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CHAPTER 4

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Trends in Total Column Ozone Measurements

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Chapter 4

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4.0 INTRODUCTION

A century ago, Hartley (1881a) explained the observed sharp 293-nm cutoff in ultraviolet (UV) radiation at Earth's surface as caused by ozone whose UV spectrum he had measured in the laboratory. By finding the same cutoff in mountaintop measurements, Hartley later showed that most of the ozone existed in the atmosphere at still higher altitudes (1881b). The initial quantitative measurements of the total ozone content in the vertical column were made with optical instruments at ground level about 75 years ago by Fabry and Buisson (1913, 1921). The subsequent discovery that concentrations of ozone in the vertical column varied with local weather conditions inspired several scientists, including G.M.B. Dobson, to begin systematic ozone measurements in the 1920's, largely with the hope of improving the capabilities of weather forecasting (Dobson and Harrison, 1926; Dobson et al., 1927, 1929; Dobson, 1930; Cabannes and Dufay, 1927; Fowle, 1929). The basic ultraviolet double monochromator spectrophotometer system developed then by Dobson is still the instrument used in the ground-based observational network for the determination of the total ozone content of the atmosphere, and the standard instrument is now known as a Dobson spectrophotometer (Dobson, 1931, 1957a,b, 1973).

Total ozone is defined as being equal to the amount of ozone contained in a vertical column with a base of 1 cm^2 at standard pressure and temperature, and can be expressed in units of pressure with a typical value of about 0.3 atmosphere cm. The more frequently used unit is milliatmosphere centimeters, commonly known as the Dobson Unit (DU). One DU represents an average atmospheric concentration of approximately one part per billion (ppb) by volume of O3, but the ozone is not distributed uniformly through the vertical column. Typical amounts of ozone vary from 230 to 500 DU's, with a world average of about 300 DU. About 90 percent of atmospheric ozone lies in the stratosphere, a fact already well known during the 1930's.

Several other instruments used to measure ozone are based on principles similar to those of the spectrophotometer designed by Dobson. These instruments include the M–83 filter ozonometers in use for the last 30 years at as many as 45 stations in the U.S.S.R., the Brewer spectrophotometers recently introduced chiefly in Canada, and the new M–124 filter ozonometers in the U.S.S.R. (Gustin, 1963, 1978; Brewer, 1973; Gustin et al., 1985). The principles of operation of these ground-based instruments, the length of their record, and their locations are described in Section 4.1 of this chapter. Several satellite-based instruments measure ozone; for the purposes of this chapter only the results from the Total Ozone Mapping Spectrometer (TOMS) are extensively discussed. Section 4.2 contains a description of this instrument as well as brief descriptions of the other satelliteborne instruments; Chapter 2 contains a fuller discussion of the satellite instruments.

If one is to have faith in the trends versus time calculated from a long time series of measurements, it is extremely important that the quality of the data is high. Critical examination of the data from the individual Dobson stations and from the TOMS satellite instrument has been carried out, and the diagnostic tools used are described in Sections 4.3 and 4.4, respectively. In both cases, the data needed some revision; the Dobson data have been corrected using information available in the records of the individual stations. Because of time and labor constraints, the process of revision treated only the monthly average ozone values from the Dobson stations, and the improved and recommended data set is, therefore, referred to as "Provisionally Revised." A full review of the Dobson data requires that each reading be examined and that the review is carried out on a station-by-station basis, with full access to all of the daily log books and records. It is hoped that individual stations will do this and that their fully revised data sets can, in time, take the place of the provisionally revised data sets presented in Appendix A to this chapter.

Sections 4.5 and 4.6 describe the statistical analysis of this provisionally revised data set; the results are presented in Appendix B to this chapter.

A drift in the calibration of the TOMS instrument was found relative to both the network of Dobson instruments and to the Dobson Primary Standard instrument. The likely cause of this drift is an imperfect correction for the known slow degradation of the TOMS diffuser plate from cumulative direct Sun exposure, as discussed in detail in Chapter 2. The TOMS data set has, therefore, been normalized to the results of the network of Dobson instruments. This continuing normalization over the whole time period provides a time-dependent correction for the diffuser plate. Because TOMS has global coverage, this procedure allows an analysis of the changes in total ozone that occurred anywhere in the world between 1979 and 1987, as described in Section 4.7.

In summary, the basic intent and philosophy of this chapter has been a very careful examination of all of the available total ozone data. Preliminary data analyses have been carried out on data sets as recorded in the archives for both the ground-based Dobson and TOMS satellite instruments. More sophisticated statistical calculations were carried out on data sets corrected by the procedures described in this chapter. The scope of these statistical analyses has also been widened in a search for any seasonal and latitudinal effects in the trends in total ozone.

4.1 GROUND-BASED MEASUREMENTS OF OZONE

Three instruments are routinely used to measure total ozone from Earth's surface: the Dobson spectrophotometer, the M–83 filter ozonometer, and the Brewer grating spectrophotometer. The Dobson and M–83 stations have data sets that are long enough for meaningful trend analysis. However, the Dobson instruments constitute the backbone of the ground-based network, as the number of stations is greater and the records are typically longer. The Brewer instrument has been in regular use for a much shorter time and currently has no long-term records suitable for such analysis. Total ozone data are routinely reported to the World Meteorological Organization–World Ozone Data Center (WMO–WODC) in Toronto, Canada, and printed regularly in a series of publications entitled *Ozone Data for the World* (ODW).

4.1.1 Dobson Spectrophotometer

4.1.1.1 Operation

The standard instrument in the Global Ozone Observing System is the Dobson spectrophotometer, containing a double quartz-prism monochromator that permits comparison of the radiances at two different wavelengths in the ultraviolet (UV). The basic design has been described by Dobson (1931) and has undergone many improvements in its optics and in the electronic evaluation of its signals. Detailed descriptions of its operation and physical accuracy have been given by Dobson (1957a,b; Dobson and Normand, 1962) and, more recently, in WMO Ozone Project Report Nos. 6 (Komhyr, 1980) and 13 (Basher, 1982). The operational principle of the Dobson spectrophotometer is based upon the knowledge that the absorption coefficient of ozone for ultraviolet radiation decreases rapidly with increasing wavelength across the Huggins absorption band (300–350 nm), providing a range in Earth's atmosphere from nearly complete to only minor absorption of incoming solar radiation. The technique utilizes the relative absorption of solar radiation from two wavelengths, one absorbed moderately strongly by ozone and one absorbed slightly. The basic measurement of ozone relies on the ratio of the intensities of UV radiation at two standard wavelengths. Measurements are made looking directly at the Sun near noontime, or symmetrically before and after noon. (At local noon the path length of the solar radiation through the atmosphere is shortest, and the air mass, μ, defined as the actual path length of the solar beam divided by the vertical path through the atmosphere, is also smallest. Measurements are made most accurately when the air mass is low because the intensity of UV light reaching Earth's surface is greatest.) The individual measurements are averaged to form the daily value. Four UV wavelength pairs have been established by the International Ozone Commission (Table 4.1), and recommended for universal use by the WMO.

Table 4.1 Ultraviolet Wavelength Pairs Used for Atmospheric Ozone Measurements With Dobson Spectrophotometers (Wavelengths in Nanometers).

Pair	Wavelength	Wavelength	O_3 Absorption Coefficient (a)
Designation			
A	305.5	325.4	1.748
B	308.8	329.1	1.140
C	311.45	332.4	0.800
D	317.6	339.8	0.360
C′	332.4	453.6	

(a) Difference in ozone absorption coefficients (in units of atm $^{-1}$cm) for the shorter wavelength minus longer wavelength (according to the 1968 recommendations by IOC and WMO based on the Vigroux coefficients (1967).

The most widely used combination, recommended as the international standard, is the pair of wavelength pairs listed as A and D in Table 4.1. The combined absorption for this "AD pair" is $(\alpha_A - \alpha_D) = 1.388$. Measurements of most physical quantities exhibit changes in the "best" or "accepted" values over time as equipment is improved or minor errors are discovered; the values for the absorption coefficients of ozone have changed several times in this manner over the last half century. The value of $(\alpha_A - \alpha_D)$ for the AD pair was defined in July 1957 for the International Geophysical Year to have the value 1.388, based upon the absorption coefficient measurements of Vigroux (1953, 1967), and has not been changed since, even though additional careful evaluations have been carried out. In this arrangement, the amount of atmospheric ozone is calculated from the UV radiation received at the two shorter wavelengths, and separately from the two longer wavelengths from the AD pair. The reported ozone content is obtained from the combined results of the four wavelengths. As the slant path of sunlight becomes longer, as in high-latitude stations in midwinter, so much light is absorbed at 305.5 nm that measurements with the A pair become very difficult and inaccurate, and observations tend to be made with the CD double wavelength pairs for which sufficient UV light is still arriving at 311.45 nm and 317.6 nm. At very low Sun angles and very long slant paths, it can become necessary to use the C′ wavelength pair for higher accuracy.

While the observation of the ratio of received UV light for standard wavelength pairs from direct sunlight is preferred, such observations are not always practicable or even feasible. In the winter months at very high latitude stations, little or no direct sunlight is received. In this situation, observations are possible using direct moonlight—but are clearly much more difficult because of the much lower UV light intensity reflected by the Moon. At other latitudes, measurements are also desirable on days in which direct sunlight is intermittent or absent. These observational data are based upon the measurement (at the same standard wavelengths) of scattered sunlight from either the clear or cloudy zenith sky, converted to the standard

AD–direct-Sun measurement by an empirically established transfer table. The accuracy of this transfer depends upon numerous carefully taken, nearly simultaneous, direct-Sun and zenith-sky observations. These are performed by alternating sequential measurements of the ratios of radiation received from the direct Sun and from either the clear or cloudy zenith sky on days when such experiments are possible. Empirical zenith sky charts must be constructed for each station as functions of the total ozone content; of the air mass (μ), i.e., the slant angle of the Sun; and of the instrument readings themselves. Sky charts are further constructed for the various kinds of cloud layers found over the particular station. Accurate sky charts require a very substantial amount of careful scientific work, and individual stations frequently use charts of less than optimum reliability, as for instance one constructed for another, geographically distant station with different average vertical ozone distributions and with different cloud conditions. The direct-Sun measurements are more straightforward than any of the others and are normally of higher accuracy. For some purposes, calculations can be carried out using only the direct Sun-data, but in most locations this may limit the information to only half or fewer of the days in some months.

No completely satisfactory method is available for estimating the scattering of ultraviolet radiation by aerosol or dust particles. In practice, because most ozone observations are made on the double AD pair of wavelengths and because both A and D pairs are approximately equally affected by aerosol scattering, any aerosol effect on UV penetration is assumed to cancel. The absorption by ozone then remains the overwhelmingly major factor causing differential removal of the different UV wavelengths from the direct path of sunlight. The effects of aerosol scattering in the presence of very large quantities of such particles, as in the aftermath of large volcanic explosions, requires careful separate consideration, but the effects of even large amounts of volcanic dust on measurements of total column ozone are very small. Such scattering from volcanic aerosol is of primary importance for attempts to determine the vertical distribution of ozone from Umkehr measurements made as the Sun approaches the horizon (see Section 4.1.4).

For the purposes of the standard observation of absorption of radiation by ozone, the altitude at which this absorption occurs is of relatively minor importance. An ozone molecule is capable of absorbing ultraviolet radiation at about 300 nm with approximately equal efficiency at all altitudes, and the net effect is the same at the arrival slit of the ground-based instrument. However, the ability of ozone to absorb ultraviolet radiation does exhibit a small temperature dependence (varying by about 0.13 percent per °C at the average temperature of the ozone layer) so that the conversion of a measured fractional UV absorption into number of molecules of ozone has a slight temperature dependence. No corrections are made in the standard Dobson measurements for these temperature effects, and the amounts of ozone are calculated as though all of the ozone molecules in the atmosphere were present at a temperature of -44°C, chosen as generally appropriate for the lower stratospheric location of most of the ozone molecules. Small errors can thus be introduced into the relative comparison of total ozone columns measured with different average stratospheric temperatures. Comparisons for the same months in different years are affected only if the average temperature of the stratosphere has changed significantly, and then only to a slight extent.

The reported amounts of ozone are also dependent upon the measured absorption cross-sections of ozone at the various wavelengths used with the Dobson instrument. These absorption coefficients have been determined more and more accurately by various research groups over the years, with the most recent being the measurements of Bass and Paur (1985) and the closely concurrent results of Molina and Molina (1986). By international convention, the world-wide Dobson network has reported all data subsequent to July 1, 1957, as calculated with the ozone absorption coefficients measured by Vigroux, and this procedure, amended in 1968, is still in force. The (α_D - α_D) value for the AD pair is 1.388 with the Vigroux coefficients and 1.428 with the Bass–Paur coefficients. A systematic bias of several percent therefore exists in any evaluation of the absolute amounts of ozone with a Dobson instrument using the Vigroux coefficients relative to the same data interpreted with the newer Bass–Paur absorption coefficients. (The instrument readings from the Nimbus–7 satellite are converted into ozone with the Bass–Paur coefficients.) Although the absolute amounts of ozone as evaluated with the Vigroux coefficients are presumably slightly in error, no bias exists in any trend measurements with the Dobson system for AD data collected from 1957 on and uniformly interpreted with the same (Vigroux) absorption coefficients. Prior to 1957, a different set of absorption coefficients (Ny and Choong, 1932, 1933) was in use as the standard, and comparisons of pre-1957 and post-1957 data with Dobson instruments must be made with correction for this change of absorption cross-sections assumed in the ozone calculations. The AD wavelength pair was adopted as the standard for ozone measurement in 1957, with the agreement that measurements made with other wavelengths should be transferred to the AD standard to eliminate systematic biases related to the absorption coefficients. The number of ozone stations operating before 1957 was relatively small, and no data taken prior to 1957 have been used in the statistical evaluations reported later in this chapter.

4.1.1.2 Sources of Errors and Ozone Data Quality

In order to determine the accuracy of ozone measurements, one needs to consider possible errors related to single-station measurements as well as potential sampling errors in the event that geographical averaging of the data is attempted. There is no simple method for combining the various error estimates into a single "accuracy" value. Most of the individual sources of error and theoretical estimates of their values are considered in detail by Basher (1982) in WMO Ozone Report No. 13. Our brief discussion here attempts incorporation of pertinent information from some other sources (WMO Ozone Report Nos. 9, 11, 12) as well as rough estimation of the accuracy of the data set used in this report.

The precision of long-term total ozone measurement from a Dobson spectrophotometer is estimated for annual means at ± 1 percent (at the 2 δ level), based on the standard deviation (δ) from the mean analysis of individual stations. However, attainment of this precision requires consideration of a number of error sources, described in detail in WMO Ozone Reports 9 and 13. These include absolute instrument calibration at various times during a solar cycle; observational and instrumental errors; aerosol effects; ozone absorption coefficient uncertainties, including temperature dependence; interfering trace gas absorbing species; ozone produced in the troposphere; and uncertainties in the empirically derived relations between direct and clear or cloudy zenith-sky observations.

The accuracy of the Dobson instrument is strongly dependent on the quality of the instrument's calibration and operation. Unfortunately, this quality can vary widely during an instrument's history, and only through the availability of periodic recalibrations can the ozone data be reevaluated.

Until 1973, instrument calibrations at different stations were conducted randomly and independently. In some cases, only the manufacturer's original calibrations were used. Theoretical error studies and field intercomparisons show that such instruments may exhibit systematic errors as large as 10 percent in the direct Sun ozone measurements at the AD wavelengths, with mean biases for the worst cases in the order of 5 percent. From 1974 on, increasing numbers of instruments have been modernized, refurbished, and calibrated by direct intercomparison with the WMO-designated World Primary Standard (Dobson No. 83) located at the World Dobson Spectrophotometer Central Laboratory at Boulder, Colorado. In subsequent intercomparisons, these instruments show typical calibration changes of 1 percent to 2 percent in AD-wavelength direct-Sun measurement, which is close to the limit of accuracy expected on the basis of theoretical and experimental studies. It should be noted immediately that, following recalibration, a step change in the ozone calculated from the instrument can appear comparable to the percentage change in the recalibration. However, in the present study, the required mean corrections were considered in reevaluation of the station data.

Instrument errors are generally not fixed percentages valid for all conditions throughout the year, but may vary with solar altitude and ozone amount and, therefore, with latitude and season. The AD wavelength ozone absorption coefficient, and therefore the absolute values of AD estimated total ozone, may have bias errors of up to 3 percent and will vary by about ± 2 percent for the maximum seasonal and latitudinal variations of about 15°C, in ozone-layer-weighted mean temperature. Actual stratospheric temperature observations indicate any long-term changes in temperature vertical profiles could contribute less than 0.5 percent per decade to any trends in total ozone data because neither season nor latitude is a variable in data sets used for evaluation of specific trends.

Errors originating from aerosol scattering are usually much less than ± 1 percent, but may rise to ± 3 percent during occasional extremely hazy conditions or nearby volcanic eruptions. Errors from interfering tropospheric absorbers (mainly SO_2, NO_2, and locally produced ozone) are usually negligible, but may raise the background error to about 1 percent. Solar irradiance changes around 300 nm are considered negligible, and therefore have no effect on instrument calibrations.

The international protocol calls, where possible, for a report of the total ozone measured for each day by each Dobson station, together with coded information indicating the wavelengths used and the technique involved—i.e., direct Sun, moonlight, clear zenith sky, etc. The daily Dobson total ozone data stored at the WMO–WODC are usually means of three or more measurements taken within a period of several hours centered on local solar noon. These individual daily ozone values are combined to form a monthly average, also reported to the WMO–WODC, and the monthly averages can, in turn, be combined to provide a yearly average ozone value. Not infrequently, weather conditions or other difficulties may prevent a successful measurement on a given day, or for several days in a row, or the measurement may be successfully made at a time not near solar noon at the station. Monthly averages are then calculated as the average of the daily values for the days with measurements, no attempt being made to interpolate or estimate the ozone values for the days without measurements. This inclusion of some days for which the data are not noontime measurements and the complete omission of other days raises the general problem of sampling errors for individual stations. Mean diurnal variations are thought to be less than 1 percent and contribute negligible sampling error. The size of day-to-day variations increases poleward with latitude, and seasonally from summer/autumn to winter/spring.

These seasonal variations range from a minimum of about 5 percent in the Tropics to about 30 percent in high-latitude winters and springs. Weather conditions and operational factors that cause great losses of data (e.g., fewer than 13 daily readings in a month) may cause biases of perhaps 5 percent in the mean ozone for some months, especially since total ozone amounts are strongly correlated with the synoptic weather conditions. Special care must be taken when analyzing winter data from high latitude stations for which the limited data may not be representative of the actual average monthly ozone amount. The uneven geographical distribution of the global Dobson spectrophotometer network is a further spatial source of sampling error when attempts are made to determine global ozone content and trends. The limited number of existing Dobson stations, their scarcity south of 30°N latitude, and the low-frequency variations of large-scale planetary waves should be accounted for in attempts for global total ozone analyses.

It is clear that the reliability of ozone measurements depends on random as well as systematic (or bias) errors. The latter are important for determination of ozone trends. If the period of variation of a systematic error is much shorter than the length of ozone record under consideration, it is treated as a random error. Sources that can promote errors with trendlike behavior are listed in Table 4.2, expressed in percent per decade.

Table 4.2 Possible Causes of Error in Ozone Trends From Dobson Stations; Estimates of the Effects on the Determined Trends Due to Instrumental and Other Experimental Causes.

Potential Error	Good case (%)	Bad case (%)	Note
Optical calibrations	0.4	2.0	(a)
Uncorrected instrument drift	<1.0	2.0	(b)
Trend in ozone layer "mean" temperature	0.2	<0.5	(c)
Extraterrestrial constant	0.1	2.0	(d)
Aerosol extinction	0.1	<1.0	(e)
Interfering absorption	0.1	<0.5	(f)
Increasing tropospheric ozone	0.2	1.0	(g)

The first number is an estimate applicable to "good" stations with reevaluated data records, as those used in the present report, while the second number refers to the "worst" conditions, occurring as exceptions.

(a) May create step-changes if the data record prior to calibration is not reevaluated using the calibration. The experience with the published data indicates an error on the order of 1 to 2 percent and, only in a few isolated cases, up to 5 percent.

(b) Can be positive or negative depending on the cause. A number of instruments have been compared with the World Primary Standard on a few occasions during the last 14 years and have shown either no drift or a drift of <1 percent.

(c) A 5°C change per decade is required to introduce a 0.5 percent error. There is no evidence for such stratospheric temperature changes except in the Antarctic in springtime in the past decade. Our statistical procedures have not been applied to these Antarctic data.

(d) The "extraterrestrial constant" is the ratio of solar intensities for each standard wavelength pair, and is, in principle, identical for all locations, being a function only of solar conditions. In practice, however, the instrument accepts a band centered on each standard wavelength, and minor variations can exist in these band passes, requiring calibration for each specific instrumental construction. Transfers from the Primary Standard through direct comparisons have assured <1 percent error, although there are isolated cases with much higher potential error.

(e) May influence the AD measured ozone only in the event of a continuous extreme increase (or decrease) of aerosol pollution.

(f) Gases such as SO_2 and NO_2 can have an effect only if measurements are carried out in the immediate vicinity of the source and if their concentrations are steadily increasing.

(g) An increase in tropospheric ozone is not a potential error in measurement of total column ozone, but a possible contributor to a trend in total ozone. Such tropospheric ozone changes only become a "potential error" when, as is often done, measurements of total ozone are used as direct estimates of possible trends in the stratospheric contribution to total ozone.

(h) The combination of biases due to bandwidth effect, airmass calculation, solar irradiance variability, and sampling practices is likely to be negligible.

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Despite the difficulty in estimation and the need to use individual judgment, one can attempt to determine the potential error, giving an overall indication of the accuracy of the Dobson data used in this report. These systematic errors are believed to be uncorrelated, with some positive and others negative, and the bounds of the accuracy can then be estimated as the square root of the sum of the squares of the individual error terms above, or from about 1.2 percent for stations with reevaluated records to 3.8 percent for the "worst" station case.

An important point is that statistical trend analyses of historical data series, if properly done, can show any substantial step changes in the data record, together with any systematic variations or excesses in the quasi-random components of the record. Clearly, in order to extract the most information from any Dobson ozone data set, it is essential for statisticians and instrument specialists to examine the data set together, preferably on a station-by-station basis. Typical error estimates, such as those given here, may result in large overestimates or underestimates of errors for a particular instrument, as well as a missed opportunity to detect, and hence correct, obvious data errors.

4.1.1.3 Geographical Distribution of Dobson Stations

For historical and geographical reasons, the Dobson stations with the longest records are spread unevenly around the world, with the greatest number located in Europe and North America. Figure 4.1 displays a global map of the location of the ground-based ozone stations

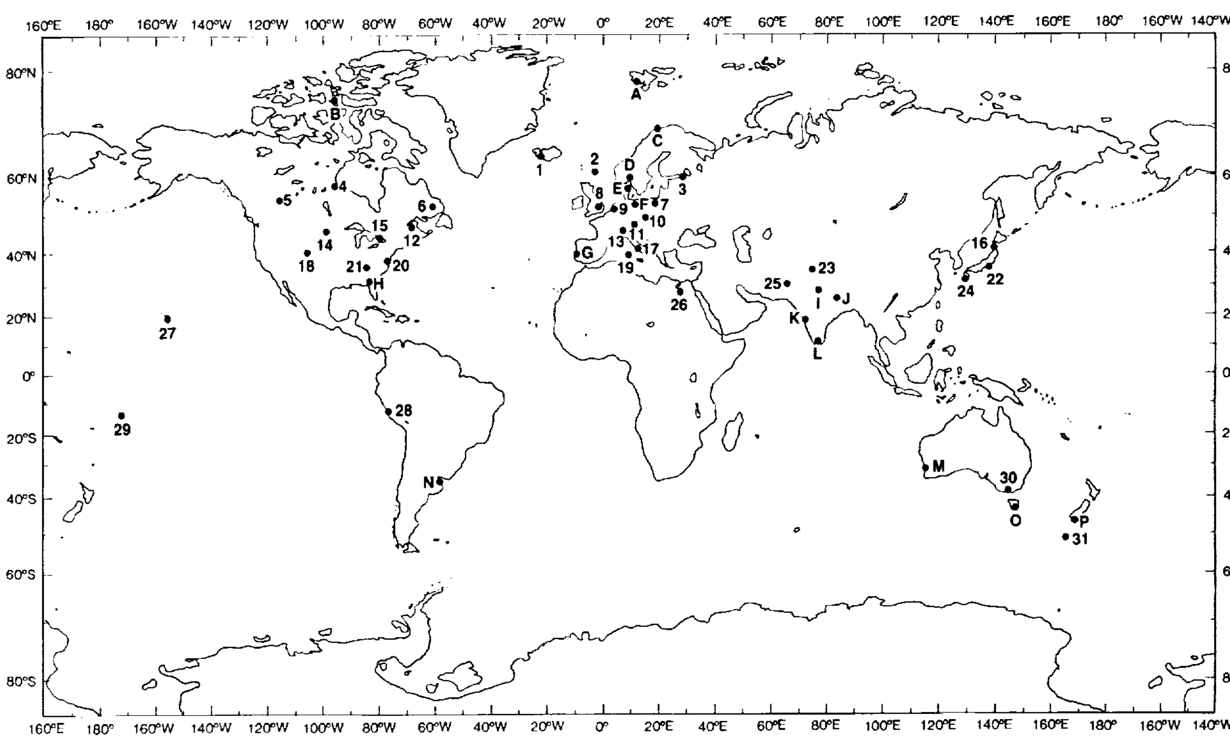


Figure 4.1 Geographical distribution of Dobson stations with long records. Revisions needed in some cases before the data are suitable for trend analysis (the letters shown correspond to those given in Tables 4.3 and 4.4).

with records over a substantial period of time. Table 4.3 provides a list of Dobson stations for which revised ozone data are available; Table 4.4 lists some additional Dobson stations whose data are mentioned in this report. More stations are now in operation, especially in the Tropics, but the coverage of the Southern Hemisphere outside the Antarctic continent is still poor. The most recent index of *Ozone Data for the World* contains a detailed listing of all of the ozone stations that have been in operation at any time during the period from 1957 to 1988.

Table 4.3 Dobson Stations for Which Preliminary Revised Ozone Data Are Available Over Time Periods Long Enough for Trend Analysis.

Station	Country	Latitude	Longitude	Altitude Meters	Dates Measured Start	Dates Measured Through
Northern Hemisphere						
1 Reykjavik	Iceland	64°08′	21°54′W	60	6/57	10/86**
2 Lerwick	U.K.	60°08′	1°11′W	80	1/57	11/86*
3 Leningrad	U.S.S.R.	59°58′	30°18′E	74	8/68	12/86
4 Churchill	Canada	58°45′	94°04′W	35	1/65	12/86
5 Edmonton	Canada	53°34′	113°31′W	668	7/57	11/86
6 Goose	Canada	53°19′	60°23′W	44	1/62	10/86
7 Belsk	Poland	51°50′	20°47′E	180	1/63	12/86
8 Bracknell	U.K.	51°23′	0°47′W	70	5/69	12/86*
9 Uccle	Belgium	50°48′	4°21′E	100	2/71	12/86
10 Hradec Kralove	Czechoslovakia	50°11′	15°50′E	285	1/62	12/86
11 Hohenpeissenberg	F.R.G.	47°48′	11°01′E	975	1/67	12/86
12 Caribou	U.S.A.	46°52′	68°01′W	192	6/62	12/86
13 Arosa	Switzerland	46°46′	9°40′E	1860	1/57	12/86
14 Bismarck	U.S.A.	46°46′	100°45′W	511	1/63	12/86
15 Toronto	Canada	43°47′	79°28′W	198	1/60	12/86
16 Sapporo	Japan	43°03′	141°20′E	19	1/58	12/86
17 Rome	Italy	42°05′	12°13′E	262	4/54	12/86*
18 Boulder	U.S.A.	40°01′	105°15′W	1634	1/64	12/86
19 Cagliari	Italy	39°15′	9°03′E	4	1/56	12/86**
20 Wallops Is.	U.S.A.	37°51′	75°31′W	4	1/70	12/86
21 Nashville	U.S.A.	36°15′	86°34′W	182	1/63	12/86
22 Tateno	Japan	36°03′	140°08′E	31	7/55	12/86
23 Srinagar	India	34°05′	74°50′E	1586	7/57	5/86**
24 Kagoshima	Japan	31°38′	130°36′E	283	4/61	12/86*
25 Quetta	Pakistan	30°11′	66°57′E	1799	7/57	12/86
26 Cairo	Egypt	30°05′	31°17′E	35	11/74	10/86
27 Mauna Loa	U.S.A.	19°32′	155°35′W	3397	1/64	12/86
Southern Hemisphere						
28 Huancayo	Peru	12°03′	75°19′W	3313	2/64	6/86
29 Samoa	U.S.A.	14°15′	170°34′W	82	1/76	12/86
30 Aspendale	Australia	38°02′	145°06′E	0	7/57	12/86
31 MacQuarie Is.	Australia	54°50′	158°57′E	6	8/62	12/86

*Stations for which further reassessment of the ozone data is recommended, with evaluation of the detailed station records.
**Interruptions in the record.

Table 4.4 Other Dobson Stations for Which the Records Are Too Short for Trend Analysis, Have Major Interruptions in Their Records, or Are Otherwise Unsuitable at the Present Time for Analysis on an Individual Basis.

Station	Country	Latitude	Longitude	Altitude Meters	Dates Measured Start	Through
Northern Hemisphere						
A Spitzbergen	Norway	78°56′	11°53′E	0	50	86
B Resolute	Canada	74°43′	94°59′W	64	57	86
Point Barrow	U.S.A.	71°19′	156°36′W	973	82	
C Tromso	Norway	69°39′	18°57′E	100	35	86
D Oslo	Norway	59°54′	10°43′E	50	57	86
Uppsala	Sweden	59°51′	17°37′E	15	57	66
E Aarhus	Denmark	56°10′	10°12′E	53	41	86
Eskdalemuir	U.K.	55°19′	3°12′W	242	57	63
F Potsdam	G.D.R.	52°22′	13°05′E	89	57	86
Oxford	U.K.	51°45′	1°11′W	140	28	67
Moosonee	Canada	51°16′	80°39′W	10	57	61
Camborne	U.K.	50°13′	5°19′W	88	57	67
Mont-Louis	France	42°30′	2°08′E	1650	62	79
Shiangher	China	39°46′	117°00′E	13	79	86
G Lisbon	Portugal	38°46′	9°08′W	105	60	86
Messina	Italy	38°12′	15°33′E	51	57	75
White Sands	U.S.A.	32°23′	106°29′W	1224	72	81
Torishima	Japan	30°29′	140°18′E	83	57	65
H Tallahassee	U.S.A.	30°26′	84°20′W	53	64	86
I New Delhi	India	28°38′	77°13′E	216	57	86
Naha	Japan	26°12′	127°41′E	27	74	86
J Varanasi	India	25°18′	83°01′E	76	63	86
Kunming	China	25°01′	102°41′E	1917	80	86
K Ahmedabad	India	23°01′	72°39′E	55	51	86
with Mt. Abu	India	24°36′	72°43′E	1220	69	84
Mexico City	Mexico	19°20′	99°11′W	2268	74	86
Poona	India	18°32′	73°51′E	559	73	86
Bangkok	Thailand	13°44′	100°34′E	2	78	86
K Kodaikanal	India	10°14′	77°28′E	2343	57	86
Singapore	Singapore	1°20′	103°53′E	14	79	86
Southern Hemisphere						
Cairns	Australia	16°53′	145°45′E	3		
Cachoeira Pau.	Brazil	22°41′	45°00′W	573	74	86
Brisbane	Australia	27°25′	153°05′E	5	57	86
M Perth	Australia	31°55′	115°57′E	2	69	86
N Buenos Aires	Argentina	34°35′	58°29′W	25	65	86
O Hobart	Australia	42°49′	147°30′E	4	67	86
P Invercargill	New Zealand	46°25′	168°19′E	1	71	86
Argentine Is.	U.K.	65°15′	64°16′W	10	57	86
Syowa	Japan	69°00′	39°35′E	21	61	86
Halley Bay	U.K.	75°31′	26°44′W	31	56	86
Amundsen–Scott	U.S.A.	89°59′	24°48′W	2835	61	86

4.1.1.4 Instrument No. 83: The Role of the Dobson Primary Standard in Long-Term Calibration

With the realization in recent years of the potential for partial destruction of the atmospheric ozone layer by manmade trace gas pollutants, the task of accurate, long-term measurement of total ozone has grown in importance. Temporal fluctuations in ozone also occur naturally—as a result of changes in circulation patterns that transport ozone, variations in solar ultraviolet intensity over the 11-year solar sunspot cycle, etc. To separate man-induced from natural changes in ozone, long-term ozone measurement precision of ± 0.5 percent is desirable. Additionally, global coverage for total ozone measurements, as provided by satellite ozone instrumentation, is highly desirable. Among the currently available ground-based instruments for measurement of total ozone, only Dobson spectrophotometers have been used for long-term calibration of satellite ozone instrumentation.

The maintenance of a Dobson spectrophotometer in calibration requires that observations with the instrument are always made on correct wavelengths (to within 0.04 nm); that the instrument's optical wedge (adjusted to provide a null signal between the two wavelengths of the measurement) is calibrated to a high degree of accuracy; that temporal changes in the instrument's spectral response are monitored routinely with standard ultraviolet lamps; and that the extraterrestrial constants (the ratio of the solar intensities of the wavelengths as they reach Earth before any atmospheric attenuation) for the instrument are known with high accuracy at the various pairs of wavelengths. Procedures for establishing correct Dobson spectrometer wavelength settings and for calibrating the optical wedge have been standardized (Dobson, 1957b).

In principle, any spectrophotometer within the global Dobson instrument station network can be maintained in calibration by the established procedures. However, scattered light within an instrument can present a problem. If the light scattering is appreciable for observations on low Sun (μ = 2.5–3.2), then the absolute calibration determined for the instrument can be significantly in error. Furthermore, should the light scattering gradually increase with time, a fictitious trend can be introduced into the measured total ozone amounts. Significant absolute calibration errors can also occur with the Dobson spectrophotometer if the measurements are made at sites where observing conditions for calibration are not ideal—i.e., where atmospheric turbidity is appreciable and large day-to-day changes occur in total ozone. Calibration of the extraterrestrial constants for the various wavelength pairs is most favorable under conditions of directly overhead Sun, clear sky, and negligible variation over the course of a day in the amount of ozone in the atmosphere. The U.S. tropical site at 3,400 meters altitude on Mauna Loa, Hawaii, provides an especially favorable location for such calibrations.

To achieve compatibility in ozone data from the global Dobson spectrophotometer station network, a procedure was established in 1976 by the Atmospheric Ozone Research Project of the WMO whereby a set of regional secondary standard Dobson spectrophotometers are calibrated at periodic intervals relative to a primary standard Dobson instrument. The secondary standard instruments serve to calibrate fieldstation Dobson spectrophotometers within their respective regions. Dobson spectrophotometer No. 83 was established in 1962 as the standard U.S. instrument for measurements of total ozone. In August 1977, Dobson No. 83 served as the reference spectrophotometer during an international intercomparison of regional secondary standard Dobson instruments held in Boulder, Colorado. In 1980, instrument No. 83 was designated by the WMO as the Primary Standard Dobson Ozone Spectrophotometer for the world. Table 4.5 lists the regional secondary standard Dobson instruments, and the dates when they were calibrated relative to instrument No. 83.

Table 4.5 Primary and Secondary Standard Dobson Ozone Spectrophotometers.

Instrument Number	Country	Calibration Dates
83**	U.S.	1962, 1972, 1976, 1978, 1979, 1980, 1981, 1984, 1986, 1987, 1988
41	U.K.	1977, 1981, 1985
64	G.D.R.	1981, 1986
71	G.D.R.	1977, 1986
77	Canada	1977, 1981, 1986*
96	Egypt	1977, 1986
105	Australia	1977, 1984, 1988
108	U.S.S.R.	1977, 1988
112	India	1977, 1984
116	Japan	1977, 1984, 1988

*Indirect calibration in 1986, involving a Brewer ozone spectrophotometer.

**Designated by WMO in 1980 as World Standard Dobson Spectrophotometer; calibrations performed at Mauna Loa Observatory, except at Sterling, Virginia, in 1962.

While calibrations of this kind ideally should occur at 3- to 4-year intervals, national or international funding for such a routine program has not been established. Nevertheless, nearly all Dobson instruments in the global Dobson spectrophotometer station network now have calibrations traceable either directly or indirectly to World Standard Dobson Instrument No. 83 (Komhyr, 1987, 1988). The conclusions drawn in this chapter and in the full report are strongly based on the provisionally revised ground-based data, and these in turn are traceable to the calibration record for instrument No. 83. The TOMS satellite data have been normalized to the Dobson network, and therefore also to the calibration record of instrument No. 83. The integrity of the conclusions concerning any trends in total ozone depend critically, therefore, on the calibration and maintenance record of instrument No. 83, for which a detailed description is now presented.

The normal calibration procedure depends on sequential total ozone observations made on the direct Sun during clear-sky half-days (i.e., A.M. or P.M.) when $1.15 < \mu < 3.2$, and total ozone remains fixed or varies only slowly with time. Graphical analysis of the changing ratios of UV light received versus path length through the atmosphere permits accurate evaluation of the ratios received at the top of the atmosphere—i.e., the extraterrestrial constant. A comprehensive series of such calibration observations was obtained over a period of many days with instrument No. 83 at Mauna Loa Observatory (MLO) in 1976. This series established, on August 26, 1976, a calibration scale according to which all other domestic and foreign spectrophotometers have been calibrated. The N values determined for a series of standard lamps at that time defined an essentially independent 1976 standard lamp calibration scale for Dobson instrument No. 83. Absolute calibrations of instrument No. 83 were also conducted at MLO in 1972, 1978, 1979, 1980, 1981, 1984, 1986, and 1987. A similar calibration was performed on the instrument at Sterling, Virginia, in 1962. Differences among the recorded values for any of these separate absolute calibrations represent a composite estimate of the precision with which such observations can be made and the stability of the instrument itself over a 25-year period.

The results of these absolute calibrations are summarized in Table 4.6. Column 4 of the table lists the mean total ozone amounts measured during each of the calibration time intervals using the August 16, 1976, calibration scale for data processing.

Table 4.6 Summary of Results of Calibrations of World Standard Dobson Spectrophotometer No. 83 With Standard Lamps and by Means of Direct-Sun Observations at Mauna Loa Observatory.

			Reference: 1976 MLO Calib.†			Reference: Std. Lamp Calib.††						
Times of Calibrations	No. Obs. Used/ Made	Wave-lengths λλ	x (1976 MLO calib.)	S	Adj. x (1970 MLO calib.)	x (Std. Lamp calib.)	S	S.e. (New MLO calib.)	x	% Error in x (Std. Lamp calib.)	% Error in x (1976 MLO calib.)	Notes
		AD	280	0.001	280	280	−0.002	±0.004	280	+0.2	−0.1	
May 14	9/12	A		−0.001	280		−0.003	±0.005	281			
to		CD	279	−0.001	277	277	−0.002	±0.003	274	+0.9	+1.6	Very clear sky.
June 22		C		−0.001	281		−0.001	±0.002	281			
1972		D		−0.001	283		0.000	±0.004	287			
		AD	274	0.000	274	—	−0.001	±0.001	274	0.0	0.0	Very clear sky
June 16	86/90	A	275	0.000	275	—	−0.001	±0.002	275	0.0	0.0	Sunspot cycle
to		CD	278	0.000	278	—	0.000	±0.001	278	0.0	0.0	minimum.
Aug. 25		C	278	0.000	278	—	0.000	±0.001	278	0.0	0.0	*Aug. 26, 1978
1976		D	278	0.000	278	—	0.000	±0.001	278	0.0	0.0	Calibration
												Scale
		AD	273	0.000	273	273	0.006	±0.002	275	−0.7	−0.5	
July 13	29/33	A		−0.002	274		0.001	±0.002	274			
to		CD	274	0.002	276	272	0.004	±0.001	276	−1.6	−0.8	Very clear sky.
Aug. 23		C		0.000	276		0.000	±0.001	274			
1978		D		−0.002	276		−0.005	±0.001	271			
		AD	282	0.002	282	282	0.006	±0.002	284	−0.7	−0.7	Very clear sky.
June 8	43/51	A		0.001	284		0.003	±0.002	284			Sunspot cycle
to		CD	282	0.002	284	282	0.003	±0.001	285	−1.0	−0.9	maximum.
Aug. 14		C		0.002	288		0.001	±0.001	284			
1979		D		0.000	289		−0.002	±0.001	283			
		AD	272	−0.002	271	272	0.004	±0.005	273	−0.4	−0.4	Poor-quality
June 20	19/23	A		0.006	277		0.009	±0.009	277			observations.
to		BD	282	−0.008	277	283	−0.007	±0.004	270	+1.4	+1.0	Sky clear,
Aug. 4		B		0.003	283		−0.003	±0.006	283			hazy, and
1980		CD	276	−0.007	266	274	−0.005	±0.002	260	+2.0	+2.5	very hazy.
		C		−0.003	277		−0.004	±0.004	274			Sunspot cycle
		D		0.006	293		0.004	±0.004	288			maximum.
		AD	274	0.002	275	274	0.004	±0.002	276	−0.5	−0.6	Clear sky.
June 8	36/47	A		−0.001	276		0.000	±0.002	276			Near sunspot
to		BD	280	−0.002	279	281	−0.001	±0.002	281	+0.1	−0.4	cycle maximum.
Aug. 7		B		−0.003	281		−0.003	±0.002	281			Discarded obs.
1981		CD	271	0.003	275	271	0.006	±0.002	277	−2.3	−2.1	made during
		C		−0.004	277		−0.002	±0.002	276			increased solar
		D		−0.004	282		−0.005	±0.002	278			activity (see
												text).
		AD	270	−0.004	269	271	0.001	±0.003	271	−0.2	−0.3	Sky hazy.
July 31	11/13	A		−0.011	268		−0.008	±0.003	288			
to		BD	277	0.000	277	279	0.002	±0.002	280	−0.3	−1.1	Observation
Oct. 23		B		−0.007	274		−0.007	±0.003	273			quality
1984		CD	271	0.005	276	273	0.008	±0.003	281	−2.9	−3.5	good.
		C		−0.002	272		−0.001	±0.002	271			Near sunspot
		D		0.007	266		−0.009	±0.003	259			cycle mini-
												mum.
		AD	276	−0.001	276	277	0.000	±0.002	277	0.0	−0.5	Generally clear
June 10	13/14	A		−0.008	276		−0.007	±0.004	276			but some
to		BD	281	0.000	281	284	−0.002	±0.002	283	+0.4	−1.0	haze.
July 11		B		−0.007	279		−0.009	±0.003	280			
1986		CD	276	0.001	277	277	0.002	±0.001	279	−0.9	−1.0	Sunspot cycle
		C		−0.006	277		−0.005	±0.002	277			minimum.
		D		−0.007	276		−0.007	±0.002	273			
		AD	292	−0.001	291	292	0.000	±0.002	292	0.0	0.2	Generally clear
May 20	36/40	A		−0.002	292		−0.002	±0.002	292			sky.
to		BD	297	−0.002	296	300	−0.003	±0.001	299	+0.6	−0.4	Excellent
July 9		B		−0.003	296		−0.004	±0.002	297			quality obs.
1987		CD	292	0.000	292	293	0.000	±0.001	294	−0.2	−0.5	Sunspot cycle
		C		−0.002	293		−0.002	±0.001	293			July 10, 1987
		D		−0.001	296		−0.002	±0.001	293			Calibration
												scale.

*Percent errors in x are expressed for indicated x and μ – 2.2
†Provisional N-tables used were those of August 26, 1976.
††Provisional N-tables used were derived from instrument 83 standard lamp readings. N values assigned to the lamps August 28, 1976, and current wedge density tables.

Column 6 gives corresponding adjusted mean total ozone amounts, deduced after application of the calibration corrections S of column 5. Note that, for direct Sun observations on AD wavelengths—the standard procedure—the ozone values in columns 4 and 6 do not differ by more than 1 DU. Columns 7 to 10 present ozone data obtained from calibrating by means of standard lamps. In deriving the ozone values in column 7, the provisional N tables used were those established from the optical wedge densities of instrument No. 83 current at the time of calibration, and standard lamp N values assigned to the lamps on August 26, 1976. The ozone amounts in column 10 are the corrected values, determined by application of the corrections S given in column 8. For observations on AD wavelengths, the mean total ozone values in columns 4, 6, 7, and 10 of Table 4.6 do not differ by more than 2 DU.

The percentage errors in total ozone relative to the 1976 standard lamp calibration scale and to the Dobson instrument August 26, 1976, calibration scale are given, respectively, in columns 11 and 12 of the table for indicated total ozone and for $\mu = 2.2$, approximately the mean μ for the series of observations. As indicated earlier, the August 26, 1976, calibration scale for instrument No. 83 and the 1976 standard lamp calibration scale are essentially independent. From the percentage error data given in columns 11 and 12, we conclude that the Dobson instrument No. 83 calibration scale for direct Sun observations on AD wavelengths has remained unchanged between June 1972 and July 1987 to within about ± 0.5 percent.

A calibration scale established on June 18, 1962, for Dobson spectrophotometer No. 83 at Sterling, Virginia, based on direct Sun observations, yields $N_A - N_D$ values that differ by only 0.003 from those given by a corresponding calibration scales based on N values for the standard lamps of instrument No. 83 on August 26, 1976. This difference corresponds to a difference of 0.4 percent in total ozone for $\mu = 2$ and an ozone content of 300 DU, or about 1 DU between the two calibration scales. Either of the scales is, therefore, suitable for use, with an uncertainty of less than about ± 1 percent relative to the August 26, 1976, calibration scale.

An analysis of errors associated with Dobson spectrophotometer calibration observations indicates a collective uncertainty of not more than several tenths of 1 percent corresponding to uncertainties in the air mass, the ratio of the actual and vertical path lengths of the solar beam through the ozone layer, the solar zenith angle, the Rayleigh-scattering coefficients, and the particle-scattering coefficients used for observations on AD wavelengths. Ozone absorption coefficients specified for use with Dobson spectrophotometers are applicable at -44°C. At MLO, the mean temperature in the region of the ozone maximum, determined from radiosonde observations conducted during June–August 1958–1987, was about -48.4°C. Because ozone absorption coefficients for the AD wavelengths increase with increasing temperature at a rate of 0.13%/°C, total ozone values computed at MLO must be increased by about 0.57 percent. The radiosonde data also indicate a long-term temperature trend at Mauna Loa of about 0.05%/year, which translates into a trend in effective ozone absorption coefficients, and therefore in total ozone, of only about 0.006 percent per year. Shorter (3- to 6-year) time-interval temperature variations, unaccounted for, lead to errors in ozone trend calculations of up to about 0.1 percent.

In an attempt to ascertain whether the extraterrestrial constants for the Dobson instrument wavelengths vary during the course of the 11-year solar cycle, calibration observations were scheduled at times of maxima and minima in sunspot numbers. No significant difference in results (Table 4.6) was obtained for observations on AD wavelengths. Data obtained for the A and D wavelengths in 1980, at the time of a maximum in sunspots, indicated an apparent need for N-value corrections of about S + 0.006, but this result has been discarded because of known systematic observer errors. In 1981, 9 half-days of calibration observations (of 47) were discarded following a marked temporary increase in solar activity about July 17. N-value corrections for AD wavelengths computed for these observations were about ± 0.035. Because the need was indicated for both positive and negative corrections that roughly cancelled, it is likely that the required assumption of constant ozone for the half-days during which observations were made was not valid in those periods. We tentatively conclude that if variations in the extraterrestrial constants occur during the course of a solar cycle, the assumption of constant value over the cycle most likely leads to errors in total column ozone not exceeding a few tenths of a percent, as determined from observations on AD wavelengths.

The Dobson instrument No. 83 calibration observations made at MLO during 1972–1987 have yielded a unique, precise total ozone data set that is separately useful for testing the calibration of satellite instrumentation for the measurement of total ozone. These data have been used (see Section 4.4) for the calibration of ozone measurements by TOMS aboard Nimbus–7 (McPeters and Komhyr, 1988).

4.1.1.5 Reporting Procedures to Ozone Data for the World

The daily total ozone column measurements are reported by the individual stations to the WMO–WODC and have been published since 1960 in ODW. The standard data report provides the value of the total ozone content for that day, the local time of the measurement, the wavelengths used (usually AD), and the radiation source: direct Sun, direct Moon, blue zenith sky, or one of five classifications of zenith cloud cover. In most cases, the data submitted by the stations for publication in ODW do not include corrections for periodic instrument calibrations or for intercomparisons with the world primary or regional standards, despite repeated recommendations by WMO (e.g., Ozone Report Nos. 9 and 12). Retroactive revisions of station data in ODW are very rare, even though later recalibration has demonstrated instrumental drift. (In almost all instances, essentially no budgetary provision has been made for personnel to carry out such reevaluations.) The uncritical use of published data can result in erroneous statements and major disagreements in apparent trends, even between stations located in the same macro-circulational region. As one of many examples, Figure 4.2 shows a sharp disruption in 1976–1977 in the Mauna Loa data published in ODW. (The regular Mauna Loa data are not recorded with instrument No. 83, which is normally in Boulder, Colorado, and is sent to Mauna Loa for periodic recalibration.)

The Dobson spectrophotometers are intended to be checked at least monthly with mercury-lamp tests, which monitor the spectral sensitivity response to a standardized exposure to UV radiation. The hoped-for result is that these monthly lamp tests indicate constancy of sensitivity; otherwise, the tests should catch any problems or mishaps that might have occurred, such as a change in the wavelength selection by the instrument slits. The extended series of monthly lamp tests can provide information pointing either to an abrupt change or to a steady change in instrument response to the UV test. However, the lamp response is not necessarily linearly related to the absolute sensitivity of the Dobson instrument for ozone, so that while the lamp test is a test of stability, the changing lamp values alone do not provide a quantitative correction when some change is indicated to have occurred. The quantitative aspect is resolved through recalibration. There is no set pattern to the frequency with which the instruments are calibrated, with some stations performing regular calibrations and some not. The individual Dobson instruments are also occasionally recalibrated by direct comparison at a common location with either the world primary standard (instrument No. 83) or with one of the secondary standards. Sometimes, recalibration produces only a small adjustment, but, occasionally, a correction of several percent is indicated. International comparisons of a few dozen Dobson instruments in 1974, 1977, 1978, 1979, 1984, and 1986 indicate average deviations of the order of only 2 percent.

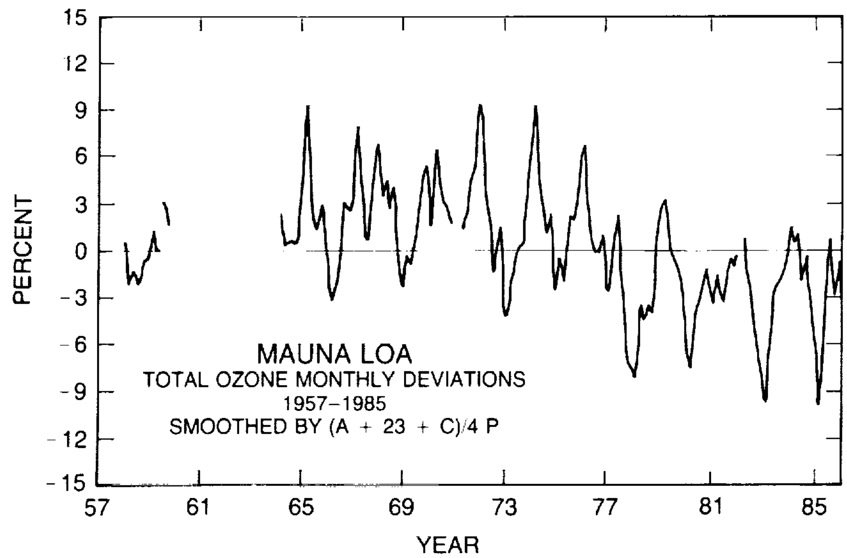


Figure 4.2 Total ozone monthly deviations at Mauna Loa (1957–1986). Calculated from the data published in *Ozone Data for the World,* showing the apparent disruption in the data in 1976–1977.

The usual procedure after calibration is the immediate installation of the new N-values, with no retrospective reevaluation of any earlier data—including the measurements made according to the old calibration scale only a short time before. In principle, such reevaluation is done by the individual stations and reported for printing in ODW. In practice, however, such published reevaluations are rare. It is worth emphasizing that, in accordance with the International Council of Scientific Unions (ICSU) principles governing the world data centers, the authority for any data adjustment resides with the individual reporting stations. Accordingly, no attempt is now made by the WMO–WODC to adjust data taken prior to recalibration, and the data are left as originally reported by the stations, with any such discontinuity intact. In almost all instances, such apparently obvious corrections are not routinely applied in the ozone data submitted for publication in ODW because the heavy workloads for other duties supersede in priority such reevaluations. Such corrections can be done if personnel time is available for such recalculations, but most ozone stations have not, in practice, been able to do any reevaluation of previously published data.

Furthermore, not all recalibrations are communicated for publication in ODW, and the information contained in routine lamp tests or other instrumental checks typically remains with the individual station records and is available only with difficulty to anyone else. Questions can then arise about the possible influence of such calibration changes upon trends in ozone concentrations inferred from the published data. The simplest question follows from the statement that, in most instances, the instrumental change that brought about the discrepancy noted during recalibration probably did not occur abruptly just prior to the recalibration. We have attempted in this chapter to revise the ozone data as published in ODW to take into account the corrections needed for these data, but not yet carried out by the individual stations. The bases for our corrections are outlined in Section 4.3.

4.1.2 Filter Ozonometer (M–83)

Since 1957, routine ground-based total column ozone measurements have been made at more than 40 stations in the USSR (see Table 4.7 and Figure 4.3) using a filter ozonometer instrument

Table 4.7 USSR M-83 Ozone Stations.

No.	WMO Index	Station	Latitude (°N)	Longitude (°E)
1	37500	Abastumani	41.45	42.50[a]
2	36870	Alma–Ata	43.14	76.56[a]
3	35746	Aralskoe More	46.47	61.40
4	22550	Archangelsk	64.35	40.30
5	38880	Ashkhabad	37.58	58.20[a]
6	32150	Bolshaya Elan (Sakhalin)	46.55	142.44[a]
7	30054	Vitim	59.27	112.35
8	31960	Vladivostok	43.07	131.54[a]
9	34560	Volgograd	48.35	45.43
10	34122	Voronez	51.42	39.10
11	35700	Gurev	47.01	51.51
12	20674	Dikson Island	73.30	80.14[a]
13	38836	Dushanbe	38.35	68.47[a]
14	23274	Igarka	67.28	86.34
15	30710	Irkutsk	52.16	104.21[a]
16	35394	Karaganda	49.48	73.08
17	33347	Kiev	50.24	30.27[a]
18	21432	Kotelnyj Island	76.00	137.54
19	29574	Krasnoyarsk	56.00	92.53[a]
20	28900	Kuibyshev	53.15	50.27[a]
21	26063	Leningrad	59.58	30.18[a,b]
22	33393	Lwow	49.49	23.57
23	25551	Markovo	64.41	170.25
24	27612	Moscow	55.45	37.34[a]
25	22113	Murmansk	68.58	33.03[a]
26	25913	Nagaevo	59.35	150.47[a]
27	31369	Nikolaevsk–Na–Amure	53.09	140.42
28	33837	Odessa	46.29	30.38[a]
29	24125	Olenek	68.30	112.26
30	28698	Omsk	54.56	73.24[a]
31	32540	Petropavlovsk–Kamchatskii	52.58	158.45
32	23418	Pechora	65.07	57.06
33	26422	Riga	56.58	24.04[a]
34	28440	Sverdlovsk	56.48	60.38[a]
35	36177	Semipalatinsk	50.21	80.15
36	30692	Skovorodino	54.00	125.58
37	37545	Tbilisi	41.41	44.57
38	21825	Tiksi	71.35	128.55
39	24507	Tura	64.10	100.04
40	33976	Feodosija	45.02	35.23[a]
41	23933	Hanty–Mansijsk	60.58	69.04
42	20046	Heiss Island	80.37	58.03[a]
43	34646	Cimljansk	47.44	42.15
44	38687	Cardzou	39.05	63.36
45	24959	Yakutsk	62.05	129.45[a]

[a] Data published and used in the formation of regional averages
[b] Dobson station

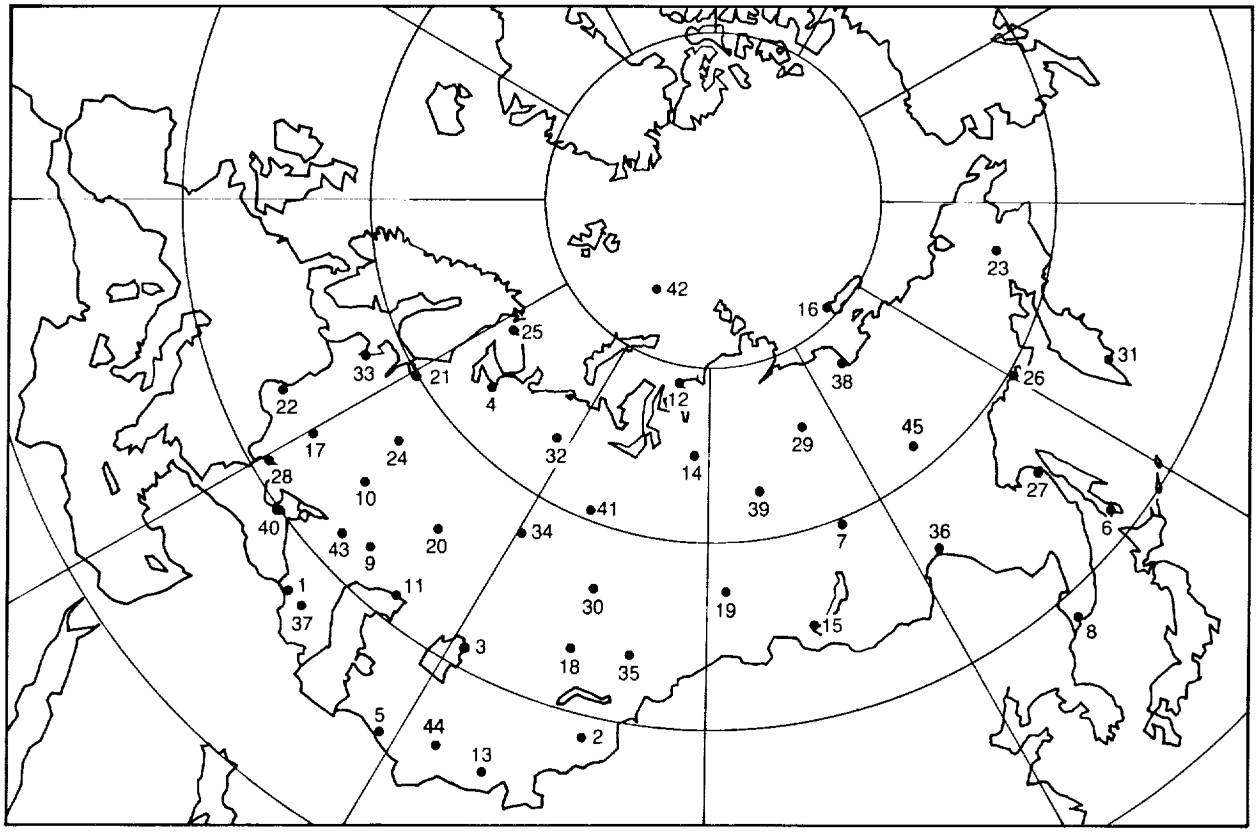


Figure 4.3 Geographical distribution of the M–83 filter ozonometers in the USSR (the numbers correspond to those given in Table 4.7).

designated as type M–83 (and not to be confused with the Standard Dobson ozone spectrophotometer, which was the 83rd instrument manufactured of the Dobson type). The filter-type instrument is based upon the same principle as the Dobson spectrophotometer in using differential absorption of UV radiation in the 300–350 nm Huggins band of ozone. The M–83 instrument, however, uses two broadband filters and measures the relative attenuation of the solar UV radiances either directly from the Sun or indirectly from the zenith sky (Gustin, 1963).

Direct intercomparisons between M–83 filter instruments and Dobson spectrophotometers prior to 1971 (Bojkov, 1969b) revealed that the M–83 recorded 6 percent less ozone when the observations were restricted to $\mu < 1.5$, and 20 percent to 30 percent more ozone when data were taken for $\mu > 2.0$. A strong dependence on turbidity was also detected, with 9 percent to 14 percent higher ozone readings when the surface visibility was less than 5 km. These strong deviations for $\mu > 2.0$ make very uncertain many of the high-latitude measurements in the USSR.

Improved filters were introduced into the M–83 instrument starting in 1972–1973 (Gustin, 1978). The new filters have maximum transmittance at 301 nm and 326 nm, and their bandpasses are less than those in the earlier version: 22 nm (291–312 nm) and 15 nm (319–334 nm). Comparison of Nimbus–4 BUV satellite overpasses over M–83 stations in the USSR demonstrated a standard deviation of about 50 DU before 1973 and about 25 DU afterward. The Nimbus–4 BUV overpasses of Dobson stations maintained a standard deviation of about 17 DU during the 1970–1977 lifetime of the satellite.

A much newer, reportedly improved instrument designated as M–124 has been installed in many stations since 1986 (Gustin et al., 1985), but no ozone data have been reported yet for this instrument. No trend data with the M–124 can be expected for about a decade unless the data can be satisfactorily cross-calibrated with the M–83 data from the same location.

4.1.3 Brewer Grating Spectrophotometer

An improved optical and electronic scheme for observations of total ozone was proposed by Brewer (1973) based in part on earlier developments by Wardle et al. (1963). The instrument has one diffraction grating (1,800 lines per mm) and five slits corresponding to five wavelengths in the 306–320 nm spectral band. The resolution is 0.6 nm as compared to 0.9–3.0 nm in the Dobson instrument. Combination of the data from all five wavelengths provides information about the total column content of SO_2, a potential interference for the Dobson measurements in SO_2-polluted air.

The Atmospheric Environment Service of Canada has been developing and testing the Brewer ozone spectrophotometer for the purpose either of replacing or supplementing the current Dobson network. Intercomparisons between the Brewer and Dobson instruments at Toronto have shown a difference in total ozone within ± 1 percent for direct-Sun observations. However, some questions about the stability of the Brewer instrument with respect to calibration and spectral sensitivity have been raised following comparisons of the Dobson and Brewer instruments in the Federal Republic of Germany at Hohenpeissenberg (Köhler and Attmannspacher, 1986) and in the USA at Wallops Island (Parsons et al., 1982). At this time, no plans for the worldwide utilization of the Brewer instrument have been announced, pending further field tests of the instrument in several regions of the globe. Brewer instruments are currently known to be operated at several Canadian stations (Kerr et al., 1988, 1988a), Salonika (Greece), Norshopping (Sweden), and Hohenpeissenberg. Only the data from Hohenpeissenberg have been published in ODW. The longest Brewer record commenced in 1983, so a long-term "Brewer-only" analysis cannot yet be carried out.

4.1.4 Measurements of Vertical Ozone Distributions: Umkehr and Ozonesondes

The measurements with the Dobson spectrophotometer are based entirely upon the ability of molecular ozone to absorb UV radiation in the Huggins band, and have produced the only long-term record of total ozone in the atmosphere measured by ground-based stations. The vertical distribution of ozone within the atmosphere can be deduced through the Umkehr technique with the Dobson spectrophotometer, and has been routinely applied at about a dozen Dobson stations. The preferred time of day for Dobson instrument measurements of total ozone is local noon, for which the slant path of the solar radiation is the shortest. For directly overhead Sun ($\mu = 1.0$) and for angles corresponding to $\mu = 2$ or 3, the radiation reaching the instrument is overwhelmingly the direct radiation from the solar source. However, as the Sun approaches the horizon, the importance of scattered radiation relative to direct radiation continues to increase. Under these conditions, the altitude of the scattering process relative to the altitude of absorption of ozone becomes important, and the ratio of wavelengths reaching the Dobson instrument begins to carry information about the altitude distribution of the ozone within the stratosphere. The ratio of radiation intensity (longer wavelength divided by shorter wavelength, e.g., 332.4 nm and 311.45 nm for the C pair) is expected to increase steadily with increasing slant path for the direct radiation because of the larger number of molecules of ozone available for absorption along the path. The radiation received from the zenith sky presents a mixture of scattering from various altitudes. When the Sun reaches a zenith angle of about 86°, the altitude dependence of the scattering process causes the intensity ratio to pass through a maximum and then to decrease again. Continued measurement beyond a zenith angle of 90° can lead to a minimum in the radiation intensity for the two wavelengths, and then an increase again. Careful evaluation of the detailed shape of such graphs of ratios of radiation intensity versus solar zenith angle provides information about the vertical distribution of the ozone in the stratosphere. The technique was developed in 1931 by Götz (1934); it is known as the Umkehr procedure from the German word for reversal because of the existence of a maximum in the graph of intensity versus zenith angle.

