, in Dobson units.

derived total ozone. There are plausible reasons for less accurate measurements due to unfavorable observation conditions for a number of cases with large deviations between data estimated by the regressions and measurements (see Tables 4 and 5). This fact justifies a recommendation of adding quality flags to both grid point satellite and ground-based ozone measurements.

3. The linear multiple regressions are useful prognostic equations for the 24-hour prediction of total column ozone, despite some loss in accuracy when predicted instead of analyzed temperatures or geopotential heights have to be used. The forecast error for 1994 was about 3% when doubtful measurements were omitted.

These results provoke a couple of new questions. Let us mention only the obvious ones: How representative are the regressions in space? Can they be expanded to larger areas without remarkable loss in accuracy? And if not, are there other relations of comparable quality? Can a multitude of regionally limited regressions be handled in an adequate manner operationally? How will the regressions be involved in

Table 5. Weather Information at Potsdam for Days in 1979 With Large Deviations Between TOMS and Diagnosed Total Column Ozone

Date	$\Omega_{TOMS} - \Omega_{re}$	Weather in Potsdam
January 10	+49	rain, no sunshine
January 29	+67	rain, no sunshine
January 30	+65	rain, no sunshine
March 30	−51	rain, no sunshine
March 31	+41	rain, no sunshine
April 5	+74	rain, sunshine duration 1.6 hours
April 17	+58	rain, no sunshine
April 30	+49	rain, sunshine duration 3.2 hours
November 20	+41	rain, no sunshine
December 2	+41	drizzle, no sunshine
December 20	+42	rain, no sunshine
December 21	+63	rain, no sunshine
December 23	+64	drizzle, sunshine duration 0.2 hours
December 27	+79	haze, sunshine duration 2.4 hours
December 30	+44 (−20)	shower, sunshine duration 4.8 hours

The value in parentheses on December 30 is the only available comparison with a Dobson spectrometer measurement.

suitable quality checks and perhaps improvements of satellite total column ozone retrievals? We plan to adress some of these questions in future studies.

Acknowledgment. The study was supported by the Bundesministerium für Forschung und Technologie, Bonn, under grant 01 L0 9204/0.

References

Allaart, M. A. F., H. Kelder, and L. C. Heijboer, On the relation between ozone and potential vorticity, *Geophys. Res. Lett.*, *20*, 811–814, 1993.

Austin, J., B. R. Barwell, S. J. Cox, P. A. Hughes, J. R. Knight, G. Ross, P. Sinclair, and A. R. Webb, The diagnosis and forecast of clear-sky ultraviolet levels of the Earth's surface, *Meteorol. Appl.*, *1*, 321–336, 1994.

Bais, A. F., C. S. Zerefos, C. Meleti, I. C. Ziomas, and K. Tourpali, Spectral measurements of solar UVB radiation and its relations to total ozone, SO_2 and clouds, *J. Geophys. Res.*, *98*, 5199–5204, 1993.

Bojkov, R. D., Vertical distribution of ozone in the Earth's atmosphere, *Meteorol. Gidrol.*, *10*, 3–11, 1965.

Bojkov, D. R., C. S. Zeferos, D. S. Balis, I. C. Ziomas, and A. F. Bais, Record low total ozone during northern winters of 1992 and 1993, *Geophys. Res. Lett.*, *20*, 1351–1354, 1993.

Brühl, C., and P. J. Crutzen, On the disproportionale role of tropospheric ozone as a filter against solar UV-B radiation, *Geophys. Res. Lett.*, *16*, 703–706, 1989.

Burrows, W. R., L. J. Wilson, and M. Vallée, A statistical forecast procedure for daily total ozone based on TOMS data, paper presented at 13th Conference on Weather Analysis and Forecasting Including Symposium on Flash Floods, Am. Meteorol. Soc., Vienna, Va., Aug. 2–6, 1993.

Burrows, W. R., M. Vallée, J. B. Kerr, L. J. Wilson, and D. W. Tarasick, The Canadian operational procedure for forecasting total ozone and UV radiation, *Meteorol. Appl.*, *1*, 247–265, 1995.