Entirely separate data on the vertical distribution of ozone over particular stations have also been obtained through the use of ozonesondes, balloonborne devices that utilize the oxidizing capability of ozone to cause a measurable chemical change. Under the usual operating conditions, the reliability of the ozone measurements by the sondes is checked by its degree of agreement, when integrated, with the total amount of ozone measured nearly simultaneously by a nearby Dobson instrument (Brewer and Milford, 1960; Komhyr, 1965; Kobayashi and Toyama, 1966).

Ozone profile data are covered more fully in Chapter 2.

4.2 SATELLITE MEASUREMENTS OF TOTAL OZONE

The first long series of measurements of total ozone from space were made in 1970 from the Nimbus–4 satellite by the BUV spectrometer. This instrument was capable of daily measurements covering the entire sunlit portion of the globe—i.e., all but the area within the 24-hour polar darkness. The Backscatter Ultraviolet (BUV) instrument worked well for about 2 years; it then encountered problems that permitted far fewer daily ozone readings, which continued into 1977.

The Nimbus–7 satellite was launched on October 23, 1978, with two instruments on board, each capable of monitoring total ozone from all of the sunlit globe. TOMS and the SBUV spectrometer are briefly described here. A detailed description of the TOMS instrument is given in Chapter 2. The SBUV instrument provides measurements of both total ozone and the ozone vertical profile up to 50 km altitude, but only in the nadir (i.e., along the satellite groundtrack). The TOMS instrument measures only total ozone, but it is not limited to the nadir and, by sweeping through a series of slant angles, it provides a much denser pattern of daily measurements of total ozone. Data from the other satellite instruments that measure ozone are not presently suitable for a discussion of possible changes in total ozone concentrations. Some instruments measure only ozone profiles, while others had only a few months of good data at the time of this report.

4.2.1. Total Ozone Mapping Spectrometer (TOMS)

The Total Ozone Mapping Spectrometer on the Nimbus–7 satellite is designed to provide daily global maps of Earth's total ozone by measuring sunlight backscattered from the Earth-atmosphere system in six wavelength bands, each with a 1.0 nm bandpass: 312.5, 317.5, 331.2, 339.8, 360, and 380 nm. The two longest wavelengths are insensitive to atmospheric ozone and are used to measure surface reflectivity, while the remaining wavelengths are used in the inference of total ozone concentrations. TOMS contains a single monochromator with a scanning mirror to measure backscattered radiation at 35 observation angles perpendicular to the orbital plane every 8 seconds—i.e., as many as 378,000 ozone data points per day. The angular swath from each satellite orbital track extends far enough to provide overlap with both the preceding and succeeding orbital tracks, and provides a complete global map of total ozone daily, omitting only the area of complete polar night.

Dave and Mateer (1967) demonstrated the feasibility of determining atmospheric ozone from measurements of backscattered solar UV radiation. The UV radiation received by the TOMS instrument in the total ozone wavelength bands consists of solar radiation that has penetrated the stratosphere and has been either scattered back by the dense tropospheric air or reflected by Earth's surface. Ozone, concentrated mostly in the lower stratosphere, lies above the region in which the radiation is backscattered, and acts as an attenuator of this radiation. By determining the differential attenuation as a function of wavelength, the amount of ozone above the reflecting surface can be accurately determined. More than 90 percent of the ozone is located above the tropopause, while all the clouds, most of the aerosols, and 80–90 percent of the atmosphere are located below it. This almost complete separation of the ozone above the scatterers and reflectors minimizes errors caused by the ozone vertical profile shape or by clouds, aerosols, and other tropospheric variables. However, the instrument has a lessened sensitivity to that fraction of ozone that lies in the troposphere in the midst of the scattering agents. The standard algorithm (see Chapter 3) for calculation of total ozone from the recorded satellite data includes the addition of a small amount of ozone to compensate for this lessened sensitivity to tropospheric ozone. The magnitude of this computed tropospheric correction is fixed from the average of other, non-satellite ozone observations, and has been assumed to be invariant between 1978 and 1988. Further, no allowance is made in the correction term for possible seasonal or latitudinal differences in tropospheric ozone. The satellite instrument is, therefore, relatively insensitive to any trends in ozone concentration with time that might occur in the lowest levels of the atmosphere.

Accurate ozone measurement is facilitated by the availability of simultaneous measurements with several wavelength pairs. Both TOMS and SBUV are programmed to infer total ozone using an A wavelength pair (312.5/331.2 nm), a somewhat less sensitive B wavelength pair (317.5/331.2 nm), and, at very large solar zenith angles, a C wavelength pair (331.2/339.8 nm). The use of wavelength pairs completely removes the effect of any wavelength-independent component of errors such as instrument calibration or aerosol scattering. The conversion of relative radiances at two different wavelengths into total ozone depends upon the differences in ozone absorption coefficients, as described earlier for the Dobson instruments. However, the total ozone data from the two instruments on Nimbus–7 have been calculated with the more recent Bass–Paur (1985) ozone absorption cross-sections. (The initially reported ozone data inferred from Nimbus–7 preceded the Bass–Paur coefficients and were calculated differently, but all of the data have now been calculated with a consistent algorithm based on the Bass–Paur coefficients, and the archived data set now contains only the data from this algorithm.)

Ozone is inferred from the UV backscattered albedo, which is defined as the ratio of the backscattered radiance to the extraterrestrial solar irradiance. The backscattered radiance is measured at each of the six wavelengths for each observation. The solar flux at each of these wavelengths is recorded once each week by measuring the solar radiation arriving from a ground aluminum diffuser plate deployed into direct view of the Sun. The use of the ratio of intensities from Earth and from the diffuser plate eliminates the effects of the solar spectrum, and the weekly remeasurement of solar irradiance tracks any changes in instrument throughput during the life of TOMS. One of the most significant instrumental changes in the 10-year life of

Nimbus–7 has been the degradation of this aluminum diffuser plate from its intermittent exposure to direct solar UV bombardment (see Chapter 2).

The orbit of Nimbus–7 determines the possible ozone coverage by TOMS. The satellite is in a Sun-synchronous retrograde polar orbit that crosses the Equator at approximately local noon on each orbit. The orbital inclination necessary to provide Sun-synchronous precession is such that the satellite reaches a maximum latitude of 80 degrees in each hemisphere. However, the cross-track scanning of the TOMS instrument permits ozone measurements all the way to the pole as long as it is sunlit. True pole-to-pole ozone measurements are not obtained except near equinox because scattered sunlight is necessary for the measurement of ozone, and data cannot be obtained in winter at high latitudes. Total ozone is measured to a maximum solar zenith angle of 88 degrees.

Total ozone data from TOMS are available continuously since November 1978. The processing of the recorded UV radiances into measurements of total ozone is currently on a near-real-time basis, with daily global maps available approximately 3 weeks after measurement. The data are archived at the National Space Science Data Center (NSSDC) at the Goddard Space Flight Center (GSFC).

4.2.2 Solar Backscatter Ultraviolet Spectrometer (SBUV)

The Solar Backscatter Ultraviolet Spectrometer, also on the Nimbus–7 satellite, is similar to TOMS but is designed to measure ozone profiles as well as total ozone. The instrument is an improved version of the BUV, flown on Nimbus–4 in 1970. It contains a double monochromator with a highly linear detector system that allows it to measure UV radiation over a dynamic range of seven orders of magnitude. SBUV and TOMS share the same ground aluminum diffuser plate for the weekly measurement of the solar irradiance, although the instruments do not look at precisely the same areas of the diffuser plate. Both SBUV and TOMS incorporate two important improvements over the BUV. First, a mechanical chopper allows accurate subtraction of any dark current signal so that measurements can be made even in the presence of energetic particles. Second, the diffuser plate is protected except during solar flux measurement in order to reduce the rate of degradation. Finally, SBUV has an additional improvement over BUV through a continuous scan mode that measures the complete UV spectrum from 160 nm to 400 nm in 0.2 nm steps.

The important difference in the total ozone measurements provided by TOMS and SBUV is that SBUV measures ozone only along the orbital track, while TOMS scans between tracks. The TOMS field of view (FOV) is 40 km $\times$ 40 km at nadir, while the SBUV FOV is 200 km $\times$ 200 km.

SBUV measures the solar backscattered radiance every 32 seconds (i.e., as many as 2,700 data points per day) at 12 wavelengths, with a bandpass of 1.1 nm: 255.5, 273.5, 283.0, 287.6, 292.2, 297.5, 301.9, 305.8, 312.5, 317.5, 331.2, and 339.8 nm. The wavelengths from 255.5 nm to 305.8 nm are used to infer an ozone profile, while the four longer wavelengths, which are identical to those in TOMS, are used to infer total ozone. Instead of separate, and still longer, wavelength channels to determine scene reflectivity, SBUV uses a photometer set at 343 nm to measure reflectivity coincident with each monochromator scene in order to compensate for satellite motion. Except for differences caused by these slight instrument variations, the algorithms used to infer total ozone for TOMS and SBUV are identical.

Total ozone and ozone profile data are available from SBUV for November 1978 through March 1988. In February 1987, the SBUV began to experience a high rate of loss of chopper synchronization—i.e., a lack of coincidence between the insertion of the dark current chopper and the recording of the signals into the correct time bins. The effect of this loss was to introduce an apparently random 2 percent noise into the radiance measurement, degrading the accuracy of the inferred ozone profiles in particular. The SBUV data are also archived at the NSSDC.

4.3 USE OF EXTERNAL DATA TO DIAGNOSE PROBLEMS AT GROUNDSTATIONS

Examination of the published ozone data from a particular ground-based station sometimes brings to light apparent incongruities within the full time series. For instance, the total ozone values recorded in ODW for Mauna Loa have been deseasonalized and plotted in Figure 4.2; a step in the mean ozone level appears sometime during 1976 or 1977. For this report, the total ozone records of about 30 stations have been examined for internal consistency and for external consistency with data from other sources. For the period from November 1978 to December 1986, every ground-based total ozone measurement can be compared with the total ozone measured by TOMS when the satellite was overhead on that same day. The search for data incongruities is more difficult prior to November 1978, but comparisons with total ozone data from proximate stations and with the recorded local stratospheric temperatures at the 100 millibar level have revealed numerous instances when Dobson recalibrations have occurred but have not been reported to the ODW. The approximate dates of such discrepancies were noted, and the stations were asked whether a recalibration had taken place at that time and, if so, the magnitude of the calibration change. The total ozone data were revised only when information regarding the operation of the instruments was available. These diagnostic tests of the quality of the total ozone data brought to light many more recalibrations than would have been detectable by examining each ozone record in isolation.

4.3.1 Comparisons of Ground-Based and Satellite Measurements

The existence of two entirely separate systems that simultaneously measure total ozone provides an excellent opportunity for the detection of flaws in either system through the comparison of overlapping observations. Because the satellites orbit Earth in less than 2 hours, an overpass not too far from each groundstation occurs daily. Such satellite overpasses of groundstations took place during 1970–1972 with the BUV ozone detector on Nimbus–4, and since November 1978 with the TOMS and SBUV instruments on Nimbus–7. The nearest daily overpass is geographically much closer with the TOMS system because, unlike SBUV, which measures total ozone only directly in the nadir, TOMS also provides ozone data for many points situated at oblique angles to the precise satellite path. The density of TOMS ozone measurements over Hawaii is illustrated in Section 4.4.2. An example of a series of TOMS–Dobson comparisons for the Arosa groundstation is shown in Figure 4.4. The center panel contains a plot of the ozone measured by the Dobson instrument at Arosa; the bottom panel shows the TOMS measurement of total ozone closest to Arosa each day, usually within 1 degree latitude and longitude; and the top panel plots the percentage difference between the two ozone measurements. Examination of the ozone values themselves (lower two panels) shows that both instruments track the large annual variation in ozone at 47°N latitude very well. The percentage-difference plot (upper panel) reveals differences that would not be clear in the individual ozone plots. The small annual modulation in the difference plot is usually interpreted as caused by a minor scattered light problem in the Dobson instrument that becomes apparent only when the

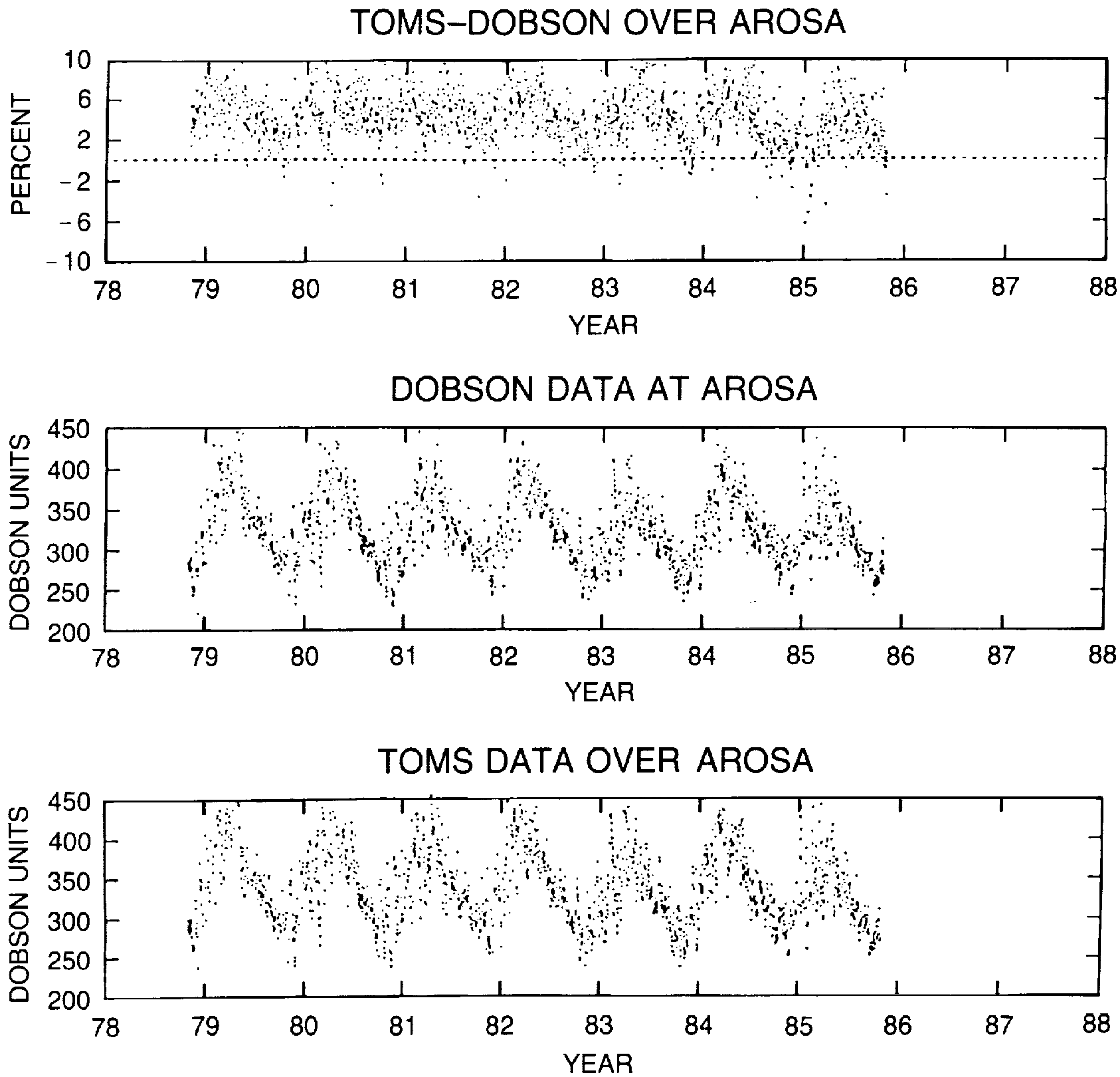


Figure 4.4 The top panel shows the percentage difference between measurements of the Dobson Spectrophotometer and the TOMS instrument at Arosa, Switzerland. The middle and bottom panels show the actual measurements of the Dobson and the TOMS instruments, respectively.

ozone is recorded with the large solar zenith angle observations necessary in midwinter at high-latitude stations. The major value of such comparison plots here is that abrupt changes in the record of an individual groundstation can be clearly detected.

Plots of the deviations at each groundstation from the first year of TOMS operation (Fleig et al., 1982) were published by the WMO–WODC, and other comparisons of the same data versus selected surface stations were made by Bhartia et al. (1984) and Fleig et al. (1986a). The TOMS data from 1979 to 1982 were further used in assessing the relative quality and performance of the Global Ozone Observing System total ozone measurements (Bojkov and Mateer, 1984b). Completely reevaluated TOMS data, applying the Bass and Paur (1985) ozone absorption coefficients, were recently provided by the Nimbus–7 processing team (Fleig et al., 1986a; Bhartia et al., 1988). With a sufficiently large number of comparisons, the effects of random errors should approach zero, leaving only the systematic bias. A systematic bias is always present because the ozone results from the groundstations, reported on the basis of the Vigroux ozone absorption coefficients, are always higher by 3–4 percent than the total ozone amounts calculated with the Bass–Paur coefficients.

In principle, either the ground-based or the satellite system could be assumed to be the standard, and the other system the one of uncertain quality to be tested against it. In practice, both systems have potentially serious errors that raise questions about the validity of the data reported from that system. Fortunately, the primary flaw for the ground-based system has a very different structure from the major flaw of the satellite system, so that useful intercomparisons can be made.

The chief uncertainty in ozone determinations with the satellite systems is the slow, relatively steady deterioration in the diffuser plate used as the calibrating agent for converting the various relative wavelength readings into absolute amounts of ozone (Chapter 2). The absolute amount of solar UV received from the diffuser plate has obviously diminished substantially at all wavelengths during the decade of operation of Nimbus–7 because of the diffuser plate degradation. However, the algorithm for converting UV radiances to total ozone is dependent primarily upon the ratio of radiances at two wavelengths rather than upon the absolute values, and was intended to compensate fully for the diffuser plate degradation. Moreover, this deterioration has occurred over a period of almost 10 years and has basically not shown erratic behavior on short time scales such as 1 week or 1 day.

Intercomparisons of satellite readings versus those of two groundstations on the same day can safely be assumed to have been made with an instrument having the same response characteristics for both overpasses. Five years later, the sensitivity of the satellite instrument is undoubtedly different, but effective intercomparisons can again be made for same-day overpasses. The satellite instruments can, therefore, provide accurate assessments of the ground-based measurement capabilities as long as this use as a transfer standard is restricted to short time periods of a few days, over which the degradation of the satellite diffuser plate is negligible.

In contrast, the most prominent flaw of the ground-based systems is the variability in the operating procedures used at each station. Although the individual Dobson instruments were very nearly identical when manufactured, their conditions of maintenance, repair, and general upkeep have diverged widely since installation. The training and supervision of operators can also be very different, so that stations with superficially identical equipment can provide ozone data of very widely different quality.

Given the distinctive characteristics of the possible flaws in the two systems, a "bootstrapping" operation becomes possible, with the result that the combined satellite–ground ozone data set is substantially better than either taken alone. The daily satellite–ground intercomparisons are used to provide tests of the quality of the data reported by individual groundstations, including the detection of suspect operating periods, and in principle allow correction and refinement of the ground data. A selected set of "good" groundstations can then be used to calibrate the slow deterioration of the satellite instrument and permit absolute comparisons of satellite data recorded a few years apart. These ground–satellite interactions are described now in greater detail.

4.3.1.1 Allowing for a Drift Between TOMS and the Groundstations

Comparisons have been made between the daily-mean total ozone concentrations measured at 92 surface-based stations (71 Dobson and 21 M–83 instruments) and the total ozone calculated from direct overpasses by the Nimbus–7 TOMS, from November 1978 to December 1985 (Bojkov et al., 1988). The satellite overpasses always occur at local noon, while the surface-based data are usually averaged from data collected symmetrically around local noon. The time difference between the satellite and ground observations is normally 3 hours or less.

The overpass analysis first established a basic Dobson–TOMS reference curve of monthly values of the network average bias, expressed as the Dobson ozone value minus the TOMS ozone divided by the Dobson ozone—(Dobson–TOMS)/Dobson. These values were calculated from the data provided by the 74 stations that reported most regularly over the period of satellite operation. Stations with short records, serious drifts (greater than 1 percent per year), or sudden steplike increases or decreases were excluded. The data for individual months from groundstations were included only if (a) at least 13 daily station vs. TOMS comparisons were available during the month, (b) the standard deviation of the daily differences contributing to the monthly mean difference was less than 5 percent, and (c) the absolute difference between the station monthly mean difference and the overall network mean difference was less than twice the standard deviation of the network mean. Application of these criteria each month reduced the number of participating stations in the monthly evaluations to a variable number between 50 and 65. These criteria for disregarding some overpasses were intended to eliminate the least satisfactory parts of the ground-based total ozone data set, including rejection of some parts of the data from stations that operated satisfactorily in other months.

The basic reference comparison curve, based on all types of ground measurements (direct Sun, zenith sky, etc.) is graphed in Figure 4.5, and the results are summarized as 6-month

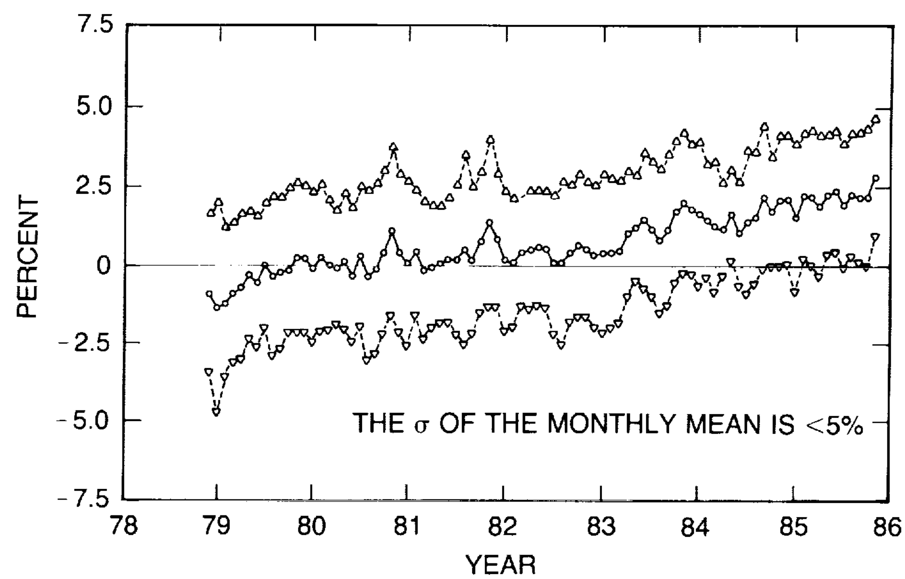


Figure 4.5 Monthly mean biases (Dobson–TOMS)/Dobson and their respective intrastation standard deviations ($\pm 1\sigma$). The solid curve is the basic reference curve based on all types of ground measurements. Positive values mean satellite underestimation of the total ozone amount relative to that measured at well-run groundstations (see text for inclusion of particular stations). The vertical markers indicate the position of the end (December) of the previous year.

averages in Table 4.8. Also included in Table 4.8 are the results found when only the direct-Sun ground-based measurements were used in the comparisons. It is clear that the set of comparisons made with only direct-Sun readings is quite similar to the results using all total ozone data. The upper and lower curves of Figure 4.5 indicate the one standard deviation limits for the mean reference curve. In most cases, these fall between 2 percent and 2.4 percent. The total drift is about 3.5 percent, varying from -1 percent in 1978 to +2.5 percent in 1985, indicating that the ozone reported by the satellite lessens with time relative to the ground-based observations. A linear regression to the data indicates that the satellite ozone needs to be increased by 0.42 ±0.02 percent per year to compensate for the TOMS drift, essentially the same as that reported by Fleig et al. (1986a), based on comparison with 41 selected Dobson stations. However, the basic reference comparison curve does not appear to be smoothly linear in its change, but instead is characterized by initially increasing values, followed by a relatively flat plateau close to the zero line from mid-1979 through mid-1981. A further slow rise until early 1984 is followed by a final period of more rapid rise through the end of the record used in the analysis. After correction for the average bias for each individual month, the standard deviation of the mean of all monthly mean differences for the 7-year period is 0.38 percent when all observations were considered and 0.43 percent when only direct-Sun readings were taken into account. The standard error of 0.02 percent from the linear regression is probably an underestimate of the yearly error in the drift coefficient.

Table 4.8 Six-Month Average Bias (Dobson–TOMS)/Dobson Centered at February 1 and August 1 of Each Year as Deduced From All and From Only Direct-Sun Observations.

	All	Six-Month Difference	Direct-Sun	Six-Month Difference
1979				
Feb.	–0.90	0.72	–1.11	0.79
Aug.	–0.18	0.23	–0.32	0.18
1980				
Feb.	0.05	0.10	–0.14	0.45
Aug.	0.15	–0.06	0.31	–0.27
1981				
Feb.	0.09	0.41	0.04	0.38
Aug.	0.50	–0.11	0.42	–0.27
1982				
Feb.	0.39	–0.05	0.15	0.23
Aug.	0.34	0.26	0.38	– .01
1983				
Feb.	0.60	0.76	0.37	0.72
Aug.	1.36	0.11	1.09	0.15
1984				
Feb.	1.47	0.17	1.24	0.27
Aug.	1.64	0.38	1.51	0.20
1985				
Feb.	2.02	0.27	1.71	0.83
Aug.	2.29		2.54	

Bias is in percent. The 6-month differences between the average biases indicate a nonuniform drift.

Possible factors that might contribute to this drift between TOMS and Dobson ozone measurements were discussed by Fleig et al. (1986b). They include residual uncorrected drift in the SBUV/TOMS diffuser plate, an overall drift in the Dobson network, and differences in the response of the two systems to actual changes in the amounts of tropospheric ozone or ozone-simulating pollutants such as SO_2. Fleig et al. concluded that drift in the Dobson network was unlikely because their TOMS–Dobson drift appeared to be independent of any objective method of weighting the individual stations for data quality. Increases over time in the concentration of tropospheric ozone or SO_2 may contribute to the drift because the satellite systems respond only partially to changes near ground level either in ozone or in interfering absorbers, while the Dobson system responds fully (Komhyr and Evans, 1980). The influence of SO_2 on ground-based total ozone measurements has been shown to be very small except in heavily polluted urban areas (Basher, 1982).

Recent studies of ozonesonde observations (Angell and Korshover, 1983b; Bojkov and Reinsel, 1985; Logan, 1985; Tiao et al., 1986; and Bojkov, 1988a) do indeed indicate an increase in tropospheric ozone at slightly less than 1 percent per year, while surface ozone measurements suggest 1 percent to 1.5 percent yearly increases over the past two decades (Logan, 1985; Bojkov, 1987a). However, because tropospheric ozone contributes only about 10 percent of the total ozone column, an increase of 1 percent per year in tropospheric ozone would correspond to an increase of only 1 percent per decade in total ozone, substantially less than the 3.5 percent change found in less than 8 years. Because the satellite systems are not completely insensitive to tropospheric ozone, the changes in tropospheric ozone appear to be only a minor part of the observed drift between the Dobson and satellite systems, with the major contributor the residual uncorrected drift in the satellite diffuser plate.

Once determined, the average biases between TOMS and the groundstations were calculated as monthly averages and removed from the differences for each station. In the subsequent illustrations in Section 4.3, this overall bias has been removed from the individual station record. In this manner, the TOMS instrument is used as a transfer standard between individual groundstations, assists in evaluation of the quality of the data for each, and in particular allows comparison of data at that station relative to the other groundstations on a month-by-month basis. Furthermore, the 7-year period of continuous data permits identification of time-dependent changes in the record from any individual station. Figure 4.6 (note the expanded vertical scale relative to other similar figures) plots the monthly mean (Dobson–TOMS)/Dobson differences after the removal of the monthly biases identified in Table 4.8. (The total data set again includes some ozone measurements that were excluded from the average bias determination, as outlined earlier.) The course of the monthly mean differences lies within the ± 0.6 percent band.

A few details can be identified:

- In 7 years, only 3 individual months (each an October) showed means significantly exceeding the 0.6 percent difference range; the largest positive monthly differences (greater than 0.4 percent) occur from September–December.
- June and July show the largest negative differences (-0.15 percent and 0.29 percent), which is a possible reflection of the strong μ dependence (relative solar slant path) exhibited by the instruments at many stations.

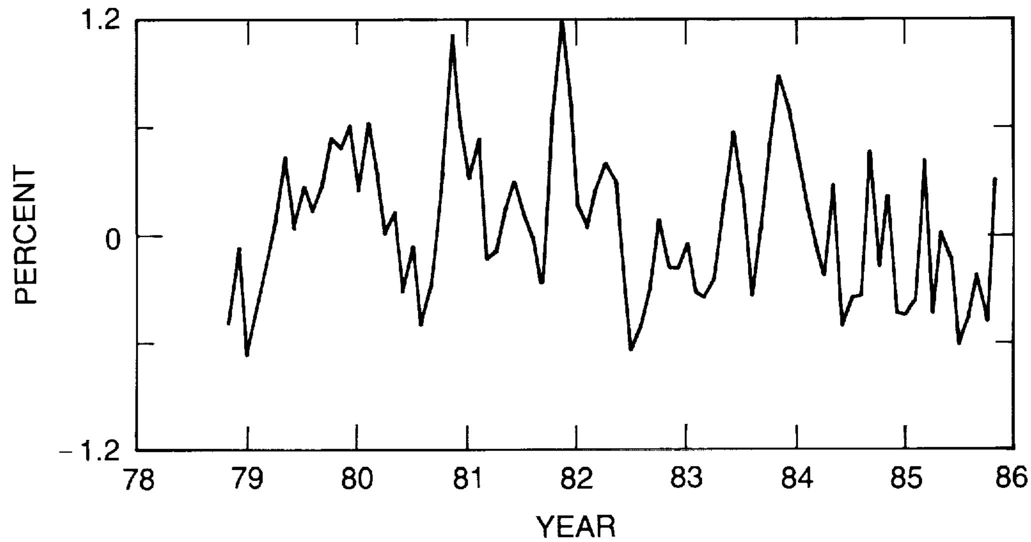


Figure 4.6 Monthly mean (Dobson–TOMS)/Dobson differences after the monthly biases have been removed. Stations where the σ of the monthly mean is less than 5 percent have not been included. The σ of the monthly averaged values is in most cases between 2 and 2.4 percent, and thus out of scale (note the expanded vertical scale relative to other similar figures).

- The standard deviations of the mean of the individual months show a small but well-pronounced annual dependence. The months with less than 0.30 percent are February–August; the smallest, 0.12 percent, occurs in February. September–January have δ greater than 0.38 percent, with the greatest value, 0.55 percent, occurring in October.

More than two-thirds of the 71 Dobson stations have less than 2 percent difference versus the network average estimated via TOMS for the entire 7-year period, as shown in the diagram in Figure 4.7. Only 20 percent of the stations have a difference greater than 3 percent. These statistics imply relatively good performance of two-thirds of the Dobson stations, while confirming stability in the short-term performance of the TOMS superimposed on the long-term drift. On the lower panel (Figure 4.7) the same plot for the 21 M–83 stations shows that only half fall within the good-performance category (less than 2 percent), and nearly 30 percent of them have differences larger than 3 percent.

Only 12 percent of the stations (seven Dobson and four M–83 filter) show absolute differences versus TOMS greater than 4 percent. These stations (with the percentage difference for TOMS versus their direct-Sun observations in parentheses) are (a) Dobson stations: Casablanca (-9.7), Cairns (-7.2), Hobart (-5.8), Brisbane (-5.7), Syowa (-5.7), Mauna Loa (-5.5), and Arosa (-4.8); and (b) M–83 stations: Heiss Island (9.6), Kuybishev (4.9), Dushanbe (4.6), and Alma Ata (4.0). In the case of Mauna Loa, for instance, an adjustment of about 2.9 percent is needed to allow for the tropospheric ozone sensed by TOMS, averaging its response over a wide oceanic area, but not by the mountaintop Dobson instrument (at 3400 meters). Similar terrain-height-induced adjustments of about 0.8 percent for Arosa and -0.6 percent for Alma Ata and Syowa (low-lying stations in mountainous regions) are also considered appropriate (Fleig et al., 1982). Such comparisons also make no allowance in judging the performance of an individual station between stations with differing natural variability. Tropical stations, for instance, show little day-to-day or seasonal variability.

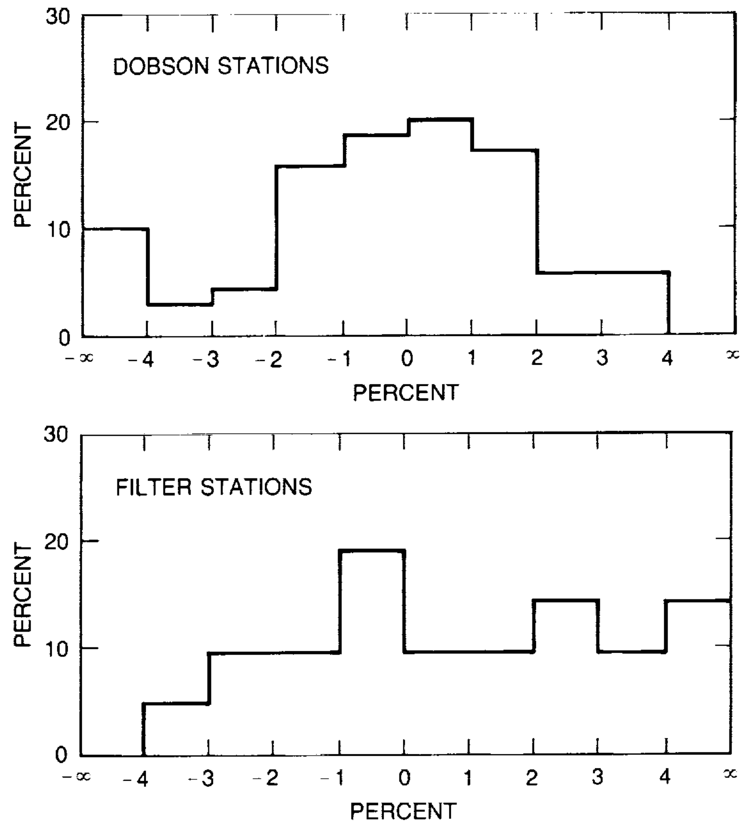


Figure 4.7 Fractional distribution of (top) 71 Dobson stations and (bottom) 21 M–83 filter stations according to the (station–TOMS)/station monthly mean differences in 1 percent intervals. More than two-thirds of the Dobsons, but only half of the M–83 stations, have less than 2 percent mean difference with the network average transferred via TOMS; 22 percent of all stations have differences ⩾ 3 percent.

The analysis of the differences should consider information for the corresponding station variability. If the scattering of the daily differences is widely spread around the zero line, the annually averaged values could be misleadingly small. Another view of the (Dobson–TOMS)/Dobson differences, as a function of their relative variability (standard deviations expressed in percent of the total ozone at the given station), is presented in Figure 4.8. The upper panel shows the fractional distribution of 92 stations according to the relative variability of their monthly mean differences, in 1 percent intervals. The continuous line is for direct Sun and the dotted line for all observations, with no great differences between the averages of the two groups of observations. An important indicator of the stability of the monthly mean differences is that 60 percent of the stations reporting direct-Sun observations show less than 2 percent variability. Greater than 4 percent variability is shown at only 7.6 percent of the direct-Sun observing stations (10.9 percent of all). Here it should be noted that, although the number of stations with variability greater than 3 percent using Dobson or filter instruments is nearly the same, the fraction from all Dobson stations is only 12 percent for direct-Sun (16 percent for all) observations, while the filter stations' fraction is 63 percent (68 percent for all). This is a clear indication of the lesser variability of the Dobson vs. the filter stations (ratio better than 1:4). Table 4.9 lists all stations for which the variability of their monthly mean differences exceeded 3 percent. When the variability for the data reported by a particular station is too high, the implication is that the cause lies with some aspect of the ground-based system and marks the station as one that might be omitted from more detailed comparisons.

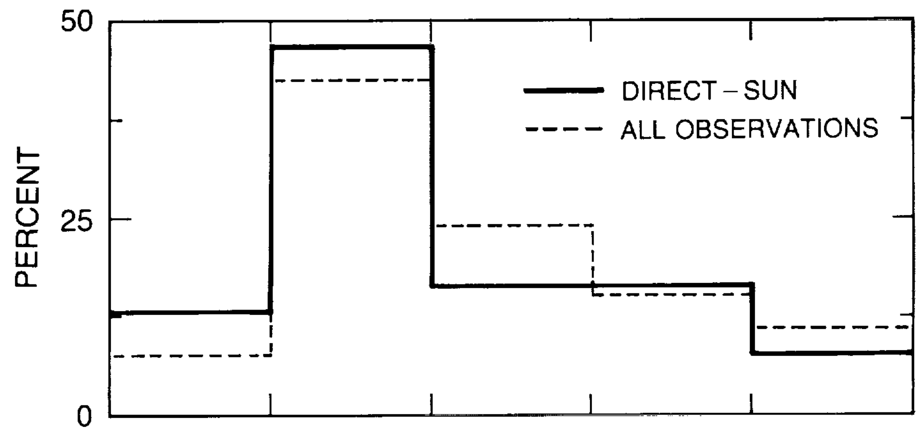


Figure 4.8 Fractional distribution of 92 stations according to the relative variability (σ in percent of the total ozone at a given station) of their monthly mean differences with TOMS. The solid curve indicates direct Sun and the dotted curve indicates all observations.

Table 4.9 Stations With Variability of Their Monthly Mean Differences With TOMS ≥3 Percent.

Station	Dobsons
Brindisi*	16.1
South Pole	8.0
Casablanca	6.6
Aarhus	5.1
Macquarie Island	4.7
Bangkok	3.7
Brisbane	3.6
Hobart	3.5
Churchill	3.5
Bracknell	3.3
Lerwick	3.2
Singapore	3.1
Resolute	3.0
Station	**Dobsons**
Dikson Island*	6.9
Heiss Island*	5.9
Nagaevo	5.2
Vladivostok	5.2
Riga	4.2
Murmansk	3.5
Odessa	3.4
Yakutsk	3.4
Kiev	3.3
Irkutsk	3.2
Maputo	3.1
Alma Ata	3.0
Sakhalin	3.0

*Limited data

4.3.1.2 Comparison of Individual Station Data With TOMS Overpass Data

A major advantage of the satellite–ground intercomparison is its identification of abrupt changes in the calibration of an individual groundstation, with the continued stable satellite–ground relationship for the rest of the network as evidence that the change should be attributed to some event at the groundstation. The intercomparison between the ODW data for Huancayo and the satellite shows an abrupt downward shift in late 1982 (Figure 4.9) that is directly traceable to recalibration of the Huancayo Dobson in October 1982. The satellite intercomparison serves as a warning to outside users that the data published in ODW are not suitable for trend analysis without reevaluation to adjust for the recalibration. Other examples of apparent calibration shifts are the changes in the satellite–ground responses for Bracknell (Figure 4.10), Singapore (Figure 4.11), and Brisbane (Figure 4.12).

By contrast, an example of great consistency in the overpasses between the ground-based readings and the corrected TOMS data set is shown in Figure 4.13 for the Shiangher station near Beijing. The data illustrate that a well-run Dobson station and an overhead satellite can provide a combined data set that creates confidence in the operation of both measurement systems. The smoothness and consistency of the observations at this station (σ of the 84 monthly differences is only 0.7 percent) will become more apparent after discussion of a few more of the less successful stations.

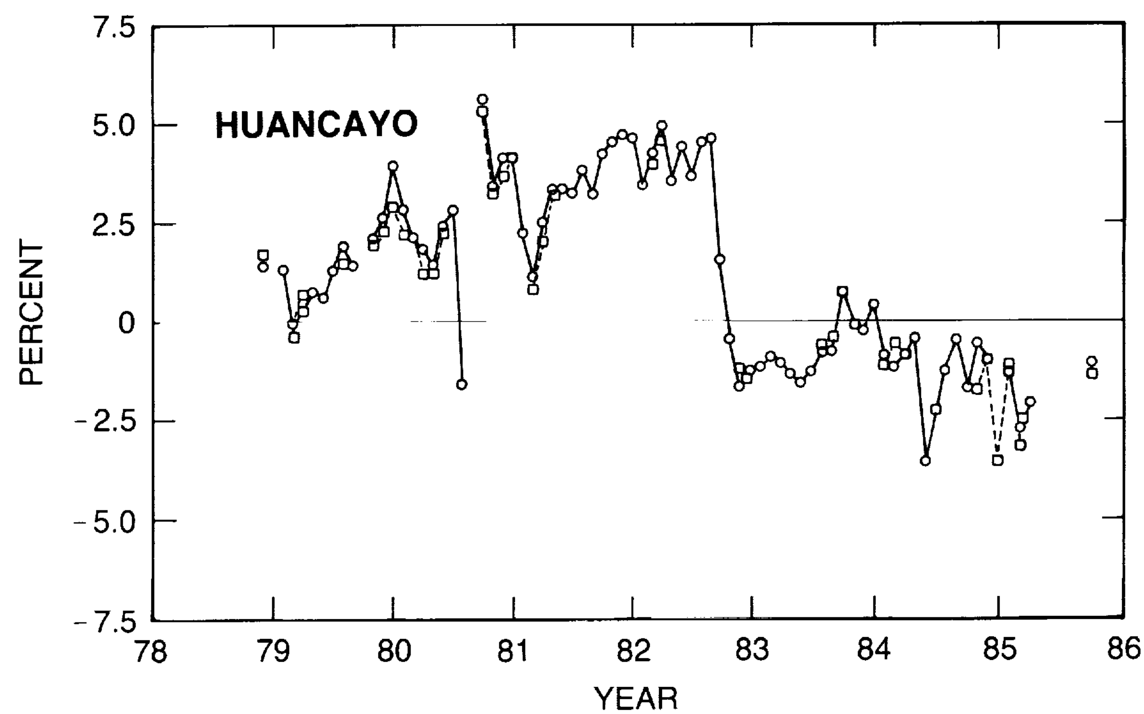


Figure 4.9 Monthly differences between ozone measured at Huancayo and by TOMS (BR is bias removed), showing a slow upward drift during the first 4 years and a sharp decline in October 1982 (result of calibration). The σ of the differences forming each monthly point is about 2.6 percent. The circles and the solid curves indicate direct-Sun observation, and the pluses and the dashed curves indicate all observations. A point is plotted only if there are at least 13 overpasses for the particular month. The record starts with November 1978.

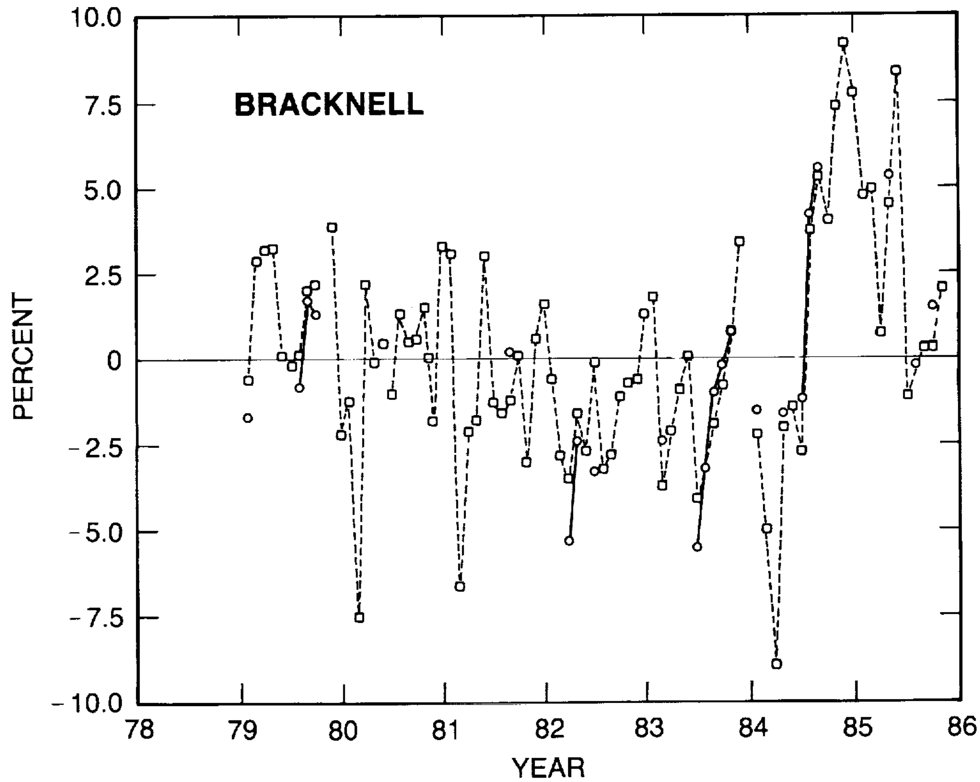


Figure 4.10 Monthly (Dobson–TOMS)/Dobson differences for Bracknell indicating a downward rift between 1981 and 1984, followed by a sudden upward shift. The σ of the differences forming each monthly point is about 5.6 percent and is among the largest in the network. The circles and the solid curves indicate direct-Sun observations, and the pluses and the dashed curves indicate all observations.

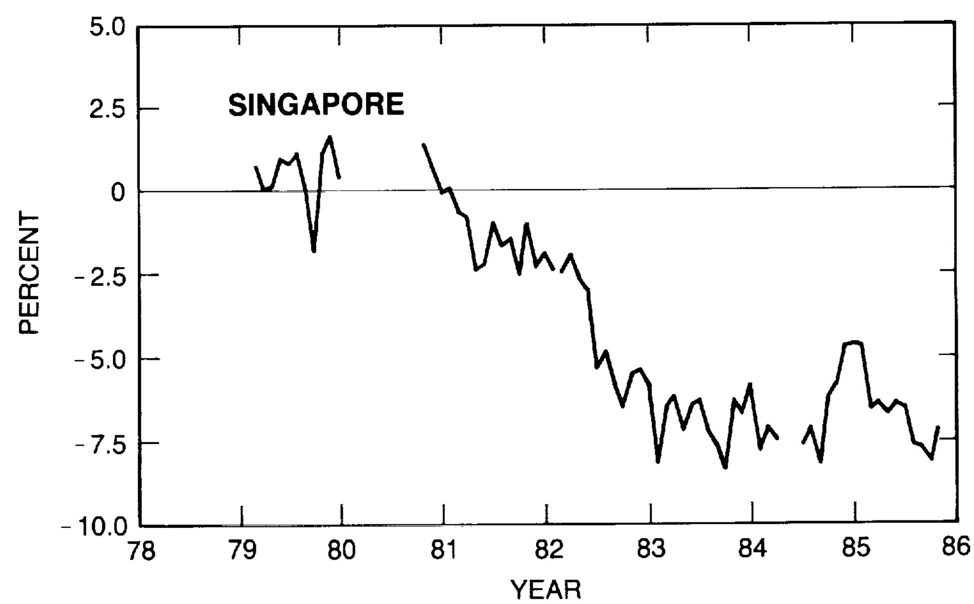


Figure 4.11 Monthly (Dobson–TOMS)/Dobson differences for Singapore showing a strong downward drift between 1980–1983, when, as a result of calibration, the instrument is stabilized but at a level about 7 percent too low. The σ of the differences forming each monthly point is about 2.4 percent. The circles and the solid curves indicate direct-Sun observations.

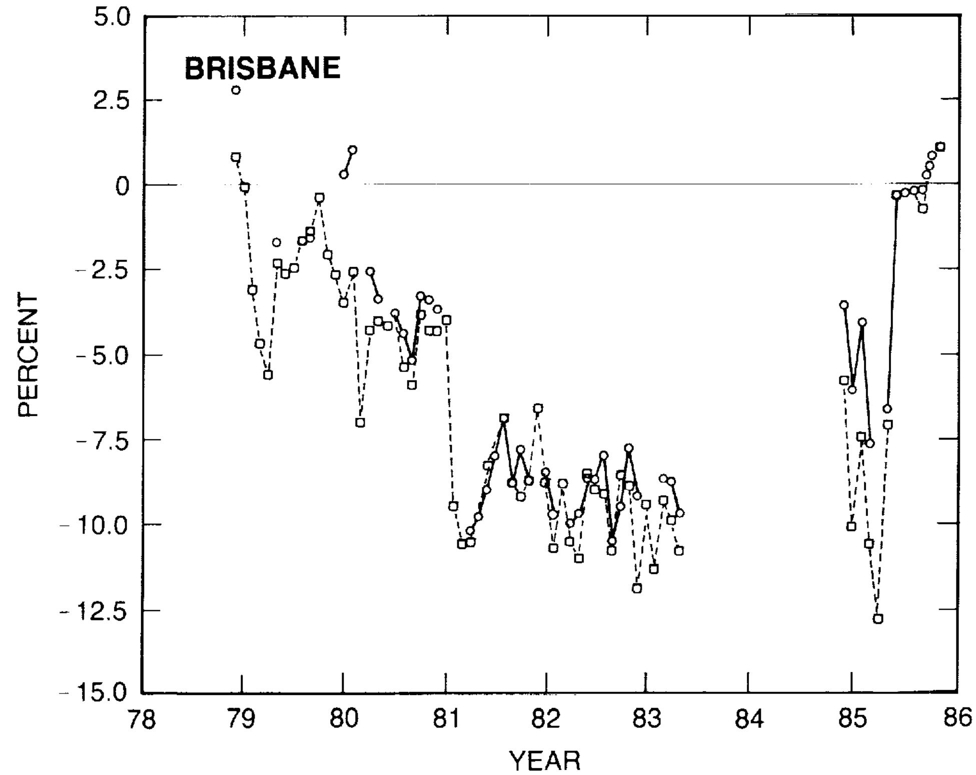


Figure 4.12 Monthly (Dobson–TOMS)/Dobson differences for Brisbane showing a downward drift until the end of 1980, followed by a sudden drop of about 5 percent. Only after calibration in early 1985 is the instrument restored to a state of agreement with the rest of the ozone network. The σ of the differences forming each monthly point is about 4.5 percent. The circles and the solid curves indicate direct-Sun observations, and the pluses and the dashed lines indicate all observations.

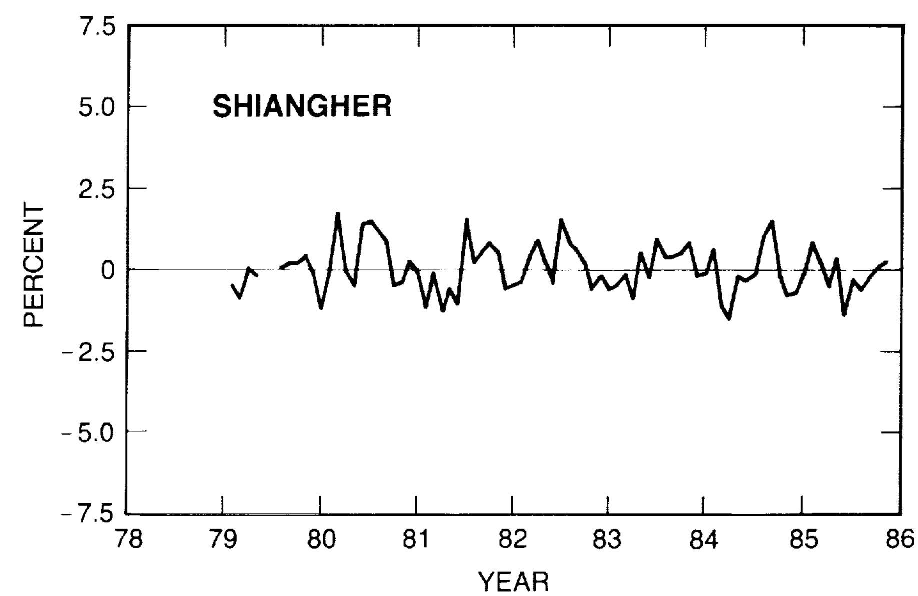


Figure 4.13 Monthly (Dobson–TOMS)/Dobson differences for Shiangher (near Beijing). The σ of the differences forming each monthly point is about 2.1 percent. The circles and the solid curves indicate direct-Sun observations.

One very common problem that appears in many stations is the strong μ-dependence of the instruments—i.e., an apparent ozone reading that is affected by the slant angle of the Sun at the time of measurement. This results in reported ozone values that are too low at high Sun during the summer months (June and July) and too high at low Sun (November–January) in the Northern Hemisphere. A good example of this problem is shown in the data from Potsdam (Figure 4.14), for which the December–January periods tend to show strong positive deviations. This data set also shows a shift in the overall comparison from mostly negative during 1979–1982 to mostly positive after 1983. Such a shift usually signifies a calibration problem, as could occur with a step-function recalibration in September 1982. The μ-dependence continues after the step function shift.

Another station whose data show a pronounced μ-dependence is Hobart, Tasmania (Figure 4.15). The deviations at Hobart are often strongly negative, corresponding to ozone readings lower by 30 or 40 DU than indicated from the satellite instrument. Identification of a strong μ-dependence from comparison with TOMS calls for a review of the extraterrestrial constant values used at the particular station. Appropriate corrections can be made to the station record given the existence and availability of an exact history of calibrations verifying the events, as is the case for Hohenpeissenberg. The top panel of Figure 4.16 shows the monthly differences for the originally published monthly ozone values: a seasonal variation is apparent. This μ-dependence is primarily an extraterrestrial-constant-related error, indicating incorrect calculation of the ΔN correction to the N-tables (see Dobson, 1957a, 1957b), and it was most probably introduced to the instrument through improper adjustments made during intercomparisons at Arosa in August 1977. This was not corrected until early 1985. When the μ-dependent variations were removed from the published record and calibration corrections for the period March 1985–August 1986 were introduced, the differences with TOMS overpasses

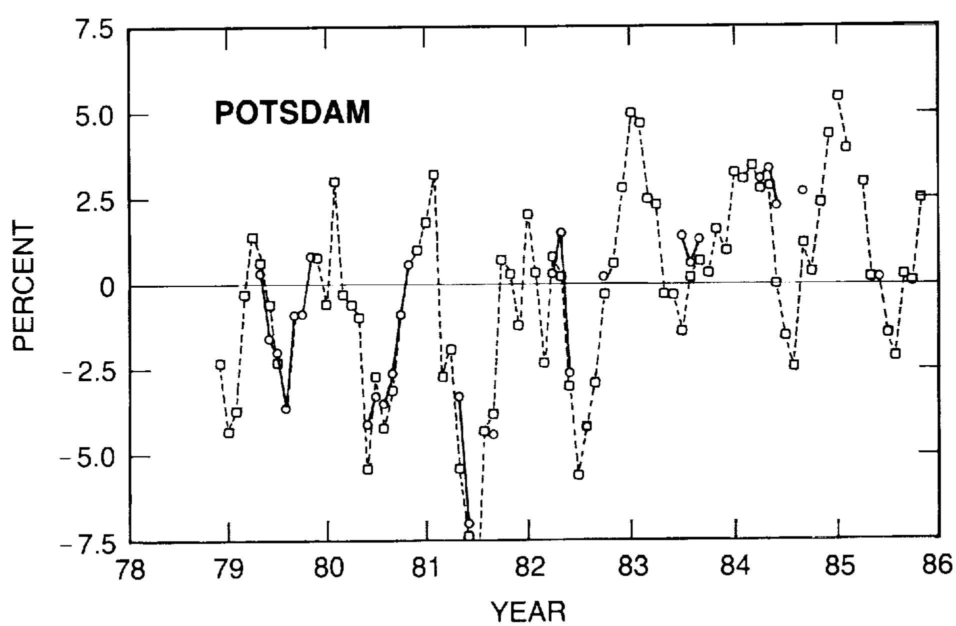


Figure 4.14 Monthly (Dobson–TOMS)/Dobson differences for Potsdam indicating a μ dependence as well as a shifting (in 1982–1983) of the level of ozone measured by the groundstation. The σ of the differences forming each monthly point is about 4.2 percent. The circles and the solid curves indicate direct-Sun observations, and the pluses and the dashed lines indicate all observations.

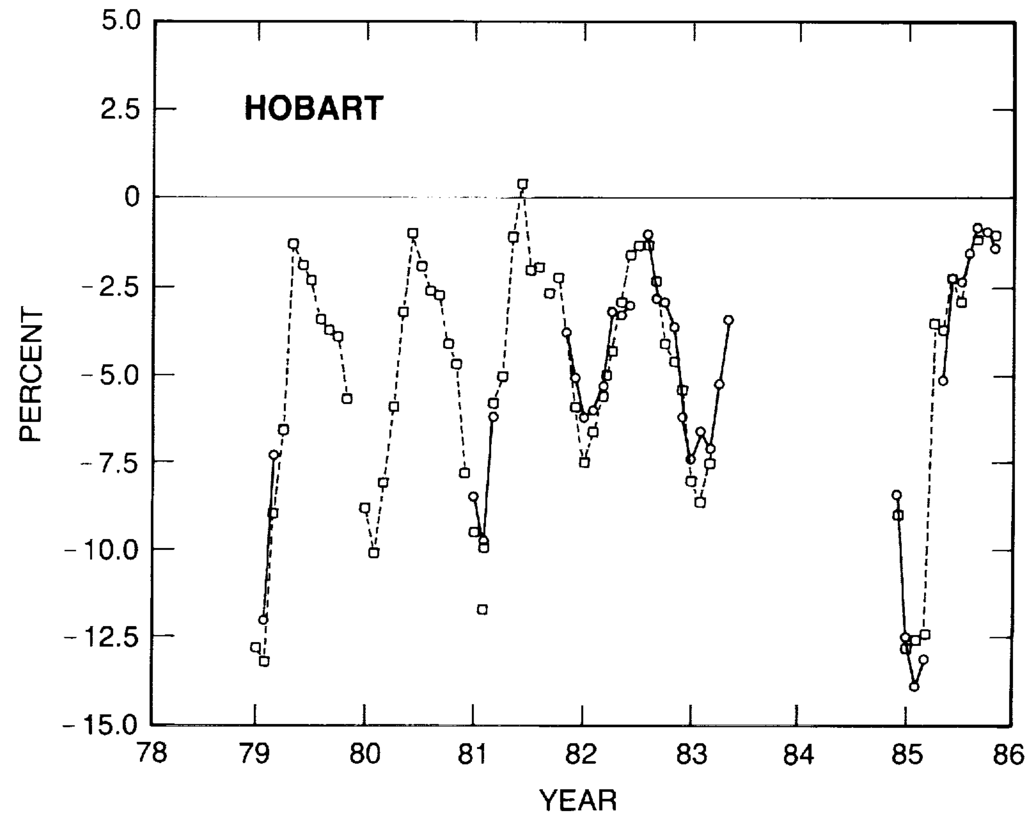


Figure 4.15 Monthly (Dobson–TOMS)/Dobson differences for Hobart showing an extremely large μ dependence and an erroneously low ozone level for the entire period of comparison. The σ of the differences forming each monthly point is about 4.7 percent. The circles and the solid curves indicate direct-Sun observations, and the pluses and the dashed lines indicate all observations.

(shown in the bottom panel of Figure 4.16) indicate a very stable record. There is a mean bias of about 2.5 percent, and this difference would probably be reduced to about 1.5 percent if a more accurate altitude correction were applied to the TOMS data to suit the elevated location of Hohenpeissenberg.

Discrepancies in a station record caused, for example, by difficulties with the transfer of zenith-sky observations (taken at very low Sun) to direct-Sun values, appear on Figure 4.17, which records the data from Churchill, Canada. For most of the year, this station shows a good ozone record having constant level differences (~2.3 percent with TOMS). However, December and January values are low by about 7 percent and 5 percent, respectively. The probable problem here is that direct-Sun observations are rarely possible in these months because of virtually constant cloudy conditions, while the zenith sky transfer charts used at Churchill were not calculated from observations made at that station.

Many more illustrative examples can be given by looking at the scatter diagrams of the daily differences with TOMS overpasses. Some of the greatest scattering is shown by Aarhus (Figure 4.18), Casablanca, and Bracknell. The σ of the differences forming each monthly point, based on the average from the annual samples for each of these stations, are 9.1 percent, 10.8 percent, and 5.6 percent, respectively. The readings from Aarhus are noteworthy not only for the very large

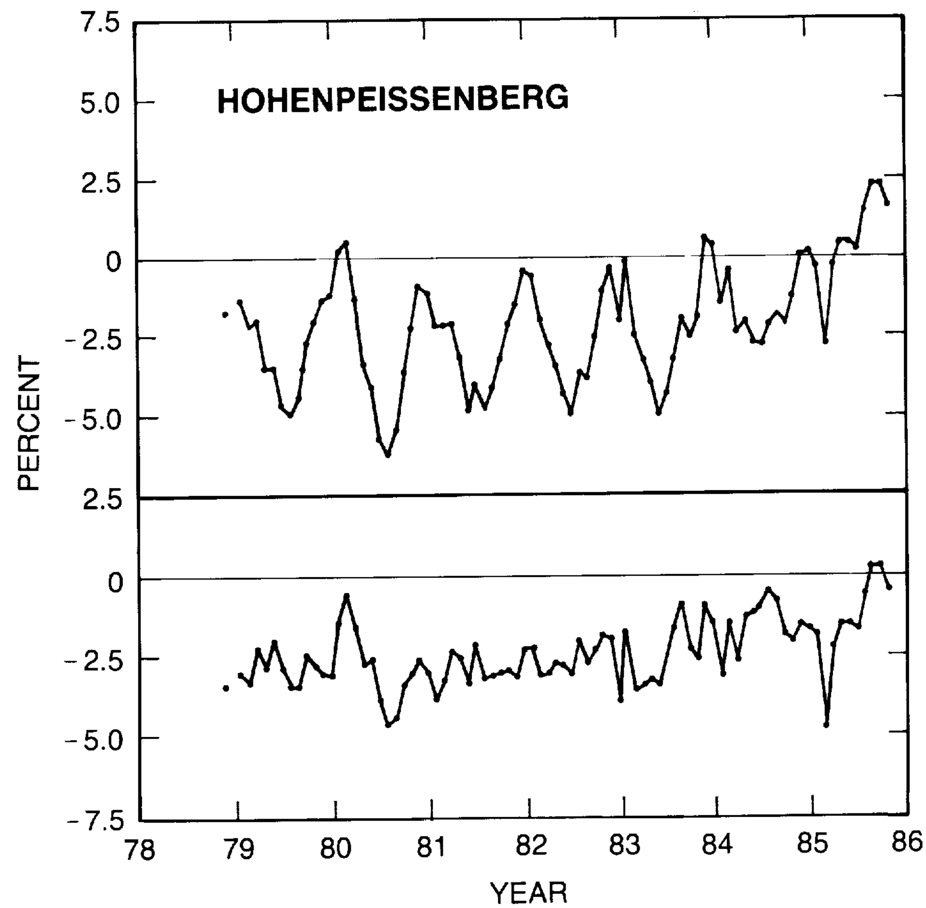


Figure 4.16 Monthly (Dobson–TOMS)/Dobson differences for Hohenpeissenberg. The top panel indicates a well-pronounced μ dependence until 1985. The bottom panel shows the same monthly differences after removal of the μ-dependent variations and application of the instrument calibration procedures, indicating a very stable course, except too low by about 2.5 percent. This difference would be reduced by about 1 percent if an altitude correction is applied to the TOMS data. The σ of the differences forming each monthly point is about 2.8 percent, and is among the smallest in the network. The circles and the solid curves indicate direct-Sun observations.

scatter versus the satellite data but also because not a single reading in the entire set represents a direct-Sun observation. Comparison of the ozone readings from Aarhus with those from nearby stations that might be expected to be in a similar meteorological regime also shows a very wide scatter. The data from Aarhus recorded in ODW have not been used either in the subsequent analysis of individual stations or in the compilation of latitudinal band averages.

At other stations, one can easily distinguish problems with zenith-sky observations. For example, the direct-Sun ozone observations from Toronto (Figure 4.19) agree well with the satellite observations, while its zenith-sky values are almost all high, with an average deviation from the direct-Sun values of +10 percent. The σ of the differences forming each monthly point is only ~2.2 percent for direct Sun but increases to a high of 4.6 percent when all observations are considered, as is usually done with the other stations. The likely explanation for such inconsistency between zenith-sky and direct-Sun observations is that the empirical zenith sky chart for Toronto is faulty.

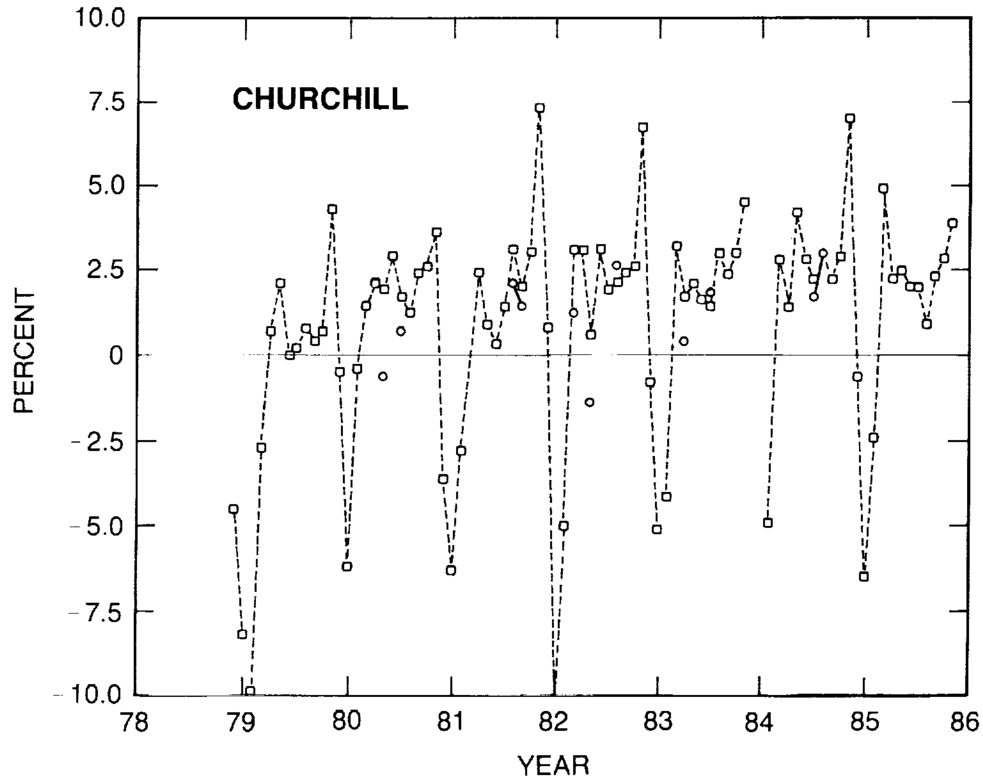


Figure 4.17 Monthly (Dobson–TOMS)/Dobson differences for Churchill indicating a constant difference of about 2.3 percent during most months, except for the winter (December and January are too low by about 7 and 5 percent, respectively). The σ of the differences forming each monthly point is about 5.1 percent. The circles and the solid curves indicate direct-Sun observations, and the pluses and the dashed lines indicate all observations.

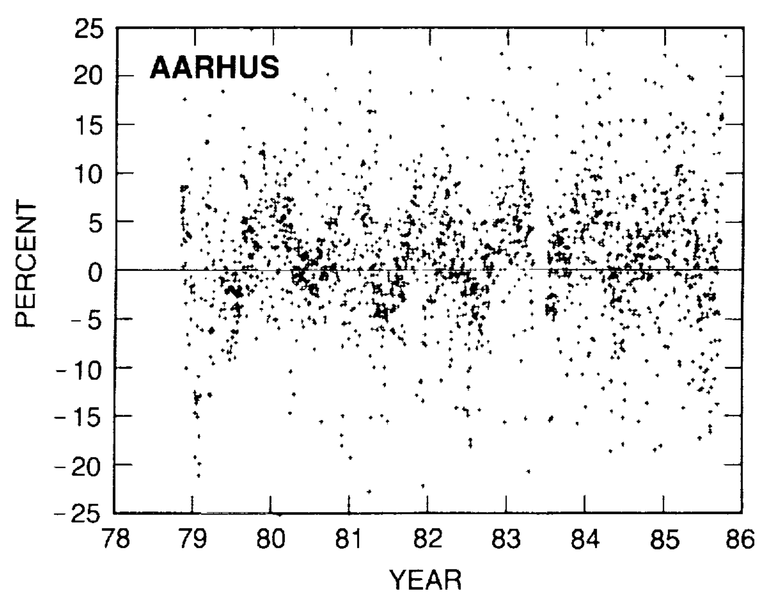


Figure 4.18 Daily differences for Aarhus indicating extremely great scattering. The σ of the difference forming the monthly points (not plotted) is about 9.1 percent, the second largest in the network.

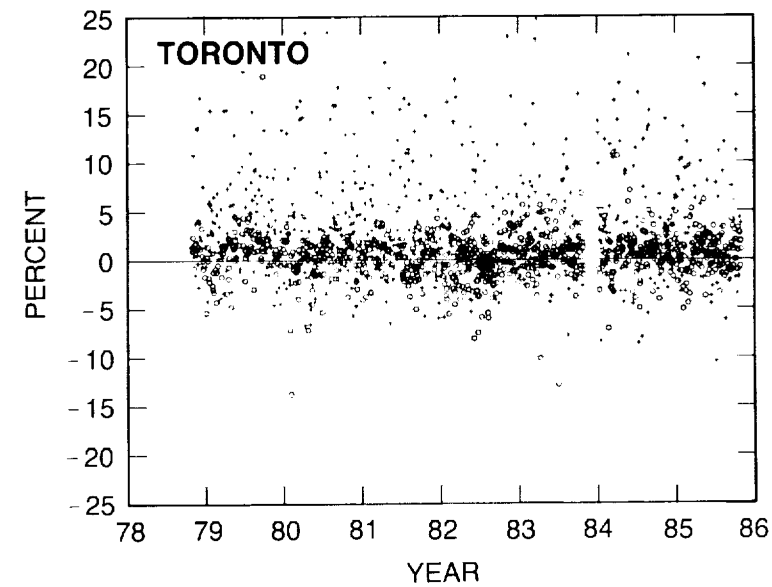


Figure 4.19 Daily differences for Toronto indicating stable direct-Sun readings (the σ of the differences of the monthly values is only about 2.2 percent) and very great scattering of the zenith-sky readings. The σ of the differences forming the monthly points from all observations (not plotted) is about 4.6 percent. The circles indicate direct-Sun observations, and the pluses show all other measurements.

4.3.2 The Station-Corrected Total Ozone Data From Belsk, Poland

The procedures for reporting data to ODW were described in Section 4.1.1.5. The pertinent points for this discussion are

- The authority and onus to report recalibrations and their effect on previous data are on the individual stations and not on ODW.

- Individual stations quite frequently are not staffed with enough trained manpower to carry out any retrospective data evaluation and correction.

The Dobson spectrophotometers are intended to be checked at least monthly with lamp tests, monitoring the instrumental spectral sensitivity response to a standardized exposure to UV radiation. The monthly lamp tests can indicate constancy, or a change in the wavelength selection by the instrumental slits. However, sometimes the monthly lamp tests provide information pointing either to an abrupt step change or to a steady ramp change in instrument response to the UV test. In addition, the individual Dobson instruments are occasionally recalibrated by direct comparison at a common location with either the world primary standard or with one of the secondary standards. The usual procedure after calibration is the immediate installation of the new calibration values. There should also be a retrospective reevaluation of any earlier data—including the measurements made according to the old calibration scale only a short time beforehand. In practice, such reevaluations are rarely performed, and unreported retrospective consideration of the data does not appear to be much more frequent.

In the ideal case, the complete station records are thoroughly investigated by the station itself following recalibration, and a revised data set is produced with the revisions made on a reading-by-reading basis—i.e., each daily measurement is corrected, and the monthly average is then recalculated. Such a procedure was performed by the personnel of the Dobson station at Belsk, Poland, for the data up to the end of 1981 (Dziewulska–Losiowa et al., 1983), and the revised data set was published in ODW. However, in general, such revisions have not been published and, in most instances, not performed. Currently, detailed reviews are known to be in process in Potsdam, Hohenpeissenberg, Sapporo, Tateno, Kagoshima, some of the Australian stations (Atkinson, 1988), Invercargill (Farkas, 1988), some of the U.S. stations (Komhyr, 1988), and some Indian stations (Andreji, 1988). As stations complete such retrospective analyses, their revised data sets will be published in ODW and will be available for statistical trend analysis. Until such reevaluations have been made, we have constructed provisionally revised ozone data for a substantial number of stations using external techniques for determining the times during which calibration problems may have occurred. Before describing further the procedures used for these provisional revisions, we shall discuss the revaluation of ozone data as carried out at Belsk.

Figures 4.20 and 4.21 show, respectively, the "revised" Belsk ozone data as published in ODW (solid line) and the "old" ozone data set from Belsk, also published earlier in ODW. Substantial differences exist between them, and the statistically calculated trends changed from positive to negative with the revision. Finally, a procedure is described in the next section for making a "fast" correction to an ozone data set in need of retroactive adjustment because of recalibrations. The "fast" method can be contrasted with the preferred, but much more labor intensive, "slow" method of day-by-day, ozone-reading-by-reading recalculation of the data by the station personnel carried out at Belsk (Dziewulska–Losiowa et al., 1983). The ozone data for the fast and slow methods are compared in Figure 4.20. While the agreement between the two methods is not complete, the fast corrections provide a very much closer approximation to the best available revised Belsk data than does the uncorrected old data set from earlier editions of ODW.

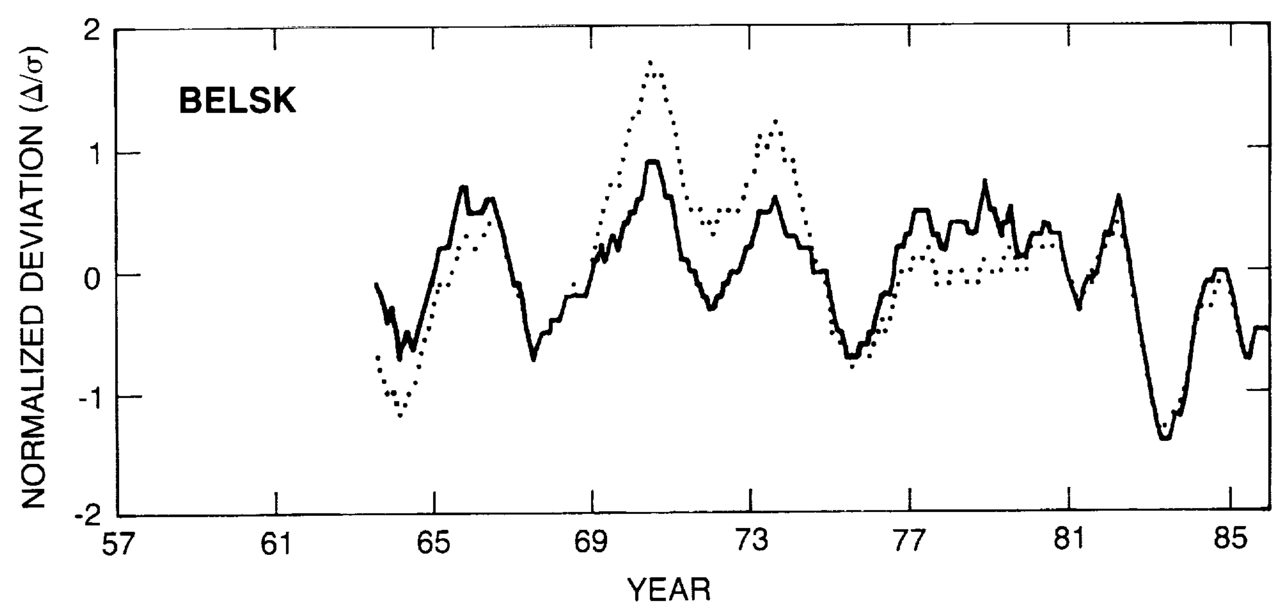


Figure 4.20 Comparison of the Belsk station-revised ozone data (—) and the "fast" revised record (. . .), including corrections found during the August 1986 intercomparisons. The data are plotted as monthly deviations that have been normalized and smoothed by taking the 12-month running mean.

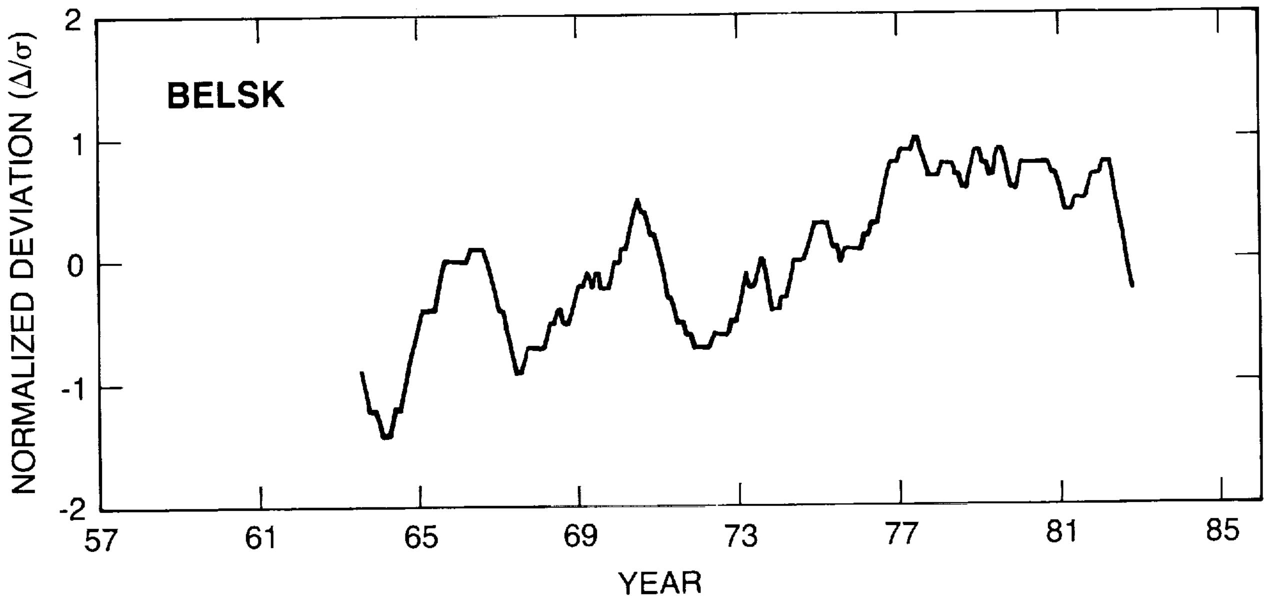


Figure 4.21 The Belsk total ozone record as it was originally published in *Ozone Data for the World.* The data are plotted as normalized monthly ozone deviations that have been smoothed.

The ozone data have been corrected in the fast method through calculation of the changes induced by recalibrations, using monthly average corrections applied to the monthly ozone averages. The times and magnitudes of the various recalibrations have all been identified by Belsk station personnel from their records, permitting ready revision of the old monthly ozone data. Application of the fast revision to data from other stations is likewise dependent upon the timing and magnitude of all recalibrations for changes in the sensitivity of the Dobson instrument; several techniques for identifying the approximate time intervals during which such calibrations probably occurred are also described below. It is worth restating that the best method of revision is the day-by-day, reading-by-reading reevaluation as carried out at Belsk. However, pending such revisions by the slow method at the individual stations, we have produced provisionally revised data sets for more than 20 Dobson stations by the fast technique. The provisionally revised data for Belsk using the fast technique were calculated for comparison purposes only and have not been used for statistical trend analysis.

4.3.3 DETECTION OF UNRECORDED DOBSON RECALIBRATIONS

4.3.3.1 Comparison of Data From Proximate Stations

The general technique for reevaluating data from a Dobson station begins with the identification of time periods during which calibration shifts have occurred. The satellite–ground intercomparison has been useful since November 1978, when Nimbus–7 data first became available. Two approaches that can be used for identifying possible calibration shifts prior to November 1978 are comparison of ozone readings from two or more nearby groundstations that are in similar synoptic scale meteorological regimes and comparisons for middle- and high-latitude stations with the local 100-millibar temperature readings.

When the 12-month running means of two nearby, well-run stations are compared, the curves should parallel each other closely, although often with a constant ozone differential. Conversely, a sudden change in the relative position of the curves is an indication that the measurements of one of the stations (or, very unlikely, of both at the same time) have gone awry, so that the detailed monthly calibrations for the two stations should be examined carefully. An excellent example of the information available from intercomparisons of two stations is given by the ozone data from two Indian stations, New Delhi and Varanasi (Figure 4.22). The patterns of the 12-month running means agree well with each other from 1977–1986 (including the entire period covered by Nimbus–7 TOMS), with the New Delhi instrument registering about 15 DU more than Varanasi. However, the earlier period, between 1969–1977, exhibited a very different pattern between the stations, with the New Delhi–Varanasi difference about -15 DU rather than + 15 DU. This shift of 30 DU, or about 10 percent, appears to occur between 1973 and 1977, and is strongly suggestive of a large calibration change in one or both instruments.

The published data from Tateno and Kagoshima are compared in Figure 4.23, and two obvious features are present. First, there is a major disagreement between the two stations around 1961, with Kagoshima recording appreciably lower relative values than Tateno. No information was available concerning this discrepancy in the Kagoshima record, and so the early measurements have been excluded in the provisionally revised data. Second, there is an excellent correlation between the two since 1977. For the rest of the time, the short-term variations in the records are similar, although the relative levels may be changing by small amounts. For instance, from around 1970 to 1977, Kagoshima is slightly higher relative to Tateno than it is in the rest of the record, and around 1969 it is slightly lower. These last two observations do not lead to the conclusion that either instrument was incorrectly calibrated in these two periods, but they do suggest that it is worth checking the records for such a case.

In Figure 4.24, the Potsdam ozone data are compared with the revised Belsk data. Again, there is good agreement since 1977. Earlier in the record, Potsdam is first higher than Belsk (1966–1969), then lower (1969–1977). The Potsdam data have subsequently been corrected by the station staff, although the data were not available for this study.

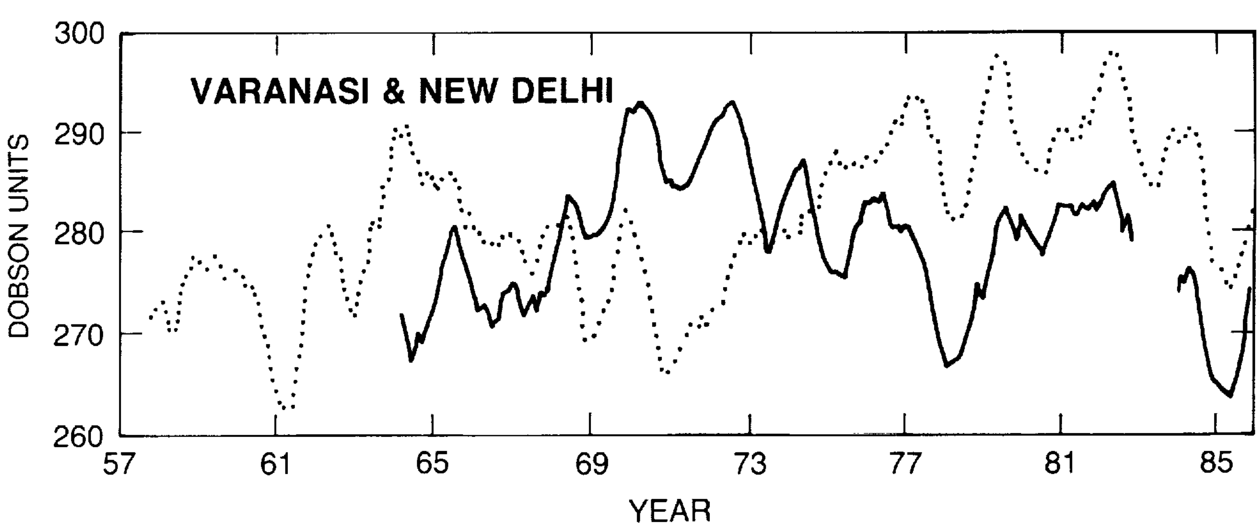


Figure 4.22 The 12-month running means of the total ozone measurements taken at Varanasi (—) and New Delhi (. . .) and that are recorded in *Ozone Data for the World*.

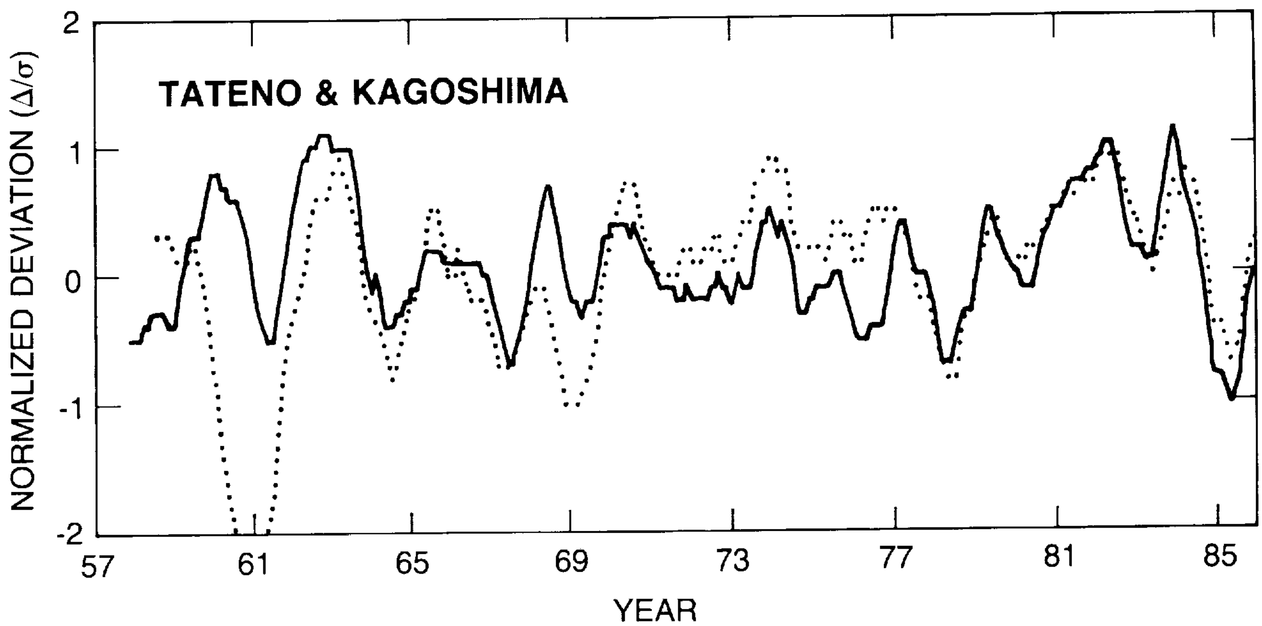


Figure 4.23 The monthly total ozone deviations (a smooth plot of the actual deviation divided by the particular month's interannual standard deviation) for Tateno (—) and Kagoshima (. . .) that are recorded in *ODW*.

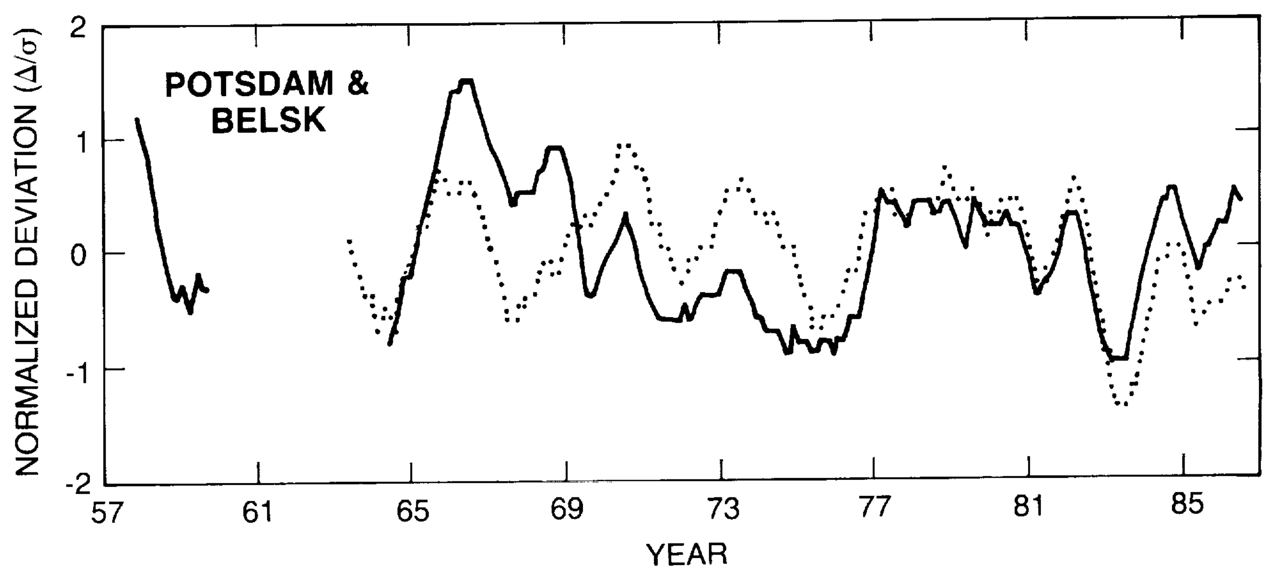


Figure 4.24 The monthly total ozone deviations (as in Figure 4.23) for Potsdam (—) and Belsk (. . .). The Potsdam data are taken from *ODW*, and the Belsk data are the station-corrected set that was also published in *ODW* and that replaced the original values reported to *ODW*.

4.3.3.2 Comparison of Total Ozone Data With 100 mbar Temperatures

The existence of a strong positive correlation between total ozone and stratospheric temperatures has been known for half a century (Meetham, 1936). Aspects of the complex physical relationships have been recently discussed by Rood and Douglass (1985) and by Douglass et al. (1985). The basic hypotheses are that warm air advection in the middle stratosphere should be associated with a positive ozone advection, and cold air advection should be accompanied by a negative ozone advection. Moreover, ascent of air causes a decrease in both ozone and temperature, while descent increases both. This picture is oversimplified: for example, the seasonal cycles of temperature and ozone are not in phase because of their different responses to the radiation balance. However, their responses to transport by the general circulation are similar. For example, at the time of Northern Hemisphere minimum stratospheric temperatures (in January), the general circulation supplies heat to the polar areas to balance the radiative cooling. This energy-balancing process is accompanied by an ozone transfer, resulting in an increase of total ozone. Sudden winter stratospheric warmings, whether caused by advection or subsidence, are accompanied by rapid increases in total ozone. The use of 100 mbar temperatures as an indicator of the course of total ozone is justified because the 100 mbar ozone and total ozone are so well correlated. When available, the 50 mbar temperatures were used as supplementary data. The effect of the differing seasonal cycles of temperature and total ozone is removed by deseasonalization of the two time series. (The correlations between total ozone and 100 mbar temperatures are never used for actual adjustment of ozone values; they serve merely as one of the diagnostic procedures used for discovery of possible unreported ozone recalibrations.)

The various versions of the Belsk ozone data are compared against the 100 mbar temperatures in Figures 4.25 to 4.27. In Figure 4.25, the 100 mbar temperatures are plotted against the old Belsk data prior to any revision, and without any corrections. Figure 4.26 contains the old data revised through 1981 plus the data recorded since 1981, all corrected by the fast method based on

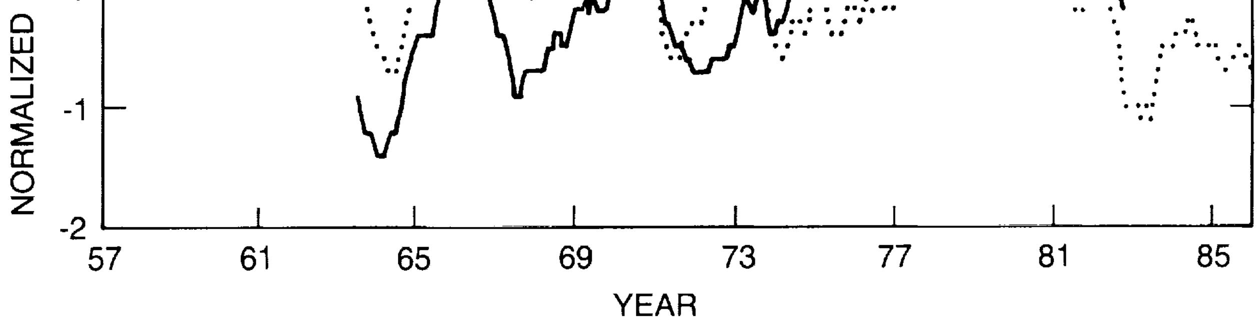


Figure 4.25 The monthly deviations (as in Figure 4.23) for the originally published Belsk total ozone record (—) and for the 100 mb temperature (. . .).

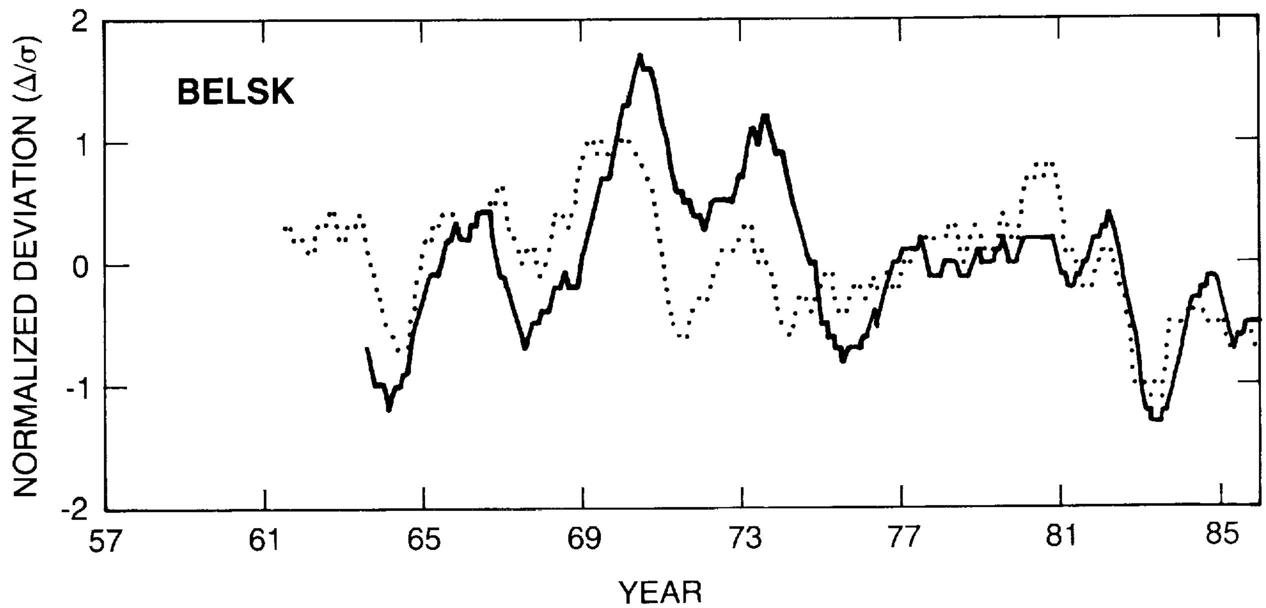


Figure 4.26 The monthly deviations (as in Figure 4.23) for the fast-revised Belsk total ozone record (—) and for the 100 mb temperature (. . .).

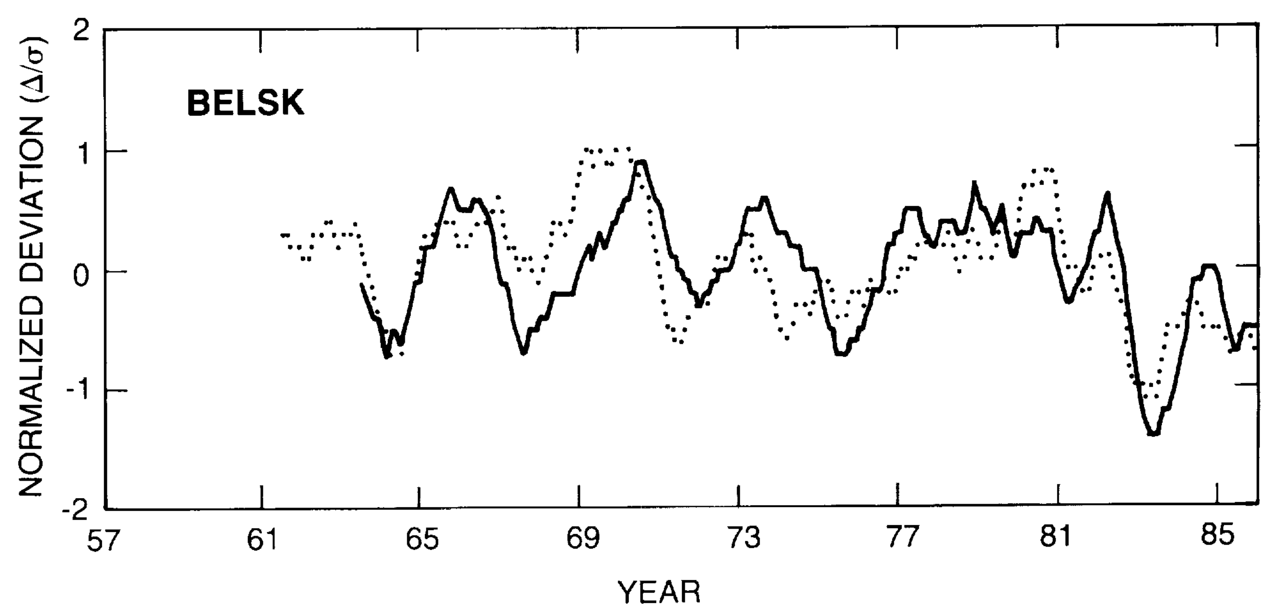


Figure 4.27 The monthly deviations (as in Figure 4.23) for the station-revised Belsk total ozone record (—) and for the 100 mb temperature (. . .). Since the station has, to date, revised the data only through December 1981, a provisional adjustment has been applied to the more recent data published in *ODW.*

monthly averages. Figure 4.27 shows the correlation between the current best revised set of Belsk data and the 100 mbar temperatures. The station-corrected data have been used to the end of 1981 in Figure 4.27 but, after 1981, a small fast correction has been made for a calibration error that was found at the international comparison at Arosa. This calibration change occurred after the major reevaluation of the Belsk data, and further post-1981 day-by-day revisions have not yet been reported from Belsk. The agreement between total ozone and 100 mbar temperatures found in such comparisons furnishes the basis for raising questions about the ozone record at other stations for which the two data records diverge.

Figure 4.28 contains the ozone and 100 mbar temperatures for Churchill. The upper panel contains the published Churchill data and the lower one contains the provisionally revised Churchill data. It can be seen that only minor changes have been made. However, around 1981, when the published ozone deviations were high compared to the temperature deviations, a small adjustment can be seen to have been made, with the result that the two series lie closer together. However, there is still a period, roughly from 1969 to 1973, during which the ozone is running higher. This, again, is a period for which a further check of station records is desirable.

Figure 4.29 contains the provisionally revised Bismarck ozone data plotted against the 100 mbar temperature. Relatively low ozone values were observed in 1983 at Belsk, Churchill, and

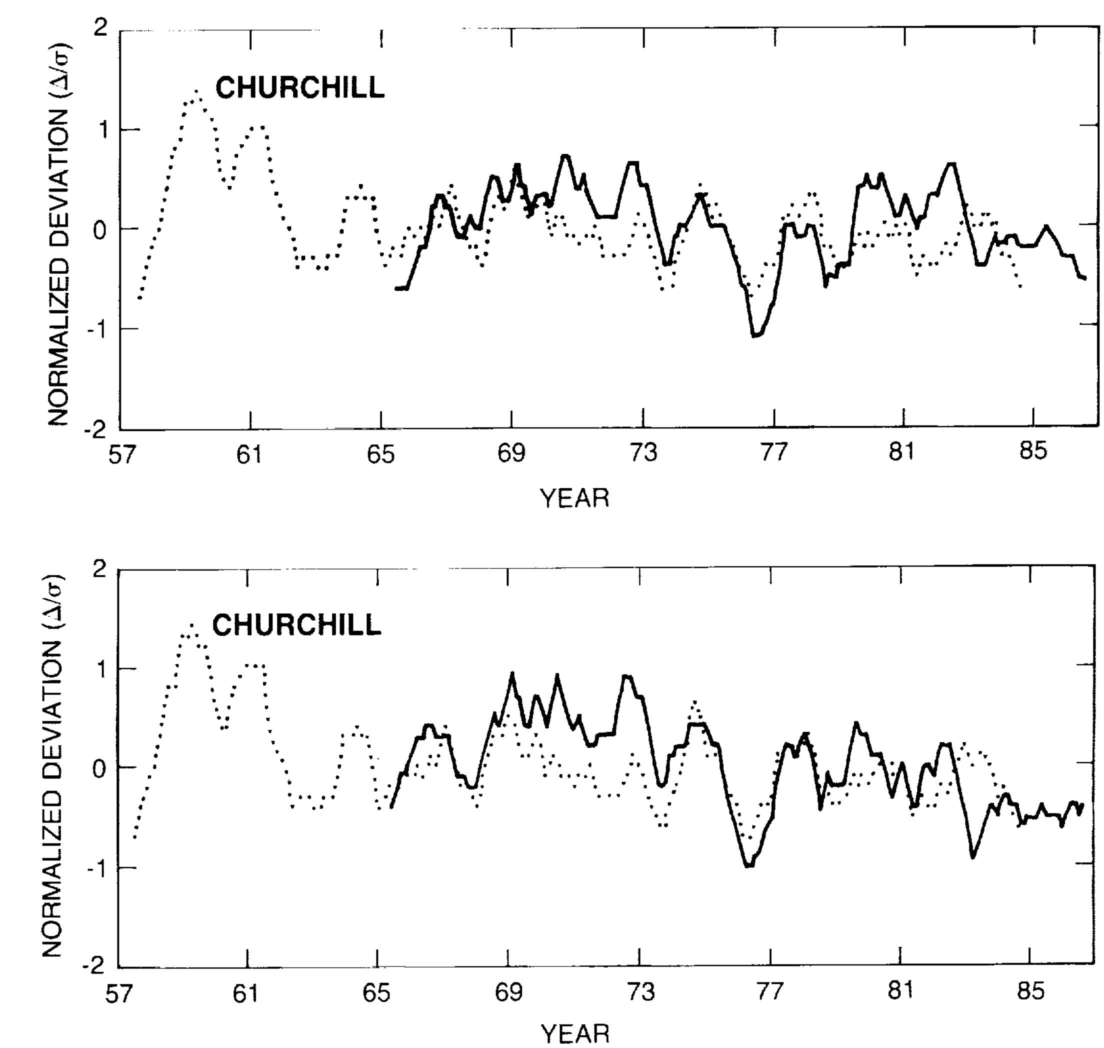


Figure 4.28 The monthly deviations (as in Figure 4.23) of the 100 mb temperature (. . .) are plotted against the total ozone data (—) from Churchill. In the upper panel, the ozone values published in *ODW* are shown, and in the lower panel the provisionally revised total ozone data set is plotted.

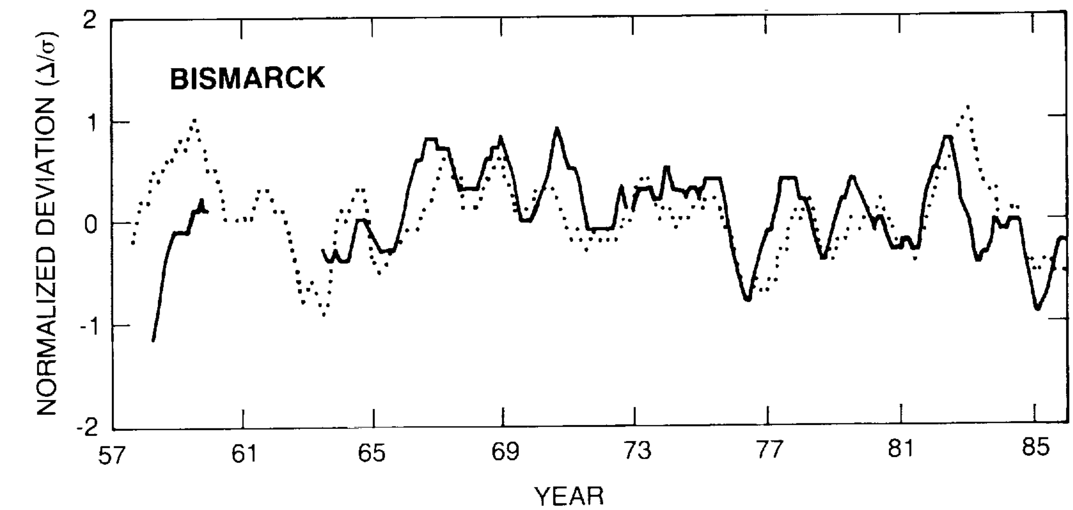


Figure 4.29 The provisionally revised total ozone data (—) and the 100 mb temperatures (. . .) for Bismarck are plotted.

Bismarck, reflecting the low northern midlatitude total ozone values of that year. The 100 mbar temperatures at Churchill and Bismarck do not exhibit the same abnormal decline as the ozone, as might be expected by analogy with the historical correlation.

4.3.4 Provisionally Revised Ozone Data Sets for Individual Stations

In the current study, the total ozone values published in ODW were examined for incongruities. The identification of problematic time periods in individual station records using the diagnostics described in the previous sections furnishes a basis for concern about the data published in ODW, but does not provide a basis for correction of such data. In many instances, however, the calibration records maintained by the individual stations but not always reported to ODW show clearly when a shift has occurred—e.g., the Huancayo data of Figure 4.9. With the additional information provided by these records of calibration changes, a revised set of total ozone data can be constructed for each station, eliminating the effects of sudden calibration shifts. The provisional revision in this report (Bojkov, private communication, 1987) applied each recalibration factor to the monthly data back to when the previous calibration took place, implicitly assuming that the changes took place abruptly. Sets of provisionally revised data for the 25 stations listed in Table 4.10 are given in Appendix 4.A(i) of this chapter. These tables are labeled "provisionally revised" (Bojkov, private communication, 1987).

Two procedures were used to handle a lack of daily measurements:

- If there was a day for which no value was recorded in ODW, but there were readings made on the days before and the days after, then an average value was inserted for the missing day.
- At least 13 daily values had to be available within the month for a legitimate monthly mean to be calculated.

Table 4.10 Provisionally Revised Station Data Used in the Time Series Analyses.

Arosa[1]	1/57–12/86
Aspendale	7/57–12/86
Belsk	1/63–12/86
Bismarck	1/63–12/86
Boulder	1/64–12/86
Bracknell	1/69–12/86
Cagliari–Elmas	1/57–12/86
Cairo	11/74–10/86
Caribou	6/62–12/86
Churchill	1/65–12/86
Edmonton	7/57–11/86
Goose Bay	1/62–11/86
Hohenpeissenberg	1/67–12/86
Hradec Kralove	1/62–12/86
Huancayo	2/64– 6/86
Kagoshima	4/61–12/86
Leningrad	8/68–12/85
Lerwick	1/57–11/86
MacQuarie Isle	1/63–12/86
Mauna Loa	1/63–12/86
Nashville	1/63–12/86
Quetta	8/69–12/86
Reykjavik	11/75–10/86
Rome (Vigna di Valle)	1/57–12/86
Samoa[2]	1/76–12/86
Sapporo	1/58–12/86
Srinigar	2/64– 5/86
Tateno	7/57–12/86
Toronto	1/60–12/86
Uccle	2/71–12/86
Wallops Island	1/70–12/86

[1]Data accepted in unrevised form from *Ozone Data for the World*.
[2]Data revised and supplied by W.D. Komhyr et al. (1987).
All other data are the monthly averages of total ozone published in *Ozone Data for the World* with the appropriate average monthly corrections applied. The amounts are given in Dobson Units.

After the first set of revised data had been prepared, the missing monthly values were treated as follows: if only 1 month was missing, the value substituted was the sum of the long-term monthly mean and the product of the interannual standard deviation of the missing month and the average of the two neighboring months' deviations (actual deviation divided by interannual standard deviation). These data sets were used for the comparison of the monthly means in two time periods. For the purpose of the full time series analyses, any other missing monthly values were replaced by the long-term monthly mean for that calendar month.

4.3.5 Sensitivity of the Method Used To Calculate the Provisionally Revised Data

If one ignores the details of the operation of the Dobson spectrophotometer, one can imagine two general cases that can be considered for the measurements prior to a hypothetical 3 percent difference after recalibration of a Dobson instrument. The first situation is a step in which a 3 percent change in calibration is introduced at one instant, as could happen if the instrument were moved, accidentally jarred, etc. The other situation is a ramp that might occur through the slow deterioration of some part of the instrument. If a hypothetical situation is considered in which the actual column of ozone to be measured is absolutely constant over the period under consideration, then the recorded values would appear as a sudden step in the first case and as a uniformly varying ramp in the second. While no problem exists in such a hypothetical situation for distinguishing between the two situations, the real measurements are very much blurred by the natural variability of ozone over a particular measuring station.

The Belsk data can be used to test whether the assumptions made in correcting data prior to each recalibration introduce artificial trends into continuing data records. The arbitrary correction forms tested are a step change introduced immediately after the previous calibration (as used in the provisional revision), and a ramp between the two calibrations (i.e., a linear variation with time). In a real situation in which either a ramp or a step at a particular time is indicated by lamp tests or some other external information, the appropriate correction would be applied. Our concern here is directed toward whether an arbitrary choice of either a ramp or a step causes a serious error in the evaluation of secular trends. It should be remembered that the data as published in ODW represent *de facto* the arbitrary choice that the physical change represented by the recalibration was not present on the day before recalibration and took place suddenly as a single step.

The statistical model used for these analyses in Table 4.11 is similar to that used by Reinsel and Tiao (1987):

$$\mathrm{Y(t)} = \mu + S(t) + W \bullet T(t) + N(t)$$

in which μ is the long-term mean; $S(t)$ is a term describing the seasonal variation, consisting of the sum of a sine wave with a period of 1 year, and its harmonics; $T(t)$ is a linear trend starting in 1970 with W as its coefficient (only a year-round model was used, not a model that allowed for different monthly trends); and $N(t)$ is an autocorrelated noise term. This model is *not* the same as that developed for the full trend analysis reported later in this chapter.

The ozone data from Belsk have been "corrected" for four different periods subject to retroactive calibration corrections, using either a ramp (R) or step (S) correction at each opportunity. The combination of the choice of R or S for each of four periods has provided 16 possible choices for how this correction should be applied—e.g., RRRR, RRRS, RRSR, etc. Comparisons with the revised data set can then be made of various versions of the fast correction—e.g., ramp or step at each recalibration, and with the old data set. The results of such trend analyses for all of these series are shown in Table 4.11. The data set used is that from March 1963 through July 1986, with just one missing monthly value.

Several points are worth noting:

- There is a large, significant difference between the trends calculated for the originally published data, $+0.68 \pm .37$ DU/yr, and the revised station data, $-0.40 \pm .29$ DU/yr.

- The trend calculated using the data set calculated by the method used in the provisional revision of other stations (designated SSSS) has a trend, $-0.47 \pm .31$ DU/yr, that is very close to that of the revised station data.

Table 4.11 Results of Trend Analyses of the Monthly Ozone Values at Belsk, Poland, for the Period 3/63–7/86. S = Step and R = Ramp Correction.

Data	W (DU/Year)
Old ODW	$+0.68 \pm 0.37$
Revised	-0.40 ± 0.29
SSSS	-0.47 ± 0.31
SSSR	-0.43 ± 0.31
SSRS	-0.46 ± 0.31
SSRR	-0.42 ± 0.31
SRSS	-0.22 ± 0.30
SRSR	-0.18 ± 0.30
SRRS	-0.20 ± 0.30
SRRR	-0.17 ± 0.30
RSSS	-0.18 ± 0.35
RSSR	-0.16 ± 0.35
RSRS	-0.18 ± 0.35
RSRR	-0.14 ± 0.35
RRSS	$+0.07 \pm 0.32$
RRSR	$+0.10 \pm 0.32$
RRRS	$+0.07 \pm 0.32$
RRRR	$+0.11 \pm 0.32$

- Although there is a substantial variation in the trends calculated among the 16 differently adjusted time series, all are closer to the trend of the station-revised data set than is the trend of the originally published data set.

Two conclusions can be drawn. First, the use of the correction factors found at the various recalibrations improves the quality of the data whether a ramp or step is assumed and, second, the use of step rather than ramp corrections is justified in the case of Belsk.

4.4 CALIBRATION OF TOMS DATA USING DOBSON DATA

In previous sections, the long-term TOMS record has been used to find abrupt changes in the records of individual Dobson stations. Relative changes that occur gradually over a period of several years could be caused either by the satellite instrument (SBUV/TOMS) or by an individual groundstation, but a drift relative to all of the Dobson stations is likely to have been caused by a calibration drift of the satellite instrument.

4.4.1 Comparison of TOMS Data With the Dobson Network

Fleig et al. (1986b) examined the drift of TOMS relative to an ensemble of 41 Dobson stations; this study was recently updated by Fleig et al. (1988). They found that TOMS total ozone values declined relative to the Dobson network at a rate of -0.25 percent per year between 1979 and mid-1982, but declined at a rate of -0.51 percent per year until October 1985, the end of the period studied. The decline for SBUV was of similar magnitude. An alternative version of this comparison is described in detail in Section 4.2 of this chapter.

While the ozone concentrations indicated by the satellite instruments clearly declined relative to the values shown by the Dobson network, further tests are desirable of the assumption that this drift originates in the degradation of the satellite instruments. One such test involves internal calibration of the satellite instrument using radiances measured at wavelengths used in the primary ozone determination, as described in Chapter 2. A second such test can exist if circumstances exist during which nonroutine, intensive measurements are being made under favorable conditions for a ground-based Dobson instrument.

4.4.2 Comparison of TOMS Data With the International Primary Standard Dobson Instrument

A special opportunity for comparison exists for the International Standard Dobson Instrument No. 83 during its periodic recalibrations at Mauna Loa, Hawaii. As described in Section 4.1.1.4, Dobson instrument No. 83 was established in 1962 as the standard spectrophotometer for total ozone measurements in the U.S., and later as the International Primary Standard Dobson Instrument. The absolute calibration of this instrument over the period 1962–1987 has been maintained to within an uncertainty of ± 0.5 percent (Komhyr et al., 1988). Intercomparison of TOMS data with the data from these Mauna Loa recalibrations provides an opportunity for testing the possible drift of TOMS (and SBUV) within the accuracy of these calibrations. The 3.5 percent drift described in Section 4.3 is clearly much larger than the ± 0.5 percent stability of the International Primary Standard.

During a calibration using the Langley method, repetitive measurements of ozone are made on an individual day with different Sun angles and air masses to permit extrapolation to zero air mass and the determination of the extraterrestrial constant. These calibrations with Instrument No. 83 are repeated on a number of different days at Mauna Loa in a short period of time in order to determine the reproducibility of the calibration. Mauna Loa is an especially favorable site for such calibrations because its tropic, mountaintop location provides clean, generally aerosol-free air, stable ozone fields over time, and nearly overhead noontime Sun reducing the extrapolation to zero air mass. Such calibrations of Instrument No. 83 were performed at Mauna Loa in the summers of 1979, 1980, 1981, 1984, 1986, 1987, and 1988. For this report, TOMS observations have been compared with individual observations for each of these years except 1988. In 1979, for example, there were 31 days between June 11 and August 14 on which both instruments measured total ozone. The dashed circle in Figure 4.30 shows that Dobson Instrument No. 83 measured 278 DU of ozone on June 29 of that year. Of all the ozone measurements made by TOMS that day, the measurement of 278 DU was most nearly collocated with the Dobson station.

The Dobson total ozone values indicated for the calibrations were increased by 0.9 percent to account for the change in effective ozone absorption coefficients at Mauna Loa stratospheric temperatures. In most instances. the ozone values indicated by TOMS and by the Dobson correlated well except for two biases for which corrections can be made. One bias is the standard practice of evaluating the measurements with different assumed sets of ozone absorption coefficients (Bass–Paur for the satellite and Vigroux for Dobson). The second bias is an FOV problem: the Mauna Loa station is at 3.4 km altitude, and the Dobson cannot have as much tropospheric ozone in its column versus that seen nearby over the ocean by TOMS. The ozone measurements made by the two instruments should not agree exactly: in Figure 4.30, adjustments have been made for the stratospheric temperature and for the tropospheric ozone below the Dobson station, but not for the different absorption coefficients.

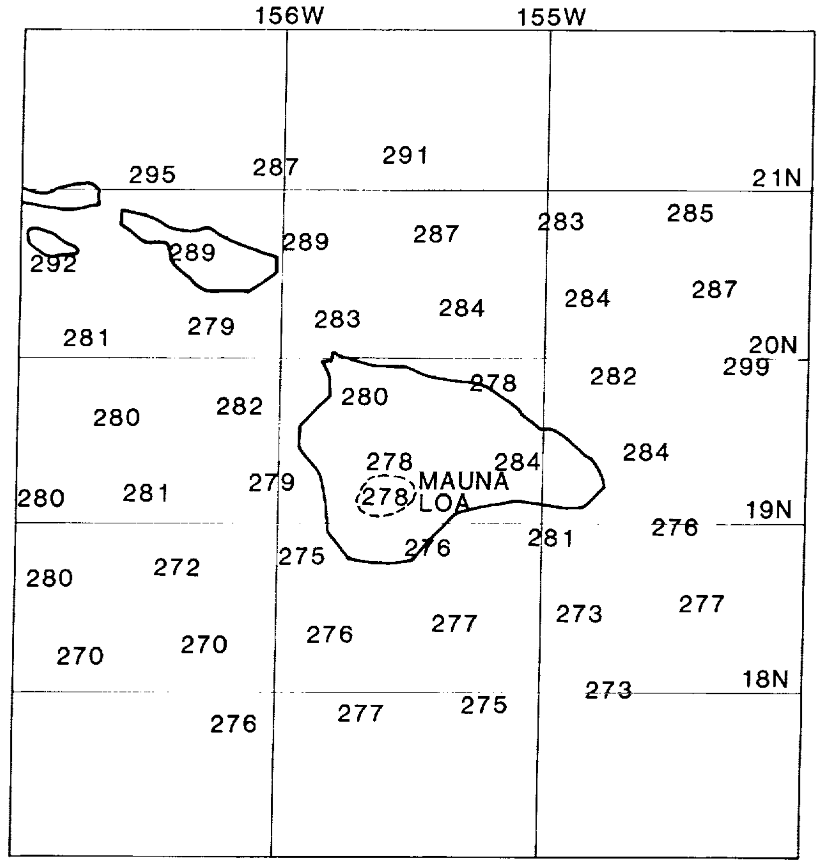


Figure 4.30 Intercomparison of TOMS overpass measurements of total ozone with World Primary Standard Dobson ozone measurements at Mauna Loa Observatory, Hawaii, June 29, 1979. The Mauna Loa measurement is enclosed in the broken circle.

The average ozone measured by TOMS in 1979 over Mauna Loa during the calibration period was 292.5 DU, while that measured by Instrument No. 83 was 279.2 DU, a difference of 4.8 percent. The comparisons can be made more comparable by the addition of a correction term to observations to account for the average amount of ozone present between the 3,400-meter altitude of the Mauna Loa Observatory and sea level, because the satellite senses an average value over a region of 1,600 km^2, almost all of which is ocean. This correction was determined from ozone vertical distribution measurements made with ECC ozonesondes released during 1983–1986 at Hilo, Hawaii (elevation 0.011 km). The added amounts of total ozone were slightly variable with the month of observation: 10 DU in May, 8 in June, 6 in July, and 7 in August. An average amount of 8 DU was uniformly subtracted from the actual TOMS values in Figure 4.30.

Corrections for the altitude mismatch in the observations reduces the average difference in 1979 from 4.8 percent to 1.9 percent, with a statistical uncertainty of ± 0.26 percent. Similarly calculated TOMS–Dobson percentage differences are plotted for each year in Figure 4.31. Two different results are given for the Dobson each year, labeled (1) and (2), that represent two slightly different calibrations for instrument No. 83. In case 1, the Dobson data are reduced using the 1976 wedge calibration for all years, while for case 2 the data are reduced using updated wedge calibrations. The results for both cases are shown to provide an estimate of the level of uncertainty in the Instrument No. 83 results.

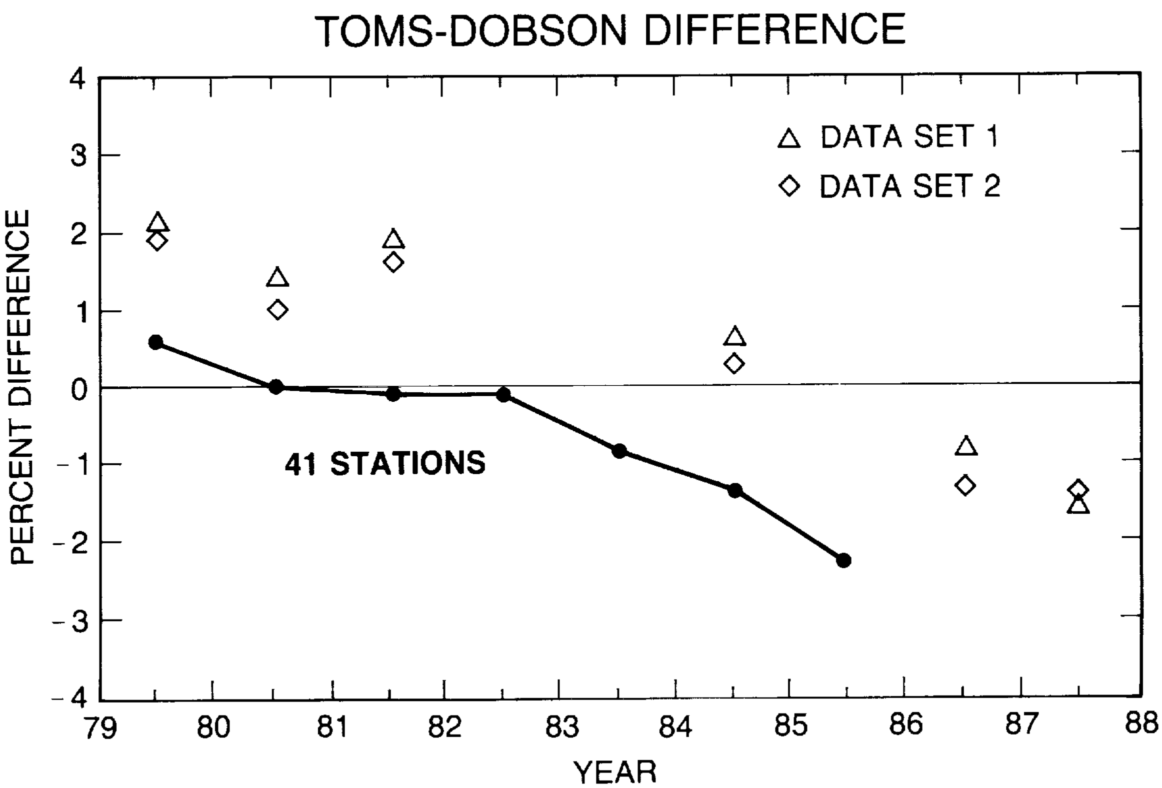


Figure 4.31 The variation of the (TOMS minus Dobson) percentage difference with time given for three different types of Dobson measurements. Data sets 1 and 2 (triangles and diamonds) are the result of comparisons of the TOMS data with slightly different calibrations of Dobson Instrument No. 83 (see text). while the circles represent the difference with an ensemble of 41 Dobson stations.

Ozone measurements with TOMS were relatively constant with respect to instrument No. 83 during the period 1979–1981. (Data for the ground-based instrument in 1980 are discounted because of known operator errors that year.) The average offset was +1.9 percent. By 1984, however, the difference was only +0.5 percent, a decline of 1.4 percent relative to the earlier period, and by 1987 the absolute difference was -1.5 percent, a relative decline of 3.4 percent. This decline relative to the International Primary Standard Dobson Instrument is consistent with the decline noted relative to the average of many individual stations, as described in Section 4.3.

Accepting the difference as real, could its origin be geophysical and not instrumental? One possibility that must be considered is that a secular increase in tropospheric ozone occurred at Mauna Loa during this period. The observed 3.4 percent TOMS–Dobson drift corresponds to about 10 DU of ozone, and a 20 DU change in tropospheric ozone (with 50 percent TOMS sensitivity) between 1981 and 1987 would be required to explain the difference. Such a change has not been observed. Measurements by ECC ozonesondes of the amount of ozone in the lowest 4 km at Mauna Loa (Komhyr, private communication) showed 8.3 DU in summer 1983 and 7.0 DU in summer 1986, a difference of only 1.3 DU. Based on these data, changes in tropospheric ozone must be discounted as a possible cause of the TOMS–Dobson difference in the experiments conducted at Mauna Loa.

Figure 4.31 shows both the TOMS/No.83 comparison and the yearly average TOMS–Dobson difference (dashed line) from the ensemble of 41 Dobson stations for 1979–1985 (Fleig et al., 1986a). The important conclusion is that the same time dependence is observed for TOMS relative to either standard. If the calibration of Instrument No. 83 has been constant, the TOMS calibration must have drifted downward.

One final question to be resolved is whether the TOMS–Dobson drift could, in part, be an instrument artifact in TOMS other than the diffuser plate degradation discussed earlier. In 1982, TOMS began to experience a small number of cases of synchronization loss in the chopper that subtracts "dark current." These "sync-loss" effects are flagged automatically by the instrument, and indicate that only a few percent of the values were affected. Nevertheless, such effects need to be considered when drifts of only a few percent over almost a decade are involved. This possible source of error was discounted by examination of the SBUV–TOMS comparison data through 1986. The independent SBUV instrument shares only the diffuser plate with TOMS and had not then developed its own sync-loss problems. The SBUV–TOMS comparison showed that TOMS total ozone agreed with that from SBUV to within half a percent for the TOMS A pair. As indicated earlier, severe sync-loss problems developed for the SBUV instrument in February 1987, and this procedure for comparison is no longer valid.

4.4.3 Implications of TOMS–Dobson Drift

The conclusion that there was about 3.4 percent drift between TOMS and Dobson between 1979 and 1987, with much of the drift occurring after 1982, seems inescapable. The fact that the same pattern, relative stability before 1982 followed by a sharp decline between 1982 and 1986, occurred in the TOMS–Dobson comparisons for so many of the ensemble of 41 independent stations, and with the larger set of 92 Dobson and M–83 stations (Table 4.8), is strong evidence in itself. The complete confirmation by comparisons with the standard Dobson Instrument No. 83 for both TOMS and SBUV furnishes compelling additional evidence that this trend relative to Dobson is real.

4.5 PRELIMINARY EXAMINATION OF GROUND-BASED TOTAL OZONE MEASUREMENTS

Analyses of total ozone readings from any Dobson station in the Temperate Zone show ozone variations correlated with one dominant physical cycle, the seasonal variation, and three other potential contributors of lesser magnitude: the approximately 26-month cycle of the quasi-biennial oscillation (QBO) of the direction of the stratospheric winds in the Tropics, the 11-year solar sunspot cycle, and the formation of nitrogen oxides by the testing of nuclear bombs in the atmosphere 25–30 years ago (Reinsel, 1981; Reinsel et al., 1981; Reinsel and Tiao, 1987; Reinsel et al., 1987). A complete analysis of the total ozone data should take these effects into account before calculating any trends in recent years. The statistical model used in this study is presented in full in Section 4.6. This section contains a brief description of ozone climatology, followed by a simple analysis of both the ozone data published in ODW and the provisionally revised data discussed in Section 4.3 and given in Appendix 4.A.(i). Finally, a detailed description of the analysis of the Bismarck data is presented as a case study to show the effects of the various geophysical relationships.

4.5.1 Basic Total Ozone Distribution

Some early observations of total ozone were made as far back as 1913; routine Dobson spectrophotometer measurements were started at Arosa (Switzerland) and Oxford (England) in the late 1920's and at Tromso (Norway), Lerwick (Scotland), and some other stations in the

1930's. However, it was not until the International Geophysical Year (1957–1958) that observations at a sufficient number of stations became available to make possible global analysis of the total ozone distribution (e.g., London et al., 1976). The uneven geographical distribution of the stations, with a heavy concentration in the north Temperate Zone and only a few in the Southern Hemisphere, introduced a spatial sampling error into the global analysis that still persists.