Chubarova, N. Y., The transmittance of global ultraviolett radiation by different cloud types (in Russian), *Isv. Russ. Acad. Sci. Atmos. Oceanic Phys.*, *29*, 639–645, 1993.

Dameris, M., D. Nodorp, and R. Sausen, Correlation analysis of tropopause height and TOMS data for the EASOE—Winter 1991/1992, *Contrib. Atmos. Phys.*, in press, 1995.

Dobson, G. M. B., D. N. Harrison, and J. Lawrence, Measurements of the amount of ozone in the Earth's atmosphere and its relation to other geophysical conditions, III, *Proc. R. Soc. London A*, *122*, 456–486, 1929.

Feister, U., *Ozon—Sonnenbrille der Erde*, 155 pp., G. Teubner Verlagsges., Leipzig, 1990.

Feister, U., Measurement of chemically and biologically effective radiation reaching the ground, *J. Atmos. Chem.*, *19*, 288–315, 1994.

Fleig, A. J., R. D. McPeters, P. K. Bhartia, B. M. Schlesinger, R. P. Cebula, K. F. Klenk, S. L. Taylor, and D. F. Heath, Nimbus 7 solar backscatter ultraviolet (SBUV) ozone products user's guide, *NASA Ref. Publ.*, *1234*, 19–25, 1990.

German Bundestag (Ed.), *Protecting the Earth's Atmosphere: An International Challenge*, pp. 310 ff, Bonn, 1989.

Gleason, J. F., et al., Record low global ozone in 1992, *Science*, *260*, 523–526, 1993.

Heese, B., K. Barthel, and O. Hov, A comparison of total ozone data from satellite and ground-based observations at northern latitudes, *J. Geophys. Res.*, *97*, 3825–3830, 1992.

Herman, J. R., and D. Larko, Low ozone amounts during 1992–1993 from Nimbus 7 and Meteor 3 total ozone mapping spectrometers, *J. Geophys. Res.*, *99*, 3483–3496, 1994.

Herman, J. R., R. Hudson, R. D. McPeters, R. Stolarski, X.-Y. Gu, S. Taylor, and C. Wellenmeyer, A new self-calibration method applied to TOMS and SBUV backscattered ultraviolet data to determine long-term global ozone change, *J. Geophys. Res.*, *96*, 7531–7545, 1991.

Komhyr, W. D., R. D. Grass, R. D. Evans, R. K. Leonard, D. M. Quincy, D. J. Hofmann, and G. L. Koenig, Unprecedented 1993 ozone decrease over the United States from Dobson spectrometer observations, *Geophys. Res. Lett.*, *21*, 201–204, 1994.

Lefèvre, F., D. Cariolle, S. Müller, and F. Karcher, Total ozone from the TIROS Operational Vertical Sounder during the formation of the 1987 "ozone hole," *J. Geophys. Res.*, *96*, 12,893–12,911, 1991.

Liu, S. C., S. A. McKeen, and S. Madronich, Effect of anthropogenic aerosols on biologically active ultraviolet radiation, *Geophys. Res. Lett.*, *18*, 2265–2268, 1991.

London, J., and J. K. Angell, The observed distribution of ozone and its variation, in *Stratospheric Ozone and Man*, edited by F. A. Bower and R. B. Ward, pp. 7–42, CRC Press, Inc., Boca Raton, Fla., 1982.

McKenzie, R. L., W. A. Matthews, and P. V. Johnston, The relationship between erythemal UV and ozone, derived from spectral irradiance measurements, *Geophys. Res. Lett.*, *18*, 2269–2272, 1991.

Mote, P. W., J. R. Holton, and J. M. Wallace, Variability in total ozone associated with baroclinic waves, *J. Atmos. Sci.*, *48*, 1900–1903, 1991.

Normand, C., Atmospheric ozone and the upper air conditions, *Q. J. R. Meteorol. Soc.*, *79*, 39–50, 1953.

Ohring, G., and H. S. Muench, Relationships between ozone and meteorological parameters in the lower stratosphere, *J. Meteorol.*, *17*, 195–206, 1960.