The average distribution of ozone over the globe for 1957–1975 is shown in Figure 4.32. The main features are:

- A pronounced minimum over the equatorial belt, with increasing concentrations poleward to about 70 degrees, and with a secondary minimum at the poles;
- The belt of ozone minimum (240 DU) lies between 10°S and 15°N latitudes;
- The total ozone increases in a poleward direction in both hemispheres, but the north and south are not symmetrical to one another;

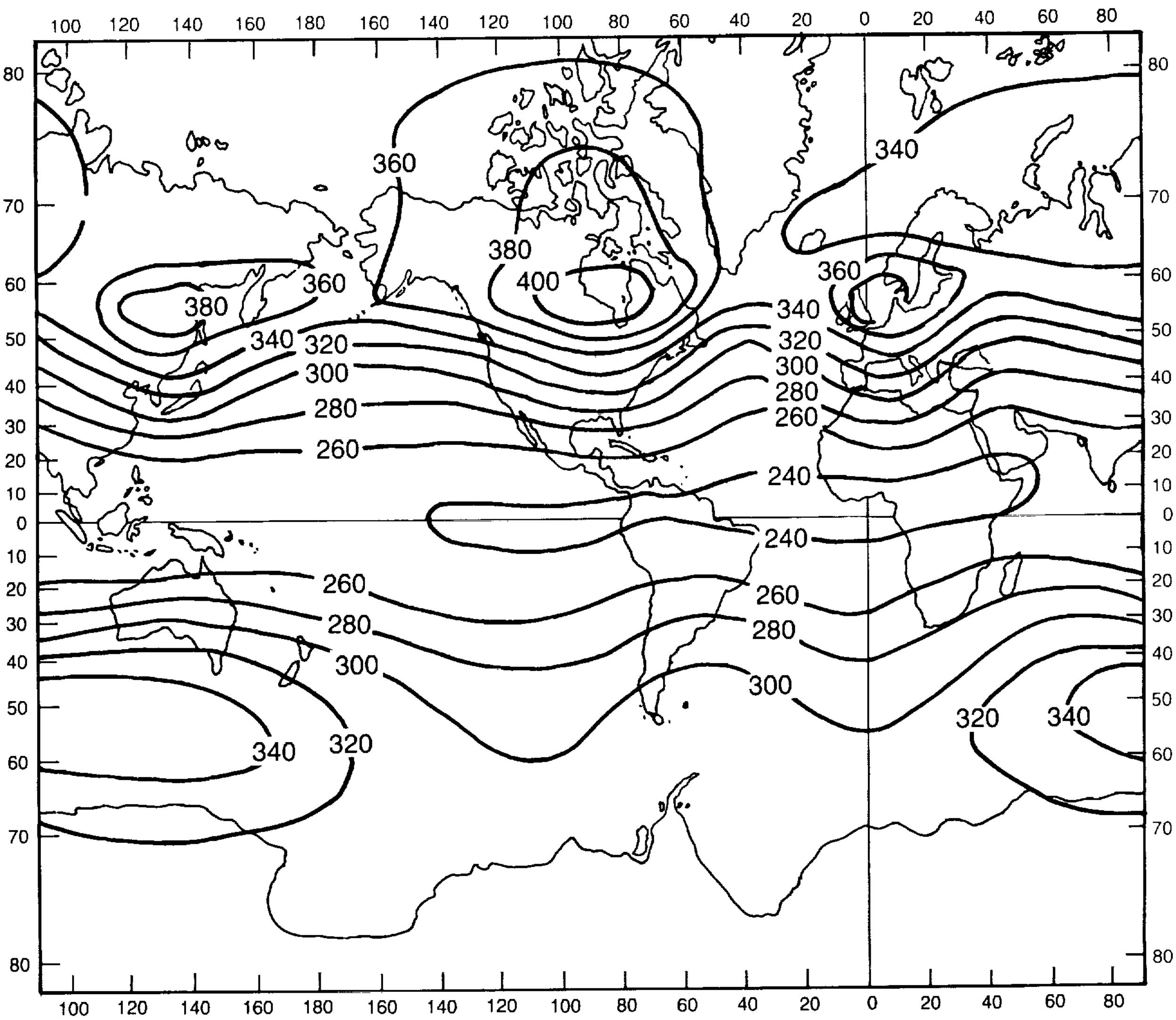


Figure 4.32 Average total ozone distribution for 1957–1975 derived from ground-based measurements.

- Pronounced longitudinal inhomogeneities exist, as indicated by ridges of higher ozone concentration over the eastern edges of the continents, a function of the climatological specifics of planetary circulation waves;

- The ozone concentration over the Antarctic is smaller than over the Arctic, reflecting differences in the patterns and behavior of the individual circumpolar vortices.

The average concentration of total ozone as a function of latitude and month is graphed in Figure 4.33 (London, 1980). In temperate and polar latitudes, substantial changes are observed with the seasons. Broad similarities exist between the two hemispheres: in each, the total ozone minimum is reached near the fall equinox and the maximum occurs near the spring equinox. There are also differences: the maximum is slightly later in the Southern Hemisphere, and the maximum rate of increase occurs in December/January (just after the winter solstice) in northern latitudes, while in the Southern Hemisphere the ozone increases fastest in September (close to the spring equinox). There are longitudinal inhomogeneities in each hemisphere that cannot be shown in Figure 4.33; these tend to be more pronounced in the Northern Hemisphere.

The rapid increase of total column ozone during the winter–spring season and its decrease during the summer toward an autumn minimum are shown in Figure 4.34 for 55 years of data from Arosa, Switzerland. The interannual standard deviations of each month are shown by the vertical bars in Figure 4.34. The long-term monthly means vary between 280 DU and 380 DU; the interannual standard deviation of the winter months is about 25 DU; and the interannual standard deviation of the summer months is about 10 DU. Data from other stations show that the variability increases at more northerly latitudes. These large natural variations make it hard to

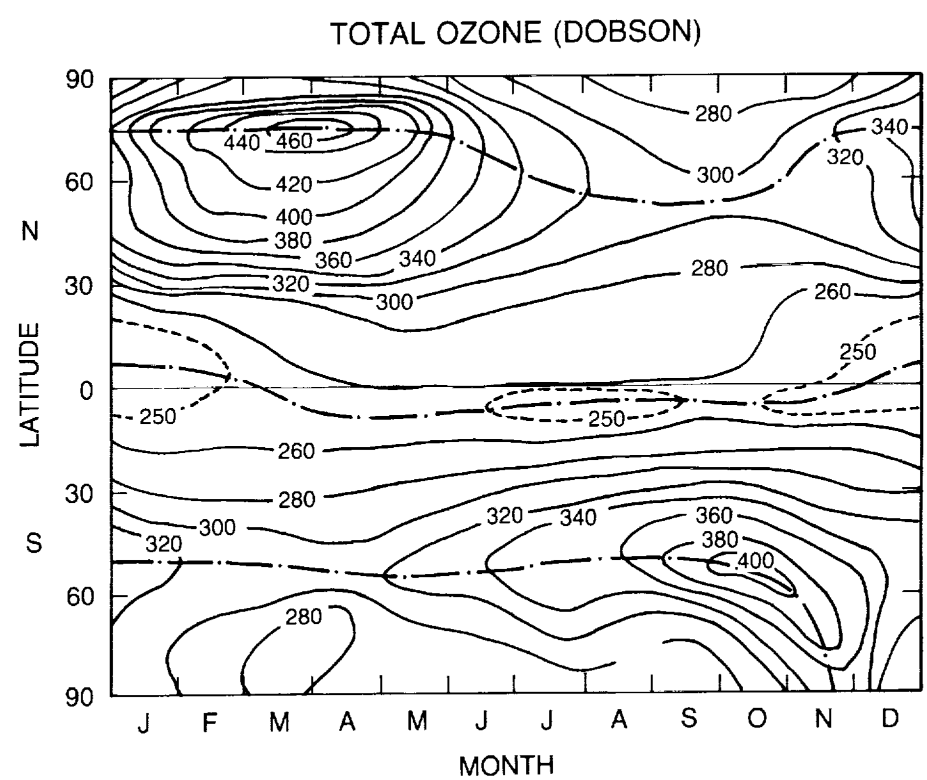


Figure 4.33 Variation of total ozone with latitude and season (from London, 1980).

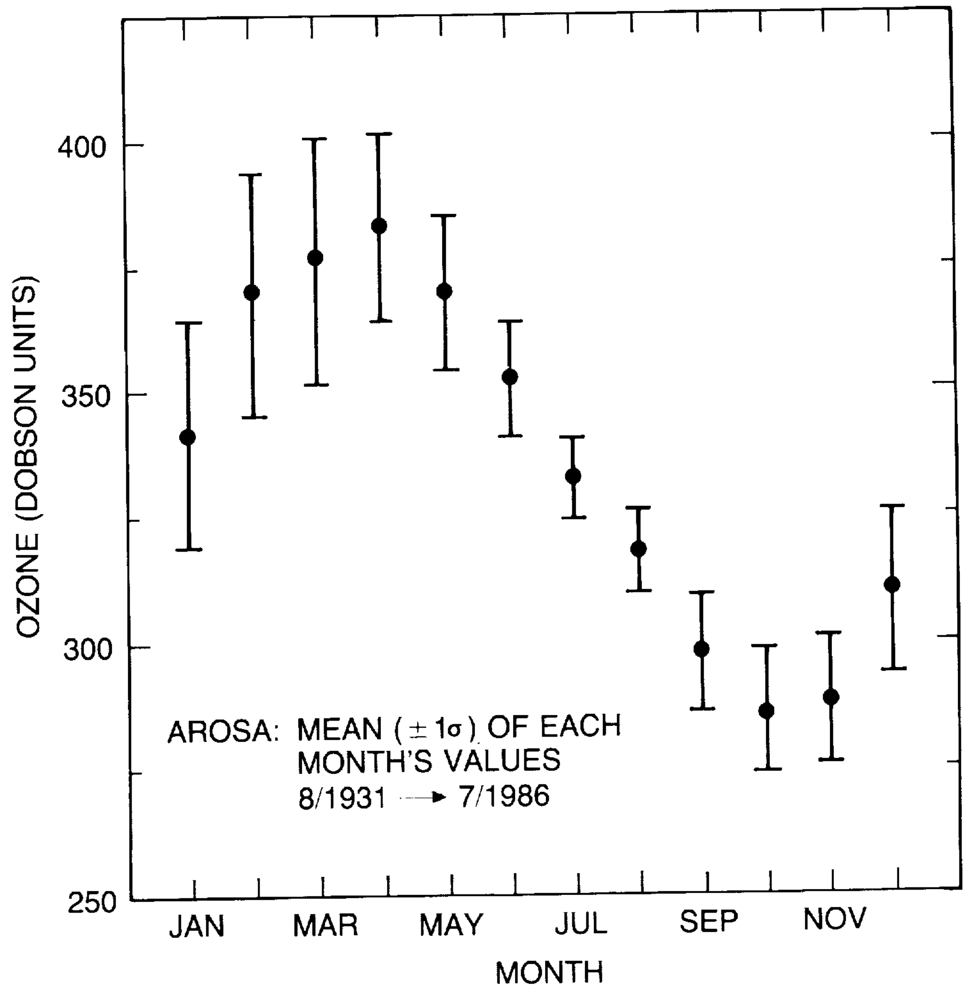


Figure 4.34 Long-term means of the monthly total ozone values at Arosa, Switzerland, for August 1931–July 1986. The associated interannual standard deviations for each month are shown as ± 1 sigma vertical bars.

detect a trend, particularly in the winter months. The annual cycle at Arosa is typical of the northern Temperate Zone, although there are longitudinal variations in the timing of the maximum and the amplitude of the annual cycle.

4.5.2 Changes at Selected Stations Deduced From the Data Published in *Ozone Data for the World* (ODW)

Harris and Rowland (1986) reported their observations that the ozone data from Arosa show strong evidence for a substantial wintertime loss in total column ozone at that location, combined with minimal losses in the summer months (Figure 4.35). They then demonstrated that a similar effect existed at other north Temperate Zone ozone stations. These patterns are illustrated in Figure 4.35 for the data as reported in ODW for five stations, four of which show a pattern similar to that found for Arosa. The Arosa data are based on the full 55-year data set, divided into two periods, August 1931–December 1969 and January 1970–July 1986. In the other five cases for which the data records are not so long, the average of the monthly total column ozone measurements over the 11-year period January 1976–December 1986 have been compared with the averages of the monthly data for a period of 11 or more years prior to 1976. The differences

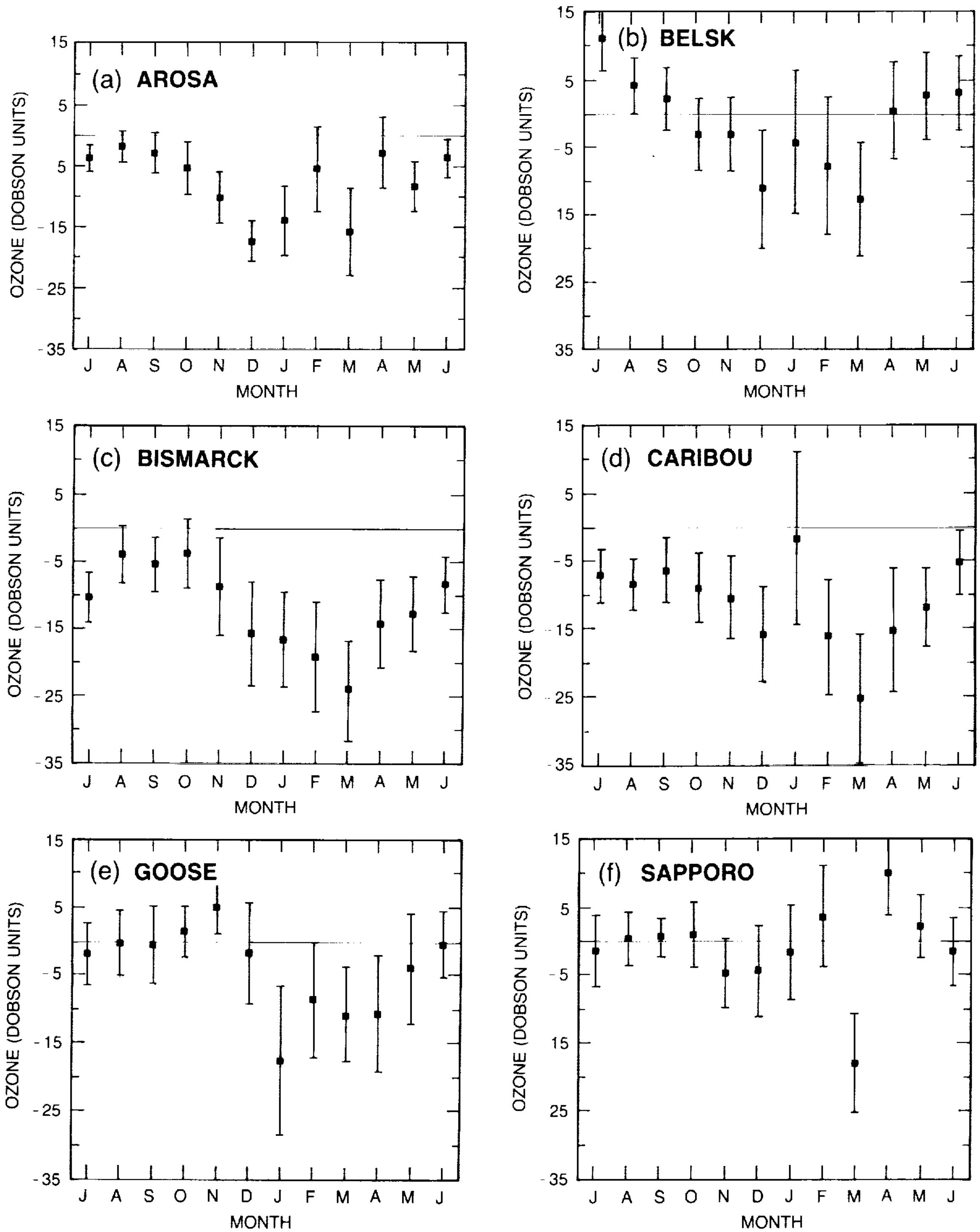


Figure 4.35 (a) Differences in the long-term monthly means at Arosa between August 1931–December 1969 and January 1970–July 1986. (b)–(f) Differences in the long-term monthly means at five other stations between the period prior to December 1975 and the period from January 1976 on. The first period has its starting date as the time when the station started making total ozone observations, and the second period ends in December 1986, except for Goose, where the data were available only through November 1986. Data are taken from *ODW*.

graphed illustrate the apparent gain or loss in ozone for each month, with negative values indicating a loss. The standard deviation of the mean is calculated for each period, and the vertical bar represents the uncertainty (±1 standard deviation) in the difference between the means for the earlier and later time periods. This procedure is satisfactory for determining whether the mean of the second time interval is significantly different from that of the first interval.

The same preliminary analyses have also been carried out for a selected set of 19 Northern Hemisphere ground-based Dobson stations between 31°–65°N latitude, using the ozone values as originally recorded in ODW. The criteria for station selection include at least 22 consecutive years of data and no special problems existing in the data sets (such as those discussed in Section 4.3). The individual station data for the 22-year period from 1965 to 1986 were used, and again the monthly averages of the earlier and later 11-year periods were compared. The choice of 11-year segments ensures that each period contains one solar cycle and about five QBO cycles, while the starting date avoids the nuclear bomb test effects almost completely.

The results are illustrated in Figures 4.36 and 4.37, in which we have averaged the differences for a 4-month "winter" season (December, January, February, March—DJFM) and a "summer" season (May, June, July, August—MJJA), rather than include all the monthly differences for all the stations. Negative values predominate especially strongly in the winter season (Figure 4.36), with 18 of the 19 stations showing ozone losses averaged over the winter period in this data set. The summer values (Figure 4.37) are more evenly distributed, with results from 11 stations showing ozone decreases, 6 showing increases, and 2 unchanged. In the annual averages, 17 of the 19 stations in Figures 4.36 and 4.37 show ozone losses. This analysis of the raw total ozone

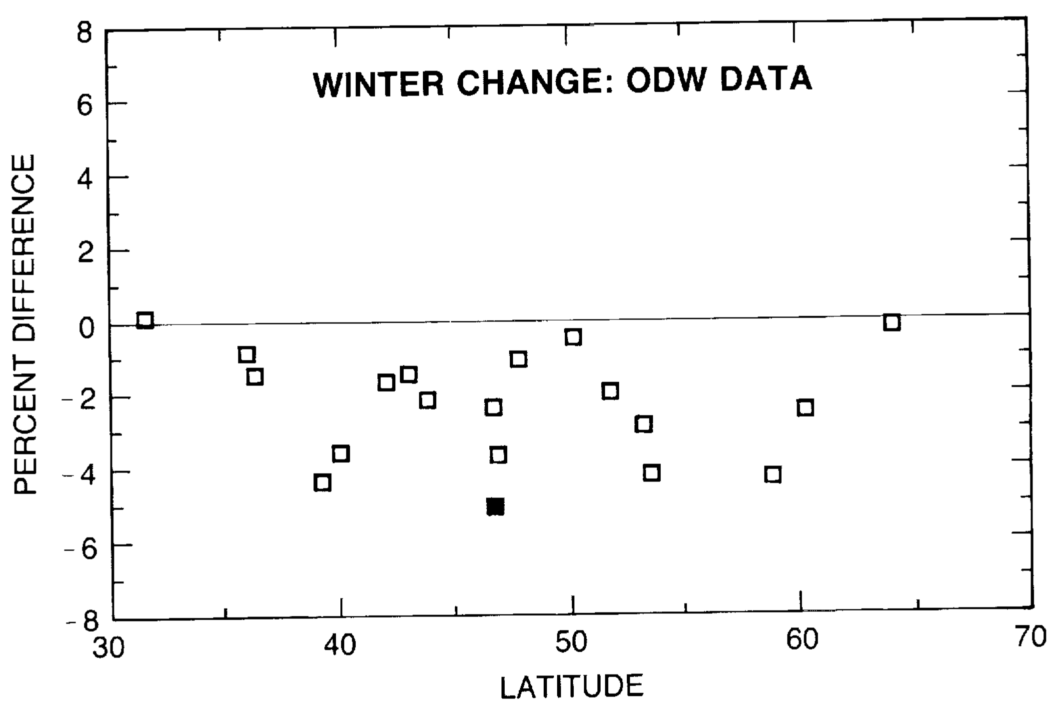


Figure 4.36 Differences in the means of the 4-month "winter" season (DJFM) for the 11-year periods from January 1965–December 1975 and January 1976–December 1986 are plotted for 19 Northern Hemisphere stations. Data are taken from *ODW*.

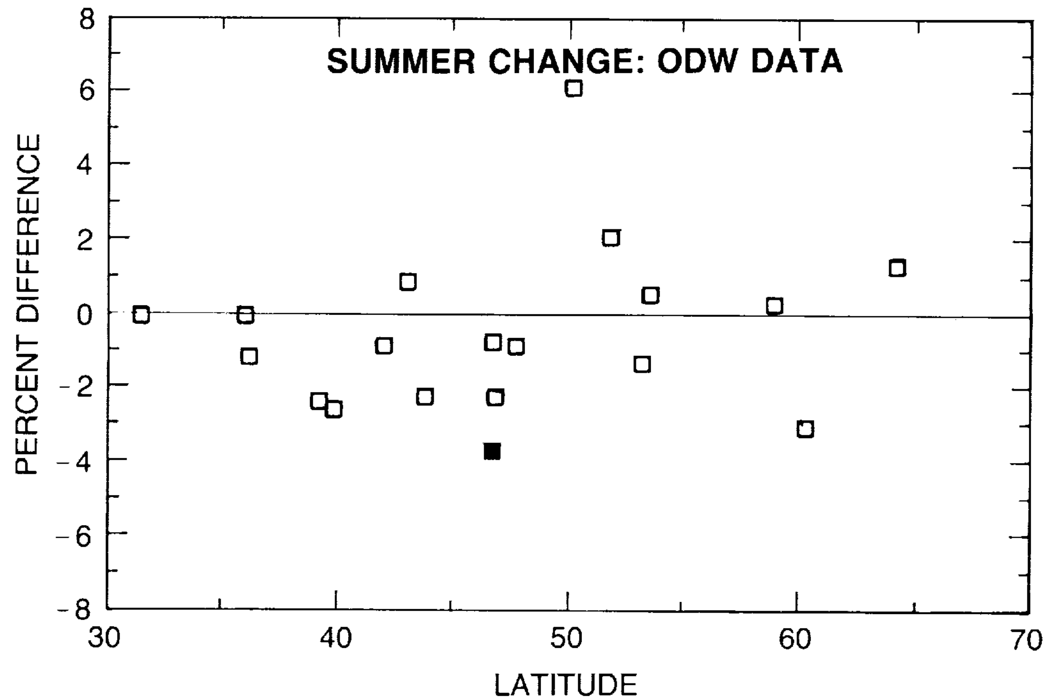


Figure 4.37 Differences in the means of the 4-month "summer" season (MJJA) for the 11-year periods from January 1965–December 1975 and January 1976–December 1986 are plotted for 19 Northern Hemisphere stations. Data are taken from *ODW.*

data published in ODW draws attention to the existence of a strong tendency for less ozone to be present during the most recent solar cycle than during the one preceding it, especially in wintertime. Because the solar cycle that peaked in 1979 was larger than that of 1969 (sunspot maximum of 165 versus 111 for the earlier maximum), any increase in ozone proportional to the cycle intensity would be greater in 1975–1986 and would therefore tend to result in positive values in Figures 4.36 and 4.37, a change opposite to the predominant observation.

The chief significance of Figures 4.36 and 4.37 is that they demonstrate an underlying change in ozone concentrations as recorded in ODW, with less ozone in the more recent years, especially in the winter months. This simple comparison of 11-year time segments provides no indications of a specific geophysical causal nature other than the apparent circumstance of larger average losses in the winter than in the summer. Subsequently, we expend most of our effort in statistical analyses of the provisionally revised set of ozone data (Section 4.3), which also shows preferential ozone losses, especially in the recent winter years (Table 4.12). However, as shown in Figures 4.36 and 4.37, this tendency is already present when the ozone data are used directly from ODW without any change. (No uncertainty analysis is presented here for these results using the data from ODW, but the statistical uncertainties given in Table 4.12 for the provisionally revised data set are approximately the same.)

4.5.3 Differences Between Published and Provisionally Revised Data

The same analysis was performed on the provisionally revised data for the same 19 stations, with the results shown in Figures 4.38 and 4.39. Comparison of these graphs with those calculated from the ODW data set discloses that, while there is more consistency within the

Table 4.12 Changes in Average Total Ozone Concentrations as Measured at Individual Dobson Stations Over the 22-Year Period 1965–1986, Inclusive. (Percentage Differences for 1976–1986 Compared to 1965–1975.)

North Latitude	Station	Winter[1]	Summer[2]	Annual
74.7	Resolute (Canada)	-1.4 ± 1.8[3]	-0.8 ± 0.9	-1.6 ± 1.0
64.1	Reykjavik (Iceland)	-2.5 ± 2.2	$+1.7 \pm 1.3$	$+0.1 \pm 2.4$
60.2	Lerwick (Scotland)	-3.8 ± 2.0	-0.9 ± 0.9	-1.6 ± 1.0
58.8	Churchill (Canada)	-4.2 ± 0.9	-1.4 ± 0.8	-2.5 ± 0.7
53.6	Edmonton (Canada)	-4.7 ± 1.3	$+0.8 \pm 0.9$	-1.8 ± 0.8
53.3	Goose Bay (Canada)	-2.4 ± 1.3	-0.1 ± 1.1	-0.8 ± 0.9
51.8	Belsk (Poland)	-3.2 ± 0.8	$+1.2 \pm 1.0$	-1.2 ± 0.9
50.2	Hradec Kralove (Czech.)	-4.7 ± 2.0	$+1.1 \pm 0.9$	-1.8 ± 1.1
47.8	Hohenpeissenberg (FRG)	-1.8 ± 1.7	$+0.2 \pm 0.9$	-1.0 ± 0.9
46.9	Caribou (Maine, US)	-2.8 ± 1.5	0.6 ± 0.8	-1.8 ± 0.9
46.8	Arosa (Switzerland)	-3.0 ± 1.3	1.1 ± 1.0	-2.0 ± 0.9
46.8	Bismarck (N.D., US)	-3.0 ± 1.2	-1.4 ± 1.0	-2.0 ± 0.7
43.8	Toronto (Canada)	-1.3 ± 1.2	-1.3 ± 0.8	-1.2 ± 0.7
43.1	Sapporo (Japan)	-0.6 ± 1.4	-0.1 ± 0.9	-0.3 ± 0.6
42.1	Vigna di Valle (Italy)	-2.9 ± 1.2	$+0.7 \pm 0.9$	-0.9 ± 0.9
40.0	Boulder (Colorado, US)	-3.9 ± 1.3	-3.1 ± 0.7	-3.3 ± 0.8
39.3	Cagliari (Italy)	-2.5 ± 1.7	-0.7 ± 1.1	-1.1 ± 1.2
36.3	Nashville (Tennessee, US)	-1.8 ± 1.4	-3.3 ± 0.7	-2.4 ± 0.8
36.1	Tateno (Japan)	-0.7 ± 1.6	-0.5 ± 0.8	-0.4 ± 0.7
31.6	Kagoshima (Japan)	$+0.9 \pm 1.7$	$+0.5 \pm 1.0$	$+0.9 \pm 0.8$
30.4	Tallahassee (Florida, US)	-1.7 ± 1.9	-0.2 ± 1.1	-1.3 ± 1.4
30.2	Quetta (Pakistan)	-1.1 ± 1.6	$+0.1 \pm 0.8$	-0.7 ± 0.8
25.5	Varanasi (India)	-0.3 ± 1.4	$+0.4 \pm 0.9$	-0.2 ± 0.9
19.5	Mauna Loa (Hawaii, US)	-1.5 ± 1.7	0.0 ± 0.6	-0.9 ± 0.6
	30°N to 60°N	-2.5 ± 1.0	-0.5 ± 0.6	-1.4 ± 0.7
	40°N to 60°N	-3.0 ± 0.9	-0.4 ± 0.5	-1.6 ± 0.6
	30°N to 39°N	-1.2 ± 1.5	-0.7 ± 1.0	-0.8 ± 1.1

[1] Winter = Dec., Jan., Feb., March
[2] Summer = May, June, July, August
[3] Resolute is above the Arctic Circle, so that only less accurate moonlight measurements are available during actual winter. These "winter" data are the averages for the months of March and April.

corrected data set, there are no real differences in overall pattern; the wintertime losses are apparent in both Figures 4.36 and 4.38. The values given in Table 4.12 also refer to the provisionally revised data set. However, the calculations have been performed in two slightly different ways. In Table 4.12, the data period is from December 1964–November 1986. The choice of December 1964 instead of January 1965 as starting date was invoked for seasonal consistency when it became apparent that combination of months into "winter" (DJFM) and "summer" (MJJA) groupings became desirable. In this sense, the data set for Table 4.12 begins with the winter of 1964–1965. In the other, the calendar years 1965 through 1986 were used. Only minor

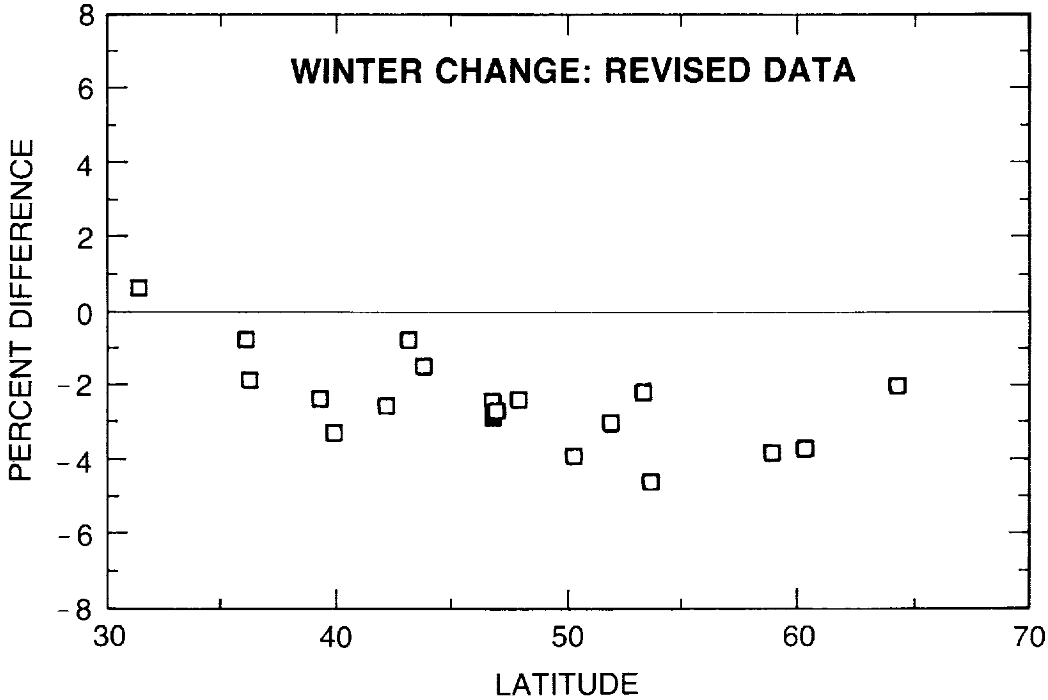


Figure 4.38 Differences in the means of the 4-month "winter" season (DJFM) for the 11-year periods from January 1965–December 1975 and January 1976–December 1986 are plotted for 19 Northern Hemisphere stations. Provisionally revised data are used.

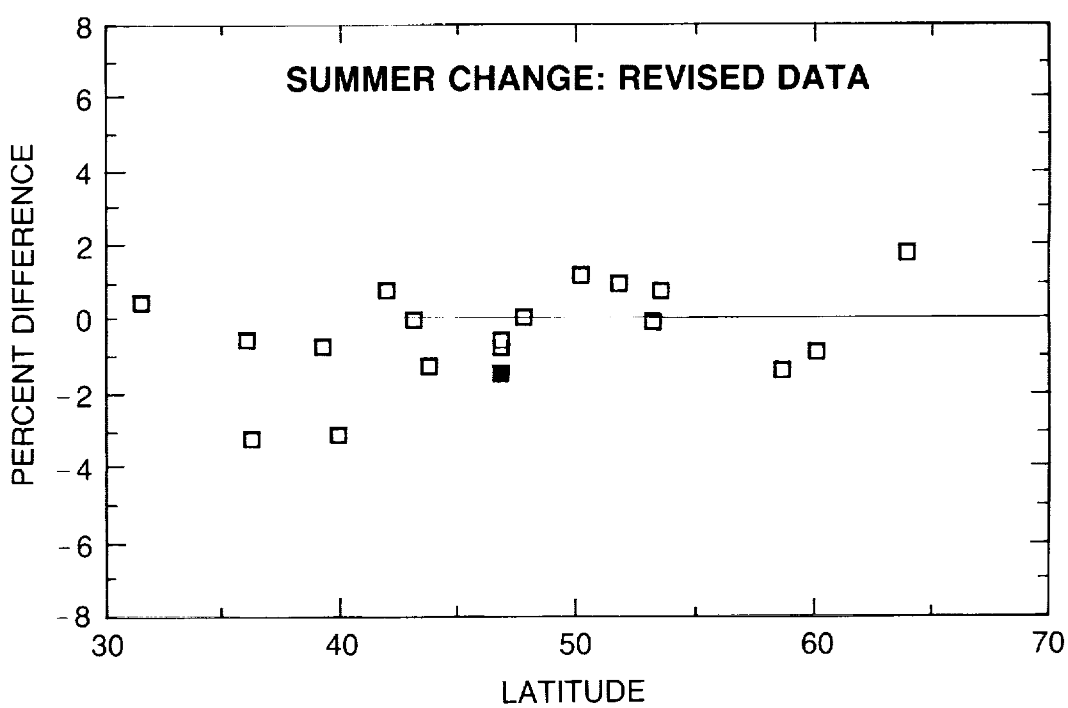


Figure 4.39 Differences in the means of the 4-month "summer" season (MJJA) for the 11-year periods from January 1965–December 1975 and January 1976–December 1986 are plotted for 19 Northern Hemisphere stations. Provisionally revised data are used.

numerical differences of no significance are found when December 1986 replaces December 1964 and the division point for the two 11-year periods is changed from December 1, 1975, to January 1, 1976.

Although there were no real differences in the pattern of a marked wintertime loss and mixed indications of summertime change found in each data set, there were major changes at particular stations. There is strong evidence of incongruities in many of the individual stations' published records, and there are sound physical reasons for all of the corrections to the data. Thus, only the provisionally revised data have been analyzed in greater detail; the results are presented and discussed in Section 4.6.

4.5.4 Bismarck: A Single Station Analysis

The complete time series statistical analyses of the provisionally revised data sets are discussed in Section 4.6. However before discussing the details, it is worth looking at the results of the analyses from a single station—Bismarck—to develop an understanding of the different phenomena that can affect total ozone. The statistical model used is described in full in Section 4.6 and will not be discussed here. The Bismarck data are marked with solid squares in Figures 4.36 to 4.39.

The daily total ozone data for Bismarck as reported to ODW covered the period from January 1963–December 1986, and are combined in ODW into 288 monthly averages. Some recalibration corrections were applied to these data to obtain the provisionally revised set of monthly average ozone values given in Appendix 4.A (i) of this chapter. When the complete 24-year data set is divided into two 12-year periods, January 1963–December 1974 and January 1975–December 1986, a decline in average ozone concentration is indicated in the second period relative to the first period, with the largest declines in the winter months, as shown in Figure 4.40. This simple observation stands out in both the ODW (Figure 4.40a) and provisionally revised (Figure 4.40b) data sets. The chief effect of the data recalibrations is (in this instance) to shift most monthly differences to less negative values without affecting the magnitude of the winter–summer spread.

The statistical assumption behind the calculations in Figure 4.40 effectively assumes that the ozone values for each calendar month are independent of one another so that the full time series can be divided into 12 separate series (i.e., all January values, etc.) without any loss of information. Phenomena such as the solar cycle, the QBO, and the atmospheric nuclear bomb tests around 1960, all of which are thought to affect total ozone, are ignored. This assumption of independence is not justified because the full time series is autocorrelated: i.e., the ozone concentrations in 1 month are influenced by the ozone concentrations in the preceding month. A more rigorous statistical analysis should consider the data set as a whole and allow for any effects on total ozone from known, or hypothesized, physical sources. Because its magnitude is clearly very large, further consideration of the complete data set normally begins with description of the seasonal cycle.

Time series statistical modeling of this data set can be most easily understood by considering the consequences from the successive inclusion of the various terms mentioned in the model description, although, in practice, many other model permutations were also calculated. The first step is to fit to the data a model containing only the seasonal term. After removal of the seasonal cycle, the residual series was then tested for autocorrelation and was found to exhibit significant autocorrelation (about 0.2) for lags of 1 month and 2 months. None of the correlations

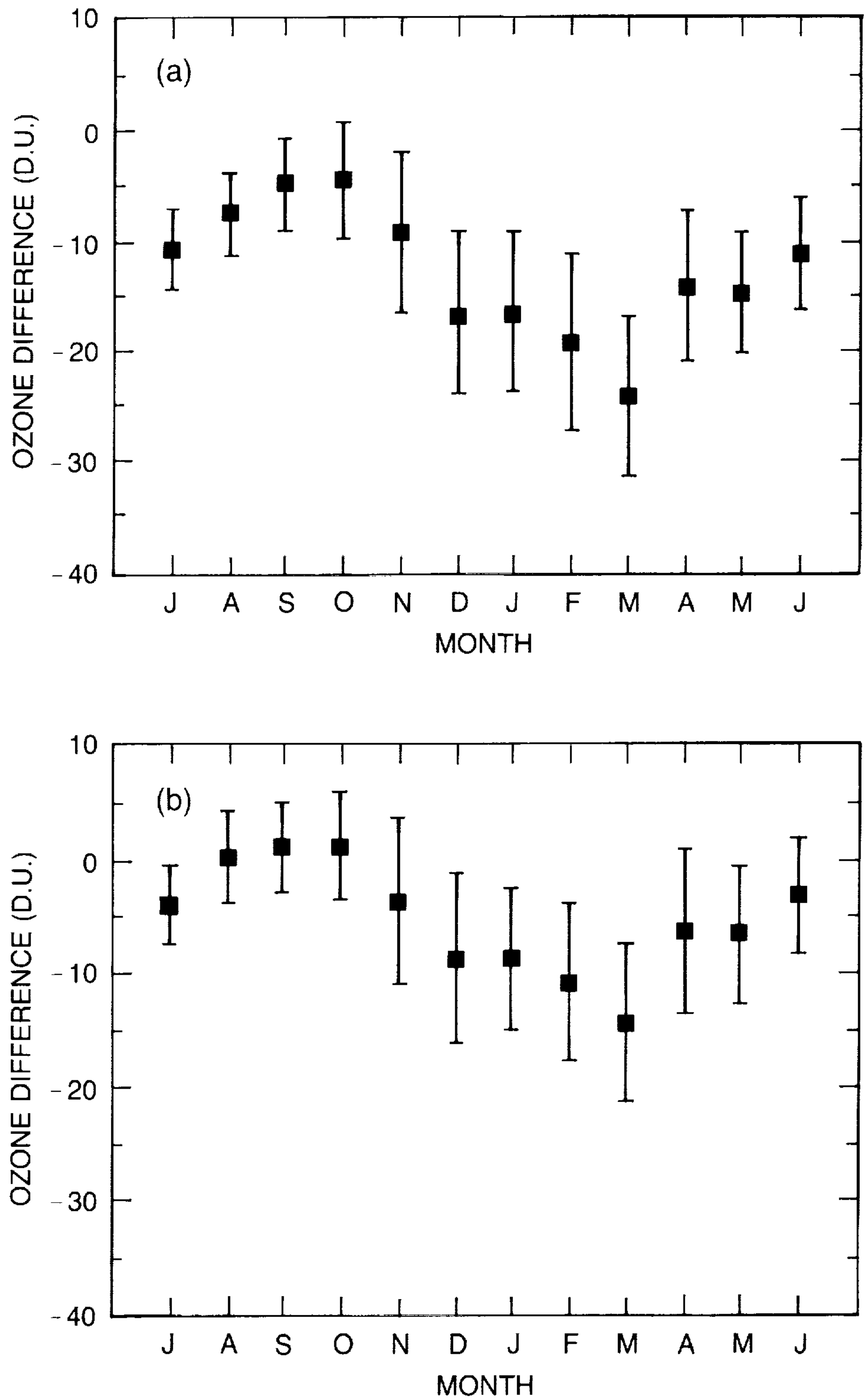


Figure 4.40 Changes in Monthly Average Ozone Total Amounts at Bismarck, North Dakota, Between January 1963–December 1974 and January 1975–December 1986. Using (a) the data as published in *Ozone Data for the World* and (b) the provisionally revised data, with monthly average corrections for instrument calibrations applied to the data recorded in *Ozone Data for the World*.

for 3 months or longer was statistically significant (all <0.1). When the terms for the autocorrelation were added to the noise model, the residual variance decreased substantially, and the autoregressive factors in the autocorrelation model were calculated to be 0.30 (1 month) and 0.16 (2 months). All subsequent calculations described below have included the autoregressive coefficients for 1 month and 2 months as part of the basic statistical model. The meteorological observations of the persistence of weather patterns are the underlying geophysical reason for the positive autocorrelations with lags of 1 month and 2 months in the monthly average ozone values.

The data were next tested for the importance of the QBO in its correlation with the ozone abundance over North Dakota. The 50 millibar Singapore wind velocity was used to describe the QBO, with westerly winds arbitrarily designated as positive. When the QBO was considered in coincidence with the total ozone over Bismarck, the multiple regression calculation showed a QBO coefficient of -8.0 ± 3.6, a decrease of 8 DU from minimum to maximum in the QBO, versus a yearly ozone average of about 350 DU. (The negative sign indicates that there is an anticorrelation between total ozone and the Singapore wind speed measured from the westerly direction; all quoted uncertainties in this section represent one standard deviation.) When tested for ozone concentrations lagging 6 months after the tropical wind speed variations, the regression coefficient was very much smaller, + 1.0 ± 3.8 DU minimum-to-maximum. Further calculations with the Bismarck data set were carried out with the zero delay QBO correlation.

The next statistical test was the inclusion of the nuclear bomb test parameter. This parameter has been scaled linearly to the model results obtained with the Lawrence Livermore National Laboratory 2-D atmospheric model using the ozone changes calculated for the latitude appropriate to the station). The joint solution for Bismarck with QBO and the bomb tests maintained the QBO parameter as -8.0 ± 3.5 DU and indicated a nuclear effect with a coefficient of -0.44 ± 0.49. The magnitude of the ozone change associated with the aftermath of nuclear testing is given for each month by the product of the coefficient and the model predictions of loss for the latitude band containing the Bismarck station. The negative value of the coefficient indicates a loss of ozone 44 percent as large as calculated in the model, but with an uncertainty (±49%) large enough that a range of values from zero effect to the full magnitude of loss expected from the model is still plausible. Because the data set for Bismarck does not begin until 1963, past the time period for the maximum ozone depletion effect expected from nuclear testing, the nuclear test coefficient is never of more than marginal significance for this data set. Greater statistical significance could be obtained only if data were available for earlier periods, preferably encompassing the entire period of atmospheric nuclear bomb testing.

The multiple regression was then repeated with the further inclusion of a smoothed sunspot series representing the parameter for the 11-year solar cycle, with the results:

QBO	–7.8 ± 3.4 DU/cycle
Nuclear	–0.21 ± 0.49 times the model calculated depletions
Solar cycle	+ 6.3 ± 3.3 DU.

The solar cycle coefficient implies that ozone readings at Bismarck were about 6 ± 3 DU (about 2 ±1%) higher in 1979–1980 than they were during the adjacent sunspot minima in 1975 and 1986. All of these coefficients represent the statistical fit on the assumption that no long-term trends exist in the total ozone data set.

The basic calculation was next extended with the inclusion of a linear yearly ramp function for which the long-term ozone concentrations were initially assumed to be constant, but then were allowed to vary after some fixed date, with the slope of this ramp determined by statistical best-fit techniques. Furthermore, the yearly ramp assumes that (a) any ozone variations that occurred after the onset of the ramp were year-round in nature, with no seasonal or monthly differences and (b) the variation is linear with time. These statistical results are the most comparable to previous calculations with the data from Bismarck, differing only in the date at which the ramp begins. Three different ramp starting dates were tested: January 1965, January 1970, and January 1976, with linear ramp coefficients k_{65}, k_{70}, and k_{76}, respectively; the coefficients determined for these three ramps are given in Table 4.13. Because the data set began only 2 years earlier, the value of the ramp coefficient k_{65} is almost the equivalent of a simple linear regression to the data.

Table 4.13 Parameter Values for Several Linear Ramp Statistical Calculations With Ozone Data from Bismarck.

Start of Ramp	1965	1970 (i)	1970 (ii)	1976
Parameter				
QBO	8.2 ± 3.2	8.6 ± 3.2	7.9 ± 3.0	8.1 ± 3.2
Solar	5.5 ± 3.5	5.3 ± 3.5	5.6 ± 3.1	5.5 ± 3.5
Nuclear	−0.92 ± 0.52	−0.70 ± 0.48	−0.67 ± 0.40	−0.50 ± 0.46
Trend (k)	−0.48 ± 0.18	−0.53 ± 0.20	−0.55 ± 0.18	−0.83 ± 0.33
Change in O_3 concentration, 1963–1986 (Dobson Units)	−10.6 ± 4.0	−9.0 ± 3.4	−9.4 ± 3.1	−9.1 ± 3.6

The units for these coefficients are: QBO—Dobson Units for a +40 meter/sec shift in wind direction from easterly to westerly (approximately the average shift at 50 mb from maximum easterly to maximum westerly direction; Solar—Dobson Units for a +150 change in sunspots, approximately the increase that occurred between solar minimum in 1975–1976 and solar maximum in 1979–1980; Nuclear—the numerical coefficient multiplied onto the calculated ozone depletion from the LLNL 2 D model; Trend—in Dobson Units per year (e.g., -0.48 ±0.18 DU/yr); for 22 years, from 1965–1986, this coefficient signifies a total ozone change of 22k, or -10.6 ±4.0 DU.

The column 1970 (i) contains the results using an autocorrelated noise term with 1- and 2-month lags, while column 1970 (ii) contains those for a noise term including just a 1-month autocorrelation coefficient.

An amplifying comment about the calculation of a "yearly ramp coefficient" is appropriate at this juncture. The natural variability of monthly average ozone values at Bismarck (and other north temperate and polar stations) is substantially larger in winter than in summer, as illustrated in Figure 4.34 for Arosa. Overreliance on fitting the highly variable winter data is normally suppressed by weighting each of the data points in the residual series according to the natural standard variation of the calendar month represented by the residual.

The coefficients for the QBO and the solar cycle are largely unaffected by the inclusion of ramps. This finding is typical of almost all of our calculations with the various stations. The apparent general conclusions from statistical modeling of the Bismarck data with the assumption of a constant ramp coefficient throughout the year are (a) a QBO effect of about 8 ± 3 DU in all calculations, (b) a year-round decrease of 9 ± 3 DU in total ozone at the beginning of 1987 relative to the concentrations observed prior to 1965, prior to 1970, or prior to 1976, (c) a solar cycle increase of about 5.5 DU for 1979–1980 versus the minima on either side, and (d) an appreciable effect from nuclear bomb testing in the early 1960's, though the significance is not statistically robust because the Bismarck data start in January 1963, roughly coincident with the maximum predicted bomb test effect. Only minor numerical differences were found for the two 1970 ramp calculations with only 1-month autocorrelation, or with both 1- and 2-month autocorrelations included.

Exceptions to the general statement that QBO and solar cycle coefficients are generally not affected by the inclusion of ramps can be found with stations for which the record is short. The correlation between the ramp and the solar cycle is then larger, but the QBO coefficient usually remains stable in these cases. The correlation of the QBO and solar cycle parameters is low—less than 0.1 in all the analyses for Bismarck and similarly low for other stations. No attempt has been made in this study to investigate the possibility that the QBO effect on total ozone might be different at different stages of the solar cycle. An analogous finding has been reported for their joint effect on stratospheric temperatures (Labitzke and Van Loon, 1988). By contrast, the nuclear bomb test parameter is fairly strongly correlated with the ramp and solar cycle parameters. For the 1963–1986 record at Bismarck, the correlations for the model, in which all three geophysical phenomena were included, are:

	Bomb Test Parameter (a) Ramp	Correlation With (b) Solar Cycle
Yearly Ramp Starting in		
January 1965	0.53	0.29
January 1970	0.40	0.31
January 1976	0.26	0.31

Addition of the terms describing these geophysical phenomena which may affect total ozone does change the noise term in some cases, nearly always simplifying it. As more of the variability in the data is explained by the inclusion of such terms, the noise is reduced and its structure should become clearer. In the case of Bismarck for the model in which the QBO, the solar cycle, the nuclear bomb testing and a linear ramp starting in January 1970 are all included, the autocorrelation factors are calculated to be 0.25 ± 0.06 for the 1-month lag and 0.11 ± 0.06 for the 2-month lag. These factors are essentially the same as those (0.30, 0.16) found without any of the geophysical parameters included. When the noise term was changed so that it included only the 1-month autocorrelation factor, little change was found in the statistically calculated geophysical parameters. In the results quoted in this chapter, the better noise term (i.e., 1-month or 2-month autocorrelation) for that particular model is used.

However, the assumption of a year-round constant loss of ozone, either in DU or in percentage of total ozone, is not consistent with the general appearance of the Bismarck data as graphed in Figure 4.39, which indicates substantially larger losses in the winter months, or of the data from many other Northern Hemisphere stations graphed earlier in Figures 4.36 and 4.38. Alternative analyses for trends have been calculated with a model that provides each calendar month with a separate linear regression coefficient after a certain date—i.e., 12 separate ramp coefficients. These calculations have also been carried out in conjunction with most permutations of the three geophysical terms. In this model, each month is treated as independent with respect to the pattern of any changes in average amount of ozone (but still with autocorrelation for 1 month and 2 months); then the values of these 12 ramp coefficients can be determined, together with their standard statistical uncertainty. The results from models with ramps beginning in 1970 and 1976 are summarized in Table 4.14. The total data set includes 24 years, or slightly more than two solar cycles. We have calculated these ramp coefficients using the entire 24 years, and with the final 22 years (i.e., two solar cycles) beginning in January 1965. In the latter case, any effects on total ozone from nuclear bomb testing are sufficiently in the past that we have not included the nuclear parameter in the linear regressions.

Table 4.14 Statistical Analyses of Ozone Data From Bismarck.

Coefficients of various analyses that allow for differing monthly trends and including some or all of the variables for the QBO, the solar cycle, and the predicted nuclear depletion. Data for 24 years, from January 1963 to December 1986.

JA70	−1.10 ± .53			−1.10 ± .51	−1.25 ± .51
FE70	−1.08 ± .57			− .98 ± .54	−1.19 ± .54
MA70	−1.53 ± .55			−1.51 ± .53	−1.73 ± .53
AP70	− .73 ± .53			− .72 ± .51	− .92 ± .52
MY70	− .78 ± .48			− .79 ± .46	− .96 ± .46
JN70	− .56 ± .37			− .59 ± .36	− .73 ± .36
JL70	− .37 ± .30			− .41 ± .29	− .53 ± .29
AU70	− .09 ± .33			− .14 ± .32	− .25 ± .32
SE70	+ .30 ± .30			+ .23 ± .29	+ .12 ± .30
OC70	− .02 ± .43			− .09 ± .41	− .22 ± .41
NO70	− .26 ± .60			− .31 ± .58	− .46 ± .58
DE70	− .69 ± .57			− .71 ± .55	− .86 ± .55
QBO				−6.74 ±2.87	−7.20 ±2.82
SUNS				+7.42 ±2.90	+5.54 ± 2.97
NUC					− .80 ± .38
JA76	−1.84 ± .82	−1.81 ± .81	−1.85 ± .79		−1.95 ± .79
FE76	−1.09 ± .89	−1.05 ± .87	−1.01 ± .85		−1.16 ± .85
MA76	−2.28 ± .86	−2.22 ± .85	−2.27 ± .83		−2.42 ± .83
AP76	−1.39 ± .84	−1.35 ± .83	−1.40 ± .81		−1.54 ± .81
MY76	−1.43 ± .76	−1.40 ± .74	−1.45 ± .73		−1.58 ± .73
JN76	− .96 ± .59	− .96 ± .58	−1.01 ± .57		−1.11 ± .57
JL76	− .62 ± .47	− .65 ± .47	− .69 ± .46		− .78 ± .46
AU76	− .40 ± .53	− .45 ± .52	− .48 ± .51		− .57 ± .51
SE76	+ .42 ± .48	+ .34 ± .47	+ .32 ± .46		+ .23 ± .46
OC76	− .04 ± .68	− .14 ± .67	− .16 ± .65		− .25 ± .65
NO76	− .48 ± .95	− .56 ± .94	− .58 ± .92		− .68 ± .91
DE76	− .92 ± .90	− .98 ± .89	− .97 ± .87		−1.08 ± .87
QBO		−7.36 ±3.28	−6.86 ±2.84		−7.20 ±2.85
SUNS			+7.45 ±6.13		+6.14 ±3.00
NUC					− .55 ± .37

The top row contains the analyses where the ramps start in 1970, while the bottom row has those for 1976. JA70 is the trend coefficient for January, FE70 that for February, etc., where the ramp starts in 1970. Similarly, for 1976 there are JA76, FE76, etc. The units are DU yr^{-1}. The QBO coefficient has units of DU per (40m s^{-1}), and the solar cycle (SUNS) coefficient is in DU per 150 sunspots. The nuclear coefficient (NUC) should be used as a multiplying factor to the function shown in Fig. 4.44.

Several comments can be made about the various statistical treatments of the same data set:

- The coefficients for the solar cycle and QBO contributions to ozone change are not significantly altered by the introduction of either yearly or monthly trend coefficients, or by the choice of 1965, 1970, or 1976 for the beginning of the ramp.

- The yearly average ozone loss calculated with monthly trend coefficients is somewhat larger than calculated from a yearly trend coefficient. The chief cause for this difference is that each month is evenly weighted in the average of the monthly trends, while the summer months, with their smaller natural standard deviation and smaller ozone changes, are more heavily weighted in the determination of an overall trend fitted to all months simultaneously.

- The indicated change in ozone for individual months is approximately the same for trends fitted since 1970 and 1976, indicating that most of the change has occurred following 1976.

4.6 DETAILED ANALYSIS OF THE PROVISIONALLY REVISED GROUND-BASED DATA

In most Temperate Zone locations, the total ozone column concentrations are observed to vary regularly with the season, peaking about the beginning of spring and reaching a minimum in early autumn. Any statistical model used to treat total column ozone data must satisfactorily allow for this seasonal cycle before it can determine whether any other significant pattern is present in the data. Most statistical analyses (Angell and Korshover, 1983b; Angell, 1987b; Bloomfield et al., 1983; Hill et al., 1977; Oehlert, 1986; St. John et al., 1981, 1982) remove the seasonal cycle by converting the monthly averages into residuals representing the deviation of the monthly average in an individual year from the long-term average for that given month. This procedure assumes a constant seasonal cycle over the years and produces a series of 360 numbers for a 30-year period, or 264 for a 22-year period. These statistical treatments then deal with the data from each station as a sequence of consecutive "deseasonalized" deviations from long-term monthly averages. Reinsel et al. (1981, 1981, 1987, 1987) use a sine curve and its harmonics to describe the seasonal cycle rather than the monthly averages, but the underlying assumption is still that the seasonal cycle does not change.

In either case, the next step in the previous statistical modeling has been to assume that any secular change introduced into the ozone pattern would have a constant effect over the year, so that it can be described by a single trend coefficient. Because this approach has been applied to the monthly average ozone data in numerous earlier publications, it has also been applied here to all of the individual station data. Summaries of the yearly ramp coefficients calculated for these stations are given in the bottom lines of Appendices (a)–(f) under B(i). However, these yearly trend coefficients are now deemed inappropriate for description of the ozone variations actually occurring in the atmosphere.

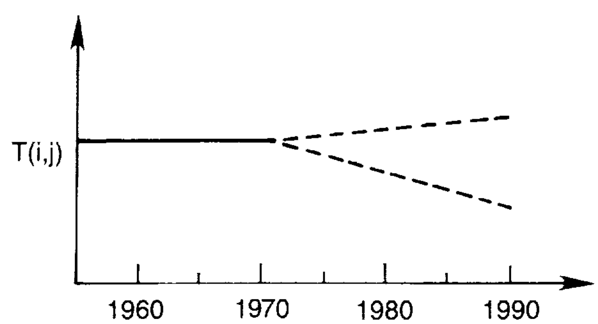
4.6.1 Method of Analysis

Concern for the possibility that man's activities might be affecting the concentrations of stratospheric ozone has continually raised the question of whether any recent change has been detectable in measurements of total ozone. The customary approach has been to ask whether changes have occurred during the past decade or two, rather than uniformly over the entire period of record. The most frequent test assumption has been the division of the data record into an earlier portion, assumed to have been constant, and a later portion to which a straight line has been fitted, joining smoothly to the constant from the early record and with the slope of the second part determined by least-squares fit to the data. This straight line, with its slope as a parameter to be fitted, has been designated as a "ramp," and the resultant combination of a constant value for the early time period and a later, usually sloped, section has been described colloquially as a "hockey stick" function (see Figure 4.41). Such a mathematical function makes no pretense of having direct geophysical significance, but is simply one approach to the question of whether or not the best statistical fit to the entire data set indicates changes from the long-term average over the most recent period. The sign of the change is not fixed, and calculations have been presented that have + signs for the ramp with certain stations, indicating more total column ozone in recent measurements than earlier, and - signs for other stations, indicating a loss of ozone in the more recent data.

A less frequently used alternative to the ramp formulation has been the application of a hypothetical trend of ozone versus time based on some approximation of the geophysical circumstances, usually from an atmospheric model. In this situation, the shape of the modeled ozone variation versus time has been assumed to be fixed, but its magnitude has been treated as a free parameter, allowed even to assume the opposite sign from that implied by the geophysical simulation. The geophysical utility of such a free parameter is obviously marginal when the fit to

DESCRIPTION OF TREND

a) MONOTONIC, YEAR-ROUND. ('HOCKEY STICK')



b) SEPARATE 'HOCKEY STICK' MODELS FOR EACH CALENDAR MONTH

$$\left.\begin{aligned} T(i,j) &= \sum_{L=1}^{12} k_j \cdot (i - i_0) \cdot \delta_{jL} \\ &= k_j\,(i - i) \end{aligned}\right\} \quad i > i_0$$

$$\text{AND } T(i,j) = 0 \qquad i \leq i_0$$

Figure 4.41 Description of trend (a) monotonic, year-round (hockey stick) and (b) separate hockey stick models for each calendar month.

the available data indicates that the sign of the change is incorrect—for example, if ozone were actually found to be increasing when ozone depletion has been calculated in an atmospheric model. In such a circumstance, the value of the parameter for the magnitude of the assumed functional form has no more significance than the value of a ramp coefficient—neither has any direct geophysical significance.

Another important difficulty that exists with this approach of using a geophysically based functional form taken from an atmospheric model calculation has been the lack of constancy in the predicted patterns of ozone change with improved measurements of pertinent parameters. The most frequent changes affecting the time pattern of ozone concentration in atmospheric modeling have originated with improvements in the chemical and photochemical bases used for the modeling, and in the expansion of the photochemical model itself from the 1-D models of the 1970's to the 2-D models of the 1980's: a new compound is proposed for inclusion, a new chemical reaction is proposed, a reaction rate constant is reevaluated, the time pattern is found to vary with latitude, etc. Over the past 10 or 15 years, in a typical atmospheric model the calculated ozone trend versus time of ozone concentrations has usually been nonlinear and often not even monotonic. Model improvements have often caused changes in the magnitude of predicted long-term ozone depletion and have usually been widely noted, but the patterns of ozone variation with time have also been altered in the process. These apparent changes in total ozone versus time have had many different functional forms over the past 14 years, including several that have called for slight minima or maxima in the ozone changes during the 1970's and 1980's. Without consistent agreement about the geophysically expected shape of ozone variation with time, each such statistical calculation would become obsolete with the next change in the evaluation of reaction rate constants. Fundamentally, the reliance on ramp coefficients fitted to the external data without any preconceived geophysical model simply tries to answer the question of whether variations in ozone concentrations are occurring in the environment, quite independent from the current state of atmospheric model calculations.

The procedure adopted in most statistical calculations until now has been the determination of a single linear ramp coefficient from the accumulated series of all of the monthly residuals. Implicit in this choice of modeling is the assumption that any ozone variation that may have taken place from the long-term averages has occurred consistently throughout the year. However, this approach will be misleading if the basic assumption is not correct: if the perturbation to the previous ozone pattern has a seasonal dependence of its own, then the assumption that the perturbation has equal effect over the entire year can produce substantial distortion in attempts to interpret the data. The distortion is more pronounced when the variability (and the statistical weighting) of the data is itself seasonally dependent, as is the case with total column ozone measurements at most Temperate Zone stations, for which the ozone distributions exhibit larger variances in the spring than in the autumn, as shown for Arosa in Figure 4.34. The situation can be further illustrated with a hypothetical two-component model.

Suppose (a) that the ozone concentrations in a particular location followed a steady pattern during the months from April through September for 20 years without change and (b) that the ozone concentrations from October through March followed a steady pattern for 10 years, and then declined linearly for the next 10 years with a ramp coefficient -k. If these two hypothetical components are equally weighted, then the resulting data fit of a single yearly ramp will produce constant values for the first 10 years, and then a declining ramp for the next 10 years, with a slope that is the direct average of the ramp for (a)—i.e., zero—and -k for (b)—and will have the value -k/2. If either of the hypothetical components has a smaller natural variance and is weighted accordingly, then minimization of the total variance will influence the composite ramp toward the slope of the component with this smaller variance. In the hypothetical extreme that one of the components is known with infinite accuracy and the other is not, then the composite ramp will fit the accurately known component and force this shape upon the other data set. A few years ago, there were no geophysical reasons that led to the expectation that perturbations to total column ozone would have equivalent effects throughout the year or, conversely, that they would not. In this situation, the assumption of a single ramp coefficient equally applicable throughout the year is the simplest to apply, and is the procedure that has been widely used. Such statistical calculations also produce results most comparable to the predictions of 1-D photochemical models because their structure does not include information on possible seasonal or latitudinal variations. However, when the actual data disclose seasonally dependent changes in the magnitude of perturbations over time, as in Figures 4.36–39, the statistical model with a single ramp coefficient applicable throughout the year is no longer an appropriate model for treatment of the data.

A much more elaborate model, which allows for the possibility of different degrees of change on a monthly basis, replaces the single yearly ramp coefficient with 12 separate coefficients, 1 for each month. An approximation to the expected results can be obtained by separating the residuals into a series for each month and then calculating the appropriate ramp coefficient for each of the 12 separate data sets. Such separation into 12 series does not take into account the existence of short-term autocorrelation and can produce misleading error estimates. An alternative calculation can be performed on the complete data set with autocorrelation included and 12 separate ramp coefficients. The latter procedure has been used regularly in our calculations.

One interesting result from this monthly component evaluation is that strong differences are found to exist among the ramp coefficients, as expected from the observations of seasonally dependent differences in Figures 4.36–39. Many of the ramp coefficients are found to be strongly negative, others zero, and some positive. In addition, the yearly ramp coefficients are not approximately equal to the average of the 12 monthly coefficients, but are often quite different from the average.

Various possible influences on total column ozone exist that should be accounted for while determining a trend. Four important processes have been identified that can lead to changes in total column ozone, but that are not part of a long-term trend. The largest such effect is the seasonal variation caused by the atmospheric circulation. All data treatments begin with a method or function to account for this. Another known, cyclic process is the variation in the intensity for some wavelengths of solar ultraviolet radiation as part of the 11-year solar cycle. Because these wavelengths correspond to UV energies large enough to photodissociate O_2 and thereby create more O_3, a plausible connection exists by which total ozone is correlated with these solar cycles. Probably the best known manifestation of the solar cycle is the waxing and waning in the numbers of sunspots, for which accurate records are available for the past 250 years. The series of measurements at an individual station can be tested for the importance of a solar cycle effect through inclusion of a term attempting to mimic the response of the atmosphere to these solar variations. In our calculations, we have used the running 12-month average of sunspots to provide the functional form of any atmospheric response, as shown in Figure 4.42. (Sunspot data are provided by the National Geophysical Data Center, Boulder, Colorado.)

A set of related geophysical phenomena exists that includes the shifting geographical origin of the Asian monsoons; the differences in atmospheric pressure over tropical locations such as Darwin, Australia, and Tahiti; and the approximately biennial change of the direction of the zonal winds at altitudes of 15–30 km in the Tropics. The tropical zonal winds in the lower

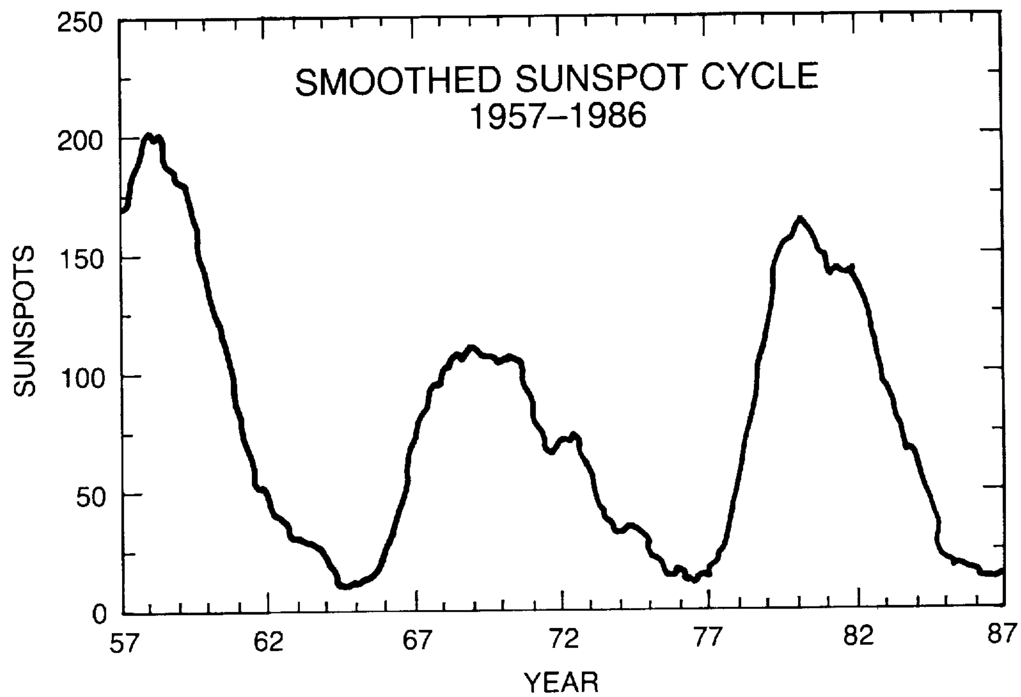


Figure 4.42 Smoothed sunspot cycle 1957–1986

stratosphere, for example, will tend to blow from a westerly direction for about a year, and then switch to an easterly direction for the following year, etc. The actual time period for a complete cycle in these tropical wind directions is somewhat irregular, averaging about 26–27 months, and is designated by the term quasi-biennial oscillation, or QBO (Reed et al., 1961). The amounts of total ozone (and the stratospheric temperatures) over particular measuring stations have long been known to have a cyclical variation in correlation with the QBO. In our statistical modeling, we have included the QBO through a term proportional to the zonal wind velocity at 50 millibars pressure (about 20 km altitude) over Singapore, as shown in Figure 4.43. The Singapore data are chosen simply because they provide an available, consistent, numerical set. Comparable changes take place at all longitudes within a few days as the winds reverse throughout the equatorial zone. However, the directional wind shift does not occur simultaneously at all altitudes, but works downward from above, so that the shift at the 30 mb level is followed in a month or two at 50 mb and then, after another delay, at 100 mb, etc. The QBO parameter could also be based on 30 mb or 100 mb wind velocities, with corresponding changes in the phase relationship between ozone and the QBO. The correlation of ozone changes with the QBO is known to be delayed at higher latitudes, and we have allowed for such delay by testing two ozone–QBO correlations for each station: no delay versus a lag of 6 months in the ozone response to a QBO shift.

Finally, nuclear bomb tests conducted in the atmosphere during the late 1950's and early 1960's are a known source of nitrogen oxides, which can change ozone concentrations in the stratosphere. The time variations of the proxy variable accounting for such changes has been shaped from the time behavior of the ozone changes at each latitude calculated with the LLNL 2-D atmospheric model, as shown in Figure 4.44. The magnitude of the coefficient for the nuclear bomb testing is then determined statistically.

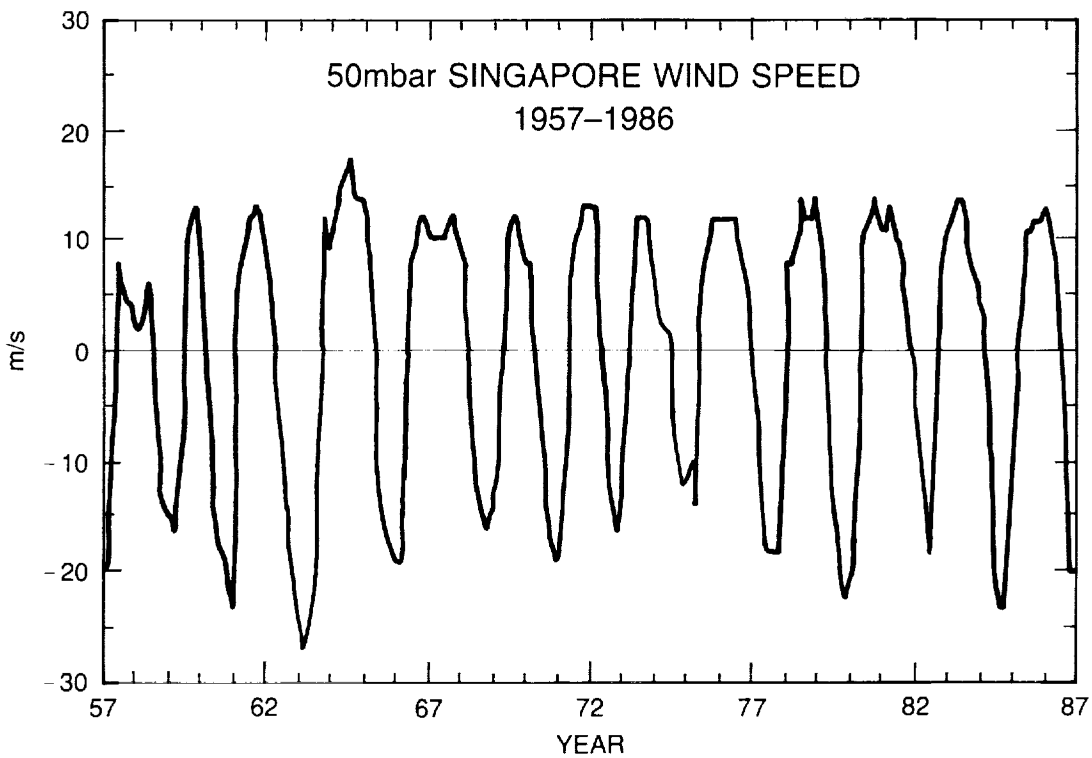


Figure 4.43 50 mbar Singapore wind speed, 1957–1986

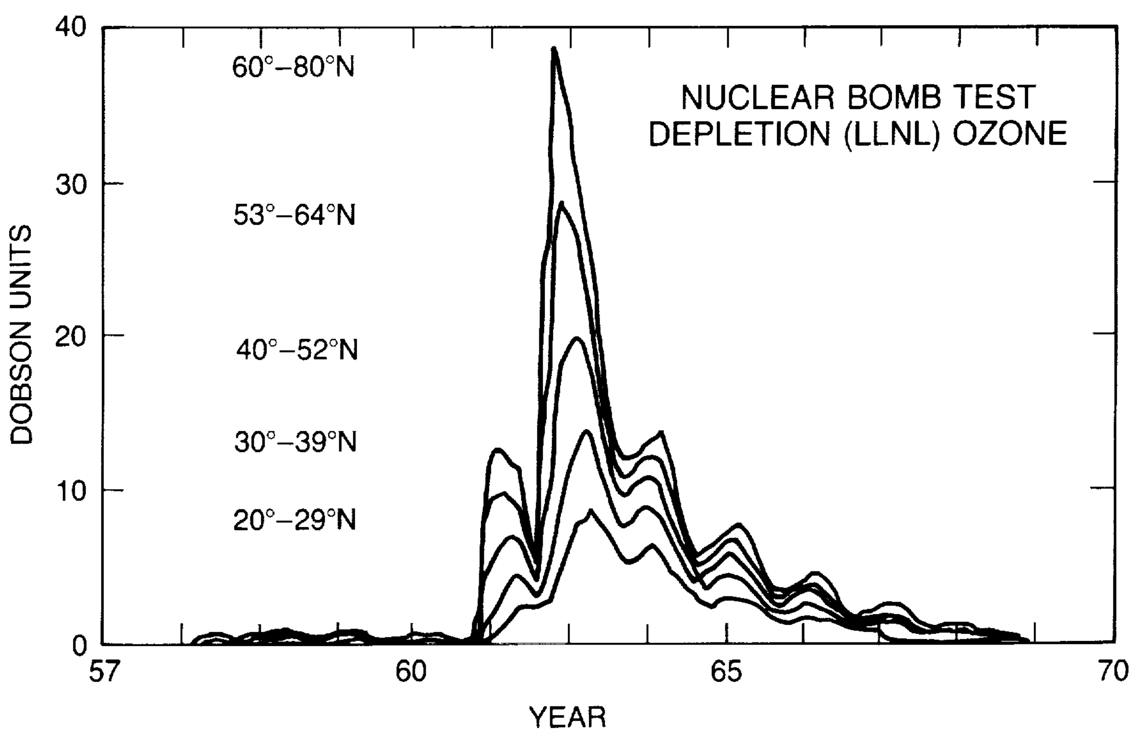


Figure 4.44 Ozone decreases caused by the atmospheric nuclear bomb tests as calculated by the 2-D LLNL photochemical model for five different latitude bands.

4.6.1.1 Description of the Statistical Model

The approach used in the analysis of the revised data has been to fit to the ozone data a model of the general form

$$oz(i,j) = S(i,j) + X(i,j) + T(i,j) + N(i,j).$$

The term $S(i,j)$ describes the seasonal behavior; $X(i,j)$ is a term that describes other phenomena (geophysical in origin) that can affect total ozone; $T(i,j)$ is a term that describes a possible long-term trend in total ozone; $N(i,j)$ is a term that describes the noise; i denotes the year; and j denotes the month. The overall approach is thus similar to that of Reinsel et al. No detailed comparisons are made here with the results from previous studies.

The seasonal variation is accounted for by allowing each month's long-term mean to be determined separately:

$$S(i,j) = \sum_{l=1}^{12} \mu_j \bullet \delta_{jl}$$

where δ_{jl} is a delta function that allows only 1 month's value to be nonzero for each reading. The chief advantage is that no predetermined functional form is forced on the data. (Note that deseasonalization of the data prior to analysis by subtracting the appropriate long-term monthly mean from each monthly value still eliminates the same number of degrees of freedom.)

The three phenomena that are thought to affect total ozone and that are included in this analysis of total ozone data are the QBO, the solar cycle, and the bomb tests in the late 1950's and early 1960's. The proxy variables used are, respectively:

- The 50-mbar east/west wind velocity at Singapore.
- A smoothed series of sunspot numbers made up of the averages of each pair of consecutive 12-month running means.
- The effect of the bomb tests on total ozone calculated by the 2-D LLNL photochemical model of Wuebbles et al. In these analyses, the bomb test effect is taken as the difference between a calculation that included the effects of the solar cycle, the nuclear bomb tests, and increases in trace gas concentrations, and one that included just the trace gases and the solar cycle. The ozone changes are calculated in this 2-D model for different latitudes but not different longitudes.

The term in the model that tests for trend has usually had the form of the hockey stick (shown in Figure 4.41). Many analyses have been performed for this report using this form with the ramp starting at three different times: January 1965, January 1970, and January 1976. The first and the last were chosen as corresponding closely to minima in the solar sunspot cycle (as is the end of the series), thus ensuring that any residual solar cycle effects not accounted for using the sunspots have as little influence on the trend coefficient as possible. This model postulates that any loss of ozone will occur as a steady year-round loss, and does not allow for the possibility that losses occur predominantly in one or two seasons. A more elaborate form of $T(i,j)$ has also been used in which a separate ramp is included for each month:

$$T(i,j) = \sum_{l=1}^{12} k_j \bullet \delta_{jl}$$

Again, δ_{jl} is a delta function and so has the effect of including only 1 month's trend coefficient for each month's data. The results from the year-round and monthly models are discussed later. Last, the autocorrelation within the time series is accounted for in the noise term $N(i,j)$.

4.6.1.2 Autocorrelation

The deseasonalized data series of monthly residuals has been tested to determine whether a correlation exists between successive monthly values. For example, if the September residual is positive in a given year, is the probability that the October residual will also be positive in that year greater than 50 percent? Such tests show that with ground-based stations, significant positive autocorrelation is always observed in the monthly values for a 1-month delay and frequently for a 2-month delay—both October and November are more likely to be positive after a positive residual in September. The autocorrelation coefficients are, in most cases, no longer statistically significant after 2 months. Such 1-month and 2-month correlations are geophysically plausible because of the tendency of weather patterns to persist. Because such conditions are often specific to geographical locations, no requirement exists that the same tendencies toward autocorrelation be exhibited at all groundstations worldwide. No tests have been made of more elaborate geophysically based hypotheses of autocorrelation—e.g., that the probability of a positive value in November following a positive October is different from that for June following a positive May.

The autocorrelation coefficients for ozone data within a latitude band, e.g., 40°N to 50°N, are larger than those for an individual station. For example, the autocorrelation coefficient for a 1-month delay is approximately 0.6 in satellite data for the average ozone concentration in a latitude band in comparison to the typical values of 0.2 found in groundstations in the same band. The difference in these coefficients presumably reflects the fact that motion eastward or westward can carry an air mass away from a groundstation, removing the autocorrelation at that station, but maintaining it in the latitude band. Thus, while a new air mass is detected at the station, the old air mass still contributes to the latitudinal average and continues to maintain some correlation between successive monthly values.

4.6.1.3 Weighting Procedures: Intra-Annual and Interannual Variations

Considerable differences exist in the year-to-year variations for the ozone values in different months. The standard deviations of the 12 monthly sets of 24 years of data from Bismarck are given in Table 4.15. These standard deviations are a measure of the year-to-year variation of the months and can be called the interannual standard deviations. Also shown in Table 4.15 are the averages of the standard deviations for the individual months calculated from the daily readings (mean intramonthly standard deviations). Both series show the same annual pattern with a maximum variability in the late winter and early spring and a minimum in the autumn.

In a least-squares analysis of the data, some kind of weighting should be used to ensure that each month contributes equally to the residual variance. If an unweighted analysis of the data is made, then the months with the largest interannual standard deviations will be the largest contributors to the residual variance, and these months will, in effect, be dominating the analysis at the expense of the months with smaller interannual standard deviations. In order to allow each month to be equally important in its contribution to the variance during the analysis, each monthly value should be weighted by the appropriate interannual standard deviation.

Table 4.15 Monthly Means and Standard Deviations at Bismarck (in DU).

	Interannual Standard Deviation	Mean Intramonthly Standard Deviation	Mean
January	16.4	34.9	367.5
February	17.7	40.6	391.8
March	17.2	35.4	400.0
April	16.9	30.8	387.2
May	15.2	26.8	370.7
June	11.9	23.8	345.9
July	9.5	16.5	324.1
August	10.6	14.9	310.5
September	9.6	20.0	301.0
October	13.6	23.3	296.5
November	19.1	26.3	317.0
December	18.2	32.5	339.0

A separate issue is whether to weight each month to allow for the variability within that month and the number of readings taken therein. To do this correctly requires using each individual standard deviation. It is a matter of debate whether the intramonthly variation need be considered in an analysis of monthly data, as the variability is on a very different time scale to that of the interannual variability and can effectively be considered unrelated. Two other factors complicate this type of analysis. First, the observed strong day-to-day autocorrelation within a month reduces the independence of the daily readings. This can be seen by looking at the ratio of the intramonthly standard deviations to the interannual ones. If all of the daily readings were independent, this ratio would be approximately the square root of the number of readings within that month, i.e., a factor of 4 to 5.5. Instead, it would appear that the number of "independent" readings in a month is, typically, about four, because the usual difference between the two columns is only a factor of two. This number is roughly the same as that for other midlatitude stations. Second, a trend versus time is found within most months so that the calculated standard deviation of a sample about a constant mean is not actually appropriate.

The statistical calculations were carried out using the SCA Statistical System (Version 3). The Gauss–Marquardt algorithm in this system implies a constant variance within the time series being analyzed, and the package does not include a weighting option. Accordingly, the monthly data of each variable were premultiplied by the inverse of the appropriate standard deviation (i.e., February values for all the variables included in the calculation were divided by February's standard deviation). Apart from the autocorrelated noise, this procedure is the same as a classical "sigma-squared weighting" routine, because the weighting by the standard deviation is squared before the calculation of the residual variance, the quantity that is minimized. Interannual standard deviations were used in all the analyses unless specific mention is made. For a few stations, the average of the intramonthly standard deviations was also tested, and no important differences were found in the estimates of the various parameters. Small differences were found in the uncertainty estimates for the parameters, but the two different weighting methods produced the same results within the uncertainties calculated. Only for the Bismarck data set was a calculation carried out in which each data point was weighted by its own intramonthly standard deviation. Again, no important differences were found in the results.

4.6.1.4 Missing Data

In most station records, months exist during which no readings were taken. These missing data might be caused by any one of a number of reasons—the instrument was undergoing calibration tests or an overhaul, the absence of the instrument technician, or some other similar reason. There are also many months in which only a few readings were taken, and, because of the large intramonthly standard deviations, the averages of these months might not be considered representative. As mentioned in Section 4.3.4, in the preparation of the provisionally revised data sets found in the Appendix to this chapter, every month with fewer than 13 daily readings was deemed to have had no usable monthly average. After the first set of revised data had been prepared, the missing monthly data were replaced as follows:

- With 2 or more consecutive months without a usable monthly average, the long-term monthly means for those months were used.

- If only 1 month was missing, the value substituted was that of the long-term monthly mean, adjusted by the product of the average of the 2 neighboring months' normalized deviations (actual deviation divided by standard deviation) and the standard deviation for the missing month.

4.6.2 Results From Individual Station Data

One major purpose of this report has been analysis of the existing record to find the magnitude, nature, and significance of any detectable changes in the amount and distribution of ozone in Earth's atmosphere. As described in Section 4.3, the published data on total ozone have been critically examined, and a set of provisionally revised data has been produced for many stations. A comparison of the results of an initial analysis of the original and revised data sets based on Dobson instruments shows that the provisional revision produces no substantive change in the behavior of the stations as a group, although in individual cases significant changes are seen (Figures 4.36–39). The data revision does result in greater consistency among the stations at similar latitudes, as might be expected if the cause(s) of any changes are global in nature rather than the consequence of some alteration in the close vicinity of the station. This greater consistency provides more confidence in the significance of latitude band averages; no attempt was made to construct latitude band averages from the original ODW data, so that no quantitative estimates are possible of reductions in the uncertainty estimates from the ODW to the provisionally revised data sets.

Various multiple regression analyses, then, have been made on the provisionally revised Dobson data, with the results described in the following sections. First, the analyses of the individual stations are considered. Next, there is a discussion of the analyses of the Dobson latitudinal band averages, together with some comments on the formation of these averages. Finally, the results from four regional averages of the total ozone data measured with the M–83 filter instruments are presented. In general, the conclusions to be drawn from the M–83 data parallel those from the Dobson data.

The statistical treatment of the total ozone data from the Bismarck station has been described in detail earlier in this chapter to illustrate the various influences acting on total ozone. Many possible statistical models have been tried with various combinations of the QBO, the solar cycle, and the effect from the atmospheric testing of nuclear weapons. The model results also depend upon whether a year-round trend is assumed or whether differing monthly trends are allowed. Still more analyses can be made by changing the time period being analyzed and the starting dates of the proposed trends. The symbols used in the Appendix to this chapter list the effects included (Q for QBO, S for solar, and N if the bomb test parameter has been included) and the last two digits of the year in which the linear trend begins; e.g., QS70 describes an analysis including parameters for the QBO, the solar cycle, and a ramp beginning in 1970. Two possible QBO parameters were tested for each station; it was found that the one with zero lag (i.e., using concurrent monthly averages for the 50-mbar Singapore wind speed and the total ozone) was the more significant for nearly all stations except those between 19°N and 40°N. When the Singapore wind speed was lagged 6 months behind the ozone value, the stations in the 19°N–40°N band showed better correlation than for the concurrent values. Thus, the concurrent values are given for all stations outside this band, while the values found using the lagged QBO variable are given for the stations inside this band. The QBO effect will be discussed in more detail later in this chapter.

The results of 12 multiple regression models used to describe the data of the individual stations are given in Appendix 4.B.(i). Two selections of possible time periods for data to be analyzed have been made. In parts (a) and (b), monthly ozone averages measured between January 1965 and December 1986 are analyzed, while in parts (c) to (f) all data after January 1957 are treated. The quality and reliability of the band average data are much better after 1963, chiefly because many more stations are available (the U.S. station data effectively begin in 1963), and the pre-1965 data are complicated by the extensive atmospheric testing of nuclear weapons. For these reasons, the primary emphasis in our determination of statistical trends has been placed on band average and station data since January 1965. However, for completeness of record, station data prior to 1963 have also been included. Data prior to the International Geophysical Year (1957–1958) are so scarce that very little consideration has been given to any records before 1957.

Year-round and monthly linear trends starting in 1970 are calculated in parts (a), (c), and (e), whereas (b), (d), and (f) represent tests for trends starting in 1976. All models include terms for the QBO and the solar cycle, and parts (e) and (f) also include the term for the calculated atmospheric bomb test effect at the appropriate latitude. The parameters given in the tables for the geophysical effects are those calculated in the models that include individual monthly trends. The equivalent coefficients found from the year-round trend model are essentially the same, as illustrated earlier with the Bismarck data. It should be noted that not all stations provide data records suitable for testing by all six models, for various reasons: stations whose data record starts after 1965 are not tested for the nuclear effect, nor are those in the Southern Hemisphere where the bomb test effect is predicted by model calculations to be negligible; stations whose records start after 1976 are tested only for a trend starting in 1976.

4.6.2.1 Changes Between 1970 and 1986 Using Data From 1965 Onward

In the first part of this discussion, only data after 1965 are considered, the linear trends are taken as starting in 1970, and terms for the QBO and the solar cycle are included. All of these results are given in Appendix 4.B.(i).(a). Table 4.16 contains the summer and winter trends for the stations for which provisionally revised data are available. This table is similar to Table 4.12, where the differences in the monthly means between two 11-year periods, 1965–1975 and 1976–1986, are given. The figures in Table 4.16 represent trends in DU per year. The stations are divided according to the latitude bands in which they lie. It can be seen that the more northerly stations have larger wintertime (DJFM) losses than the more southerly stations: the simple arithmetic DJFM averages for the three sets of stations north of 30°N are -1.62, -1.09, and -0.28 DU per year for 53°–64°, 40°–53°, and 30°–39°N, respectively. These compare to average summertime (MJJA) trends of +0.02, -0.39, and -0.36 DU per year for the same three bands.

Table 4.16 Winter and Summer Trends for Individual Stations

Station	Summer Trend	Winter Trend
53°–64°		
Reykjavik*	+1.49 ± .79	−2.98 ± 1.51
Lerwick	−0.53 ± .27	−1.59 ± .47
Leningrad*	−0.18 ± .35	−1.58 ± .75
Churchill	−0.44 ± .32	−1.37 ± .48
Edmonton	+0.05 ± .31	−1.56 ± .55
Goose	−0.27 ± .31	−0.65 ± .53
40°–52°		
Belsk	+0.02 ± .29	−1.55 ± .57
Bracknell*	−0.62 ± .30	−1.43 ± .57
Uccle*	−1.31 ± .45	−0.87 ± .80
Hradec Kralove	+0.20 ± .32	−2.06 ± .60
Hohenpeissenberg*	−0.19 ± .26	−0.69 ± .52
Caribou	−0.35 ± .26	−1.48 ± .55
Bismarck	−0.54 ± .29	−1.15 ± .41
Arosa	−0.51 ± .23	−0.96 ± .50
Toronto	−0.56 ± .28	−0.82 ± .53
Sapporo	0.00 ± .29	−0.43 ± .46
Rome	+0.10 ± .26	−0.70 ± .44
Boulder	−0.96 ± .23	−0.96 ± .40
30°–39°		
Cagliari Elmas	−0.48 ± .28	−0.64 ± .45
Wallops Is.*	−0.39 ± .34	−0.30 ± .70
Nashville	−1.02 ± .25	−0.74 ± .42
Tateno	−0.19 ± .25	−0.10 ± .48
Srinigar	−0.25 ± .22	−0.30 ± .38
Kagoshima	−0.19 ± .24	+0.19 ± .30
Quetta*	+0.01 ± .26	−0.23 ± .47
Cairo*	−0.34 ± .42	−0.76 ± .95
Mauna Loa	−0.07 ± .16	−0.36 ± .33
Southern Hemisphere		
Huancayo	−0.16 ± .09	−0.20 ± .10
Samoa*	−1.24 ± .39	−1.13 ± .30
Aspendale	−0.69 ± .20	−0.61 ± .31
MacQuarie Isle	+0.15 ± .39	+0.36 ± .53

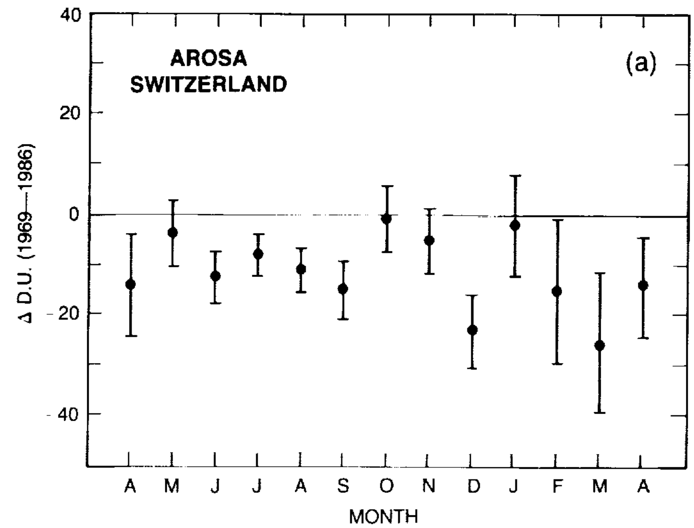
Trends are shown as Dobson Units per year. They are calculated using the data from 1965 onward with the ramp starting in 1970. An asterisk (*) denotes those stations whose records start after January 1965.

Notes: 1. Northern Hemisphere winter is December through March; Northern Hemisphere summer is May through August; Southern Hemisphere winter is June through July; and Southern Hemisphere summer is November through February. 2. Errors are estimates: the correct method is to include the covariance terms for each month. The approximation used here is to assume that the ratio of the covariance to the variance of each latitude band (as shown in Table 4.26) is the same as that for the individual stations.

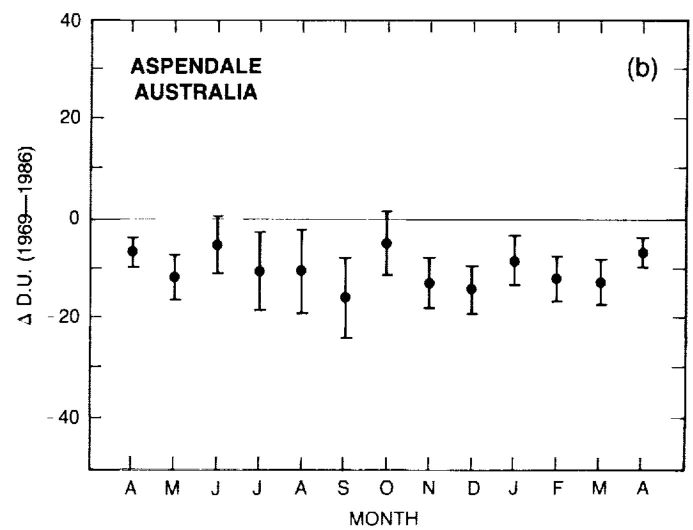
A second point is that there is a larger difference between the winter–summer values for the more northerly stations. Some of the stations shown do not have 22 years of data from 1965 through 1986, and the results from those stations should be treated with more care. For instance, Reykjavik shows a very large winter loss of –2.98 DU per year compared to a mean for the six stations in that band of –1.62 DU per year. The summer value is also extreme, though this time in a positive sense, being +1.49 DU/yr compared to the band average of +0.02 DU/yr. The overall pattern of trends found by analyzing the individual station data is reassuringly similar to that found from the analyses of the band data. (Uncertainty estimates for the average trends from several stations are not given because the correlations between the data from nearby stations are not calculated. It is reasonable to suppose that the uncertainties are similar to those calculated for the latitude band averages discussed in Section 4.6.3, and slightly less than the individual station uncertainties given for the monthly trends in Appendix 4.A of this chapter. Reinsel et al. make allowance for the correlation involved when two stations measure ozone in the same parcel of air producing two sets of data not completely independent of one another.

The ozone changes for the 17 years after 1986 as calculated from the monthly trend coefficients are shown in Figure 4.45 for 17 different Dobson stations. Taking initially only the stations north of 40°N, the winter time loss and its contrast with summer are clearer at some stations (e.g., Bismarck, Edmonton, Belsk, Caribou, and Hradec Kralove) than at others (e.g., Bracknell, Uccle, Hohenpeissenberg, and Sapporo). Much of this apparent difference in behavior is the result of the natural variability of total ozone at any particular site, but there may be some systematic features at work as well. The rationale behind making latitude, and not longitude, the second dimension of a 2-D photochemical model is that latitudinal differences in ozone distribution and behavior are generally greater than longitudinal ones. This can be seen most clearly in the average global distribution of ozone shown in Figure 4.12. Longitudinal differences at comparable latitudes may be detectable through comparison of individual station results.

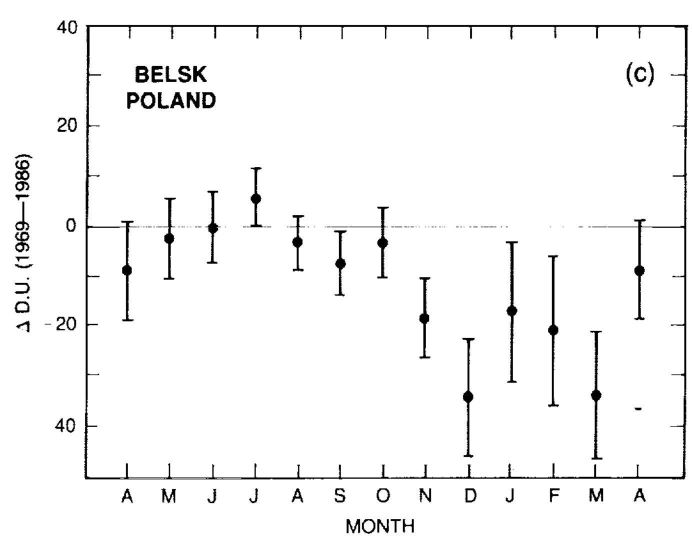
However, examination of the trends of seven stations in both Europe (Lerwick, Belsk, Bracknell, Hradec Kralove, Hohenpeissenberg, Arosa, and Rome) and North America (Churchill, Edmonton, Goose, Caribou, Bismarck, Toronto, and Boulder) reveals no difference in the seasonal trends over the two continents. These stations were chosen by the length of their record, and the same number was chosen for each continent. The unweighted numerical averages of the monthly trend coefficients for these stations are shown in Table 4.17. Also given in Table 4.17 are the ozone values for Sapporo, which is in a different meteorological region. There is very little difference between the European and North American blocks, and they can be contrasted with Sapporo, which does not exhibit a significant loss or gain of ozone at any season of the year. Losses appear in the Sapporo ozone record for December and March, but no shape is apparent in Figure 4.45. It is unfortunate that there is only one Dobson station in this region because of the possibility that any single station may be responding strongly to specific local effects. The other two Japanese stations, Tateno and Kagoshima, show a similar lack of significant wintertime change in ozone, but they are at lower latitudes, so that a fair comparison cannot be made between their observations and those from Western Europe and North America poleward of 40°N. The two Far Eastern M–83 stations also are not directly comparable because of their location, instrument, and time of record, but the indicated trends from the Far Eastern M–83's are generally similar to the Sapporo observations. In contrast, the Siberian and European M–83 ozone results do show the wintertime loss and winter–summer differences characteristic of North America and Western Europe.



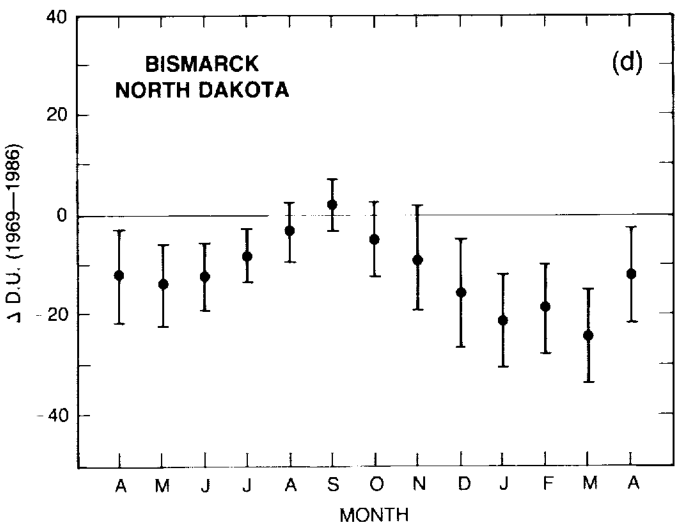
40
20
0
-20
-40
Δ D.U. (1969—1986)
AROSA
SWITZERLAND
(a)
A M J J A S O N D J F M A
MONTH

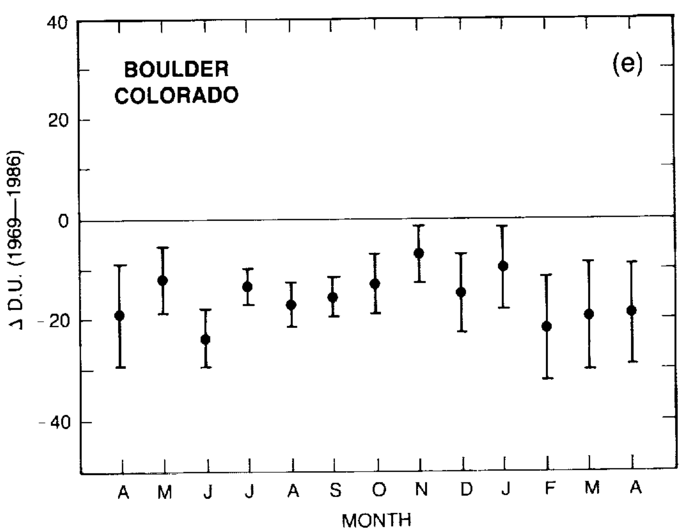


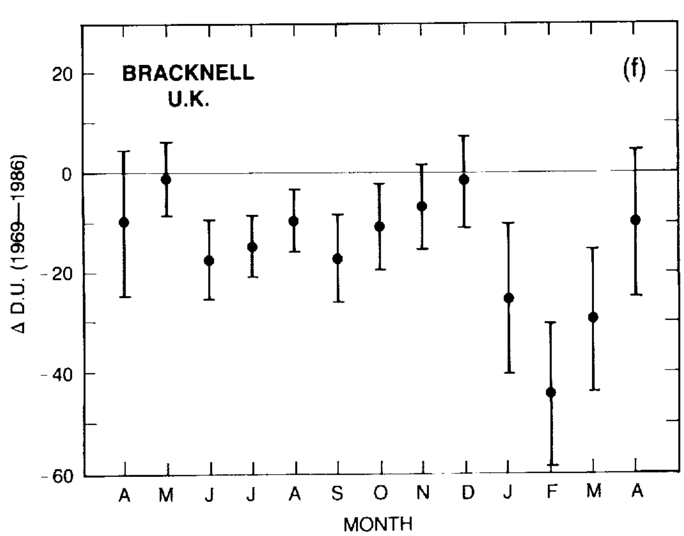
40
20
0
-20
-40
Δ D.U. (1969—1986)
ASPENDALE
AUSTRALIA
(b)
A M J J A S O N D J F M A
MONTH

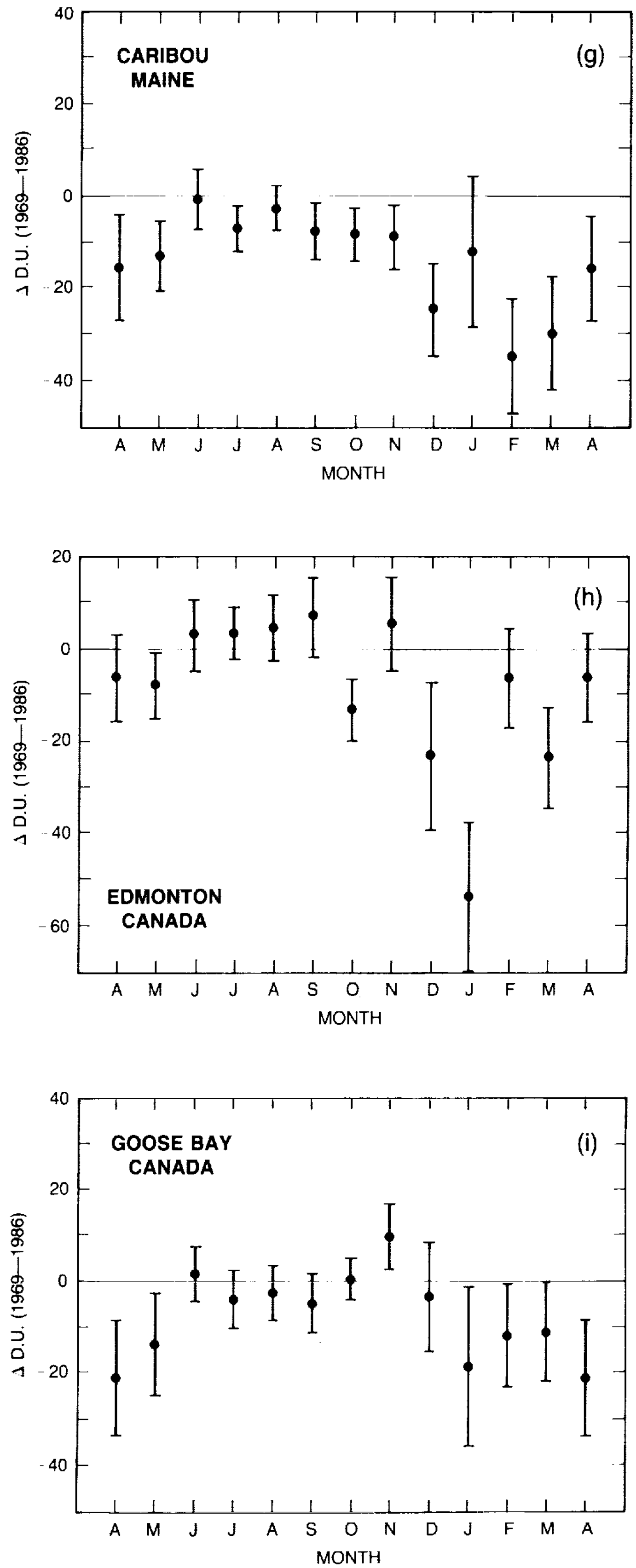


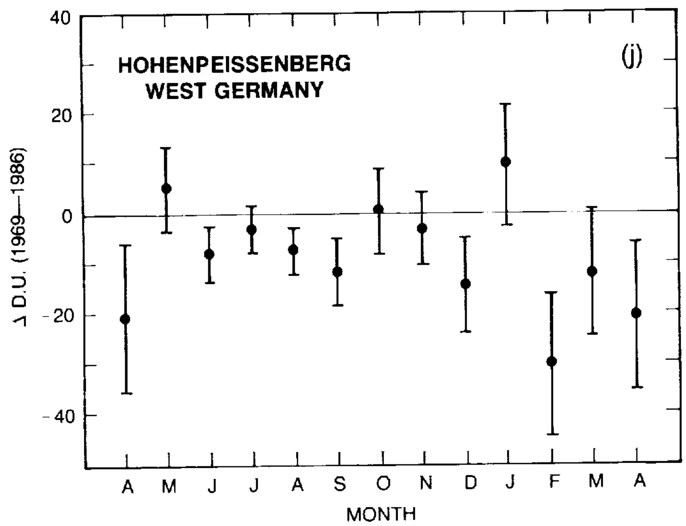
40
20
0
-20
40
Δ D.U. (1969—1986)
BELSK
POLAND
(c)
A M J J A S O N D J F M A
MONTH


BISMARCK
NORTH DAKOTA
(d)
Δ D.U. (1969—1986)
40
20
0
-20
-40
A M J J A S O N D J F M A
MONTH

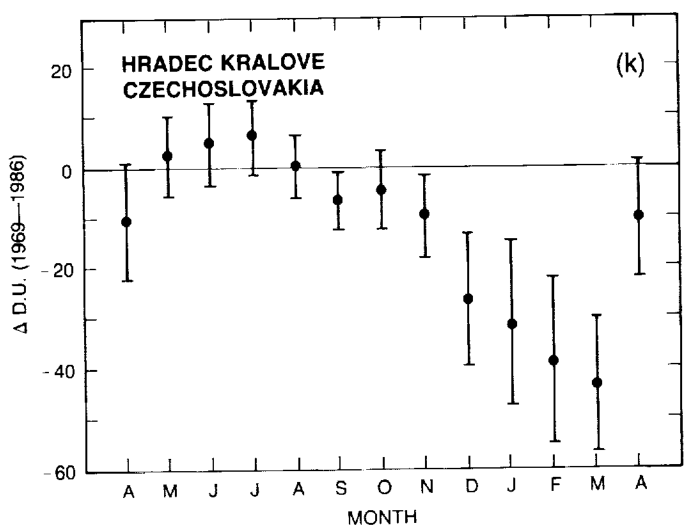

BOULDER
COLORADO
(e)
Δ D.U. (1969—1986)
40
20
0
-20
-40
A M J J A S O N D J F M A
MONTH


BRACKNELL
U.K.
(f)
Δ D.U. (1969—1986)
20
0
-20
-40
-60
A M J J A S O N D J F M A
MONTH

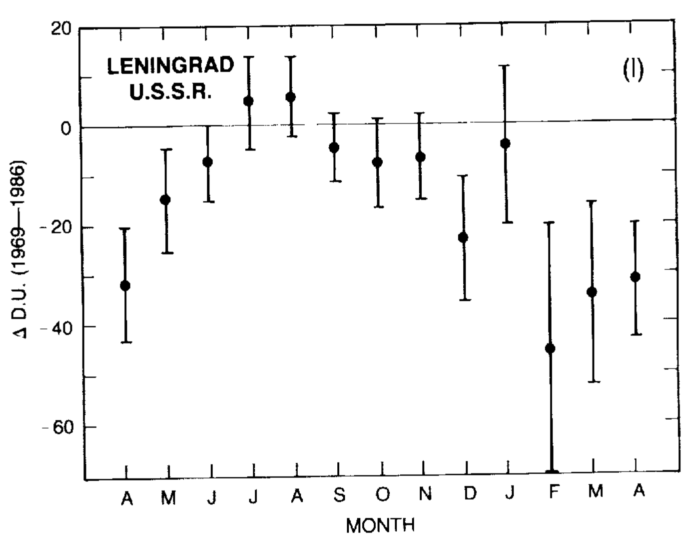

CARIBOU
MAINE
(g)
Δ D.U. (1969—1986)
40
20
0
-20
-40
A M J J A S O N D J F M A
MONTH
EDMONTON
CANADA
(h)
Δ D.U. (1969—1986)
20
0
-20
-40
-60
A M J J A S O N D J F M A
MONTH
GOOSE BAY
CANADA
(i)
Δ D.U. (1969—1986)
40
20
0
-20
-40
A M J J A S O N D J F M A
MONTH



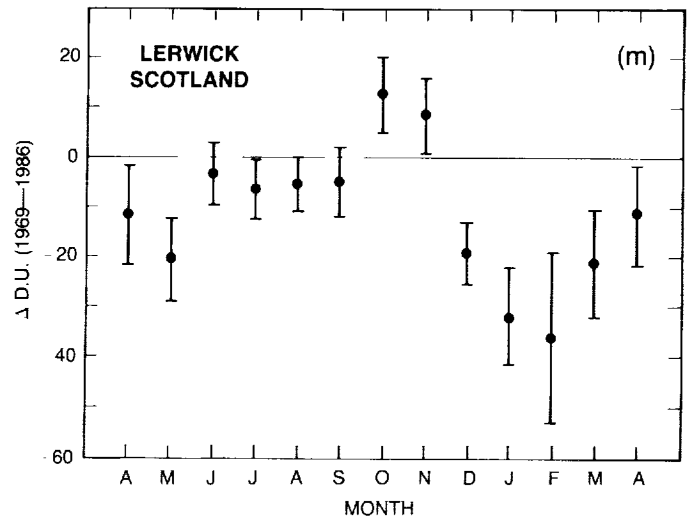
HOHENPEISSENBERG
WEST GERMANY
(j)
40
20
0
-20
-40
Δ D.U. (1969—1986)
A M J J A S O N D J F M A
MONTH

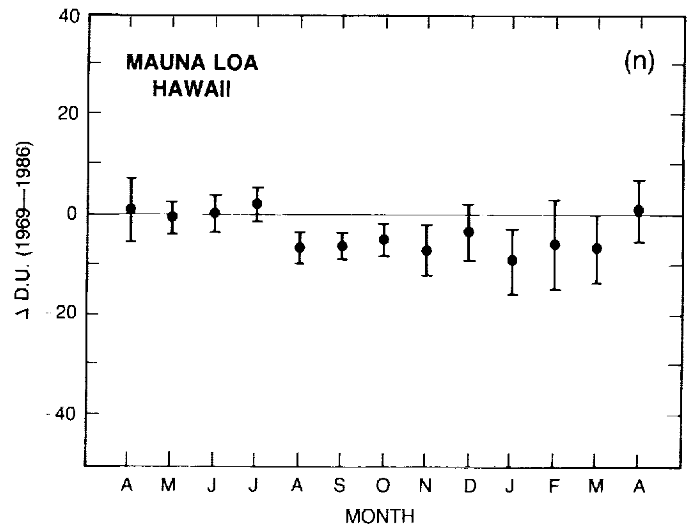


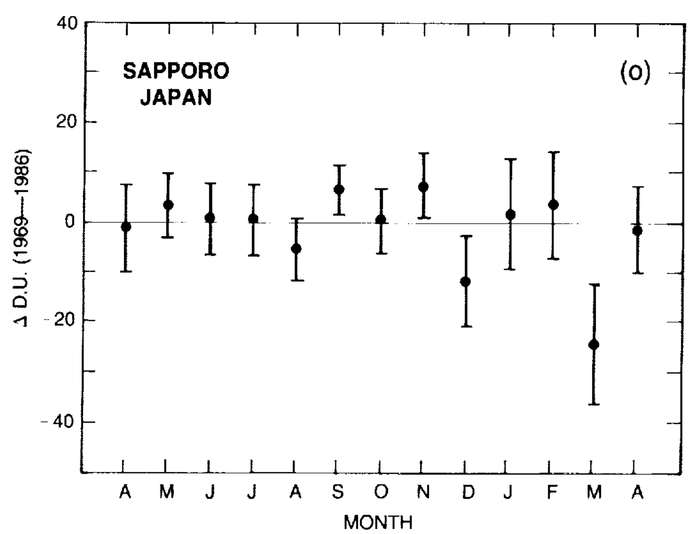
HRADEC KRALOVE
CZECHOSLOVAKIA
(k)
20
0
-20
-40
-60
Δ D.U. (1969—1986)
A M J J A S O N D J F M A
MONTH

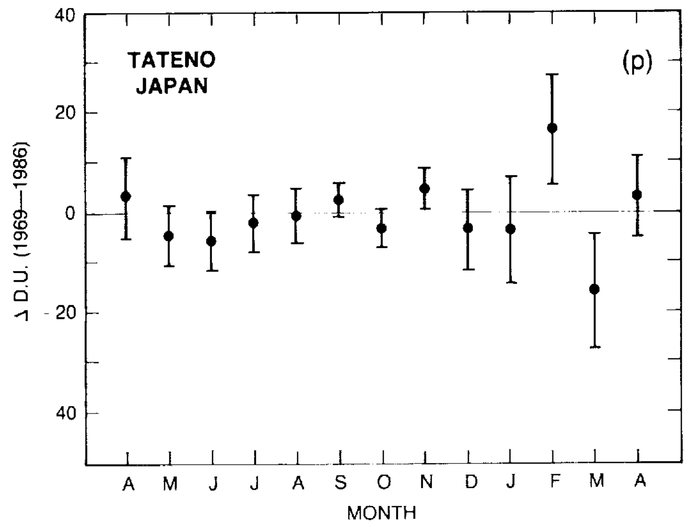


LENINGRAD
U.S.S.R.
(l)
20
0
-20
-40
-60
Δ D.U. (1969—1986)
A M J J A S O N D J F M A
MONTH


LERWICK
SCOTLAND
(m)
20
0
-20
40
-60
Δ D.U. (1969—1986)
A M J J A S O N D J F M A
MONTH


MAUNA LOA
HAWAII
(n)
40
20
0
-20
-40
Δ D.U. (1969—1986)
A M J J A S O N D J F M A
MONTH


SAPPORO
JAPAN
(o)
40
20
0
-20
-40
Δ D.U. (1969—1986)
A M J J A S O N D J F M A
MONTH



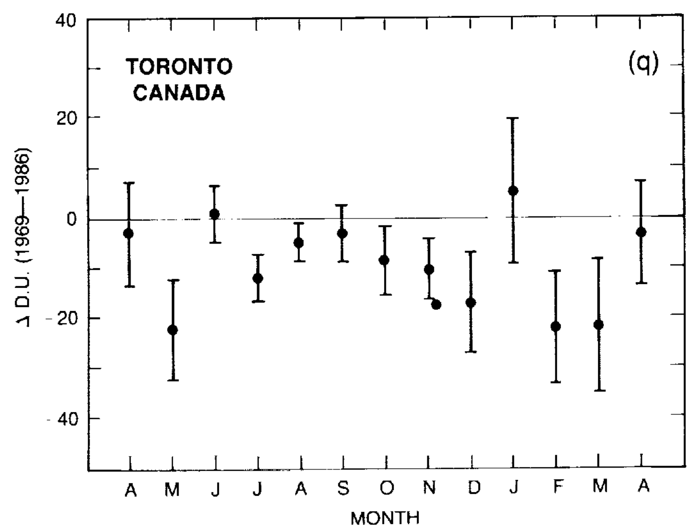


Figure 4.45 Ozone changes for various stations between 1970 and 1986. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation, and data from 1965 (or when the station started making total ozone measurements if it did so after 1965) to 1986 were used. The ozone change in each month was assumed to have occurred in a linear fashion after 1969. The monthly ozone changes plotted are not trends; they are found by multiplying the calculated trend by the 17-year period over which the loss was assumed to have occurred. The vertical bars represent ± one standard error in the estimate of the change. (a) Arosa, Switzerland, (b) Aspendale, Australia, (c) Belsk, Poland, (d) Bismarck, USA, (e) Boulder, USA, (f) Bracknell, UK, (g) Caribou, USA, (h) Edmonton, Canada, (i) Goose Bay, Canada, (j) Hohenpeissenberg, FRG, (k) Hradec Kralove, Czechoslovakia, (l) Leningrad, USSR, (m) Lerwick, UK, (n) Mauna Loa, USA, (o) Sapporo, Japan, (p) Tateno, Japan, (q) Toronto, Canada.

Two possibilities exist: either Japan is in a meteorological regime that does not allow the processes that are causing the winter loss to occur, or there is an instrumental problem that has not been identified. The latter is unlikely: the Japanese operate their own version of the Dobson, but satellite overpasses do not indicate any problems in recent years and there are no known reasons that would cause a seasonal change in total ozone to have been exactly cancelled by a

Table 4.17 Average Monthly Ozone Changes for Different Continents, 1970–1986 (Data for 1965–1986).

	Europe	North America	Japan (Sapporo)
January	−0.96	−1.15	+0.13
February	−1.56	−1.19	+0.22
March	−1.51	−1.14	−1.40
April	−0.69	−0.78	−0.06
May	−0.13	−0.82	+0.21
June	−0.28	−0.23	+0.05
July	−0.19	−0.41	+0.04
August	−0.27	−0.30	−0.31
September	−0.55	−0.18	+0.40
October	−0.02	−0.60	+0.04
November	−0.32	−0.14	+0.45
December	−1.10	−1.09	−0.67
Average	−0.63	−0.67	−0.08

The average trends of seven European and seven North American stations are given in the first two columns. In the third column are the trends for Sapporo, Japan. The trends cover the period 1970–1986 and are given in Dobson Units per year. They are taken from the model that contains terms for the QBO and the solar cycle with only the data after January 1965 used. The North American stations are Churchill, Edmonton, Goose, Caribou, Bismarck, Toronto, and Boulder. The European stations are Lerwick, Belsk, Bracknell, Hradec Kralove, Hohenpeissenberg, Arosa, and Rome. All are north of 40°N.

seasonal change in the instrument response. A scattered light or μ-dependence problem would be expected to show up most at the solstices in December and June. The most probable explanation is that Sapporo is sampling a meteorological regime less influenced by the processes causing wintertime loss over the major northern continental regions. Figure 4.46 does show that

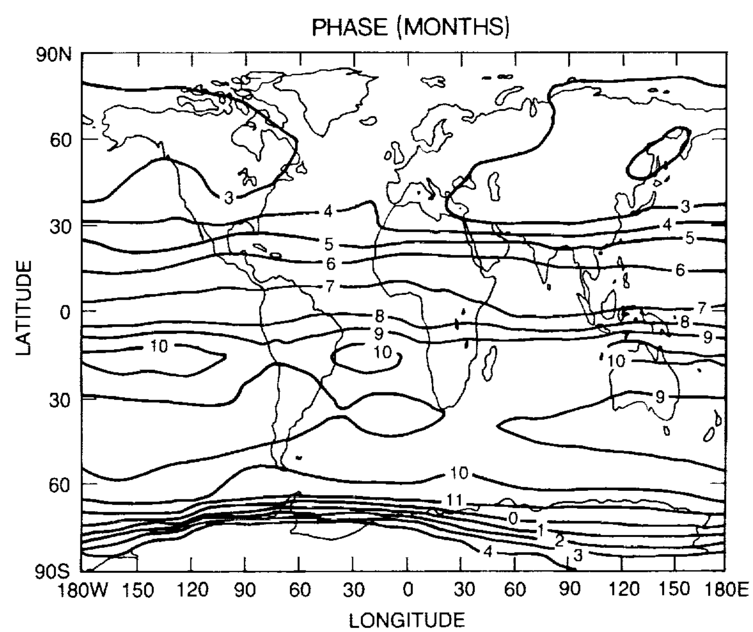


Figure 4.46 Phase of total ozone maximum (from Bowman and Krueger, 1985).

the total ozone maximum at Sapporo is reached at the beginning of March, one of the earliest ozone maxima in the Northern Hemisphere.

Between 30°N and 40°N, provisionally revised data have been prepared for eight stations. No strong seasonal variation is found in the trends at any of these stations, so that the yearly trend has as much meaning as any of the monthly trends. The average of the ramps using the year-round model is −0.16 DU/yr, while the average of the means of the monthly coefficients is −0.23 DU/yr, which indicates that there still is a greater loss in the months with the greater interannual variation. Propagation of the standard errors of the year-round trends gives an uncertainty of .06 for the former of these two annual loss estimates. There is a wide geographical distribution of these eight stations so that the interstation correlation is small and this uncertainty estimate is reasonable, although probably on the low side. Thus, between 30°N and 40°N, there is a year-round loss without any obvious seasonal character.

South of 30°N, the number of stations for which provisionally revised data sets have been produced is smaller, and we can have less confidence in the quality of the data as there is less detailed information available on the day-to-day running of the stations. The main exceptions are Mauna Loa, whose record is in the process of being totally reprocessed, and Samoa, whose record only starts in January 1976. The paucity of Dobson data for the three-quarters of the atmosphere that lies south of 30°N is very unfortunate. The records at Mauna Loa and Samoa (Appendix 4.B.(i).(b)) both show an ozone decrease in recent years. Neither shows much sign of any seasonal nature to the change. The 22-year record from 1965 at Mauna Loa exhibits a year-round trend of −0.24 ±0.13 DU per year since 1970, which corresponds to a drop of 1.5% ±0.8% between 1970 and 1986. Samoa, with its 11-year record from January 1976–December 1986, shows a year-round trend of −0.85 ±0.25 DU per year over the entire time period. This corresponds to a decrease of 3.7% ±1.1% over just 11 years. The 1976 annual average is the highest in the 11 years of Samoan measurements. The station closest to Samoa in latitude is Huancayo, Peru, which also shows a significant year-round loss of −0.33 ±0.10 DU per year (−1.4% ±0.43% over 11 years) from 1976 through to 1986, but only −0.18 ±0.06 DU per year (−1.2% ±0.43% over 17 years) when the ramp is started in 1970. The Huancayo data taken by themselves suggest that this ozone loss of about 1.3 percent occurred between 1976 and 1986. The yearly average of total ozone at Huancayo in 1976 is the highest in its 23 years of observations, with 4 months posting long-term highs and 3 others being the second highest on record. Some of the larger decrease seen at Samoa versus Huancayo (or Mauna Loa) could, thus, be the result of an unusually high year at the start of the Samoa record, and these calculated trends should be treated with appropriate caution.

Aspendale and MacQuarie Isle are the only two Southern Hemisphere stations outside the Tropics for which provisionally revised data have been produced. Of these, the Aspendale station is the more reliable, as MacQuarie Isle has traditionally had problems because of its unfavorable position both for the observer and for the actual observations, with most taken from cloudy skies with cloud transfer tables that need improvement (Atkinson and Easson, 1988). A decrease in total ozone is observed at Aspendale (−3.0% ±0.8% year-round from 1970 to 1986) but no season shows a greater change than any other. No significant change has been recorded at MacQuarie Isle.

4.6.2.2 Changes Between 1976 and 1986 Using Data From 1965 Onward

Faith in the robustness of the conclusions that have been drawn can be increased by examination of the observed differences when the start of the trend is set at 1976 rather than 1970.

Comparison of the results for the individual stations reveals that, in general, a more negative trend is found if the linear ramp is started in 1976. The error estimates of the trends at the individual stations also increase by about 50 percent, so that the significance of the coefficients of the shorter slopes is less. Table 4.18 contains the monthly trend averages for the same European and North American stations shown in Table 4.17, but using the results given in Appendix 4.B.(i).(b), and the results can again be taken as representative of more northerly latitudes. The differences between the two continents are again neither large nor significant, with the wintertime losses in each case being larger than the summertime loss.

Table 4.18 Average Monthly Ozone Changes for Different Continents, 1976–1986.

	Europe	North America	Japan (Sapporo)
January	−0.82	−1.38	+0.62
February	−1.62	−1.51	+0.55
March	−1.85	−1.77	−1.77
April	−1.29	−1.38	−0.47
May	−0.40	−1.29	+0.31
June	−0.58	−0.47	+0.44
July	−0.70	−0.67	+0.42
August	−0.36	−0.54	−0.65
September	−0.82	−0.36	+0.66
October	−0.38	−0.93	+0.33
November	−0.59	−0.21	+0.68
December	−1.11	−1.44	−0.72
Average	−0.88	−0.99	+0.03

The average trends of seven European and seven North American stations are given in the first two columns. In the third column are the trends for Sapporo, Japan. The trends cover the period 1976–1986 and are given in Dobson Units per year. They are taken from the model that contains terms for the QBO and the solar cycle with only the data after January 1965 used. The North American stations are Churchill, Edmonton, Goose, Caribou, Bismarck, Toronto, and Boulder. The European stations are Lerwick, Belsk, Bracknell, Hradec Kralove, Hohenpeissenberg, Arosa, and Rome. All are north of 40°N.

Comparing the trends given in Table 4.18 with those given in Table 4.17 reveals that the measured rates of loss at all times of year are generally greater when the hockey stick is pivoted at 1976 rather than 1970, although none of the results from particular months at individual stations shows linear trends from 1976 on that are significantly greater than the 1970 trends. In every month, the average trends over North America are larger when measured over the shorter time period, and the same is true over Europe, with the sole exception of January. The largest changes are seen for April–July. The lack of similarity to Sapporo is still marked. Not only is there no sign of any seasonal change there, but the trends of 8 of the months become more positive while the trends at the other 4 become more negative. The fitting of a linear trend to the data is, of course, simply a convenient, nonphysical treatment of the data. If the changes in ozone concentrations really were linear for the entire period from 1970 on, then the fitting of a ramp from 1976 on should result in a lesser apparent change in total ozone because the pretrend mean would have a lower value from the inclusion of 1970–1975 in the assumed stable mean before 1976. However, a first approximation check can be made by comparing the separately estimated ozone losses from 1970 and 1976 linear trends. For the European stations, the indicated average losses are 10.7 DU for the 1970 linear trend ($17 \times k_{70}$), and 9.7 DU for the 1976 trend ($11 \times k_{76}$). The comparable values for North America are −10.4 DU and −10.9 DU, respectively, and for Sapporo −1.4 DU and +0.3 DU. These differences are all small, indicating that the major contributions to the calculated losses of ozone over Europe and North America occurred after 1976.

Moving south, less of an effect on the monthly or annual trends is observed. The year-round average trends for all the individual stations between 30°N and 40°N are all more negative when the linear ramp is started in 1976. The average of the station ramps using the year-round model is now −0.25 DU/yr, while the overall average of the station averages of the monthly coefficients is −0.30 DU/yr. The propagated standard error is +.08 DU/yr, without any allowance for interstation correlation.

As already mentioned, it is risky to apportion the same importance to the results of the remaining stations as would be warranted by the area that they cover. The calculated trend at Mauna Loa becomes slightly more negative without any sign of a seasonal pattern, and those at Huancayo and Samoa have been discussed. Aspendale shows more negative trend coefficients (k_{76} vs. k_{70}) for every month of the year. Two points are worth making here: (1) the increases in the absolute magnitude of the trend coefficients are spread very evenly throughout the year and (2) the most reliable data are those after 1978, and here a sizeable decrease is found (Atkinson and Easson, 1988). It is hard to see any pattern in the changes observed between the 1970 and 1976 linear trend regressions at MacQuarie Isle.

It is difficult, if not impossible, to say whether the observed more negative linear trends calculated for 1976–1986 over those calculated for 1970–1986 implies that there is a nonlinear decrease in total ozone. Superficial examination of the results would indicate this to be true, but the years 1983 and 1985 both were remarkable for the low level of total ozone, albeit in different parts of the globe. The plots of TOMS total ozone vs. year for various latitude bands (see Section 4.7) show the different latitudes that were affected in these years. Large negative deviations occurred at higher latitudes in the Northern Hemisphere in 1983, while 1985 was a relatively normal year there. (This can also be seen in the provisionally revised tables of data in Appendix 4.A.) At lower latitudes and in the Southern Hemisphere, larger negative deviations were seen in 1985. If these low levels were the result of a natural fluctuation that is not described by the statistical model, their position near the end of the record would cause a false impression that there has been a nonlinear decrease in total ozone. The large natural variability of total ozone makes it hard to pick up any weak signals.

4.6.2.3 Changes Between 1970 and 1986 Using All Available Data

The provisional revision of the data was carried back to the beginning of the station's record, or to January 1957 if observations were made before that date. As indicated earlier, the quantity and perhaps the quality of the data from 1957–1964 were not as high as later, when more stations were in operation and more regular intercomparisons were conducted. Further, the nuclear bomb testing in the atmosphere complicates the interpretation of pre-1965 data. For these reasons, less emphasis is placed in our conclusions upon the results of the statistical data analyses in this section.

Statistical Analyses Without Consideration of the Atmospheric Bomb Tests

These statistical analyses have an inherent lack of geophysical reality because they ignore an important known phenomenon affecting stratospheric ozone—namely, the testing of nuclear weapons in the atmosphere. This unreality is augmented by both the atmospheric modeling of the nuclear tests and the significant contributions from such testing indicated by statistical calculations allowing for such effects. The results in this section are of interest primarily in numerical comparisons with the more complete geophysical description in the next section, and not for significant statements about the atmosphere itself.