Petzoldt, K., B. Naujokat, and K. Neugebohren, Correlation between stratospheric temperature, total ozone, and tropospheric weather systems, *Geophys. Res. Lett.*, *21*, 1203–1206, 1994.

Planet, W. G., J. H. Lienesch, A. J. Miller, R. Nagetani, R. D. McPeters, E. Hilsenrath, R. P. Cebula, M. T. DeLand, G. G. Wellemeyer, and K. Horvath, Northern hemisphere total ozone values from 1989–1993 determined with the NOAA-11 Solar Backscatter Ultraviolet (SBUV/2) instrument, *Geophys. Res. Lett.*, *21*, 205–208, 1994.

Poulin, L., and W. F. J. Evans, METOZ: Total ozone from meteorological parameters, *Atmos. Ocean*, *32*, 285–297, 1994.

Reed, R. J., The role of vertical motions in ozone-weather relationships, *J. Meteorol.*, *7*, 263–267, 1950.

Rood, R. B., and A. R. Douglass, Interpretation of ozone temperature correlations, *J. Geophys. Res.*, *90*, 5733–5743, 1985.

Schubert, S., and M. Munteanu, An analysis of tropopause pressure and total ozone, *Mon. Weather Rev.*, *116*, 569–582, 1988.

Seftor, C. J., S. L. Taylor, C. G. Wellemeyer, and R. D. McPeters, Effect of partially clouded scenes on the determination of ozone, in Proceedings of Quadrennial Ozone Symposium, Charlottesville, Va., 1992, *NASA Conf. Publ.*, *3266*, 919–922, 1994.

Smith, W. L., H. M. Woolf, C. M. Hayden, and A. J. Schreiner, The simultaneous retrieval export package, in *Technical Proceedings of the 2nd TOVS Study Conference*, Univ. of Wisconsin, Igls, Austria, February 18–22, 1985.

Spänkuch, D., Erkennung atmosphärischer Strukturen und Prozesse aus Satellitendaten, *Ann. Meteorol.*, *29*, 51–92, 1994.

Spänkuch, D., and W. Döhler, Statistische Charakteristika der Vertikalprofile von Temperatur und Ozon und ihre Kreuzkorrelation über Berlin, *Geodät. Geophys. Veröff.*, *2*(19), 132 pp., 1975.

Spänkuch, D., W. Döhler, and H. Kubasch, Statistical characteristics of the vertical ozone distribution in midlatitudes, *Pure Appl. Geophys.*, *106–108*, 1208–1218, 1973.

Thompson, A. M., D. P. McNamara, K. E. Pickering, and R. D. McPeters, Effect of marine stratocumulus on TOMS ozone, *J. Geophys. Res.*, *98*, 23,051–23,057, 1993.

Tung, K. K., and H. Yang, Dynamic variability of column ozone, *J. Geophys. Res.*, *93*, 11,123–11,128, 1988.

United Nations Environmental Programme, *Environmental Effects Panel Report*, Nairobi, Kenya, 1989.

Vaughan, G., and D. A. Begum, Correlation between total ozone and potential vorticity, *in Ozone in the Atmosphere*, edited by R. D. Bojkov, and P. Fabian, Hampton, Va., pp. 91–94, A. Deepak, 1989.

Vaughan, G., and D. J. Price, On the relation between total ozone and meteorology, *Q. J. R. Meteorol. Soc.*, *117*, 1281–1298, 1991.

Vogel, G., D. Spänkuch, E. Schulz, U. Feister, and W. Döhler, Regional short-term forecast of total column ozone, *Atmos. Environ.*, *29*, 1155–1163, 1995.

Wang, P., and J. Lenoble, Comparison between measurements and modeling of UV-B irradiance for clear sky: A case study, *Appl. Opt.*, *33*, 3964–3971, 1994.

E. Schulz and D. Spänkuch, Meteorologisches Observatorium Potsdam, Deutscher Wetterdienst, P. O. Box 600552, D-14405 Potsdam, Germany.

(Received December 26, 1994; revised April 28, 1995; accepted April 30, 1995.)