Of the seven European stations that have been considered above as a group, only Lerwick, Arosa, and Rome have records that start in January 1957, while, for the North American stations, the station whose record starts earliest is Edmonton (July 1957). The time periods for which revised station data are available are given in Table 4.10. The wide variety of starting dates makes unwise the comparison of the two groups of stations as before, and it is better to examine them on an individual basis only. The record for Sapporo starts in January 1958, providing 1 year less than the 30-year record of the three European stations. The average of the monthly trends observed at Lerwick, Arosa, and Rome are shown in Table 4.19, together with those calculated at Edmonton and Sapporo. The results from Appendix 4.B.(i).(c) are used. There are clear signs of a wintertime loss in Europe and at Edmonton, although at Edmonton only the March trend is significant at the 2σ level of confidence. (The trend uncertainty estimates for the stations are given in the Appendix to this chapter.) The magnitude of the trends is more positive than those in Table 4.17 for every month except May. The year-round average is calculated as -0.22 DU/yr when the European data from 1957 is used as opposed to -0.66 DU/yr when the shorter time period is used. The reduction in the size of the decrease is not the consequence of using three European stations rather than seven. The average monthly trends for Lerwick, Arosa, and Rome using their data from 1965 to 1986 are shown in parentheses in the first column of Table 4.19, and the magnitudes of these trend coefficients are very similar to those shown in Table 4.17 for the group of seven European stations. Comparison of the annual averages of the two time periods for the 12 stations north of 40°N shows that 8 stations have more negative trends when the shorter time period is considered, 2 have more positive values, and 2 show little change. Little

Table 4.19 Average Monthly Ozone Changes, 1970–1986 (Data for 1957–1986).

	Arosa/Lerwick/Rome 1957–1986 (1965–1986)	Edmonton	Sapporo
January	−0.63 (−0.98)	−1.45	−0.22
February	−0.67 (−1.01)	−0.81	+0.18
March	−0.82 (−1.21)	−1.47	−1.14
April	−0.31 (−0.64)	−0.62	+0.40
May	−0.23 (−0.56)	−0.56	+0.36
June	+0.07 (−0.26)	+0.30	+0.24
July	−0.06 (−0.34)	+0.52	+0.19
August	+0.08 (−0.26)	+0.23	−0.10
September	0.00 (−0.46)	+0.34	+0.34
October	+0.49 (+0.30)	−0.31	+0.56
November	+0.14 (−0.02)	+0.72	+0.62
December	−0.76 (−1.14)	−0.19	−0.22
Average	−0.22 (−0.55)	−0.28	+0.10

The average trends of three European stations (Lerwick, Arosa, and Rome) are given in the first column. In the second and third columns are the trends for Edmonton, Canada, and Sapporo, Japan. The trends cover the period 1970–1986 and are given in Dobson Units per year. They are taken from the model that contains terms for the QBO and the solar cycle with all the available data used. The figures in parentheses in the first column are the average trend coefficients for the same three European stations using only the data from 1965. All these stations are north of 40°N.

noticeable change is found in the magnitude of the trends for the stations between 30°N and 40°N: using the shorter period, one annual average is lower, two show little change, and two show a slight increase. Similar comments apply to the more southerly stations.

Considering the Atmospheric Nuclear Bomb Test Effects

The observation that less negative trends in total ozone are observed only north of 40°N when measurements prior to 1965 are included in the calculations implies that lower ozone values were recorded at these more northerly stations only in the pre-1965 years. It is noteworthy in this respect that the major atmospheric bomb tests were conducted at high latitudes in the Northern Hemisphere and that the largest effects on total ozone from the subsequent injection of large quantities of nitrogen oxides into the stratosphere are calculated to be at these higher latitudes (see Figure 4.44).

Reinsel (1981) investigated the effect on ozone that the program of atmospheric testing of nuclear weapons might have had and concluded that the results of his analysis were "consistent with a maximum decrease in ozone of approximately 2 to 4.5% due to nuclear testing effects in the early 1960s." The function used was similar to that produced by the 1-D photochemical model of Chang et al. (1979) and consisted of a linear decrease from 1961 to 1963 followed by an exponential return with a halflife of about 2 years. Since it was based on a 1-D model, there was no allowance for a possible seasonal variation in response, an effect seen strongly in the current 2-D LLNL calculations. Aside from the seasonality, the two functions are very similar.

Only stations with records starting prior to January 1965 are statistically tested for a possible nuclear effect in the current calculations. Many of these station records start in the years after 1962, and the calculated nuclear coefficient for these stations should be treated carefully. Table 4.20 contains the nuclear coefficients and the standard error estimates for all these stations together with the latitudes and starting date for each station. The stations are split into two categories: those whose records start prior to 1960 and those whose records start between 1960 and 1965. In order to calculate the effect of the bomb tests on total ozone, one multiplies the coefficient shown in Table 4.20 by the value in Figure 4.44 corresponding to the time period of interest and the station's latitude.

For the purpose of this discussion, the maximum effects will be considered and Lerwick will be treated as lying in the 53°–64°N latitude band. The maximum predicted effect at Lerwick from the 2-D calculations is about 30 DU at the beginning of 1963, and, as Lerwick's bomb test coefficient is -0.71, the observed decrease is about 21 DU, or 6 percent. Approximately the same loss is seen at Edmonton, while at Arosa the maximum effect is found to be about -12 DU (20×-0.6), about a 4 percent drop. Similar calculations for the other stations show smaller, but similar, losses over Europe and North America in good agreement with Reinsel's analysis. The significance of the bomb test coefficients varies: those for Lerwick, Edmonton, and Arosa are all significantly different from zero at the 2 sigma level and that for Rome is 1.7 standard errors from zero. These four stations are the most likely to pick up a strong ozone signal from atmospheric testing, as their records start well before the major effect is calculated to have occurred and they are at latitudes where there should have been a large depletion.

There is some indication of a different response over Japan: Sapporo has a smaller coefficient than Arosa or Rome—the two most latitudinally similar of the stations with the long records—and Tateno has a coefficient of $+0.65 \pm 0.46$, which indicates that there was an increase of about 8 DU in early 1963. Cagliari, which is 3 degrees north of Tateno, has a coefficient of -0.38 ± 0.63.

Table 4.20 Statistical Evaluations of Ozone Depletion From Atmospheric Nuclear Testing Using Data From Individual Stations

Station	Bomb Test Coefficient	Observations Began	Latitude (°N)
Lerwick	−0.71 ± .27 (−0.70)	1/57	60
Edmonton	−0.62 ± .27 (−0.60)	7/57	54
Arosa	−0.60 ± .25 (−0.47)	1/57	47
Sapporo	−0.18 ± .31 (−0.22)	1/58	43
Rome	−0.55 ± .33 (−0.58)	1/57	42
Cagliari	−0.38 ± .63 (−0.33)	1/57	39
Tateno	+0.65 ± .46 (+0.58)	7/57	36
Goose	−0.04 ± .21 (−0.01)	1/62	53
Belsk	−0.37 ± .43 (−0.28)	1/63	52
Caribou	+0.09 ± .32 (+0.29)	6/62	47
Bismarck	−0.80 ± .38 (−0.54)	1/63	47
Toronto	+0.38 ± .29 (+0.42)	1/60	44
Boulder	−1.14 ± .67 (−0.27)	1/64	40
Nashville	−0.54 ± .49 (−0.10)	1/63	36
Srinigar	−0.72 ± .75 (−0.53)	2/64	34
Kagoshima	+0.46 ± .56 (+0.17)	4/61	32
Mauna Loa	−2.73 ±1.21 (−2.28)	1/63	20

The upper table contains the bomb test coefficients for stations whose records started before 1960, and the lower table contains the same information for stations whose records started between 1960 and 1965. The bomb test coefficients have no units and should be used as multipliers for the appropriate latitudinal function shown in Figure 4.13. The statistical model contained terms for the QBO and the solar cycle and assumed that there was a linear decrease in total ozone starting in 1970. The numbers in parentheses are the nuclear coefficients for the same model except that the linear decrease is started in 1976.

In all cases, however, the error bars are sufficiently large that the differences are only suggestive. Two interesting points are worth noting. First, the error estimates get larger as latitude decreases. Presumably, this inflation occurs because the signal being sought is smaller at lower latitudes. Second, when the bomb test coefficients for the model where the ramps are started in 1970 are compared with those for the model that starts the ramps in 1976, no change can be seen in the upper half of the table. However, in the case of the 10 stations whose data sets start after 1960, all of the bomb test coefficients are more positive for ramps beginning in 1976. Why this is so is not clear. Two main conclusions can be made from this discussion, each of which is in good agreement with those of Reinsel (1981):

- There was a decrease of several percent in total ozone in the early 1960's, which is consistent with the hypothesis of an effect from the atmospheric testing of nuclear weapons. Further, the more northerly stations with the longer records show the decrease more clearly, as would be expected if this hypothesis were true.

- The observed decrease is smaller than that calculated by the LLNL 2-D model. However, neither the significance of the disparity nor its possible causes is clear.

The effect of the inclusion of the bomb testing term on the trend coefficients is closely related to the size of the total ozone depletion from the bomb tests. The consequence of finding and allowing for a depletion of ozone prior to the start of the linear ramp is that the unperturbed ozone levels are calculated to be higher than they would be if the depletion were not allowed for. If the unperturbed ozone levels are higher, then the trend coefficients that are calculated will be more negative. The average monthly trends for the three European stations (Lerwick, Arosa, and Rome) are shown in the first column of Table 4.21, and those for the Edmonton and Sapporo stations are given in the second and third columns. The equivalent trends calculated using the model that did not allow for the bomb test effect are shown in Table 4.19; comparison reveals that every single trend is more negative in the case where the bomb test term is included. This effect on recent trends is expected, as ozone depletions are calculated to have been caused by the atmospheric bomb tests for all of these stations.

Table 4.21 Monthly Trends in Ozone When Allowance Is Made for Depletion by Nuclear Testing.

	Arosa/Lerwick/Rome	Edmonton	Japan (Sapporo)
January	−0.81	−1.64	−0.26
February	−0.84	−1.00	+0.13
March	−0.98	−1.65	−1.19
April	−0.46	−0.79	+0.36
May	−0.36	−0.71	+0.32
June	−1.04	+0.17	+0.21
July	−0.16	+0.41	+0.16
August	−0.04	+0.09	−0.13
September	−0.13	+0.18	+0.30
October	+0.33	−0.50	+0.52
November	−0.04	+0.50	+0.58
December	−0.95	−0.39	−0.27
Average	−0.37	−0.44	−0.06

The average trends of three European stations (Lerwick, Arosa, and Rome) are given in the first column. In the second and third columns are the trends for Edmonton, Canada, and Sapporo, Japan. The trends cover the period 1970–1986 and are given in Dobson Units per year. They are taken from the model that contains terms for the atmospheric bomb testing effect as well as the QBO and the solar cycle with all the available data used. All these stations are north of 40°N.

Comparison with the results in Table 4.17 reveals that the negative trends calculated using only the data after 1965 are greater than is the case when all of the data are used and the bomb test term is included. Again, the significance of this difference is not clear, but examination of the raw data reveals that the measurements made in the years around 1960 were also low historically. This last fact is pertinent in the discussion of the effect of the solar cycle on total ozone. On the other hand, if the contributions to ozone loss were assumed to be correctly calculated by the atmospheric models (i.e., greater losses than indicated by the statistical calculations), then better agreement would be found between the negative trends for data starting in 1957 and 1965.

4.6.2.4 Effect of the Circulational Quasi-Biennial Oscillation

A quasi-biennial oscillation (QBO) in temperature, zonal winds, and column ozone at the Equator has been widely noted (Reed, 1960; Veryard and Ebdon, 1961; Wallace, 1973; Angell and Korshover, 1978; Coy, 1979; Tolson, 1981; Hasebe, 1983; Naujokat, 1986). A QBO in total ozone also exists at other latitudes, and Coy, for example, pointed out that the relationship between the QBO in the equatorial winds and total ozone at different latitudes varies according to latitude (see Figure 4.47). A similar variation has been found in our analysis both in terms of the phase

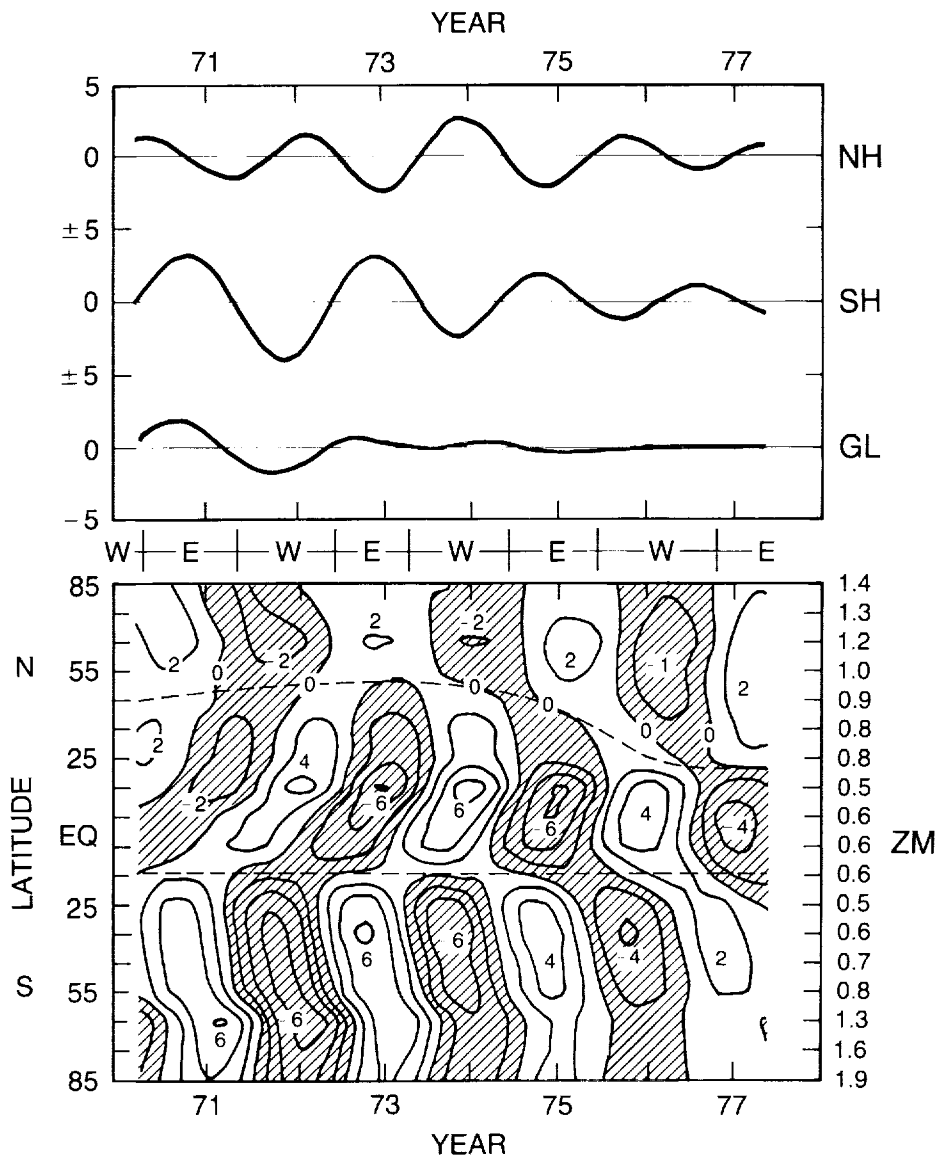


Figure 4.47 Quasi-biennial oscillation of total ozone (Dobson Units—DU) in the mean values of Northern Hemisphere (NH), Southern Hemisphere (SH), globe (GL), and zonal mean values (ZM). Vertical bars and the numerals on the right-end column of ZM indicate the estimates of errors as the confidence limits of about 70 percent. The isopleths in ZM are drawn with the interval of 2 DU, and the shaded areas correspond to those of negative deviations. Letters E and W situated between GL and ZM indicate the easterly and westerly phase, respectively, of the quasi-biennial zonal wind oscillation in the equatorial stratosphere at 50 mbar (taken from Coy, 1979).

and the magnitude. For simplicity, only two phases were tried in this analysis: no lag at all and a 6-month lag. There are four main points:

- Above 40°N, total ozone is found to be low when the Singapore 50-mbar winds are in the westerly phase.
- A minimum in the magnitude of the calculated QBO coefficients is found in the vicinity of 40°N latitude.

- Between 10°N and 40°N, a better correlation is found if the Singapore 50-mbar wind speeds lag the total ozone measurements by 6 months in the statistical model.
- The relatively high frequency of the QBO (there are about 10 cycles in the period 1965–1986) makes its inclusion or exclusion have a negligible effect on the trend estimates.

The first three points are in good agreement with previous analyses as well as with the results of a recent 2-D model (Gray and Pyle, 1988).

The statistical model postulates a simple linear relation between the 50-mbar wind speed at Singapore and total ozone, and such a correlation is observed. Figure 4.48 shows a plot of the magnitude of the QBO coefficients against latitude. All of the stations north of 40°N were tested with the concurrent wind speeds, while those south of 40°N were tested with the wind speed lagged by 6 months. The chances that the relationship is actually so simple are small. Labitzke and van Loon (1988) have proposed that the effect of the QBO and the solar cycle are interdependent. Larger ozone anomalies might then be observed when the solar cycle activity is high at the same time as the tropical 50-mbar winds are westerly. Schuster et al. (1988) examined the high-resolution TOMS data and concluded that, although there is a relationship between equatorial and extratropical QBO signal in the stratosphere, the interannual variability that can be seen in longitudinal time series at high latitudes implies that the equatorial QBO is not a good indicator of the high-latitude interannual variability. Further, they report that the QBO may be modified by a 4-year oscillation or by the eruption of El Chichón in April 1982. Thus, there are good reasons to suppose that the treatment of the QBO in this analysis is too simple. However the high significance of the calculated coefficients (especially at high and low latitudes) indicates that the simple model used does manage to extract much of the QBO's effect on total ozone.

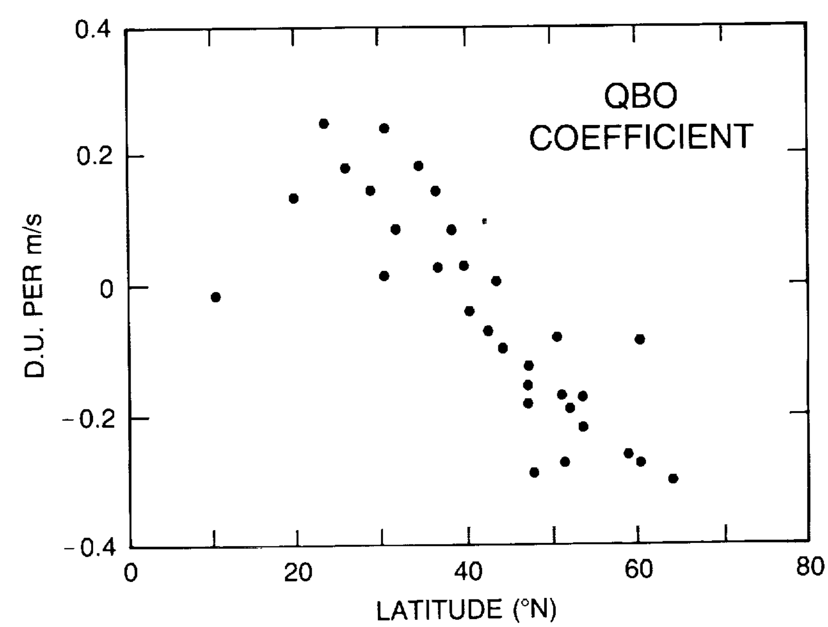


Figure 4.48 The calculated coefficients for the quasi-biennial term are plotted for 31 stations. At all latitudes except those between 30–39°N, the Singapore wind speed was kept concurrent with the total ozone (so that they are anticorrelated in northern latitudes). Between 30–39°N, a 6-month phase lag was imposed on the Singapore wind speed.

In view of the possible factors that are capable of perturbing the atmosphere's response to the QBO, it is worth reconsidering the possible nonlinearity of a decrease in ozone discussed earlier in this section. If there had been no exceptional natural events in the last few years, it would be reasonable to say that there is weak evidence to support the view that there has been a nonlinear decrease, with the rate of loss increasing in more recent years. However, both 1983 and 1985 were years in which low levels of ozone were observed, and they were also both years in which the QBO would be expected to cause negative deviations in total ozone. Two additional events occurred that might have affected total ozone in 1983: the El Chichón volcano erupted in April 1982, injecting large amounts of particulate matter, especially sulfate, into the stratosphere, and in 1983 there was an El Niño. Either the El Chichón eruption or the El Niño might modulate the QBO effect on total ozone as well as having an effect of their own, and because such a modulation is not included in the statistical model, the effects are not accounted for mathematically. In this context, it is worth recalling that in 1983, the 100-mbar temperatures diverged from their historical relationship with total ozone at Bismarck and Churchill, although not at Belsk.

The mechanism through which the QBO of the stratospheric winds at the Equator affects total ozone at other latitudes must be properly understood before it is realistically possible to judge how other events might modulate this effect. Further statistical analyses should be performed to elucidate the character of the relationship as much as possible.

4.6.2.5 Effect of the 11-Year Solar Cycle

The relationship of total ozone with the amount of solar radiation passing through the atmosphere is very complex. The amount of ozone at any place in the atmosphere is dependent on both photochemical and meteorological processes. Variations in the levels of solar radiation reaching the atmosphere will affect the rates of photochemical reactions and the amount of solar energy absorbed. Changes in the heating rates and the temperature distribution in the atmosphere will occur, leading to changes in the circulation patterns as well as affecting the rates of those chemical reactions that are temperature dependent. Further, it is possible that the responses of ozone concentrations to the natural variations in solar radiation are dependent on latitude, altitude, and season. Many studies have looked at the statistical relationship between the solar cycle and total ozone, some of which looked at the short time-scale of 27 days (e.g., Gille et al., 1984c; Hood, 1984; Chandra, 1985; and Keating et al., 1985). Others investigated the link with the 11- and 22-year cycles (e.g., Keating, 1981; Natarajan et al., 1980–1981; Brasseur and Simon, 1981; and Garcia et al., 1984). In a trend analysis where the changes might have occurred over a decade or so, it is important to allow for any total ozone variations that might have occurred on a similar time scale, i.e., the 11- and 22-year cycles. Because of the complexity of the relationship between the solar irradiance and total ozone, the proxy used in most trend analyses is a measured quantity that, it is hoped, is related to the total solar flux. A calculated response such as that for the atmospheric bomb tests has not been used. The 10.7 cm solar flux series was used by Reinsel et al. (1987) and Oehlert (1986). Reinsel et al. found that there was a positive change in global total ozone from solar minimum to maximum of about 1 percent, while Oehlert calculated the change to be +1.3 percent. These are compatible with the model estimates of Garcia et al. (1984). Similar trend studies using the SBUV data from Nimbus–7 are hampered by the fact that the total ozone measurements were started in 1979, near the maximum of the last solar cycle.

The current trend analyses use the smoothed sunspot series shown in Figure 4.42. Bishop (private communication) noted that the response of total ozone to the solar cycle is more significant when the solar cycle indicator is smoothed and that it is more reasonable on physical grounds to use a smoothed series. (In this case the smoothing is performed by taking the mean of each pair of consecutive 12-month running means of the monthly values.) The calculated solar cycle coefficients for each station are given in Table 4.22 for the model whose results are shown in Appendix 4.B.(i).(a). It is hard to pick out any features within these values, except that there are occasional inconsistent results from geographically proximate stations. Any proportional relationship between the solar activity and total ozone appears to be marginally statistically significant. As mentioned, no attempt has been made to determine whether solar activity modulates the QBO or any other meteorological phenomena in this study.

Table 4.22 Statistical Evaluation of Ozone Variations in Response to the Solar Sunspot Cycle.

Station	Sunspot Coefficient
Reykjavik*	+14.6 ±4.4
Lerwick	+ 6.2 ±3.2
Leningrad	+ 1.4 ±3.9
Churchill	+ 6.0 ±3.2
Edmonton	+ 3.8 ±3.2
Goose	+ 7.6 ±3.0
Belsk	+ 4.4 ±3.3
Bracknell	+ 1.5 ±2.8
Uccle*	+ 4.2 ±3.5
Hradec Kralove	+ 2.6 ±3.8
Hohenpeissenberg	− 0.3 ±2.7
Caribou	+ 7.6 ±3.2
Bismarck	+ 6.2 ±3.0
Arosa	+ 2.7 ±2.2
Toronto	− 0.4 ±3.0
Sapporo	+ 7.0 ±3.2
Rome	+ 4.2 ±2.8
Boulder	+ 0.4 ±2.4
Cagliari	+ 7.6 ±3.6
Wallops Isle*	+ 0.3 ±2.4
Nashville	+ 5.4 ±2.7
Tateno	+ 3.0 ±2.7
Srinigar	+ 5.0 ±2.1
Kagoshima	− 0.3 ±3.6
Quetta	+ 3.0 ±2.8
Cairo	+ 2.0 ±1.6
Mauna Loa	+ 1.5 ±2.4
Huancayo	+ 1.2 ±1.2
Aspendale	+ 2.2 ±2.7
MacQuarie Isle	+ 9.9 ±4.6

The solar cycle coefficients for the individual stations from Appendix 4.B.(i).(a). The units are in Dobson Units per 150 sunspots. The (*) indicates stations whose record starts after January 1970 so that they cover 1.5 solar cycles or less.

4.6.3 Results of the Analysis of Latitudinal Averages of Dobson Data

The provisionally revised data were analyzed with the same sets of statistical parameters after the records from all the stations were combined to form latitudinal band averages. The use of these composite time series enables the inclusion of measurements from stations for which provisionally revised data have been prepared but that are not suitable for time series analysis on their own for reasons associated with length and completeness of records. For instance, measurements were taken at Uppsala, Sweden, from 1950 to 1966: obviously, they can not be tested for a decrease in recent years, but their inclusion increases the number of stations used in forming the early part of the latitudinal band averages.

The deviations of the yearly averages from their long-term means are plotted in Figure 4.49 for four latitude bands: 60–80°N, 53–64°N, 40–52°N, and 30–39°N. The deviations are shown as percentages of the respective belt average for 1957–1986, with the belt averages marked on the right-hand axis. The vertical bars above and below the curves show the approximate single

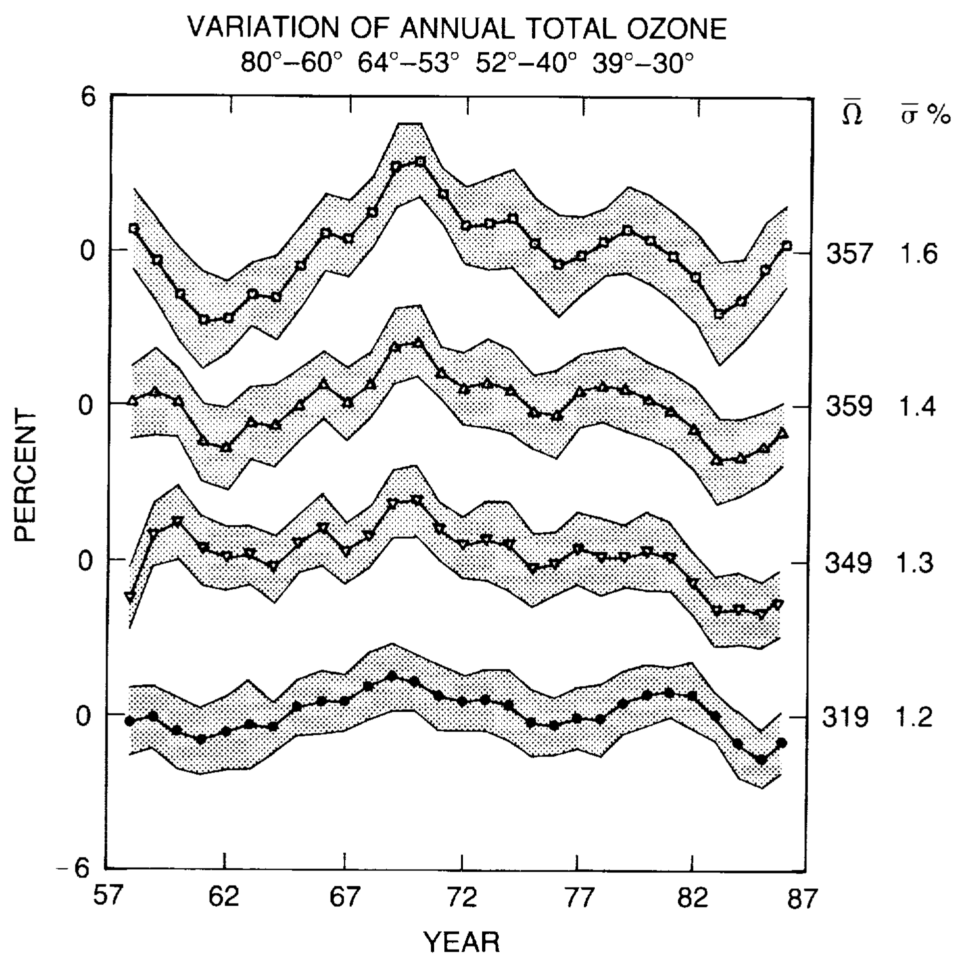


Figure 4.49 Variation of annual total ozone percentage deviations for the three latitude bands 53–64°N, 40–52°N, and 30–39°N. The curves are smoothed by a (1:2:1)/4 smoother. The vertical bars represent ± 1 standard deviation where the standard deviation is calculated from the combination of the individual stations' intramonthly standard deviations with no allowance made for any effects such as regional correlation between stations. The most northerly band has the highest ozone values.

standard deviation uncertainty associated with each point. (The possible uncertainty is found by combining the standard deviations for all the monthly values from the stations that are used to calculate that particular point in the latitudinal band average. No allowance for spatial correlation or autocorrelation is made.) Figure 4.50 shows the deviations and associated uncertainties for the winter values, and Figure 4.51 is the equivalent plot of the summer values for the same belts. The relative quality of the stations' data used to establish the combined files is considered to be moderate, better, best, and better, respectively. It should be noted that the stations located between 60°N and 65°N are included in two latitude belts. This was done to compensate for the scarcity of data at these latitudes and to try to reflect the extremely intensive meridional exchange existing there. However, the stations north of 65°N have varying periods of total polar darkness, and hence lack of data, throwing a heavy weighting onto the 60–65°N stations in the winter months. This 60–80°N latitudinal band average was formed to investigate the behavior of total ozone in the far north. The results should not be compared with the results of the more southerly bands, because there is less data and because some data are also used in the 53–64°N band average.

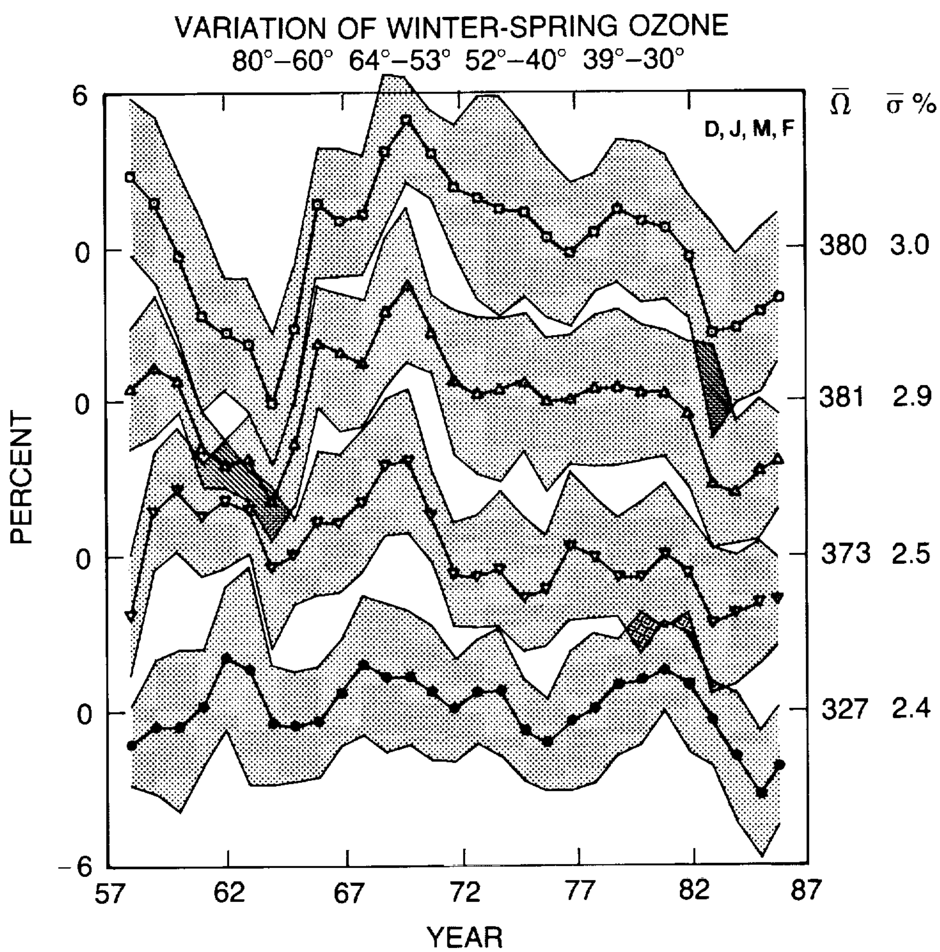


Figure 4.50 Variation of winter total ozone percentage deviations for the three latitude bands 53–64°N, 40–52°N, and 30–39°N. The curves are smoothed by a (1:2:1)/4 smoother. The vertical bars represent ± 1 standard deviation where the standard deviation is calculated from the combination of the individual stations' intramonthly standard deviations with no allowance made for any effects such as regional correlation between stations.

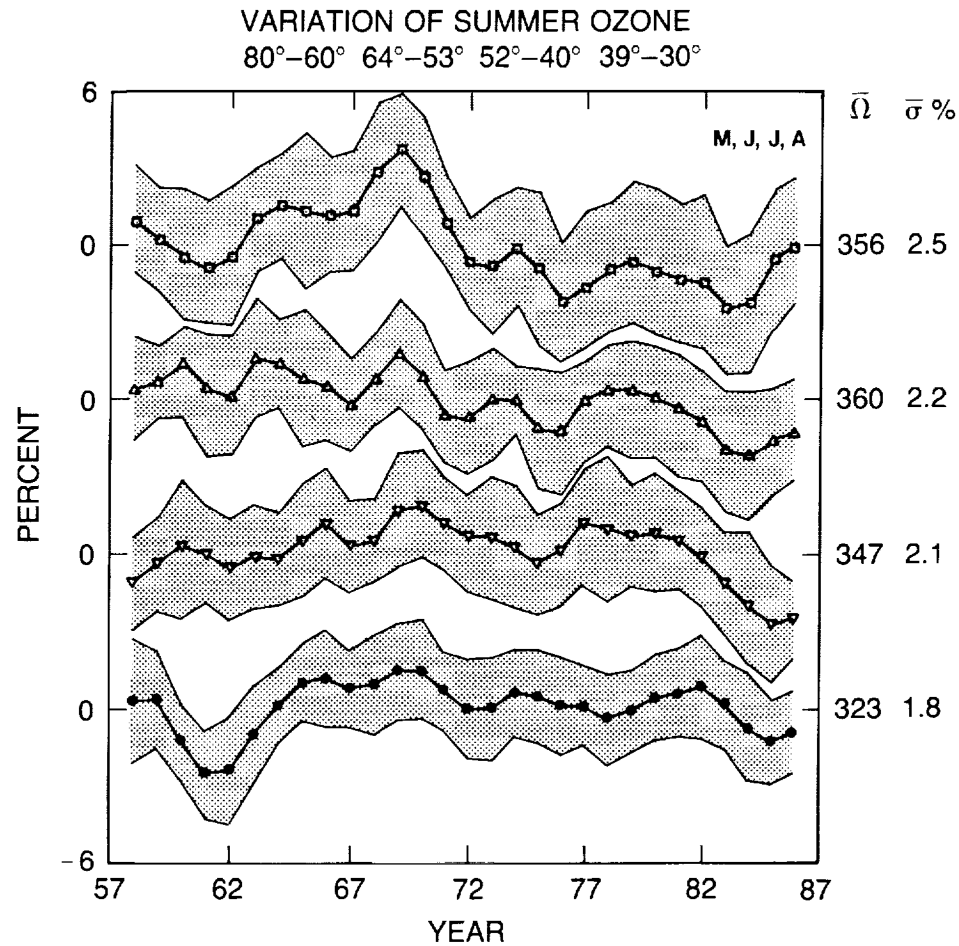


Figure 4.51 Variation of summer total ozone percentage deviations for the three latitude bands 53–64°N, 40–52°N, and 30–39°N. The curves are smoothed by a (1:2:1)/4 smoother. The vertical bars represent ± 1 standard deviation where the standard deviation is calculated from the combination of the individual stations' intramonthly standard deviations with no allowance made for any effects such as regional correlation between stations.

4.6.3.1 Results

The coefficients for the latitudinal band averages found from the six types of analyses described for the individual stations are given in Appendix 4.B.(ii). Table 4.23 contains the results of the model that uses the data from January 1965–1986, starts the ramps in 1970, and includes terms for the QBO and the solar cycle. The monthly losses corresponding to these trend coefficients over the period 1970–1986 are shown in Figure 4.52 for the three main bands. Table 4.24 contains the results of the model that used all the data and that included terms for the QBO, the solar cycle, and the atmospheric bomb tests. The main conclusions are in good agreement with the results of the station analyses:

- There is a high-latitude wintertime loss occurring in the Northern Hemisphere.

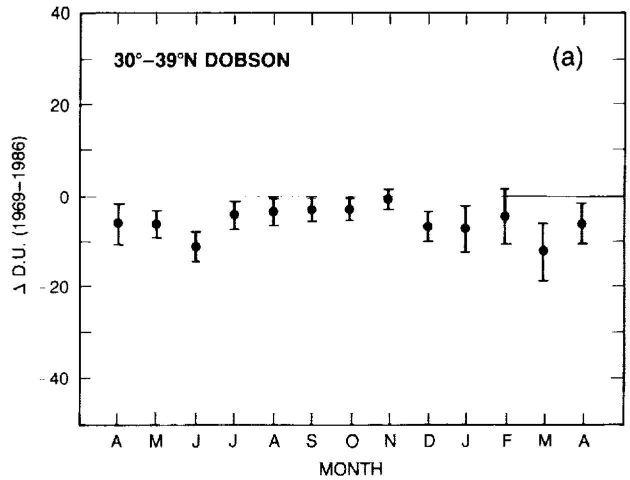
Table 4.23 Monthly Coefficients (in DU/Yr) for the Three Latitude Bands for 1965–1986 Data.*

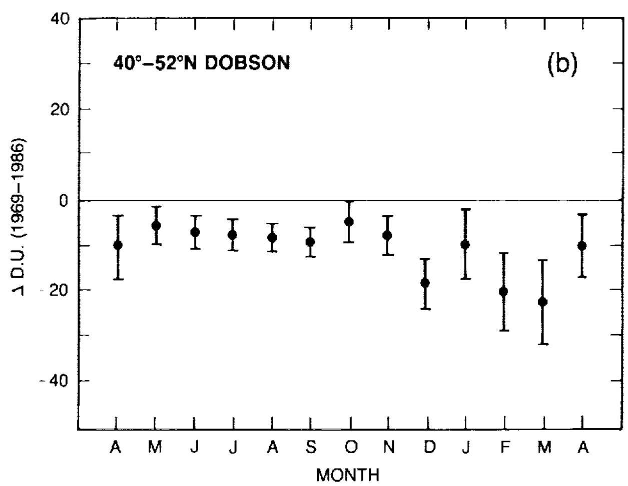
Model Time Period	53–64°N 1/65–12/86	40–52°N 1/65–12/86	30–39°N 1/65–12/86
January	−1.84 ±0.50	−0.56 ±0.45	−0.42 ±0.30
February	−1.79 ±0.71	−1.18 ±0.51	−0.25 ±0.37
March	−1.07 ±0.36	−1.33 ±0.55	−0.72 ±0.38
April	−0.52 ±0.34	−0.58 ±0.41	−0.35 ±0.27
May	−0.52 ±0.27	−0.30 ±0.24	−0.35 ±0.18
June	+0.22 ±0.20	−0.39 ±0.21	−0.64 ±0.19
July	0.00 ±0.22	−0.43 ±0.20	−0.23 ±0.18
August	+0.03 ±0.24	−0.46 ±0.18	−0.18 ±0.18
September	+0.03 ±0.21	−0.53 ±0.19	−0.17 ±0.15
October	−0.19 ±0.21	−0.27 ±0.26	−0.15 ±0.14
November	+0.27 ±0.32	−0.44 ±0.25	−0.02 ±0.13
December	−1.17 ±0.46	−1.08 ±0.33	−0.38 ±0.20
Average	−0.55	−0.63	−0.32
QBO ($DU/40ms^{-1}$)	−6.40 ±2.36	−4.40 ±2.28	+6.00 ±2.00
Solar (DU/150 sunspots)	+5.88 ±2.63	+2.64 ±2.48	+0.33 ±2.00
Yearly Coefficient	−0.14 ±0.13	−0.47 ±0.13	−0.16 ±0.11

*The data from 1965–1986 were analyzed, and trends from 1970, the QBO, and the solar cycle were allowed for in the model (QS70).

- The QBO coefficient is significant at all latitudes and is anticorrelated above 40°N and 6 months out of phase between 30° and 39°N.
- The solar cycle relationship is less clear: according to the band analyses, the effect on total ozone is minimal in the 30–39°N band. However, this is not clear from the results of the station analyses (see Table 4.23).
- The atmospheric nuclear bomb tests had a greater effect at higher latitudes.

The LLNL predictions of the nuclear bomb test effects on ozone appear to agree better at higher latitudes. However, the uncertainties associated with the bomb test parameters are sufficiently high that firm conclusions are difficult. During the early 1960's, ozone deficiency is most pronounced in the winter season plots. While it is possible to attribute these deficiencies to the nuclear bomb tests carried out in the atmosphere, one should not ignore that the QBO was in its westerly phase during 1961 and 1963–1964, and that there was an ENSO in 1964. Both these geophysical events are circulational conditions that could cause (or be coincident with) ozone deficiencies in the northern latitudes. The strongest known ENSO in this century occurred in 1982–1983, overlapping with the westerly phase of the 1983 QBO, and might have contributed substantially to the negative ozone deviations in the mid-1980's (Bojkov, 1987b).





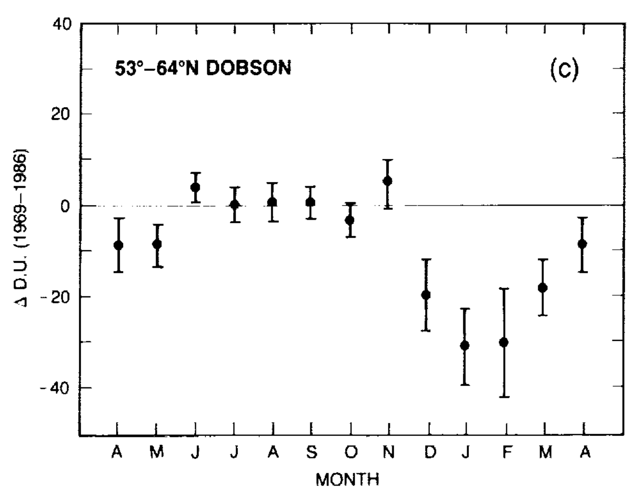


Figure 4.52 Ozone changes for the three latitude bands 53–64°N, 40–52°N, and 30–39°N between 1970 and 1986. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation, and data from 1965–1986 were used. The ozone change in each month was assumed to have occurred in a linear fashion after 1969. The monthly ozone changes plotted are not trends; they are found by multiplying the calculated trend by the 17-year period over which the loss was assumed to have occurred. The vertical bars represent ± 1 standard error in the estimate of the change. (a) 54–64°N, (b) 40–52°N, and (c) 30–39°N.

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Table 4.24 Monthly Coefficients (in DU/Yr) for the Same Bands as in Table 4.23 for 1957–1986 Data.*

Model Time Period	53–64°N 1/57–12/86	40–52°N 1/57–12/86	30–39°N 1/57–12/86
January	− 1.10 ± .47	− 0.81 ± .43	− 0.31 ± .29
February	− 1.70 ± .66	− 1.15 ± .49	− 0.11 ± .36
March	− 0.83 ± .34	− 1.35 ± .53	− 0.43 ± .37
April	− 0.35 ± .33	− 0.48 ± .39	− 0.38 ± .27
May	− 0.51 ± .26	− 0.28 ± .24	− 0.28 ± .18
June	− 0.04 ± .19	− 0.17 ± .21	− 0.44 ± .19
July	− 0.06 ± .21	− 0.20 ± .20	+ 0.08 ± .18
August	− 0.22 ± .23	− 0.12 ± .18	+ 0.23 ± .18
September	+ 0.09 ± .20	− 0.21 ± .19	+ 0.13 ± .15
October	+ 0.10 ± .21	− 0.05 ± .26	+ 0.14 ± .14
November	+ 0.61 ± .32	− 0.44 ± .25	+ 0.12 ± .14
December	− 0.38 ± .44	− 1.14 ± .33	− 0.26 ± .20
Average	− 0.37	− 0.53	− 0.13
QBO (DU/ms^{-1})	− 6.80 ± 2.16	− 5.60 ± 2.28	+ 5.20 ± 1.88
Solar DU/150 sunspots)	+ 1.23 ± 2.02	− 2.52 ± 2.33	+ 0.96 ± 1.83
Nuclear	− 0.48 ± .19	− 0.50 ± .30	− 0.09 ± .32
Yearly coefficient	− 0.09 ± .14	− 0.24 ± .15	+ 0.05 ± .12

*The data from 1957–1986 were analyzed, and trends from 1970, the QBO the solar cycle, and the atmospheric bomb tests were allowed for in the model (QNS70).

4.6.3.2 Combination of Incomplete Station Data Into Band Averages

Although all of the groundstations in the north Temperate Zone exhibit very similar seasonal variations in total ozone, with maxima in March or April and minima in September, October, or November, difficulties can arise when these data sets are combined to form latitudinal band averages. A band average is supposed to be a set of data that are representative of the ozone levels within that band, and that can thus be directly compared to the results from 2-D model calculations for various latitudes. The 2-D model necessarily ignores any longitudinal variations in ozone concentrations. The process of combining the data from different stations is seemingly simple, and yet is actually the opposite.

From a statistical point of view, the ideal case would be one in which each station within a band is taking readings of total ozone drawn from the same parent population—i.e., the statistical behavior of the total ozone (seasonal means, standard deviations, etc.) is the same above each station; the measurements at one station are not correlated with those from any other station; and each station has been operating for the same length of time. In practice, none of these conditions is met. No two stations in a band measure from the same parent population because the meteorology at each station is different in at least some respects from that at any of the others. The observed differences include different mean ozone levels, different timings for the ozone maxima, and different magnitudes of the yearly cycle (Bowman and Krueger, 1985). The first of these factors has been overcome in these calculations by normalizing the series from each station through division by its long-term mean, while the last of these factors was not accounted for in the analyses presented here.

The difference in the timing of the maxima does pose some problems when the data are analyzed for seasonal changes. There are two cases where special caution is needed. First, a large number of Soviet stations were improved by the introduction of the M–83 filter ozonometer in 1972; the measurements from these stations were not included in the latitudinal band averages because the ozone maximum over most of the USSR occurs later than over most Western stations (Figure 4.46). Second, for the cases where all the data from 1957 are analyzed in the two most northerly bands (53–64°N and 60–80°N), only a few stations were making measurements in the very early years. This problem has nothing to do with the quality of the data, and is caused only by the combination of incomplete sets of data that have different statistical characteristics. It is also well known that the readings from one station are correlated with those of nearby stations. Indeed, this fact was one of the criteria used in looking for possible errors in the ozone record from an individual station that might signify an unrecorded calibration of the basic instrument. Finally, Tables 4.3, 4.4, and 4.7 indicate that the station records are not fully coincident, but instead show wide variations in the period of time covered.

The problems involved in the combination of records of different length when the ozone maxima are displaced in time can be illustrated with the data from the Dobson stations at Belsk and Bismarck. These two stations experience approximately 1 month's difference in the timing of their ozone maxima and minima (see Figure 4.53) and so provide a good example. The available records for both stations cover the entire 24-year period from January 1963–December 1986, and show similar decreases in total ozone during the winter when the second 12-year period is compared with the first 12-year period (see Figure 4.35), or in an 11-year vs. 11-year period

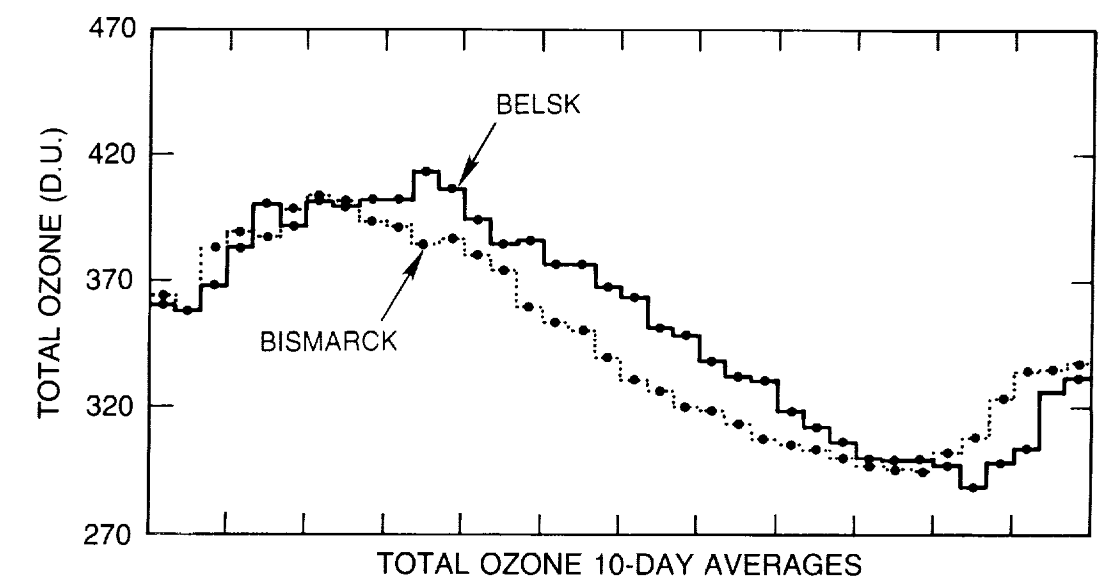


Figure 4.53 Annual total ozone cycles at Belsk and Bismark. The points represent the 10-day averages at each station calculated from 24 years of measure.

comparison for the final 22 years. The combination of these 24-year data sets has been carried out by first normalizing each by division of the long-term mean, and then averaging the normalized monthly concentrations to obtain a two-station value. The purpose of this combination is solely to illustrate the inherent problems in this process.

A hypothetical test of the combination of records of differing lengths can be obtained from these real data by assuming that the data from Bismarck are available only from January 1975 on, and not during the first 12-year period. Combination of the Belsk and Bismarck data for 1975–1986 can provide average values for this period. In this hypothetical instance, with only the Belsk data available for the first period, the 1963–1974 "average" will be just the Belsk data. An alternative illustration can be gained by using "Bismarck only" for the earlier period. Comparison of these average values presents a very different picture of the months in which ozone losses have appeared in the second period relative to the first (Figure 4.54). The full average is shown by the solid circles, with an average wintertime loss similar to that found for the individual stations. Both incomplete combinations displace the timing of ozone losses in Figure 4.54.

The addition of data from a large group of stations with different mean timing of their ozone maxima to a longer set of data could result in distortion of the seasonal observations. For this reason alone, the total ozone data collected with the M–83 instrument have not been blended into the overall band data, because their useful record begins only in 1972 and not in the early 1960's. Similarly, the monthly results for the 53–64°N and 60–80°N bands when all the data from 1957 are included should be treated carefully, as only a few stations were making measurements in the early years, with many joining in later on. These are the conditions that can tend to blur possible seasonal differences in ozone loss. However, in the basic analysis where the data from

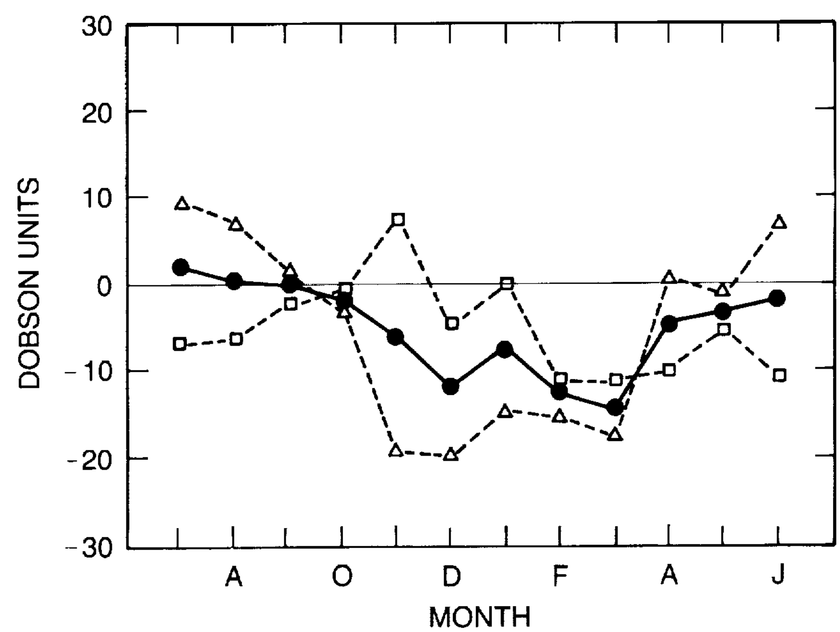


Figure 4.54 The points using the symbol ● are the differences in the monthly averages for the periods January 1963–December 1974 and January 1975–December 1986 for a combined series of the data from Belsk and Bismarck. The equivalent results when only Belsk was taken as operating in the former period are shown with the symbol □, while those for the case where just Bismarck was taken for the first period have the symbol ▲. In all cases, both stations' data were used in the second period.

1965–1986 are considered, there is no significant disagreement between the seasonal trends calculated from the latitudinal band averages and the average seasonal trends of those stations within the latitude bands that have records that are long enough for time series analysis. The winter losses over the 17-year period from 1970–1986 for the three bands are (1) 53–64°N, -6.2 ±1.5%, and -7.2%, where the first value is for the analysis of the latitudinal band average (from Table 4.23) and the second value is the average of the individual station losses in Table 4.16 converted to a percentage; (2) 40–52°N, -4.7 ±1.5%, and -5.0%; and (3) 30–39°N, -2.3 ±1.3%, and -1.5%. Similarly, the summer (MJJA) losses are (1) 53–64°N, -0.2 ±0.8%, and +0.1%; (2) 40–52°N, -1.9 ±0.7%, and -1.9%; and (3) 30–39°N, -1.9 ±0.8%, and -1.9%. None of these pairs of estimates for the average loss in the different latitude bands shows any inconsistency in the results using the two methods for calculating the changes. Despite the potential problems in assembling latitudinal band averages, they do provide extra insight into the changes in total ozone because they include data from stations with short or incomplete records.

4.6.3.3 Year-Round Versus Monthly Loss Models

A comparison of the results from the year-round and monthly models illustrates how important the underlying assumptions for the two models are. Table 4.25 contains the yearly trend estimates calculated in three different ways for three latitude bands: (1) the coefficient from the year-round model, (2) the weighted mean of the monthly coefficients (using the square of the inverse of the standard error as the weighting factors), and (3) the unweighted mean of the monthly coefficients. For each band, the largest loss is that found by taking the unweighted average of the monthly trend estimates. The difference among the estimates is much greater in the more northerly belts, where there is a very pronounced seasonal difference between the monthly loss rates. Because the largest losses are occurring in the winter months, during which the uncertainty in the trend coefficient is greatest, the weighted average reduces the effect of these months on the year-round estimate. In each band, the winter months are the dominant contributors to the estimate of the unweighted mean because their absolute values are bigger, while the summer months are the more important in determining the weighted mean because their error estimates are smaller. Statistically, the assumption required to attach much meaning to an average is that each sample is drawn from the same parent population—i.e., the underlying losses for each month are the same. Because the current photochemical models predict different losses at different times of the year, and the data themselves show such behavior, this assumption is broken, and thus it is not clear exactly what a year-round average represents.

Table 4.25 Different Ways of Calculating an Annual Rate of Loss.

		Latitude band	
	53°–64°N	40°–52°N	30°–39°N
(a)	- 0.14 (.13)	- 0.47 (.13)	- 0.17 (.11)
(b)	- 0.19 (.13)	- 0.49 (.11)	- 0.25 (.09)
(c)	- 0.52 (.20)	- 0.63 (.17)	- 0.32 (.14)

In the top row (a) are shown the values calculated using a uniform year-round trend term, the classical "hockey stick," for the three latitudinal band averages. In row (b) are shown the weighted averages of the monthly loss rates calculated from the model that allows each calendar month to vary differently, while the bottom row contains the unweighted averages of the same monthly coefficients. One standard error bar is in parentheses. Allowance is made for the correlation between the different monthly coefficients.

The validity of the year-round hockey stick model is subject to the same criticisms as the averages from the monthly models. Unless supported by the data, the assumption of a constant year-round loss should not be used, because the model is then misspecified. In the current analyses, this misspecification leads to rates of ozone loss that are smaller than either the weighted or unweighted means of the monthly values and it does not indicate the presence of the relatively large wintertime losses that are observed at higher latitudes.

4.6.3.4 Variation With Time of the Latitude Band Monthly Ramp Coefficients

The observation that the linear regression analysis with monthly ramp coefficients demonstrates losses of ozone for many of the months in each latitude band does not provide much information as to when the ozone loss occurred. The reasonable agreement between total ozone losses estimated for 17 years after 1969 (i.e., $17 \times k_{70}M$) and 11 years after 1975 (i.e., $11 \times k_{76}M$) indicates that much of the total loss occurred after 1976, but does not severely test the underlying assumption that ozone loss is spread over a 10–17-year period. With other geophysical events such as the large oceanic El Niño of 1982–1983 and the El Chichón volcanic eruption (April 1982) prominent during the period of indicated ozone loss, the possibility needs to be considered that such an event might have triggered a sudden large ozone loss, superimposed on a background of little or no loss for other reasons. Such hypotheses have been statistically tested by examining the linear regression coefficients as successive years of ozone data are included in the analysis. For these tests, the latitude band data from January 1965 on have been analyzed with the addition of 1-year increments of ozone data from 1980–1986. For each of the three latitude bands, the regression analysis was carried out successively for 16 years of data (1965–1980), 17 years (1965–1981), 18 years (1965–1982), and so on through 22 years (1965–1986), with monthly linear ramps from 1969–198x (i.e., $k_{70}M$).

The monthly linear coefficients for the seven calculations are graphed for latitude bands 53–64°N, 40–52°N, and 30–39°N in Figures 4.55–57. The standard errors become steadily smaller as the number of years of data is increased. For 31 of the 36 monthly coefficients, the one-sigma standard errors of all seven (1980–1986) of the yearly coefficients overlap one another. For 4 consecutive months (AMJJ) in the 40–52°N band, the regression coefficients become steadily more negative and the one-sigma errors do not overlap. For the month of December in the 40–52°N band, the linear regression coefficients become steadily less negative and the one-sigma errors also fail to overlap. The relatively small changes in the trend coefficients over this period suggest that the geophysical events of 1982–1983 did not dominate the sign or magnitude of the monthly trend coefficients. In particular, the strong trend toward negative coefficients is already apparent in 1980 and 1981 for the winter months (DJFM) in both the 53–64°N and 40–52°N latitude bands.

A simple evaluation of the general suitability of the linear relationships for fitting the ozone data can be made by calculating the numerical change in the linear regression coefficients as the endpoint of the data goes from 1980 to 1986, scaled by the standard errors of the analyses. Figure 4.58 shows the distribution of these numerical changes divided by the standard errors for the 36 monthly coefficients in the three bands. For example, the linear coefficients for March in the 53–64°N band were -0.40 ± 0.62 for an endpoint of 1980 and -1.07 ± 0.35 for 1986. The scaled change in the coefficient, -0.67 divided by the combined error of 0.71, is graphed as -0.94. As indicated, 31 of the 36 monthly coefficients have values within $\pm 1\sigma$, indicating that the linear model is generally satisfactory. The median value of the change in regression coefficients from 1980 to 1986 is negative, suggesting a tendency toward more ozone loss in the 1980's than during the 1970's.

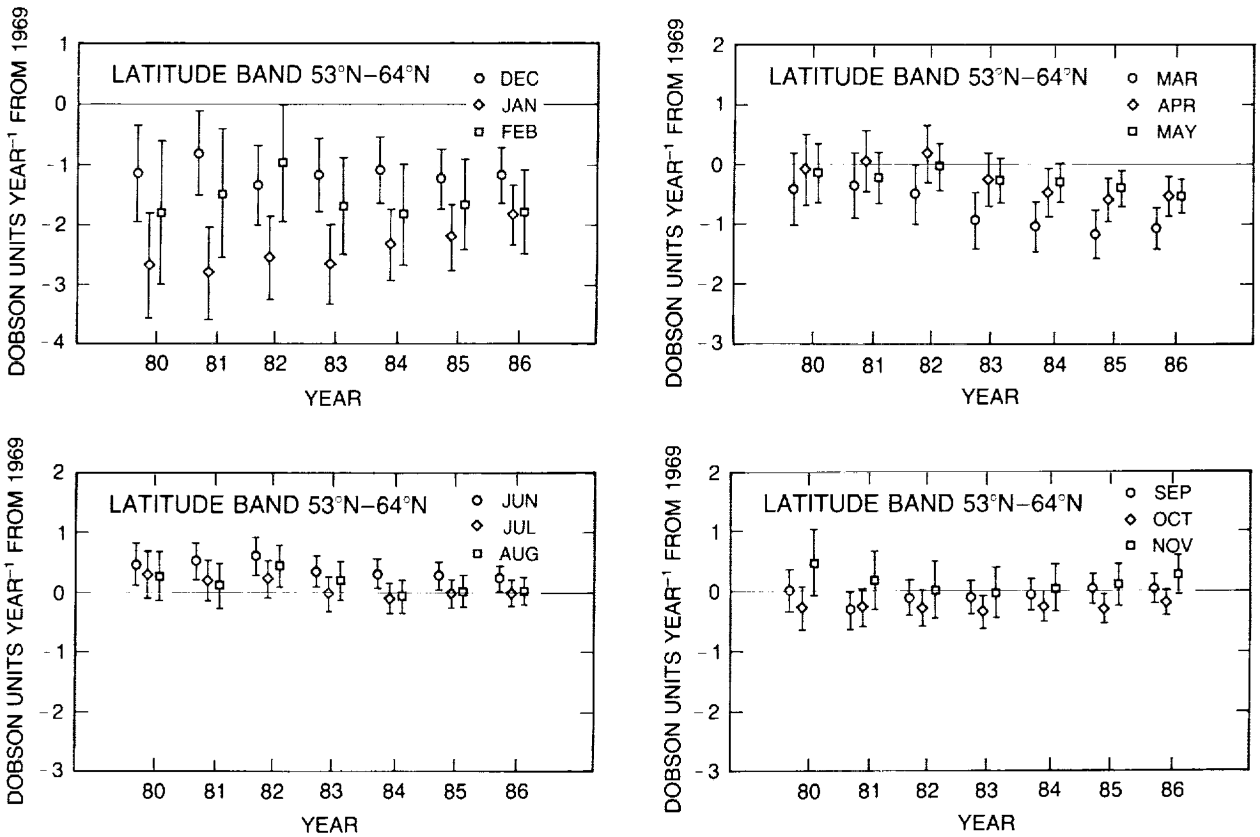


Figure 4.55 The total ozone trends for the individual months are shown for the latitude band between 53°N and 64°N illustrating the effect of the addition of successive years of data. The ozone change in each month was assumed to have occurred in a linear fashion from 1969 until the year shown, and the data used were from 1965 until the year shown. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation. The monthly ozone trends are given in DU/yr.

The regression coefficients have also been calculated for an alternate model in which the ozone changes are not evaluated with linear ramps, but with changes proportional to the organochlorine (CL) burden of the troposphere—i.e., about twice as much as yearly change in 1986 as in 1970. These coefficients for the successive models from 1980–1986 are shown in Figures 4.59–61, and the changes in the values of the coefficient are graphed in Figure 4.62. The conclusions from these calculations are very similar to those from the linear model, with a small drift toward more negative regression coefficients in 1986 than in 1980. In this statistical model, the magnitude of the indicated ozone losses are marginally higher for 1965–1986 than from the linear regression model. Such a result is expected if an overall ozone loss has occurred because the CL model also fits a loss from 1965–1969, while the linear model fits a constant value for the same period. The data fits are comparable with either the linear or CL statistical models, and neither is enough superior to warrant its choice as the clearly better model.

4.6.3.5 Calculation of the Seasonal Error Estimates

The standard error, $\sigma_{\bar{k}}$, for the 4-month winter and summer season trend coefficients given in Table 4.23 are calculated according to Equation 1.

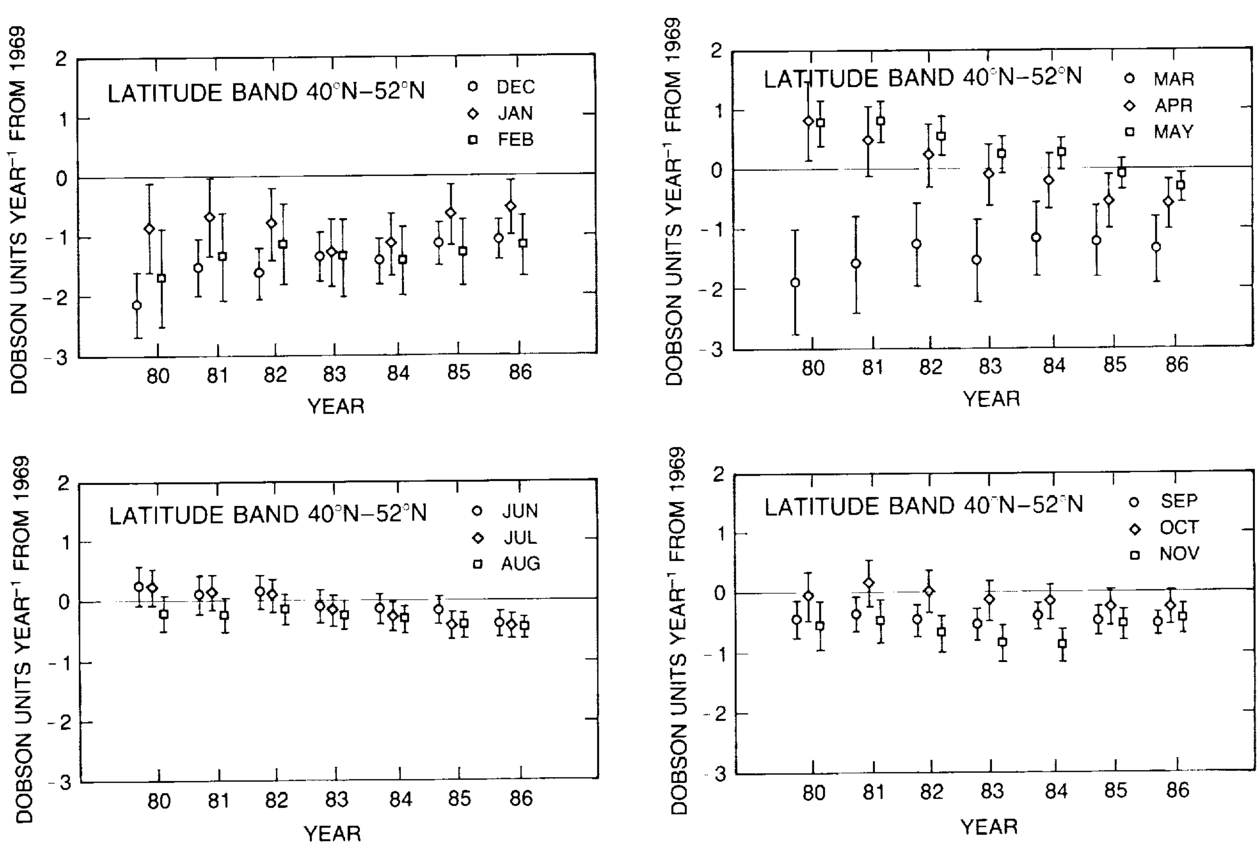


Figure 4.56 The total ozone trends for the individual months are shown for the latitude band between 40°N and 52°N illustrating the effect of the addition of successive years of data. The ozone change in each month was assumed to have occurred in a linear fashion from 1969 until the year shown, and the data used were from 1965 until the year shown. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation. The monthly zone trends are given in DU/yr.

$$\sigma_{\bar{k}}^2 = \frac{1}{4^2}\cdot\left(\sum_{i=1}^{4}\sigma_i^2 + 2\sum_{i=1}^{3}\sum_{j=i+1}^{4}\sigma_{ij}\right) \tag{1}$$

where σ_i is the standard error for each monthly trend coefficient (so that σ_i^2 is the variance estimate); σ_{ij} is the covariance between months i and j and is the product of the standard error for the 2 months with the correlation coefficient of the two monthly trend parameters as shown in Equation 2.

$$\sigma_{ij} = \rho_{ij} \cdot \sigma_i \cdot \sigma_j \tag{2}$$

Because an unweighted seasonal loss rate is calculated, it is appropriate to use these expressions to find the standard error. The same method is used in calculating the standard error of the unweighted annual mean trend in the discussion compares the year-round coefficient with the unweighted and weighted means of the monthly trends. Equation 3 is used to calculate the standard error of the weighted mean, $\sigma_{\bar{k}_w}$.

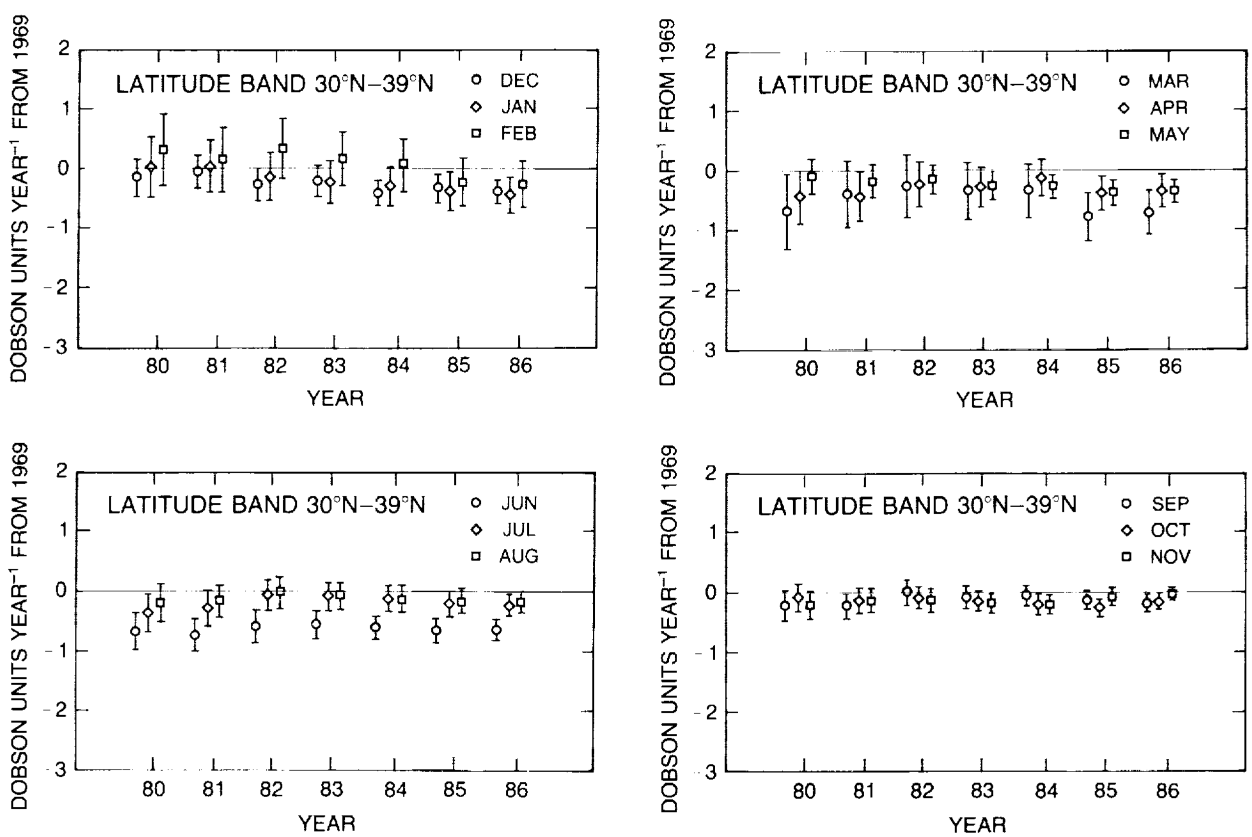


Figure 4.57 The total ozone trends for the individual months are shown for the latitude band between 30°N and 39°N illustrating the effect of the addition of successive years of data. The ozone change in each month was assumed to have occurred in a linear fashion from 1969 until the year shown and the data used was from 1965 until the year shown. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation. The monthly ozone trends are given in DU/yr.

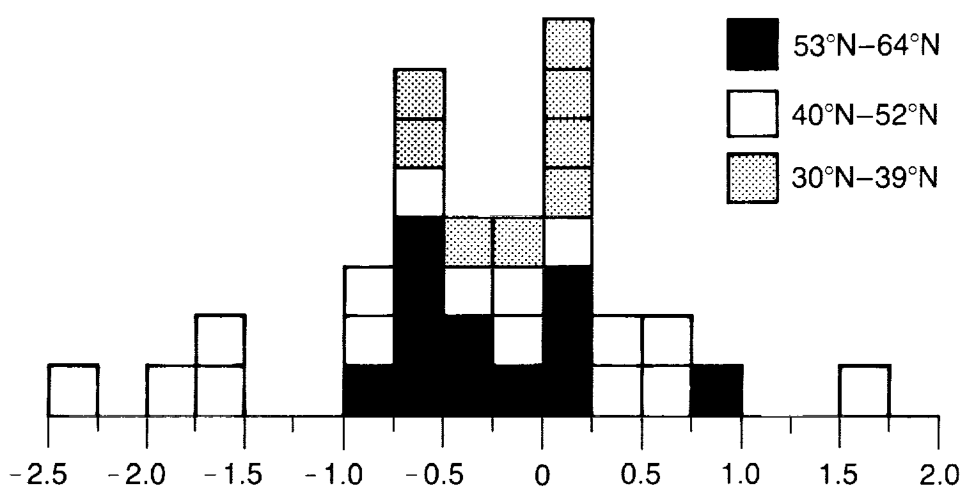


Figure 4.58 Distribution of the changes between 1980 and 1986 in the 36 monthly trend coefficients for the three latitude bands shown in Figures 4.55, 4.56, and 4.57. The difference between the trends calculated for any particular month when the data through 1980 are used and when the data through 1986 are used is divided by the combined standard error of the two trend coefficients.

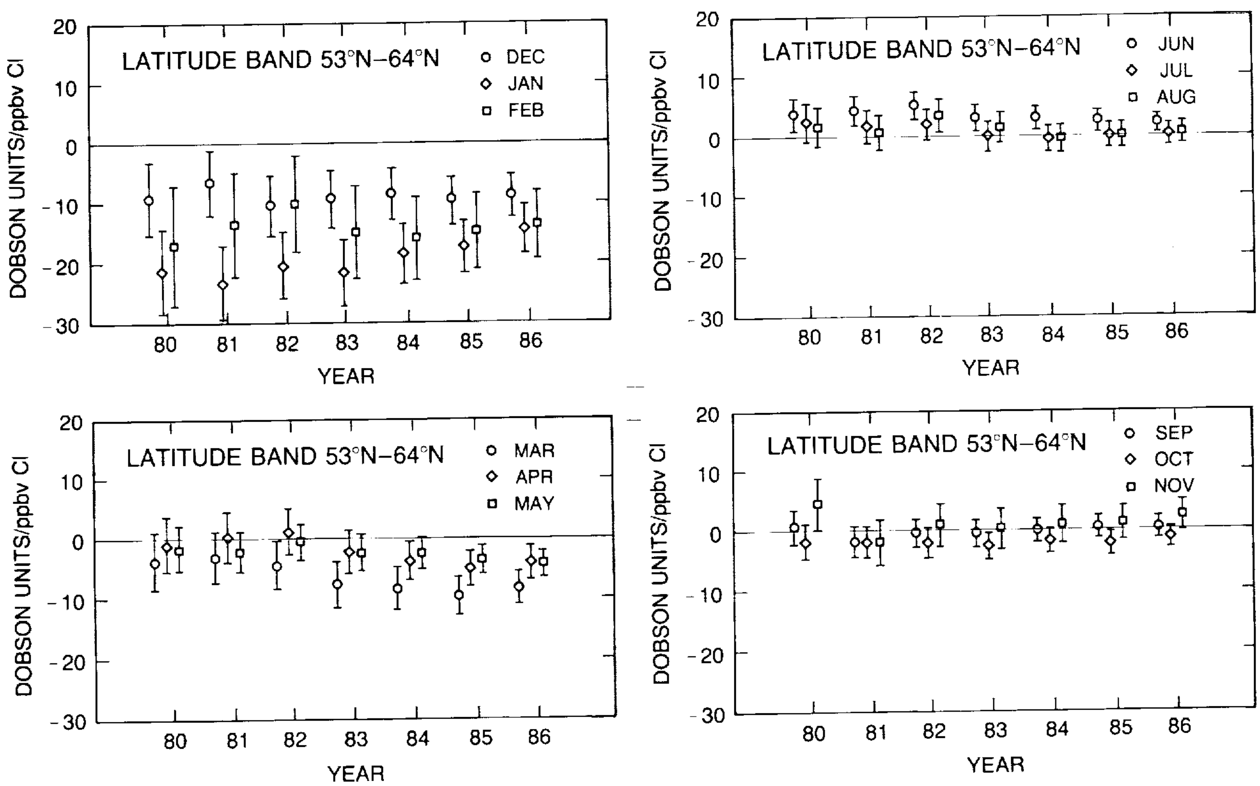


Figure 4.59 The total ozone trends for the individual months are shown for the latitude band between 53°N and 64°N illustrating the effect of the addition of successive years of data. The ozone change in each month was assumed to have occurred in proportion to the organochlorine burden of the troposphere, i.e., in a nonlinear fashion until the year shown, and the data used were from 1965 until the year shown. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation. The monthly ozone *trends* are given in DU/yr.

$$\sigma_{\bar{k}_w}^{2} = \left(\sum_{i=1}^{n} \frac{1}{\sigma_i^2} \right)^{-2} \bullet \left(\sum_{i=1}^{n} \frac{1}{\sigma_i^2} + 2\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sigma_{ij} \bullet \frac{1}{\sigma_i^2} \bullet \frac{1}{\sigma_j^2} \right) \tag{3}$$

The relative sizes of the first and second terms in Equation 1 are shown in Table 4.26 for the winter and summer seasons of three latitude bands. The greater importance of the cross term in the southern band is due to the higher autocorrelation present, which causes the monthly trend parameters to be more dependent on one another.

4.6.4 Results From M–83 Regional Averages

As described in Section 4.1.3, the instrument used in the USSR, the M–83, uses a filter rather than a grating to separate the incoming UV light. Since the filter has a larger bandwidth than a grating, the measurements taken show greater scatter, which shows up in the statistical analysis in the form of larger uncertainties. There is also the potential for greater μ-dependent errors when measurements are taken in winter or away from local noon. The upgraded M–83 instruments have been operated since 1972, so that the length of record is shorter than for most Dobson stations. However, the M–83 monitoring system covers a large area and provides valuable

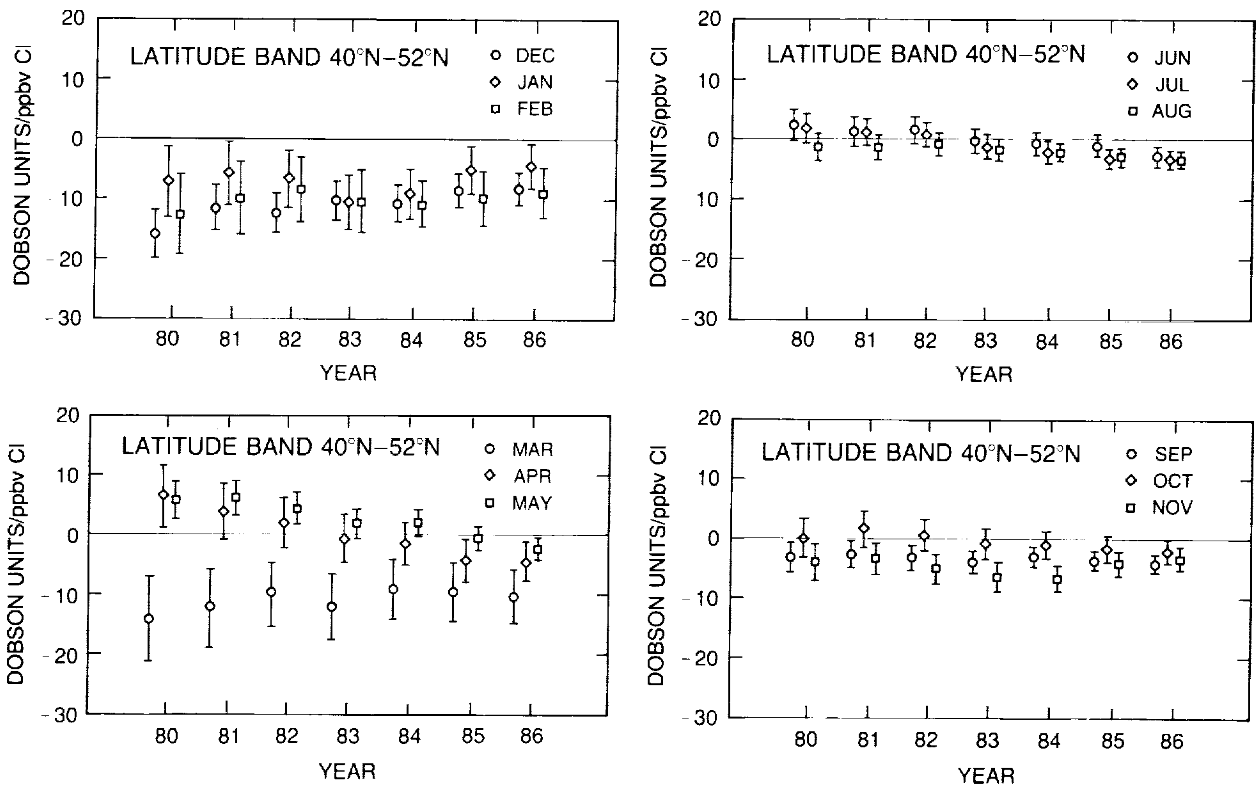


Figure 4.60 The total ozone trends for the individual months are shown for the latitude band between 40°N and 52°N illustrating the effect of the addition of successive years of data. The ozone change in each month was assumed to have occurred in proportion to the organochlorine burden of the troposphere, i.e., in a nonlinear fashion until the year shown, and the data used were from 1965 until the year shown. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation. The monthly ozone *trends* are given in DU/yr.

Table 4.26 Variance and Covariance of the Monthly Trend Estimates Used in Calculating Seasonal Averages.

	Variance	Covariance	Error Estimate
Winter (DJFM)			
53–64°N	1.06	0.95	0.35
40–52°N	0.87	0.94	0.34
30–39°N	0.41	0.60	0.25
Summer (MJJA)			
53–64°N	0.22	0.19	0.16
40–52°N	0.17	0.20	0.15
30–39°N	0.14	0.21	0.15

The relative magnitudes of the variance and covariance of the monthly trend estimates used in calculating seasonal averages. The units are Dobson Units per year.

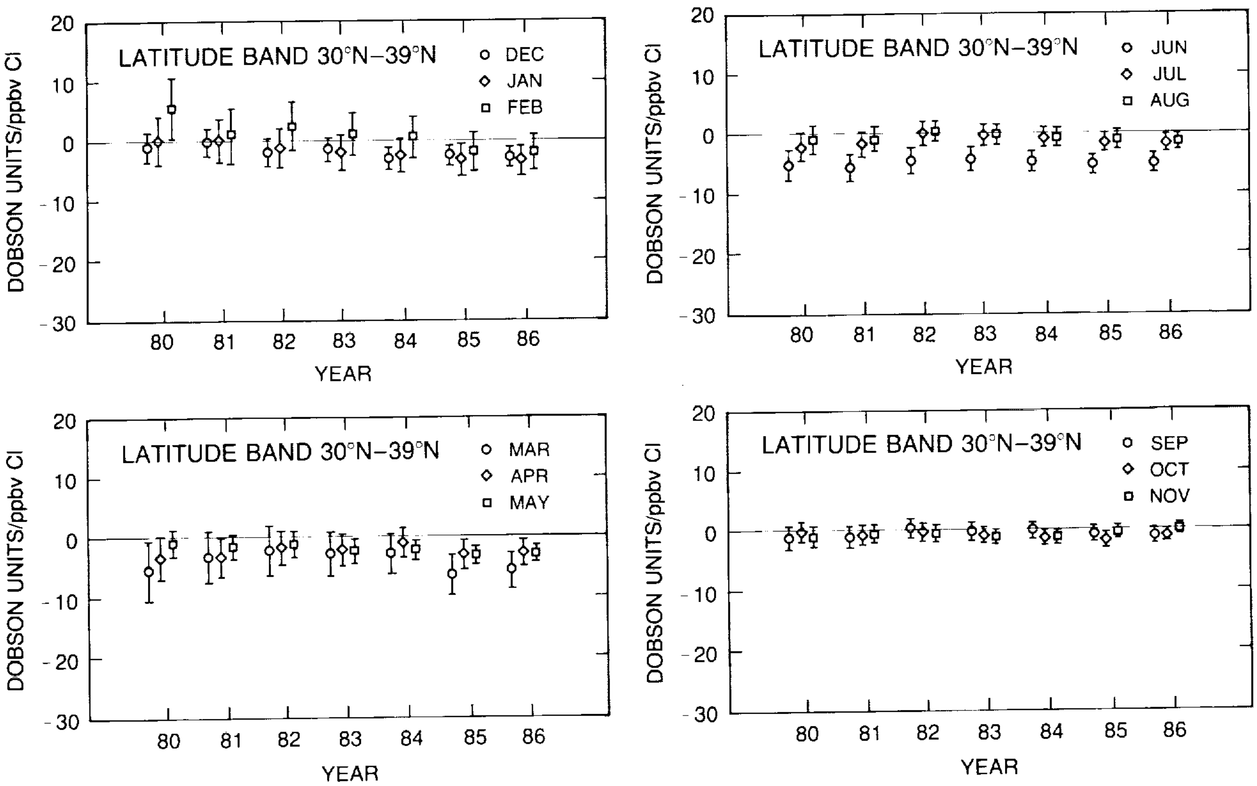


Figure 4.61 The total ozone trends for the individual months are shown for the latitude band between 30°N and 39°N illustrating the effect of the addition of successive years of data. The ozone change in each month was assumed to have occurred in proportion to the organochlorine burden of the troposphere, i.e., in a nonlinear fashion until the year shown, and the data used were from 1965 until the year shown. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation. The monthly ozone *trends* are given in DU/yr.

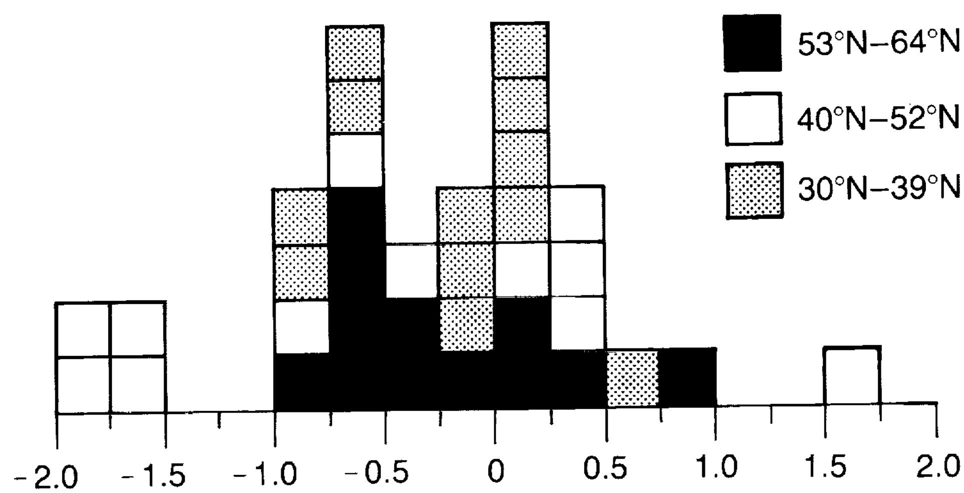


Figure 4.62 Distribution of the changes between 1980 and 1986 in the 36 monthly trend coefficients for the three latitude bands shown in Figures 4.59, 4.60, and 4.61. The difference between the trends calculated for any particular month when the data through 1980 are used and when the data through 1986 are used is divided by the combined standard error of the two trend coefficients.

information where no other ground-based measurements are taken. For the purposes of this report, the data from the M–83 stations were combined to form regional averages, which were analyzed with the same time series technique. The results of these analyses are presented in Appendix 4.B.(ii).

Plots of the monthly losses over 1972–1985 are shown in Figure 4.63 for the four chosen M–83 regions—the European, Siberian, South Central Asian, and Far Eastern parts of the USSR. In both the European and Siberian areas, losses appear to occur in both the fall (September, October, and November) and in the late spring (March, April, and May). The former tendency is

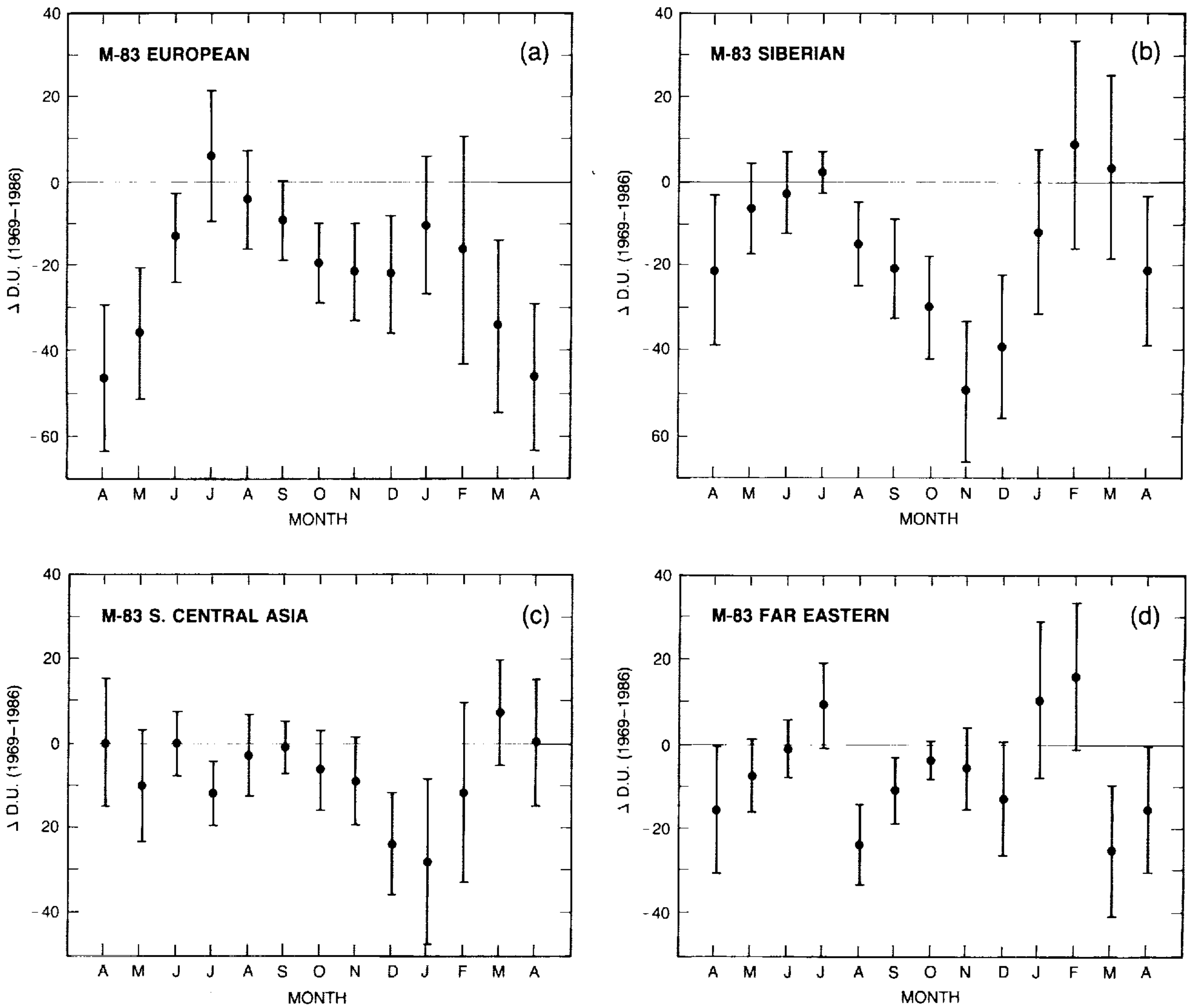


Figure 4.63 Ozone changes for four regional averages composed from the USSR M–83 data taken between 1972 and 1986. The statistical model used allowed for effects of the solar cycle and the quasi-biennial oscillation, and all the available data were used from 1972. The ozone change in each month was assumed to have occurred in a linear fashion. The monthly ozone changes plotted are not *trends*; they are found by multiplying the calculated trend by the period over which the loss was assumed to have occurred. The vertical bars represent ± 1 standard error in the estimate of the change. (a) European region, (b) Siberian region, (c) South Central Asian region, (d) Far Eastern region.

stronger in Siberia while the latter is stronger in the European part. The losses in January and February are small. In the data from the South Central Asian region, there is not much evidence for a loss; the 2 months with the largest negative trends are December and January. The Far Eastern results (from only two stations) show no pattern at all toward a loss or a gain. It is worth recalling that the Japanese stations have observed ozone losses different from the European and North American stations. Sapporo (43.1°N) does not show a wintertime loss; decreases in total ozone are observed in both December and March, but not in January or February. Thus, there is some sign of the bimodal losses measured in the European and Siberian parts of the USSR at equivalent latitudes. However, the statistical significance of these patterns is not strong enough to reach any firm conclusions at the current time.

4.7 ANALYSIS OF TOMS DATA NORMALIZED TO THE DOBSON NETWORK

The primary advantage of a satellite instrument is its ability to make truly global measurements (all but the regions in polar darkness). The TOMS instrument has been described in Section 4.2 of this chapter, and the slight adjustment to its data to use the long-term calibration of the Dobson network has been described in Section 4.4. All of the data reported in this section use this adjusted data set. The adjustment corresponds to about 3 percent added to the data in 1987.

4.7.1 Global and Hemispheric Trends

Figure 4.64 shows the latitudinal–seasonal variation of the TOMS total ozone measurements averaged over 9 years from 1979–1987. The distribution is very similar to that constructed from the ground-based measurements shown in Figure 4.32 earlier in this chapter. Figure 4.65 shows

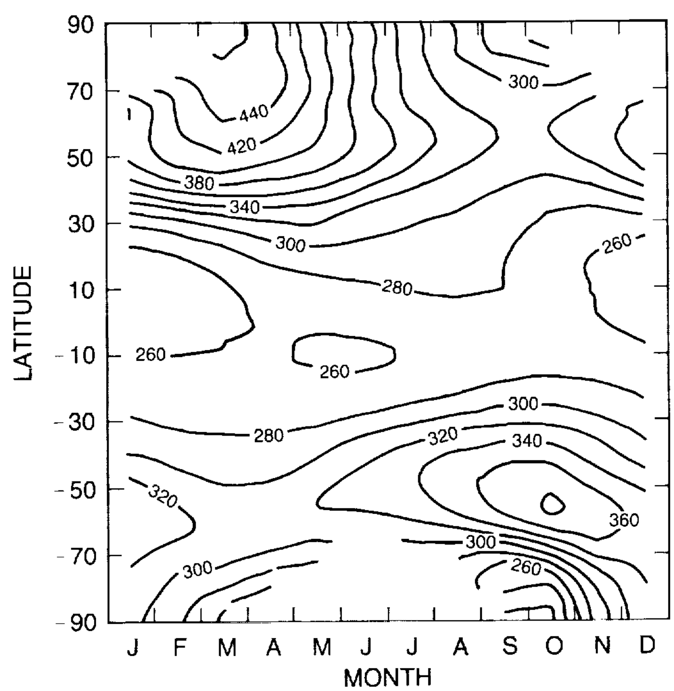


Figure 4.64 Variation of total ozone with latitude and season derived from TOMS measurements between 1979 and 1987.

the same latitudinal–seasonal total ozone distribution for each of the 9 years of TOMS data. Evident in the figure is that the distribution is similar for each year, with some important differences. The Northern Hemisphere springtime maximum shows interannual variability with the maximum already appearing to have occurred during the polar night in some years. Similarly, significant interannual variability exists in the magnitude of the Southern Hemisphere springtime maximum. Finally, the growth of the springtime Antarctic minimum is evident.

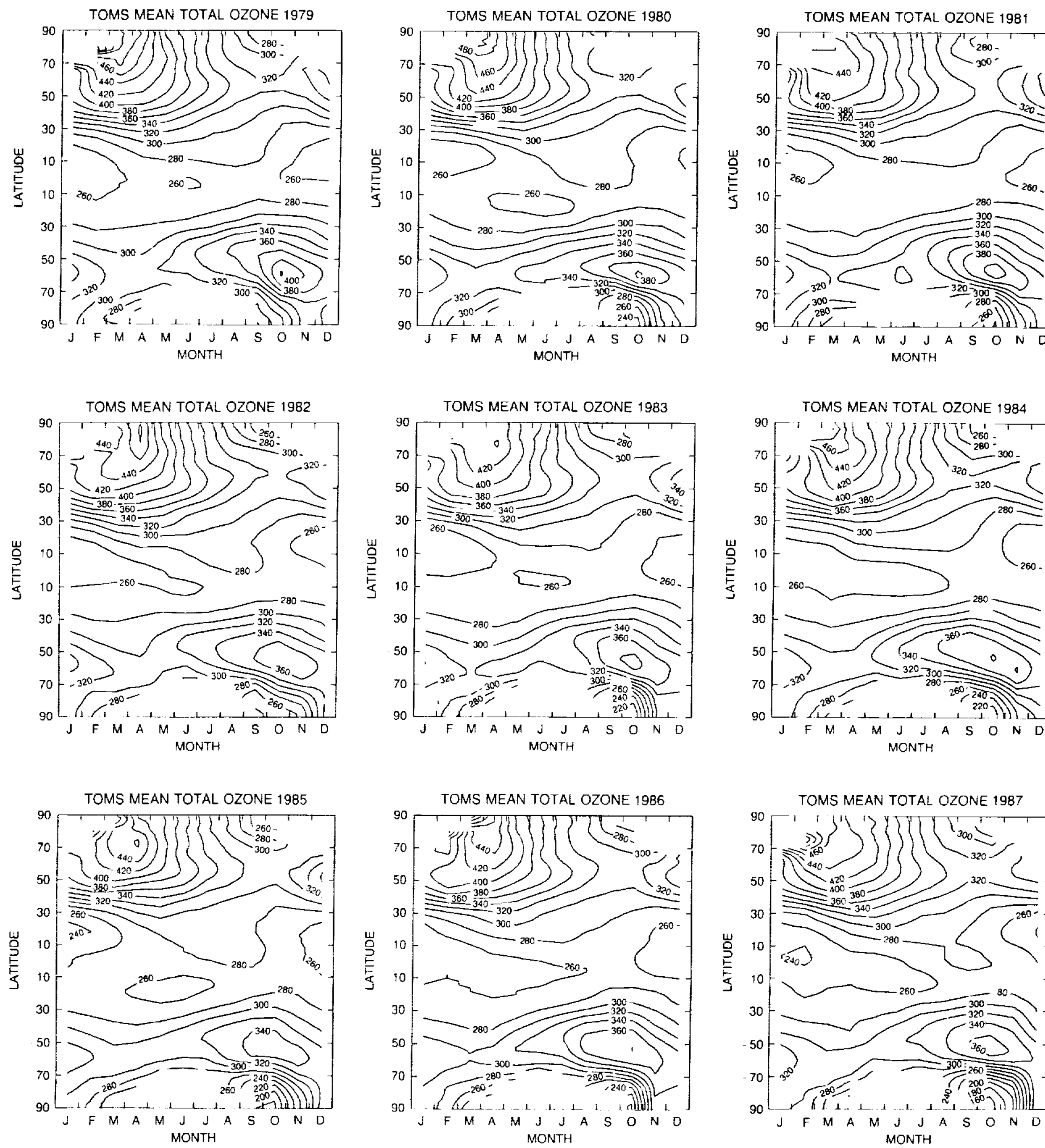


Figure 4.65 Variation of total ozone with latitude and season derived from TOMS for each year from 1979 to 1987.

A useful evaluation of global ozone change can be obtained from these data by integrating over the globe. Figure 4.66 is a plot of the daily global ozone column as measured by TOMS from November 1978–December 1987. Each year has two maxima, one in the Northern Hemisphere and one in the southern spring when midlatitude ozone is peaking in the Southern Hemisphere. The solid line is a simple linear least-squares regression line through the data, giving a linear trend of -0.4 percent per year. Figure 4.67 shows the same data with the characteristic seasonal cycle removed. The result is plotted as deviation from the seasonal mean. It is clear that the data during the first few years of the record are some 2–3 percent higher than the data near the end of the record. It is difficult to say from this short data record whether the observed decrease is the result of a negative linear trend or of a significant 11-year solar cycle variation. Figure 4.67(b) shows a similar integration of the TOMS data in which the integral is extended only to 53 degrees latitude to eliminate the effects resulting from any direct changes in polar ozone. Again, the record shows higher ozone in the period around 1980 than in the mid- to late 1980's. A linear trend has been calculated from these data with an autoregressive model. The results are given in the first row of Table 4.27. The trend was fit first from the beginning of the data in November 1978–October 1985, a period of 7 years, most of which was during the declining phase of the solar cycle. The result was a cumulative change of -2.6 ±0.5%. A similar linear trend analysis extending from November 1978–November 1987, or 9 years of data, showed a cumulative change of -2.5 ±0.6%. This confirms the conclusion that there appears to be a flattening of the ozone change over the last 2 years of the record, and is not inconsistent with the notion that there is some solar cycle component to the global total ozone change.

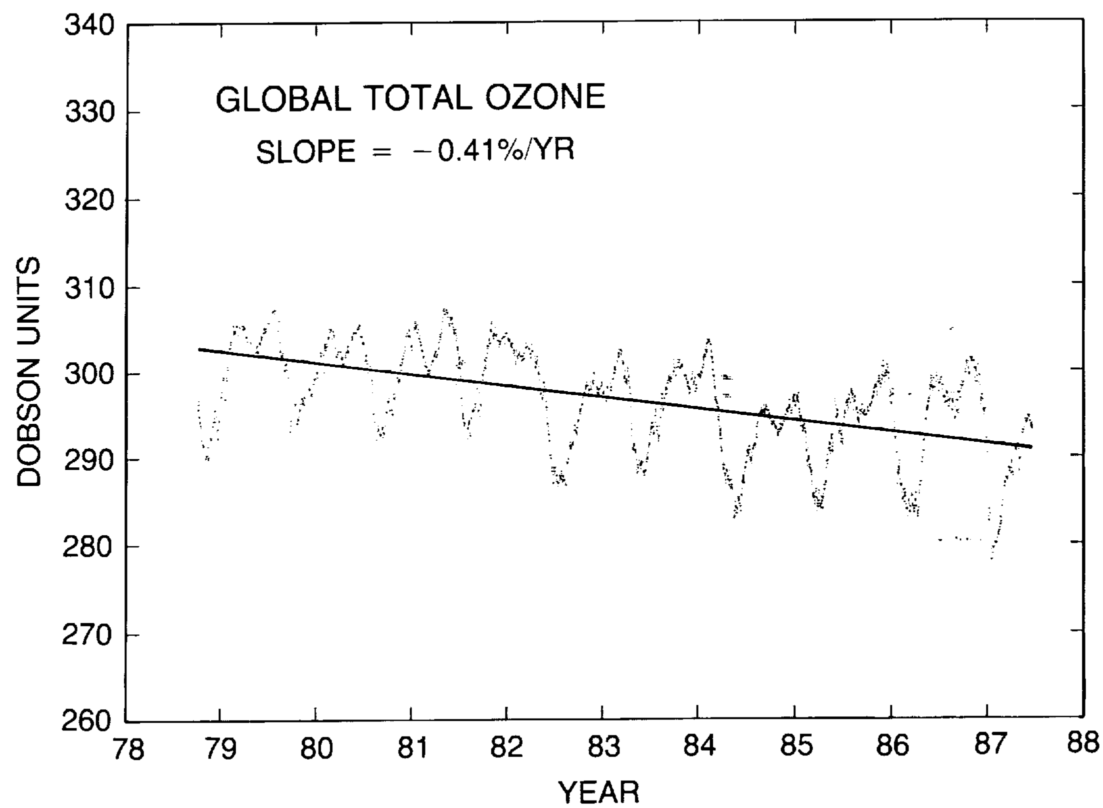


Figure 4.66 Globally averaged total ozone from November 1978–December 1987 derived from TOMS measurements. The solid line is a simple linear least squares fit of the data with a slope of -0.4% yr^{-1}.

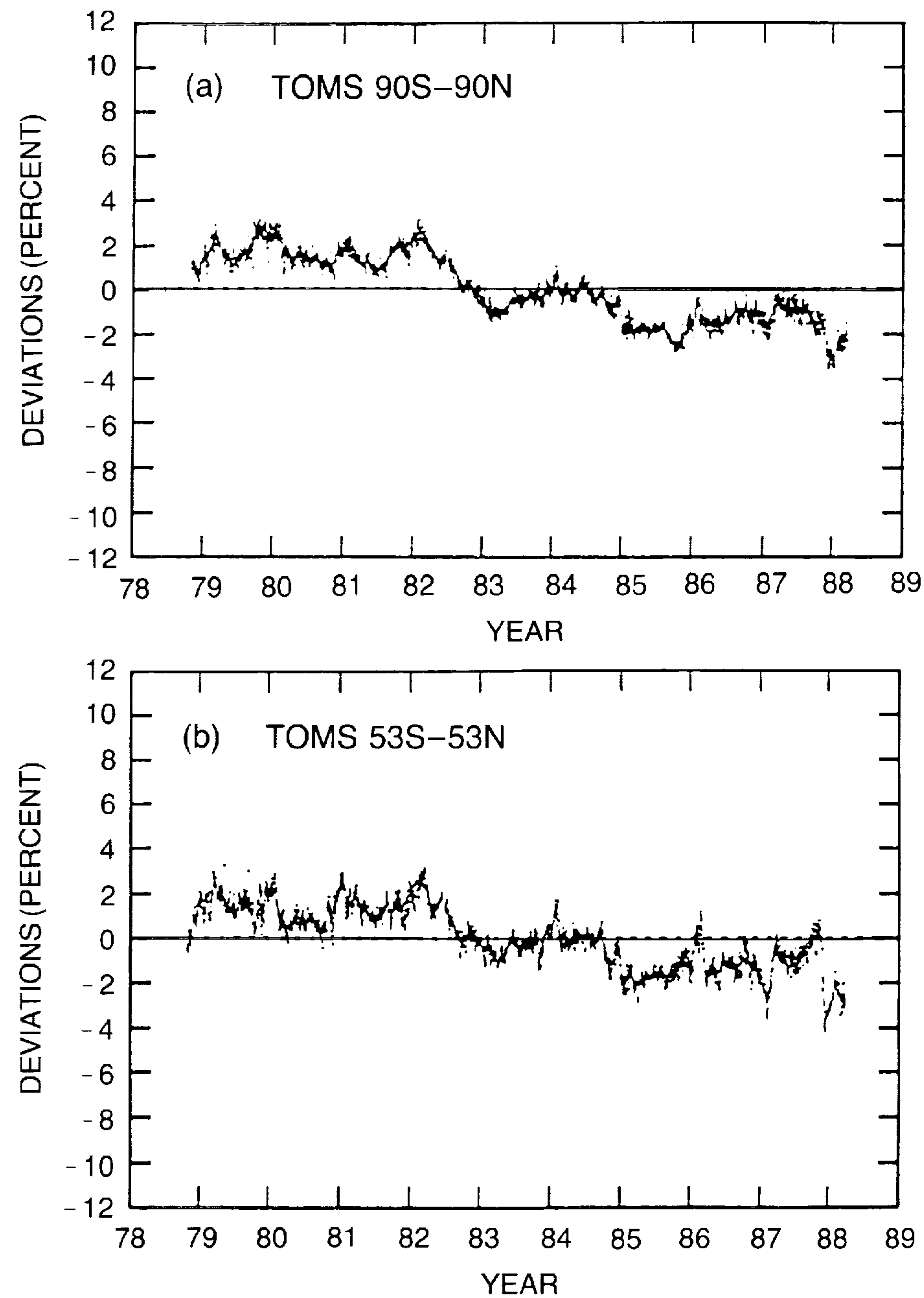


Figure 4.67 (a) Deseasonalized global total ozone derived from TOMS. (b) Deseasonalized total ozone between 53°N and 53°S derived from TOMS. Percentage deviations from the seasonal means are plotted.

Figure 4.68a,b shows the same area means, again plotted as deviations from the seasonal mean, broken down into Northern and Southern Hemispheres. Both the Northern and Southern Hemisphere means show more deviation than the global mean. The Northern Hemisphere has significant negative deviations in the winters of 1982–1983 and 1984–1985, as has been previously demonstrated from ground-based data (e.g., Bojkov, 1988). The Southern Hemisphere shows a

Table 4.27 Percentage Changes in Total Column Ozone (Measured by TOMS on Nimbus–7, Calibrated by Comparison With Ground-Based Measurements)

Latitude Band	Total Change From 11/1978–10/1985	From Table C-12 (1969–1986)	Total Change From 11/1978–11/1987
Global, except high latitudes			
53°S–53°N	−2.6 ± 0.5		−2.5 ± 0.6
Hemisphere			
0–53°S	−2.6 ± 0.9		−2.9 ± 0.9
0–53°N	−2.1 ± 1.5		−1.8 ± 1.4
Bands			
53°S–65°S	−9.0 ± 1.8		−10.6 ± 1.6
39°S–53°S	−5.0 ± 1.8		−4.9 ± 1.8
29°S–39°S	−3.2 ± 2.4		−2.7 ± 2.1
19°S–29°S	−2.5 ± 1.9		−2.6 ± 1.5
0–19°S	−1.1 ± 0.8		−2.1 ± 0.8
0–19°N	−1.1 ± 1.5		−1.6 ± 1.3
19°N–29°N	−3.5 ± 2.2		−3.1 ± 1.9
29°N–39°N	−3.7 ± 2.0	−1.7 ± 0.7	−2.5 ± 1.7
39°N–53°N	−2.7 ± 1.7	−3.0 ± 0.8	−1.2 ± 1.5
53°N–65°N	−2.4 ± 1.6	−2.3 ± 0.7	−1.4 ± 1.4

(Linear trends with an autoregressive model through TOMS data, with uncertainties at the one sigma level of significance.)

significant apparent quasi-biennial oscillation with a particularly large negative deviation in the summer of 1985–1986. The fitted linear trends using an autoregressive model are again given in Table 4.27. As with the global change, the 9-year trends are approximately equal cumulatively to the 7-year trends. The Southern Hemisphere has a slight increase in the downward change with the added 2 years, while the Northern Hemisphere actually shows somewhat less total change. (Note added: Inclusion of data through October 1988 indicates a tendency toward reversal of the downward trend in the Southern Hemisphere, but not in the Northern Hemisphere.) Any conclusions about whether there is any reversal or flattening of the trend are made on variations that are within the one-sigma limits of the data and should, therefore, be viewed with caution. Likewise, it should be remembered that this analysis did not include any evaluation of a contribution from the 11-year solar cycle.

4.7.2 Trends in Latitude Bands

The TOMS data can be further broken down by latitude bands. Figure 4.69a–j shows the daily deviations of TOMS total ozone data from weekly means. Deviations are given in percent, and, as above, all data have been normalized to the observed mean drift of TOMS with respect to the Dobson stations during the overpasses of Nimbus–7 over 41 stations. The latitude regions shown were chosen to correspond to an analysis of the Dobson network by Bojkov (1988). They are a) 53–65°S, b) 39–53°S, c) 29–39°S, d) 19–29°S, e) 0–19°S, f) 0–19°N, g) 19–29°N, h) 29–39°N, i) 39–53°N, and j) 53–65°N. Note that the scale of the deviations has been doubled compared to the global and hemispheric plots.

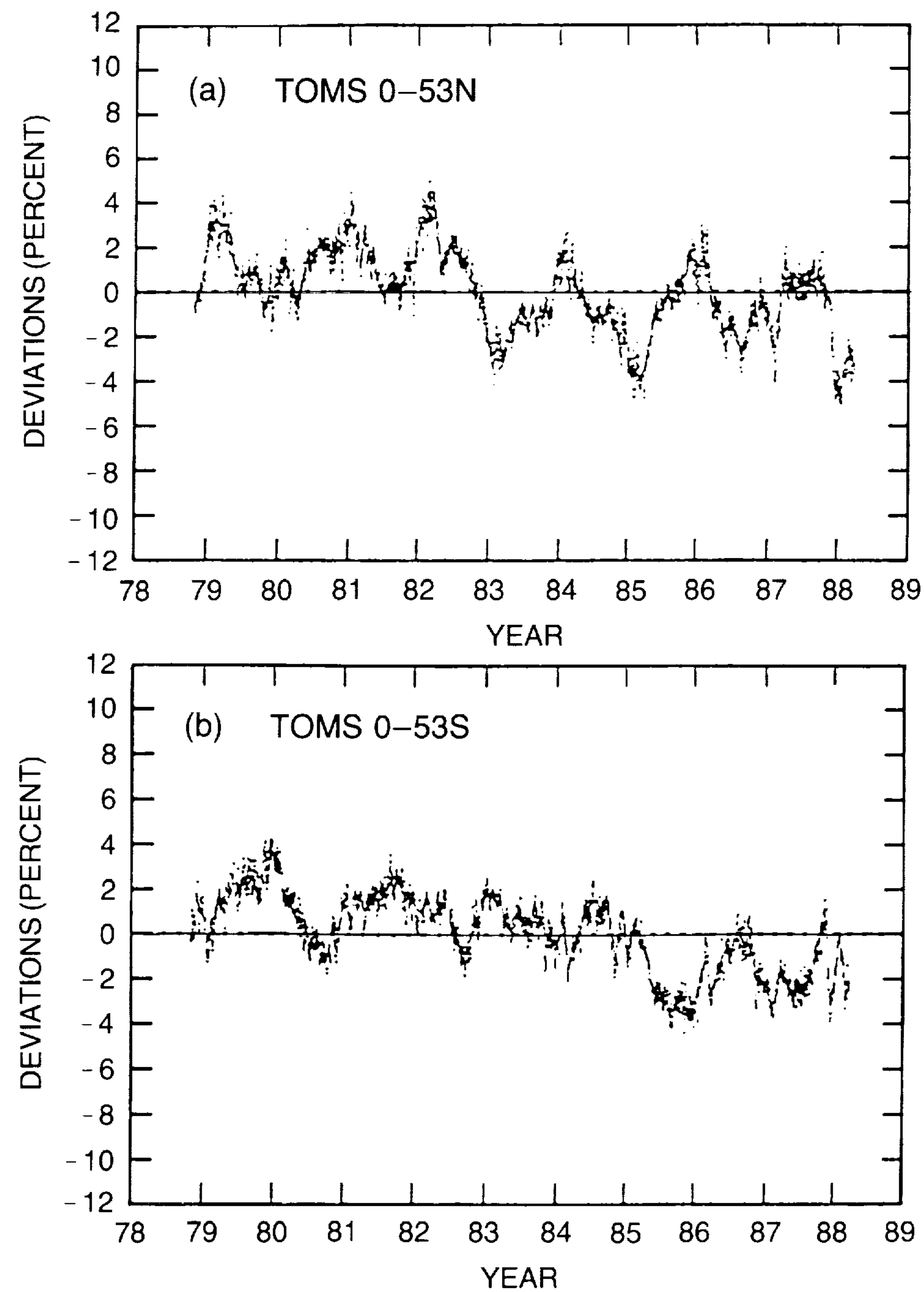
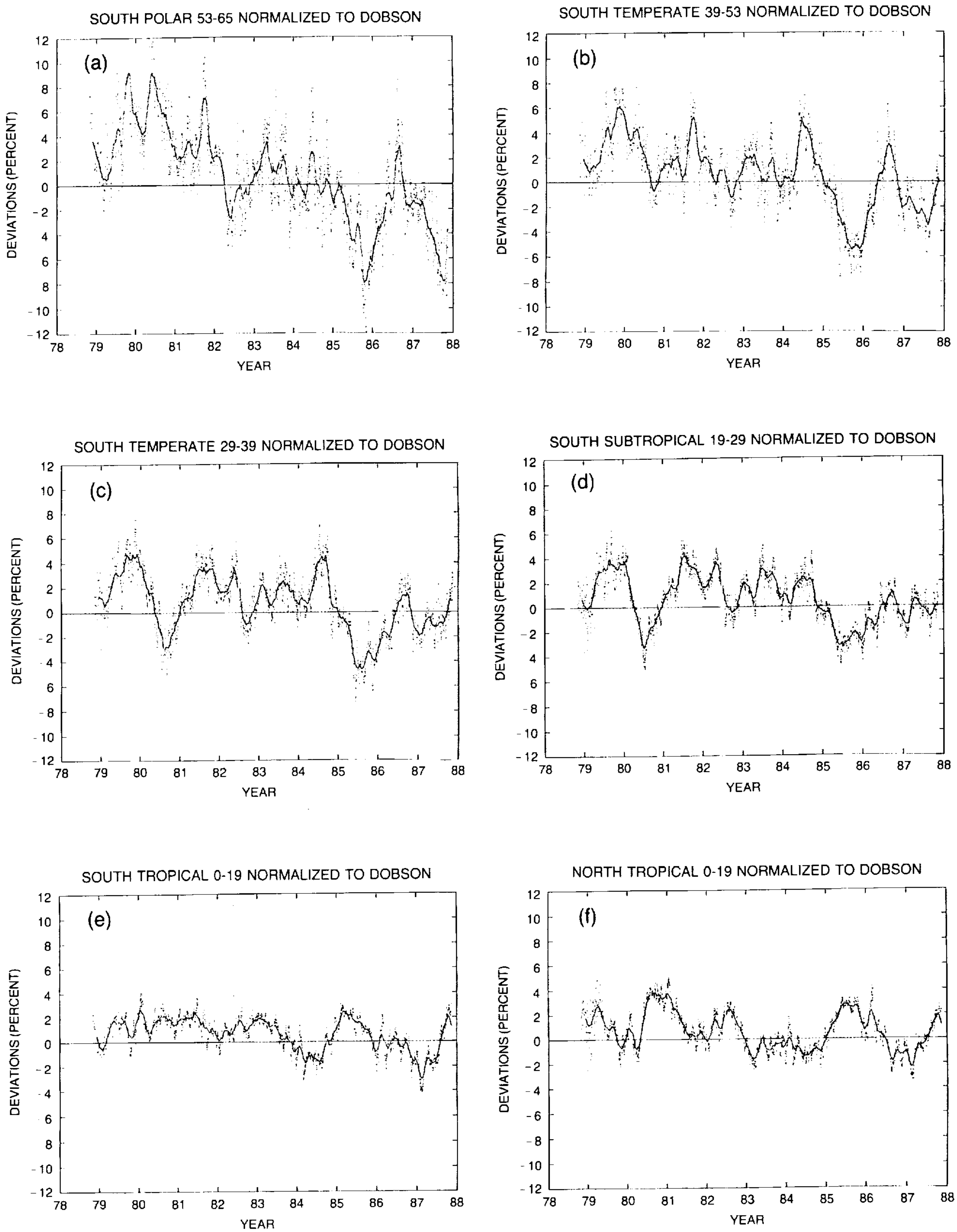


Figure 4.68 Zonal means of total ozone derived from TOMS for the areas between (a) 0–53°N and (b) 0–53°S. Percentage deviations from the seasonal means are plotted.

The Northern Hemisphere minimum of the winter of 1982–1983 does not appear in the tropical data from the Equator to 19°N but does appear in the rest of the latitude bands up to 65°N. The minimum of the winter of 1984–1985 also is not in the tropical data, nor is it in the 53–65°N data. However, it is more pronounced in the data from 19–39°N than is the minimum of the winter of 1982–1983. It is suggestive that this northern hemispheric minimum is coincident with the spread of aerosol from the El Chichón eruption throughout the Northern Hemisphere,


SOUTH POLAR 53-65 NORMALIZED TO DOBSON
(a)
SOUTH TEMPERATE 39-53 NORMALIZED TO DOBSON
(b)
SOUTH TEMPERATE 29-39 NORMALIZED TO DOBSON
(c)
SOUTH SUBTROPICAL 19-29 NORMALIZED TO DOBSON
(d)
SOUTH TROPICAL 0-19 NORMALIZED TO DOBSON
(e)
NORTH TROPICAL 0-19 NORMALIZED TO DOBSON
(f)
DEVIATIONS (PERCENT)
YEAR

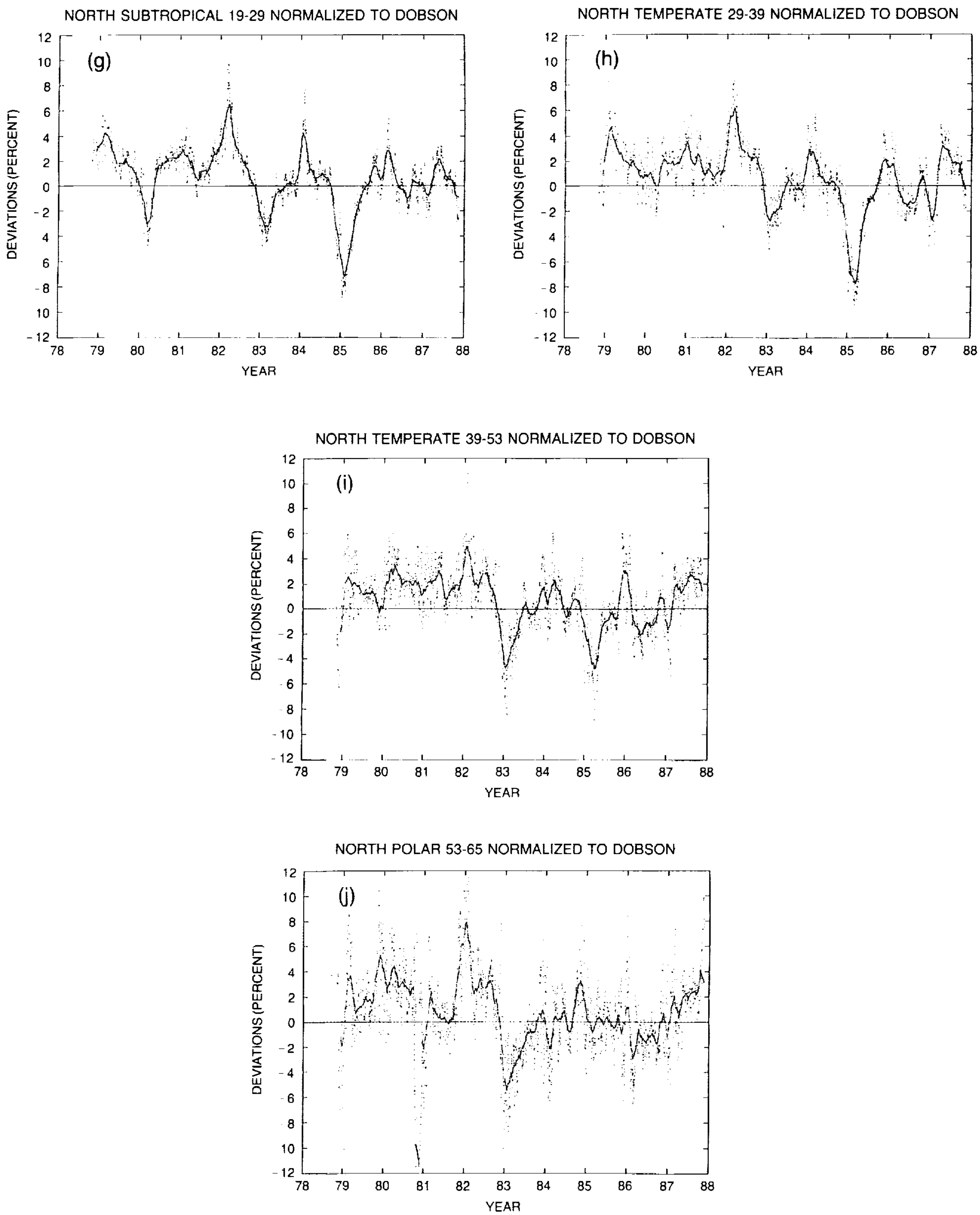


Figure 4.69 Zonal means of total ozone derived from TOMS for various latitude bands are plotted as percentage deviations from the weekly means. (a) 53–65°S, (b) 39–53°S, (c) 29–39°S, (d) 19–29°S, (e) 0–19°S, (f) 0–19°N, (g) 19–29°N, (h) 29–39°N, (i) 39–53°N, (j) 53–65°N.

although no cause and effect relationship has been established, and Schuster et al. (1988) have proposed that the observed perturbation to total ozone levels could be due to a modification of the QBO signal by the El Chichón aerosol. Another possible cause was the strong El Niño in 1982–1983. The Southern Hemisphere minimum that spans mid- to late 1985 extends over all latitudes from 19–65°N, and another strong minimum appears between 19–39°N in late 1980.

The linear trends for the first 7 years and the entire 9-year data set deduced with an autoregressive model are shown in Table 4.27. The trends are all negative, but generally not significant at the two-sigma level. The main exceptions are the two most southerly latitude bands. The decreases in these bands occur primarily in the southern circumpolar ring of high ozone and have been noted in previous studies of the Antarctic ozone hole (e.g., Stolarski et al., 1986; Stolarski and Schoeberl, 1986).

4.7.3 Global Maps of the Difference Between 1986–1987 and 1979–1980 Total Ozone

The behavior of many of the time series shown in the previous section is that the total ozone amount is relatively constant for the first few years of the record and then again relatively constant at a lower value near the end of the record. This suggests that some understanding of the change may be gained by comparing these two portions of the record as a function of season, latitude, and longitude. Figure 4.70 is a contour plot of the difference in total ozone between the

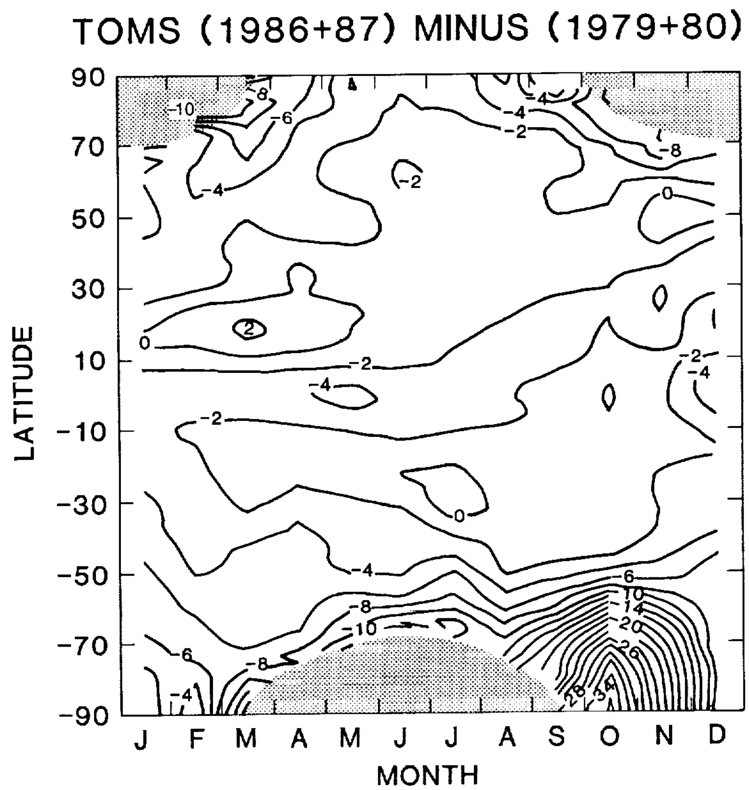


Figure 4.70 Changes by month and latitude in total ozone between 1979–1980 and 1986–1987 as measured with TOMS on the Nimbus–7 satellite (2-year averages are used to minimize differences originating with the QBO). Contour plots are given for intervals of 2 percent change. The TOMS instrument operates with sunlight scattered from the atmosphere and, therefore, provides no data from the areas in the polar night.

last 2 full years of the record (1986 and 1987) and the first 2 full years (1979 and 1980) as a function of latitude and season. The most obvious feature of this figure is the springtime Antarctic ozone hole. A general decrease of greater than 5 percent also appears at all latitudes south of 50°S for all seasons. The rest of the globe shows smaller changes, which are more negative than positive. The northern high-latitude spring has a small region of greater than 5 percent decrease, which raises the possibility that this is related to processes occurring in the northern winter (see section above on ground-based data).

Further details of the ozone change from 1979–1980 to 1986–1987 can be obtained by examining global maps versus latitude and longitude for specific months; these are shown in Figure 4.71a–l. The Antarctic springtime ozone hole is again obvious. Changes over most of the globe are negative, but significant positive change regions also exist. It is not clear from these data whether there is any physical significance to these positive regions. More likely, if other years are taken, the regions of positive and negative will move around but will still be predominantly negative. The north polar region shows interesting behavior in a number of months. For example, in March a large negative change is observed over the northern USSR, while a large positive region is observed over northeastern Canada and Greenland. This pattern results primarily from a shift in the pattern of the pole-centered high between the two sets of years that have been compared.

TOTAL OZONE CHANGE FOR JANUARY
(1987 + 1986) — (1980 + 1979)

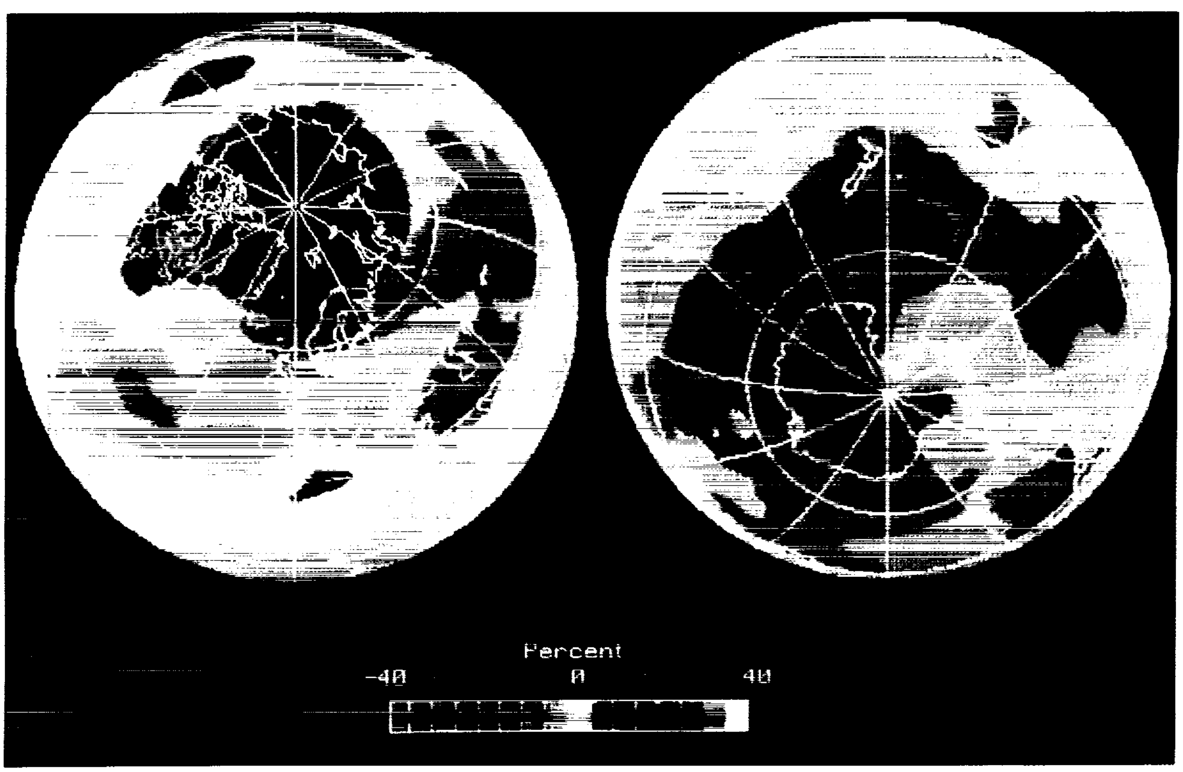
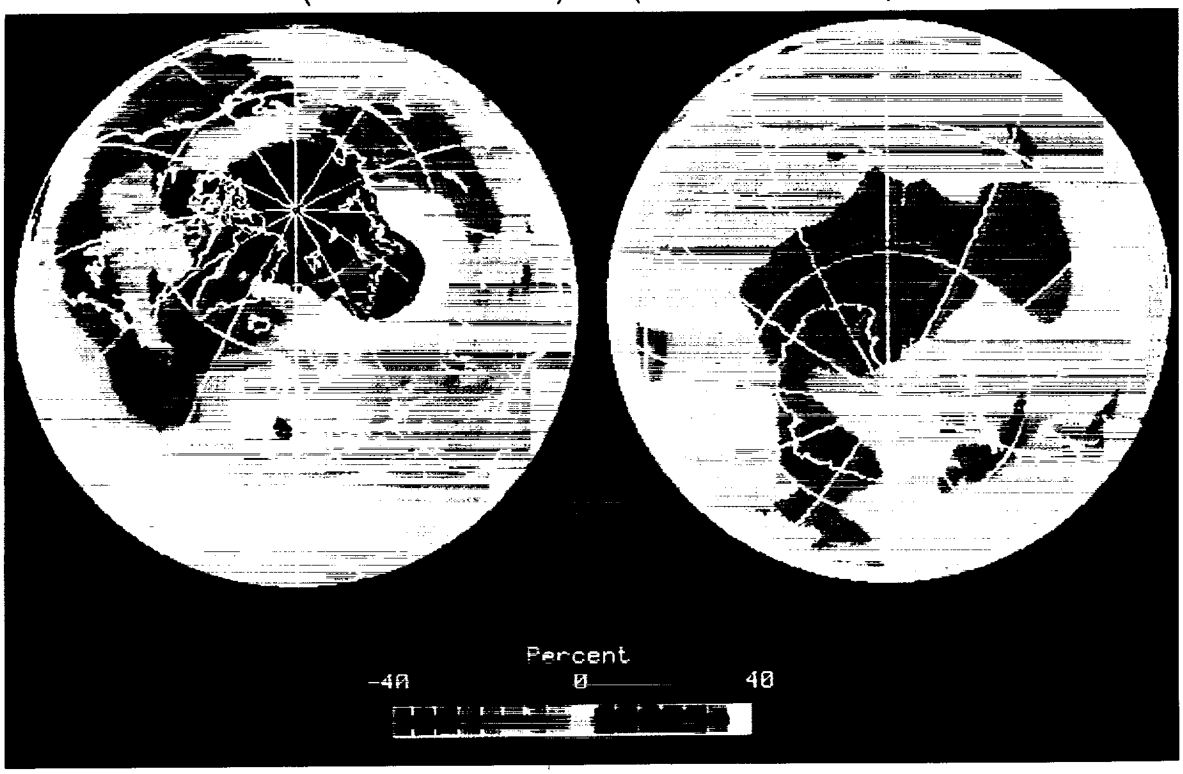
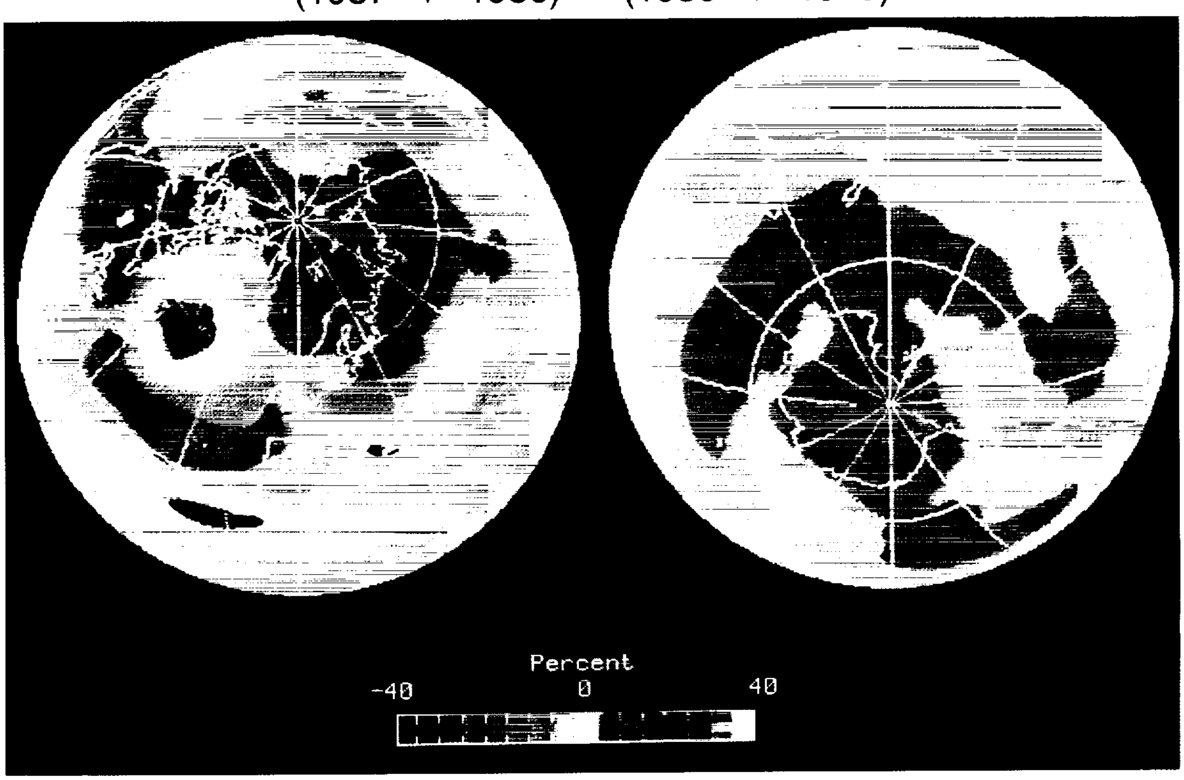


Figure 4.71 (a–1) TOMS maps of monthly (January through December) total ozone change averaged from 1979 through 1987. Left side of each panel shows Northern Hemisphere; right side of panel shows Southern Hemisphere. Total ozone is given in Dobson Units (milli-atmosphere-cm) as indicated in color bar.

TOTAL OZONE CHANGE FOR FEBRUARY
(1987 + 1986) — (1980 + 1979)



TOTAL OZONE CHANGE FOR MARCH
(1987 + 1986) — (1980 + 1979)



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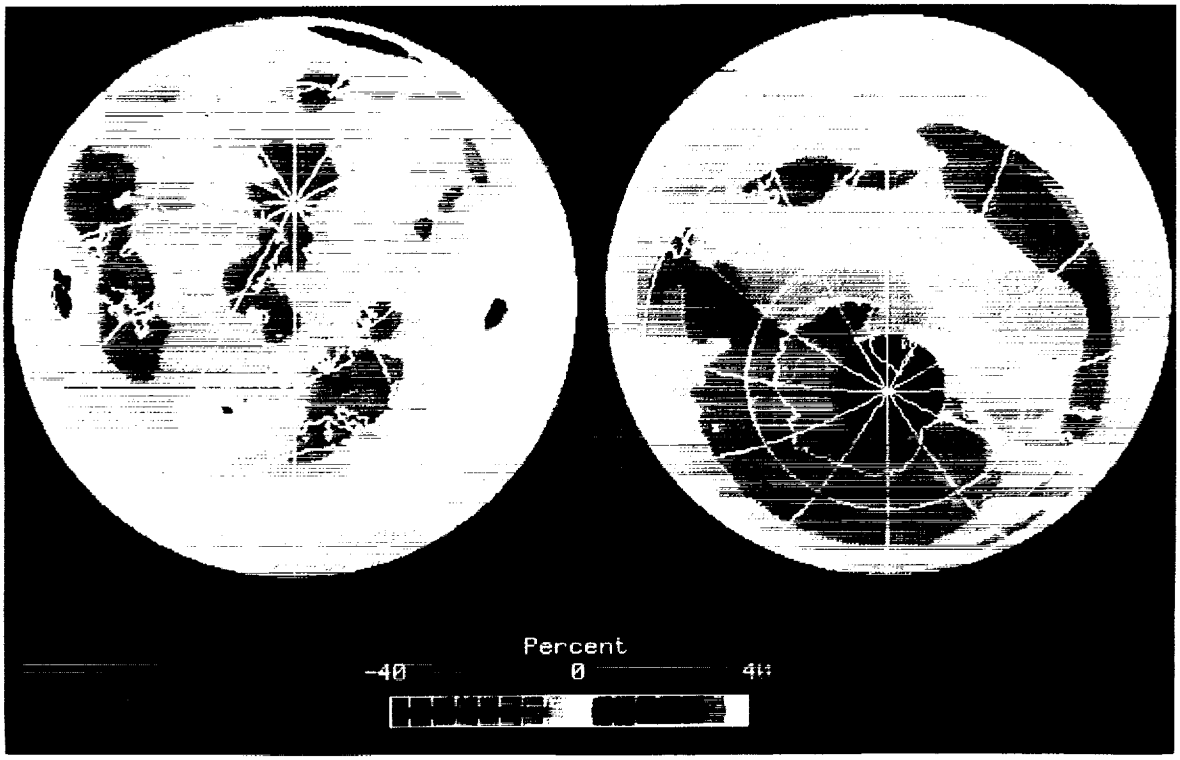
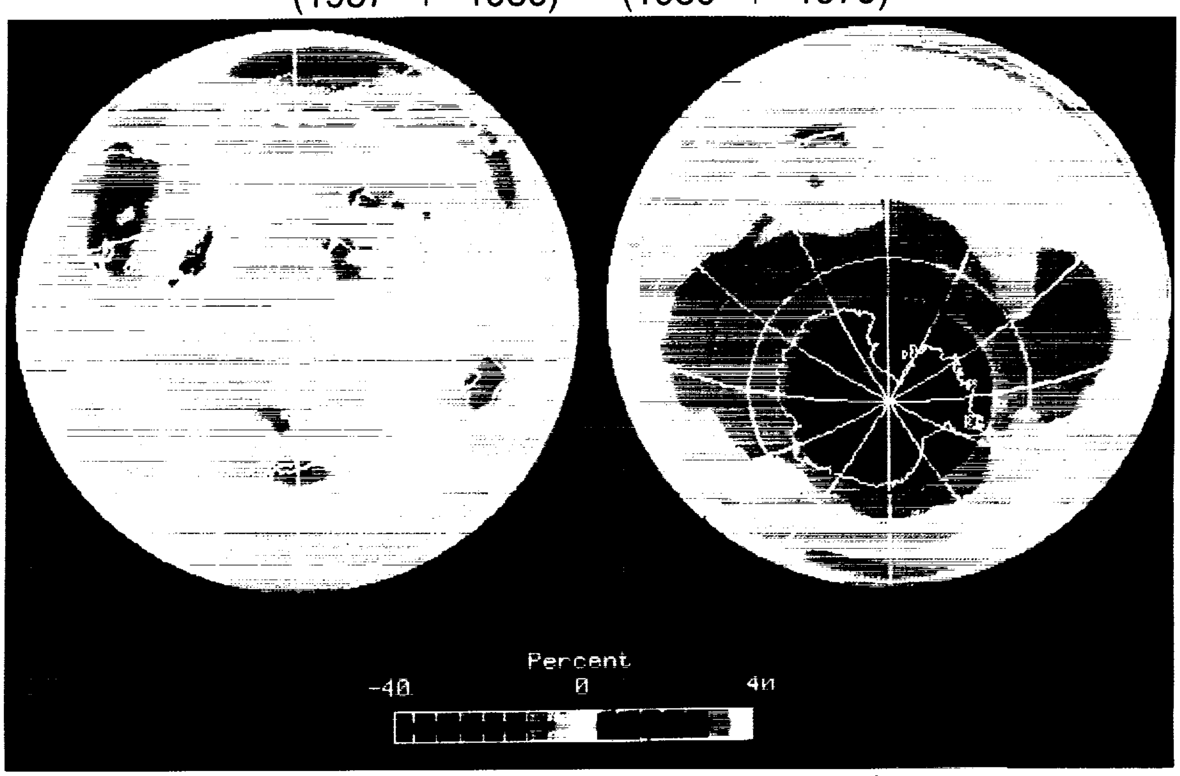
COLOR PHOTOGRAPH

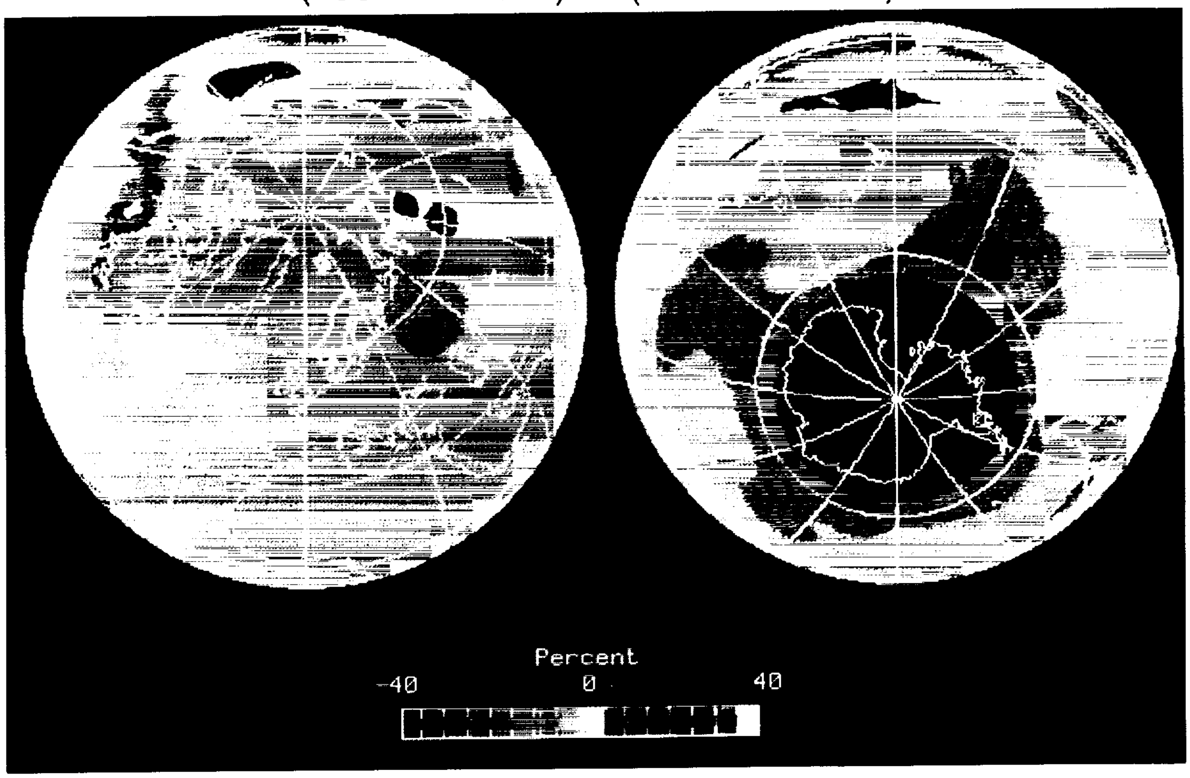
TOTAL OZONE CHANGE FOR APRIL
(1987 + 1986) — (1980 + 1979)



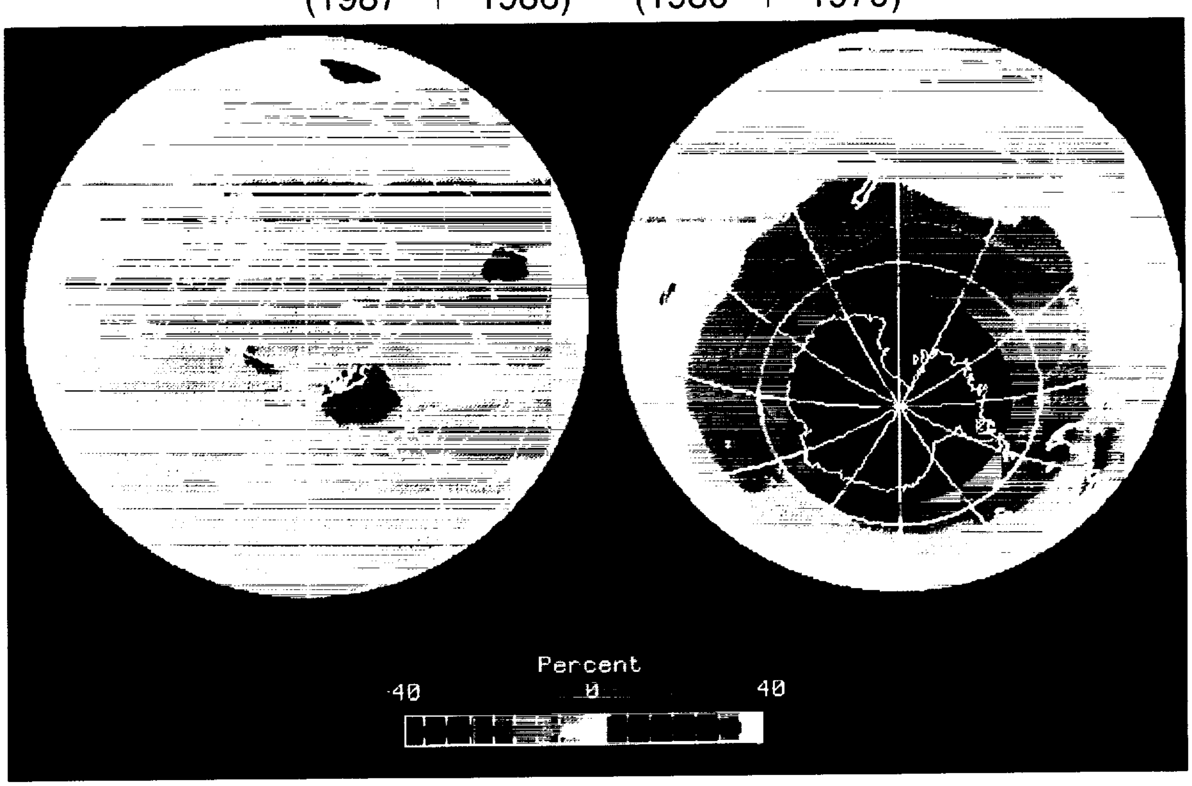
TOTAL OZONE CHANGE FOR MAY
(1987 + 1986) — (1980 + 1979)



TOTAL OZONE CHANGE FOR JUNE
(1987 + 1986) — (1980 + 1979)



TOTAL OZONE CHANGE FOR JULY
(1987 + 1986) — (1980 + 1979)



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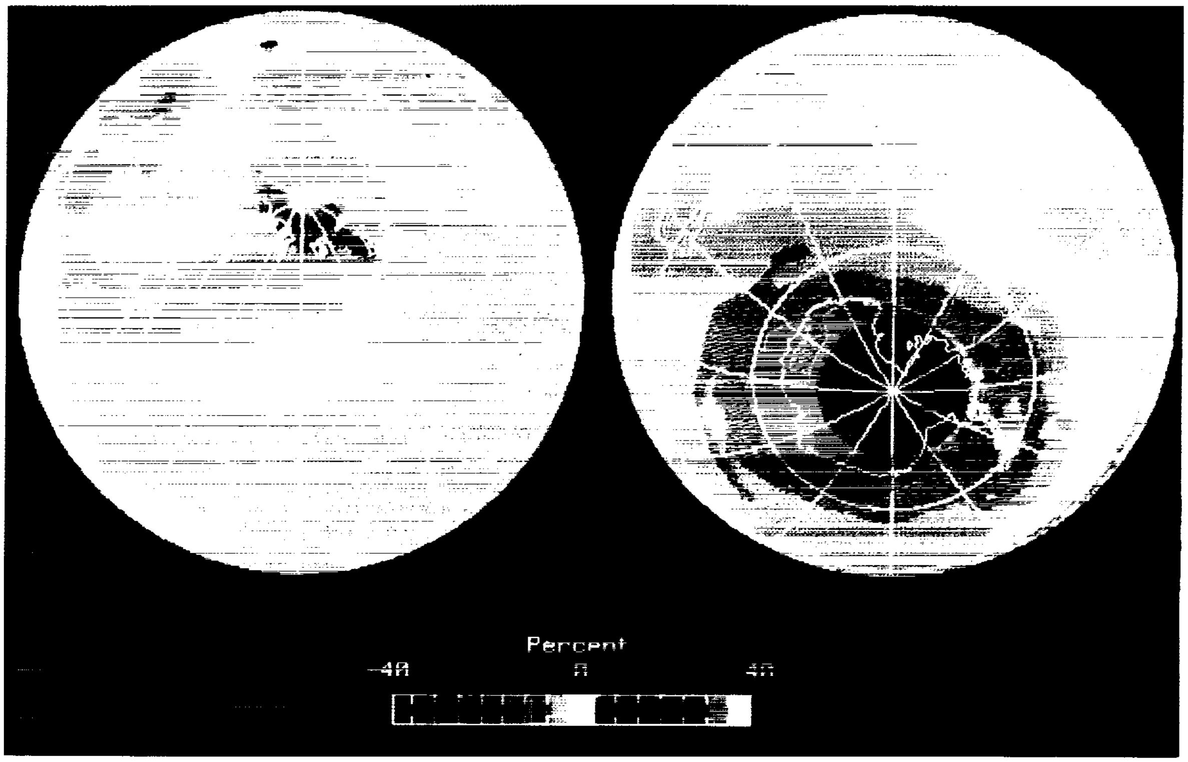
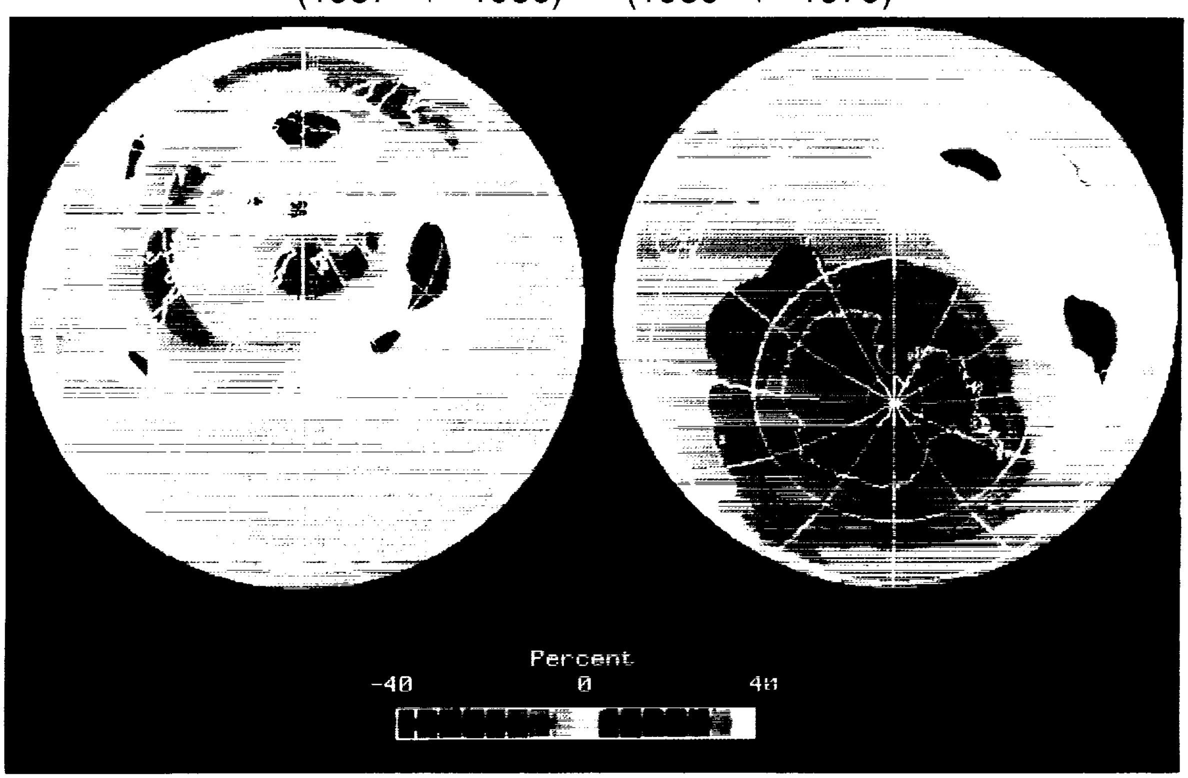
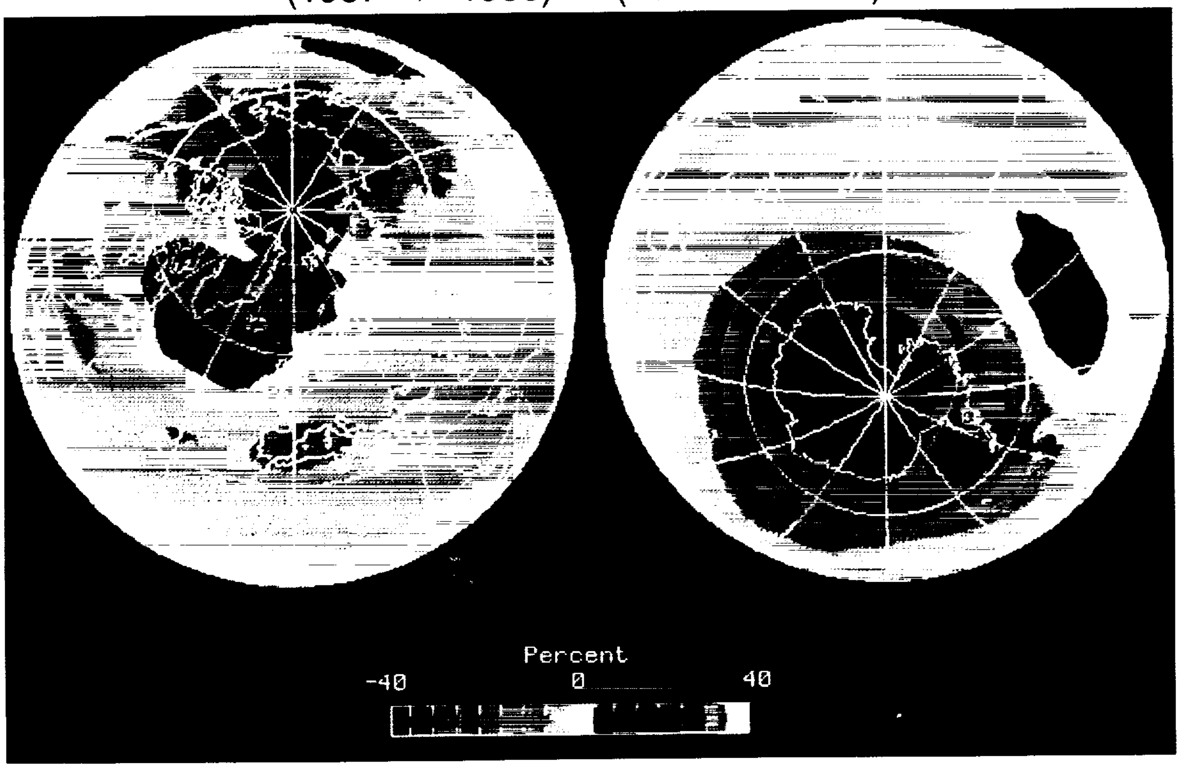
TOTAL OZONE CHANGE FOR AUGUST
(1987 + 1986) — (1980 + 1979)



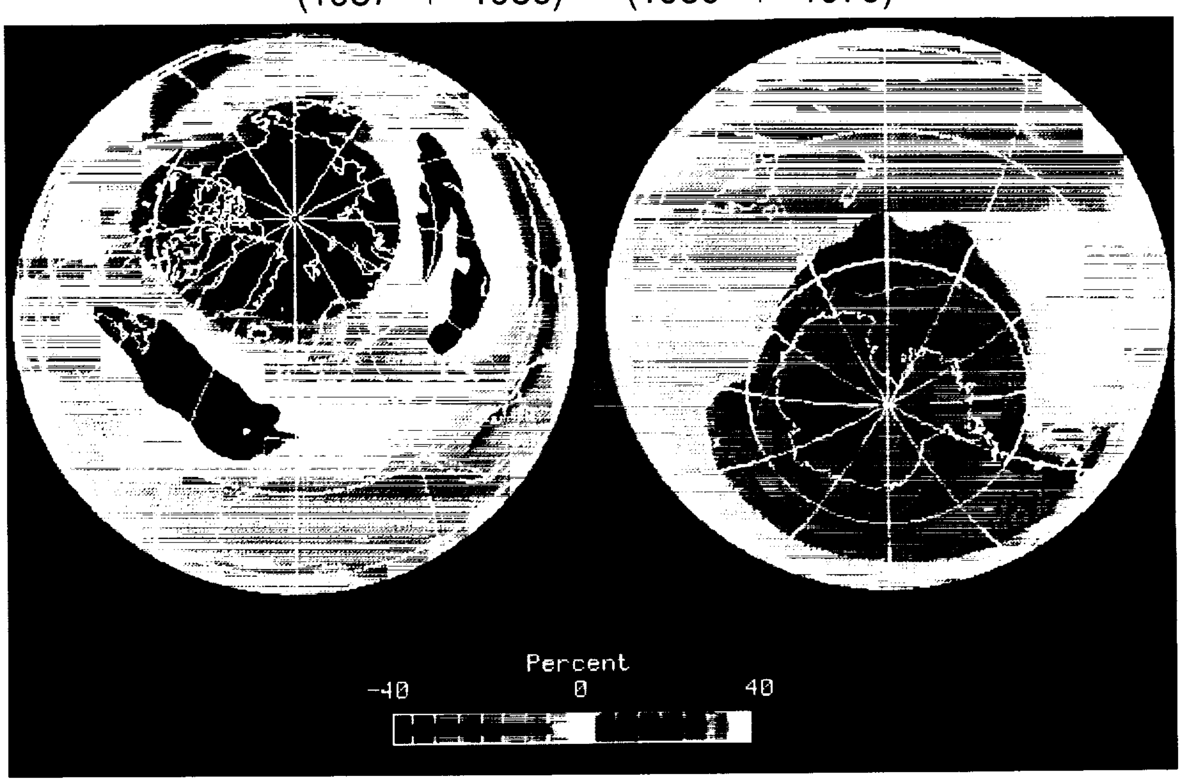
TOTAL OZONE CHANGE FOR SEPTEMBER
(1987 + 1986) — (1980 + 1979)



TOTAL OZONE CHANGE FOR OCTOBER
(1987 + 1986) — (1980 + 1979)



TOTAL OZONE CHANGE FOR NOVEMBER
(1987 + 1986) — (1980 + 1979)



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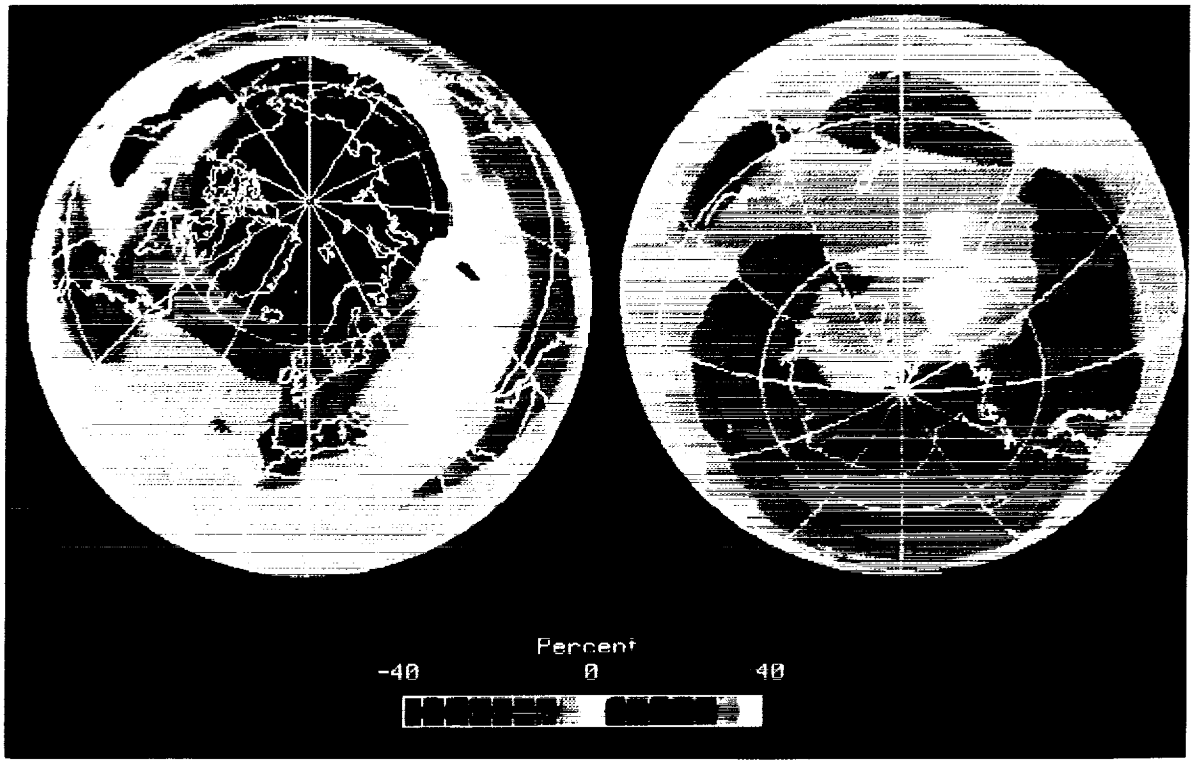
TOTAL OZONE CHANGE FOR DECEMBER
(1987 + 1986) — (1980 + 1979)



4.8 SUMMARY

It is important to ensure that the best available data are used in any determination of possible trends in total ozone in order to have the most accurate estimates of any trends and the associated uncertainties. Accordingly, the existing total ozone records have been examined in considerable detail. Once the best data set has been produced, the statistical analysis must examine the data for any effects that might indicate changes in the behavior of global total ozone. The changes at any individual measuring station could be local in nature, and in this study particular attention has been paid to the seasonal and latitudinal variations of total ozone, because 2-D photochemical models indicate that any changes in total ozone would be most pronounced at high latitudes during the winter months. The conclusions derived from this detailed examination of available total ozone can be split into two categories, one concerning the quality and the other the statistical analysis of the total ozone record.

Data Quality

The published data of both ground-based and satelliteborne instruments have been shown to contain incongruities that have been traced back to instrument calibration problems. In the case of the ground-based record, the corrections for these calibrations have not been applied to the data before publication in ODW. Correcting the data for known calibrations is essential if one is to believe the results of statistical analyses of the data set. Fortunately, complete revisions of the total ozone data set can be performed at many ground-based stations because good day-to-day records have been kept. At stations whose daily records have been lost, the correct adjustments to the total ozone data are irrecoverable. For the purposes of this report, a provisionally revised data set was prepared, with the corrections caused by recalibrations being applied to the monthly averages and not to the individual daily measurements. The provisionally revised data are taken as being the best currently available set for two reasons: the effects of the known, periodic recalibrations of the Dobson instruments are accounted for and the consistency of external data such as measurements from proximate stations, stratospheric temperatures, and satellite overpasses is found to be greater with the provisionally revised data sets than with the data published in ODW.

The TOMS satellite data have been compared with measurements taken by the International Primary Standard Dobson Instrument (No. 83) while it was being calibrated at Mauna Loa; it was found that the two instruments had drifted relative to each other. A similar result was found in a TOMS–Dobson data comparison during overpasses of the TOMS instrument at 92 ground-based stations. The SBUV data have been drifting in a similar manner, and the conclusion was reached that the cause of this effect was the degradation of the diffuser plate on Nimbus–7, the only common component of the TOMS and SBUV systems. The TOMS data were then normalized to agree with the 92 ground-based stations. Because Instrument No. 83 is used as the main calibrating instrument for the Dobson network and because the TOMS satellite data revision is also based partially on the results of a comparison with Instrument No. 83, a detailed review of the absolute calibrations used with this instrument was made and no problems were discovered.

Analysis

Initial examination of both the published (ODW) and provisionally revised data sets indicates that, in recent years, a decrease in total ozone has occurred at latitudes poleward of 40°N, particularly in the winter months (see Figures 4.45–48). This result showed the need for a statistical analysis of the revised data that investigated the effects of season and latitude on any changes. Unfortunately, the spatial distribution of the Dobson stations is poor, with most of the instruments placed in Europe or North America, so that the portion of the globe for which there is reasonable coverage is limited to the latitudes from 30–80°N. Even in this area, the longitudinal coverage is poor, although it was greatly extended in 1972 when the upgraded M–83 filter ozonometers were introduced in the USSR. A time series model for the ground based total ozone record was used that included terms for the natural seasonal cycle, the natural autocorrelation, the effects of such geophysical phenomena as the quasi biennial oscillation, the solar cycle, and the atmospheric nuclear bomb testing that took place between 1957 and 1963. Statistical tests for possible trends in recent years were conducted using both the older assumption of no seasonality in any ozone trends, and with allowance for different trends for each calendar month.

The analysis of the provisionally revised data from 1965–1986 again showed that there had been a significant wintertime loss at higher latitudes since 1969, and that between 30°N and 39°N there had been a year-round decrease. The data period from 1965–1986 is advantageous for three reasons: it contains two complete solar cycles, minimizing any residual effects from an inadequate modeling of the effects of the solar cycle on total ozone; any effects of the atmospheric nuclear bomb tests ending in the early 1960's will be small; and before 1965, fewer stations were taking measurements. When the data from 1957–1986 was considered, the wintertime loss was still apparent. The trends were slightly smaller than those calculated using the shorter time period, but they easily lay within the combined uncertainties. The modeled effect of the atmospheric bomb tests was found to be slightly larger than that derived from the statistical analysis of the measurements, although within the calculated uncertainty. The effect of the QBO on total ozone was statistically significant at most latitudes, while the effect of the solar cycle was marginally significant. When the earlier data were included in the analysis, the calculated effect of the solar cycle was reduced, making it hard to reach any firm conclusions about the relationship between the solar cycle and total ozone. The period of low total ozone values over the Northern Hemisphere in 1982–1983 was not the dominant cause of the measured ozone decreases since 1969. In particular, the seasonal nature of the losses is evident in the data record through 1981.

Conclusions

The main conclusions of this chapter can be listed as follows:

- Examination of the published total ozone record reveals a need for a revision of the data.
- Provisionally revised sets of measurements have been prepared for both the ground-based stations and the TOMS satellite instrument.
- Statistically significant losses have occurred in the late winter and early spring in the Northern Hemisphere. For example, in the latitude band from 53–64°N, a loss of 6.2 percent is measured for December, January, February, and March from 1969–1986 when the data from 1965–1986 are considered.
- The seasonal and the latitudinal variations of these losses agree with the results of current 2-D photochemical models in nature, if not in magnitude.
- There is some evidence for longitudinal variations in the measured trends.

Chapter 4 Appendix

Contents

*If the enclosed ozone data are used in future work, consideration should be given to the method of revision utilizing calibration, intercomparison data, stratospheric temperatures, and TOMS data for flagging major discrepancies.

A. (i) Provisionally revised station data used in the time series analyses.

Arosa[1]	1/57–12/86	Leningrad	8/68–12/85
Aspendale	7/57–12/86	Lerwick	1/57–11/86
Belsk	1/63–12/86	MacQuarie Isle	1/63–12/86
Bismarck	1/63–12/86	Mauna Loa	1/63–12/86
Boulder	1/64–12/86	Nashville	1/63–12/86
Bracknell	1/69–12/86	Quetta	8/69–12/86
CagliarivElmas	1/57–12/86	Reykjavik	11/75–10/86
Cairo	11/74–10/86	Rome (Vigna di Valle)	1/57–12/86
Caribou	6/62–12/86	Samoa[2]	1/76–12/86
Churchill	1/65–12/86	Sapporo	1/58–12/86
Edmonton	7/57–11/86	Srinigar	2/64– 5/86
Goose Bay	1/62–11/86	Tateno	7/57–12/86
Hohenpeissenberg	1/67–12/86	Toronto	1/60–12/86
Hradec Kralove	1/62–12/86	Uccle	2/71–12/86
Huancayo	2/64– 6/86	Wallops Island	1/70–12/86
Kagoshima	4/61–12/86		

[1]Data accepted in unrevised form from *Ozone Data for the World*.
[2]Data revised and supplied by W.D. Komhyr et al. (1987).
[3]All other data are the monthly averages of total ozone published in *Ozone Data for the World* with the appropriate average monthly corrections applied. The amounts are given in Dobson Units.

Average Ozone Values at AROSA

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	327	326	336	359	372	338	320	312	292	271	287	321
1958	346	336	393	398	358	349	336	311	286	291	287	308
1959	356	362	366	382	375	355	324	319	304	289	297	321
1960	342	381	405	388	365	341	335	314	307	304	285	318
1961	356	324	334	357	364	339	328	304	279	277	294	299
1962	341	360	425	383	358	342	323	300	293	267	295	299
1963	359	410	379	377	372	348	318	310	284	275	278	295
1964	304	337	348	374	362	324	315	311	293	288	272	307
1965	331	384	379	372	374	332	329	317	304	276	280	314
1966	347	339	395	375	366	344	324	317	297	279	314	315
1967	354	358	351	366	343	346	316	312	292	273	269	301
1968	338	386	381	372	346	344	324	328	306	276	274	332
1969	335	418	362	377	347	356	327	327	290	278	305	334
1970	325	408	408	416	382	355	329	321	296	286	274	312
1971	344	351	409	366	361	352	324	305	314	276	292	303
1972	345	363	382	369	363	350	327	309	315	291	291	308
1973	320	384	363	428	348	343	342	311	290	286	270	299
1974	329	369	343	378	361	350	316	308	289	327	297	282
1975	308	340	368	365	353	344	317	310	283	283	295	289
1976	340	352	360	375	351	346	325	326	309	277	286	311
1977	358	391	347	373	369	352	335	322	302	271	291	301
1978	328	363	346	386	373	355	330	315	289	287	277	294
1979	345	378	373	402	365	337	328	314	289	287	281	306
1980	327	334	358	390	378	354	328	305	286	278	285	300
1981	324	378	357	365	370	329	323	310	295	290	281	309
1982	334	375	389	367	359	345	318	318	284	282	273	288
1983	291	354	331	359	344	333	313	314	287	273	270	296
1984	339	371	378	364	369	339	318	316	299	284	279	291
1985	355	336	353	344	342	332	312	295	279	276	301	288
1986	356	386	356	380	342	331	320	303	286	279	286	298

Provisionally Revised Average Ozone Values at Aspendale

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	0	0	0	0	0	0	348	354	358	345	328	311
1958	309	294	294	280	295	345	376	366	399	382	341	322
1959	291	300	292	279	308	323	318	332	350	346	318	316
1960	293	285	288	287	318	341	353	383	388	367	341	315
1961	302	303	283	283	292	300	313	337	329	335	315	303
1962	293	288	288	282	308	316	344	378	374	386	339	319
1963	306	292	294	286	304	338	356	359	369	346	340	317
1964	311	317	284	283	302	337	357	365	364	359	327	326
1965	304	292	286	295	301	328	357	361	358	352	338	305
1966	301	287	289	286	302	309	333	334	356	341	323	307
1967	296	286	288	278	296	306	347	361	367	355	340	330
1968	287	293	283	287	314	321	342	368	370	364	333	324
1969	297	291	286	282	300	320	317	328	355	340	340	325
1970	310	297	297	289	308	333	349	373	389	368	341	327
1971	312	300	285	287	315	329	337	356	359	362	336	319
1972	300	301	286	277	297	322	362	364	376	361	345	312
1973	300	297	301	289	296	323	332	351	358	357	325	310
1974	288	298	285	289	308	329	359	378	380	367	342	319
1975	317	294	292	289	296	322	330	357	348	354	328	298
1976	288	287	295	292	299	319	333	353	365	374	342	317
1977	303	291	287	284	307	331	346	356	356	350	323	298
1978	290	288	300	286	308	329	351	375	384	360	333	327
1979	290	287	288	295	306	317	335	366	374	366	349	313
1980	309	293	286	284	298	316	325	326	339	338	323	303
1981	291	284	293	272	296	333	348	367	344	361	342	310
1982	294	289	290	292	312	324	334	322	357	356	317	310
1983	280	270	261	281	286	314	329	353	346	361	334	302
1984	291	283	274	278	301	321	354	358	370	348	330	309
1985	292	284	272	279	284	299	311	334	337	335	309	297
1986	295	280	271	272	284	315	333	350	356	356	323	310

Provisionally Revised Average Ozone Values at Belsk

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1963	370	430	410	386	395	391	347	327	295	293	288	314
1964	318	371	386	414	395	344	339	334	307	295	275	328
1965	358	407	423	413	405	367	352	335	304	289	319	354
1966	402	393	445	397	388	363	354	330	316	296	311	353
1967	380	371	401	383	356	362	338	323	296	282	280	347
1968	406	400	401	385	368	355	347	333	310	291	273	361
1969	366	415	408	417	375	375	344	345	298	291	303	353
1970	360	452	428	427	381	383	356	334	327	313	312	328
1971	352	406	415	406	379	384	333	304	334	296	298	317
1972	365	365	404	395	381	370	340	327	315	315	307	321
1973	345	399	399	438	385	374	367	333	304	311	321	335
1974	351	383	355	405	403	380	355	326	300	331	296	302
1975	340	358	387	402	367	359	346	324	294	295	303	302
1976	354	363	397	392	384	368	348	338	316	288	297	349
1977	380	427	388	408	383	376	367	337	316	287	307	316
1978	364	400	379	410	400	390	364	340	315	288	290	306
1979	386	401	427	438	395	359	366	333	300	298	294	339
1980	343	360	402	428	406	376	370	332	310	297	300	323
1981	347	376	378	392	396	356	347	329	308	316	298	340
1982	352	404	421	410	392	385	352	342	301	298	273	291
1983	309	355	371	372	355	355	337	326	293	290	281	301
1984	356	354	391	400	384	382	358	328	324	301	277	305
1985	375	399	383	382	372	371	343	307	303	283	295	323
1986	388	404	363	396	374	361	354	330	295	294	285	321

Provisionally Revised Average Ozone Values at Bismarck

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1963	387	394	406	398	382	337	321	302	282	276	311	322
1964	371	398	420	383	365	345	323	313	302	295	304	343
1965	358	383	415	379	355	334	319	302	311	288	296	352
1966	390	418	398	411	383	363	323	326	296	314	326	357
1967	373	446	385	383	387	353	338	322	287	294	323	329
1968	375	402	406	389	383	356	334	324	310	304	334	365
1969	366	397	430	365	366	361	319	299	293	303	304	353
1970	388	392	429	408	367	348	330	309	312	330	370	333
1971	373	381	407	376	373	342	328	304	308	286	304	343
1972	368	392	390	387	366	343	332	301	315	299	339	350
1973	365	369	376	404	390	352	331	314	302	306	316	339
1974	369	399	423	391	373	340	321	332	304	283	321	348
1975	377	390	402	412	378	359	319	318	312	299	312	331
1976	349	371	384	360	354	334	315	308	294	302	335	334
1977	400	380	418	376	359	348	331	324	304	309	319	372
1978	374	386	374	373	370	340	322	313	292	288	307	334
1979	376	399	403	404	391	347	334	313	299	303	333	312
1980	356	391	406	382	371	346	326	320	307	298	307	294
1981	355	392	385	390	378	353	320	317	292	304	311	360
1982	388	414	403	412	380	366	343	312	297	295	313	339
1983	338	361	393	400	385	342	311	300	310	300	302	358
1984	363	389	405	379	370	346	320	302	314	301	308	318
1985	336	371	370	354	332	345	315	322	308	306	349	355
1986	366	396	368	356	341	308	316	302	306	287	308	322

Provisionally Revised Average Ozone Values at Boulder

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	345	370	399	380	352	338	299	312	294	281	279	335
1965	328	346	382	350	347	325	312	302	295	278	285	313
1966	354	385	366	378	367	340	318	319	297	301	296	321
1967	324	354	335	342	353	343	311	315	295	272	283	319
1968	324	347	377	376	355	333	314	313	304	288	291	308
1969	304	352	392	362	336	346	306	310	305	296	289	312
1970	328	342	398	387	368	345	315	314	305	313	298	302
1971	329	366	359	372	365	335	322	315	310	292	295	317
1972	345	347	339	359	348	329	311	296	290	285	316	313
1973	342	318	379	390	348	332	318	305	303	286	302	308
1974	344	357	364	380	340	334	315	313	299	281	284	332
1975	328	344	365	384	364	338	310	317	305	290	288	308
1976	310	326	364	349	344	325	304	303	299	300	294	295
1977	342	361	387	364	347	324	318	305	284	278	274	298
1978	312	315	337	328	339	319	309	304	291	278	282	286
1979	347	361	369	372	358	319	314	301	289	280	305	294
1980	314	340	372	361	360	312	303	299	290	286	279	281
1981	316	341	357	335	361	315	307	301	293	287	283	298
1982	336	361	370	379	361	339	308	304	290	270	284	314
1983	302	316	370	376	364	324	306	289	285	273	277	336
1984	336	353	374	368	333	321	304	300	289	299	289	289
1985	319	335	322	336	322	313	295	293	289	272	308	295
1986	319	314	340	328	334	311	300	300	288	278	280	305

Provisionally Revised Average Ozone Values at Bracknell

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1969	365	415	413	404	409	384	360	352	313	291	306	313
1970	375	412	436	434	389	382	368	358	329	302	300	327
1971	394	391	412	397	393	384	352	341	316	296	295	318
1972	369	418	419	401	403	395	359	331	313	315	290	324
1973	338	374	379	445	399	369	364	336	308	302	282	294
1974	378	400	396	401	394	392	350	343	332	332	327	298
1975	330	374	419	401	406	375	357	338	318	304	297	299
1976	339	369	374	384	393	355	348	344	321	301	303	333
1977	365	390	396	422	414	386	363	335	295	286	306	320
1978	353	379	382	420	386	369	345	326	283	283	292	310
1979	353	381	418	435	408	372	353	346	302	304	295	332
1980	336	360	398	403	406	387	365	333	303	303	306	312
1981	310	371	393	399	405	368	361	326	317	316	287	337
1982	366	402	411	386	388	371	352	347	304	294	287	289
1983	332	340	346	417	401	358	334	331	298	287	267	309
1984	363	360	410	384	426	374	348	335	320	311	299	312
1985	360	363	384	370	381	384	341	335	292	284	308	317
1986	347	376	386	445	391	361	356	352	316	292	304	327

TOTAL COLUMN OZONE

Provisionally Revised Average Ozone Values at Cagliari

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	330	326	345	360	366	333	310	301	292	284	303	309
1958	342	349	384	394	348	349	319	307	312	293	319	308
1959	340	355	363	378	371	351	321	312	304	299	298	338
1960	340	346	371	381	344	340	322	313	324	297	279	334
1961	341	328	343	345	351	347	312	303	301	286	299	306
1962	347	363	383	367	351	337	311	292	296	280	297	316
1963	348	393	380	385	386	355	327	314	303	297	292	312
1964	319	329	339	356	359	334	325	317	304	301	280	327
1965	343	385	371	394	364	346	312	315	314	299	306	312
1966	338	327	382	382	381	350	340	320	327	300	309	328
1967	354	360	347	361	347	353	314	316	306	292	297	334
1968	379	371	385	360	349	338	322	316	316	309	307	344
1969	334	356	360	374	342	358	333	332	334	315	312	351
1970	361	363	374	387	381	353	334	327	323	301	310	332
1971	348	380	401	376	364	343	314	324	309	313	323	334
1972	366	379	385	394	380	350	347	328	325	317	300	327
1973	343	382	381	368	341	340	318	320	306	295	295	323
1974	346	372	386	395	360	333	319	311	297	306	297	301
1975	307	348	370	354	362	347	318	321	287	280	294	308
1976	320	351	362	365	346	346	322	310	301	286	302	321
1977	360	371	357	373	370	345	323	325	322	299	297	303
1978	357	334	362	391	376	349	330	324	320	302	311	300
1979	350	383	380	412	378	349	323	327	323	300	306	322
1980	331	336	376	391	388	351	338	317	310	298	303	320
1981	342	359	369	374	360	337	330	320	310	298	303	331
1982	376	406	385	378	348	322	326	313	311	300	311	312
1983	309	344	351	355	340	330	321	320	309	299	298	326
1984	344	370	395	378	360	335	325	323	319	306	303	311
1985	316	322	343	340	336	317	312	315	303	292	312	322
1986	342	359	369	374	360	343	330	310	302	295	325	315

Provisionally Revised Average Ozone Values at Cairo

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1974	0	0	0	0	0	0	0	0	0	0	266	291
1975	291	294	310	314	324	316	308	297	291	276	275	294
1976	307	314	329	318	320	309	302	297	288	282	276	290
1977	318	311	320	327	329	322	302	298	290	286	271	293
1978	267	286	302	301	300	302	294	293	284	286	301	289
1979	306	298	323	321	328	316	305	302	295	280	275	296
1980	297	310	306	312	318	308	303	300	291	281	282	282
1981	318	317	339	329	335	311	304	298	289	286	292	293
1982	300	359	351	325	339	315	310	302	293	281	291	280
1983	302	300	322	319	324	305	300	298	290	282	281	289
1984	301	294	311	333	319	305	300	295	293	281	279	277
1985	250	279	291	309	316	298	298	294	288	279	284	293
1986	294	303	322	318	338	296	293	298	287	284	0	0

Provisionally Revised Average Ozone Values at Caribou

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1962	0	0	0	0	0	360	344	324	310	306	315	366
1963	413	439	428	419	411	368	345	348	316	308	326	373
1964	382	418	434	425	390	377	346	337	312	313	319	358
1965	380	399	431	420	384	361	350	335	304	318	331	378
1966	388	432	432	441	417	369	367	344	342	324	319	363
1967	388	430	435	401	409	361	347	330	314	303	334	348
1968	426	440	412	396	398	364	351	339	306	311	332	365
1969	364	415	447	430	405	360	367	334	324	321	314	361
1970	427	444	447	432	379	379	348	340	323	322	328	362
1971	395	420	421	416	371	382	348	330	309	286	311	354
1972	364	404	414	412	378	369	342	331	299	336	339	342
1973	364	415	378	395	395	357	344	326	329	307	339	340
1974	368	419	459	423	391	361	355	334	313	324	319	356
1975	369	406	410	418	387	362	339	327	316	310	321	337
1976	376	395	384	360	389	347	346	318	315	316	326	353
1977	475	396	423	441	405	392	349	324	318	315	302	362
1978	373	425	422	410	371	355	346	319	315	315	291	340
1979	376	422	409	437	378	365	353	336	313	312	323	361
1980	380	449	424	415	408	382	360	326	327	309	316	366
1981	386	374	419	427	397	382	359	331	318	318	333	337
1982	394	414	417	420	386	376	359	357	313	308	304	318
1983	344	369	383	383	381	355	345	332	304	302	312	341
1984	366	390	427	409	382	362	343	331	322	304	322	316
1985	402	405	384	402	385	370	341	333	310	312	326	373
1986	382	397	401	388	374	352	338	327	294	304	325	321

Provisionally Revised Average Ozone Values at Churchill

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1965	400	445	451	431	411	351	356	339	332	334	331	398
1966	422	464	460	449	417	380	362	341	318	347	366	388
1967	397	464	463	442	416	374	351	334	301	334	343	369
1968	433	440	438	456	412	382	379	355	315	336	370	398
1969	417	425	482	443	455	420	366	331	309	325	329	389
1970	430	503	469	470	443	367	362	350	334	346	356	365
1971	410	456	465	447	419	389	373	331	317	333	351	374
1972	406	469	473	452	419	376	378	341	366	339	371	398
1973	401	484	436	448	405	383	364	334	329	333	328	354
1974	379	443	518	459	420	388	365	343	331	329	363	391
1975	411	438	479	454	407	378	353	372	317	330	337	362
1976	351	432	459	412	404	359	345	314	320	320	349	368
1977	390	428	486	453	382	389	375	370	322	326	366	370
1978	380	403	493	452	411	394	365	346	303	318	322	349
1979	404	466	464	444	420	396	357	355	319	330	378	370
1980	403	436	494	412	397	392	367	336	338	316	358	345
1981	360	442	457	475	426	392	351	318	310	303	360	400
1982	416	444	460	472	408	402	367	339	311	310	355	356
1983	379	420	438	422	437	359	340	322	327	319	356	390
1984	396	451	454	410	420	371	358	314	330	306	370	361
1985	380	434	448	436	407	373	359	334	316	332	342	327
1986	404	428	454	430	391	393	360	345	327	318	331	344

Provisionally Revised Average Ozone Values at Edmonton

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	0	0	0	0	0	0	326	305	278	283	294	317
1958	319	407	431	425	365	350	334	296	315	296	354	357
1959	384	419	436	422	399	360	334	335	312	309	306	376
1960	377	442	422	400	399	379	322	328	301	296	341	329
1961	366	413	407	430	386	332	325	297	310	309	322	338
1962	325	452	432	400	371	355	331	308	292	282	301	305
1963	346	383	418	387	402	365	343	312	277	301	323	306
1964	387	409	448	404	388	360	330	321	320	294	310	359
1965	374	415	415	388	388	362	328	302	313	300	302	392
1966	403	426	430	417	381	386	350	329	293	320	344	366
1967	405	403	433	394	374	352	327	301	280	309	323	316
1968	376	377	405	410	382	368	342	333	309	318	336	376
1969	414	412	417	379	382	344	344	310	297	295	312	375
1970	423	406	442	422	387	334	333	316	316	312	331	351
1971	397	389	423	398	368	366	336	290	303	305	322	360
1972	397	412	402	405	371	345	357	301	335	297	359	384
1973	391	415	402	406	376	364	344	318	292	311	330	340
1974	386	423	460	401	396	354	340	311	277	289	361	379
1975	392	396	419	417	400	374	324	315	290	319	319	358
1976	337	408	415	372	374	367	336	304	277	289	319	354
1977	363	380	451	404	393	362	361	333	318	309	350	359
1978	366	375	388	388	381	352	337	323	299	285	299	335
1979	374	433	394	415	402	376	342	317	295	306	336	336
1980	375	397	443	377	373	369	349	339	306	297	328	309
1981	339	397	393	418	382	390	347	304	294	294	327	378
1982	398	428	410	437	391	360	352	324	291	294	323	364
1983	347	380	407	380	376	354	336	306	313	290	335	376
1984	364	409	393	393	387	361	334	309	319	305	351	361
1985	319	390	399	381	358	361	330	322	310	320	342	303
1986	373	405	400	394	353	344	348	309	314	280	321	0

Provisionally Revised Average Ozone Values at Goose Bay

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1962	326	305	278	283	294	317	319	407	431	425	365	350
1963	334	296	315	296	354	357	384	419	436	422	399	360
1964	334	335	312	309	306	376	377	442	422	400	399	379
1965	322	328	301	296	341	329	366	413	407	430	386	332
1966	325	297	310	309	322	338	325	452	432	400	371	355
1967	331	308	292	282	301	305	346	383	418	387	402	365
1968	343	312	277	301	323	306	387	409	448	404	388	360
1969	330	321	320	294	310	359	374	415	415	388	388	362
1970	328	302	313	300	302	392	403	426	430	417	381	386
1971	350	329	293	320	344	366	405	403	433	394	374	352
1972	327	301	280	309	323	316	376	377	405	410	382	368
1973	342	333	309	318	336	376	414	412	417	379	382	344
1974	344	310	297	295	312	375	423	406	442	422	387	334
1975	333	316	316	312	331	351	397	389	423	398	368	366
1976	336	290	303	305	322	360	397	412	402	405	371	345
1977	357	301	335	297	359	384	391	415	402	406	376	364
1978	344	318	292	311	330	340	386	423	460	401	396	354
1979	340	311	277	289	361	379	392	396	419	417	400	374
1980	324	315	290	319	319	358	337	408	415	372	374	367
1981	336	304	277	289	319	354	363	380	451	404	393	362
1982	361	333	318	309	350	359	366	375	388	388	381	352
1983	337	323	299	285	299	335	374	433	394	415	402	376
1984	342	317	295	306	336	336	375	397	443	377	373	369
1985	349	339	306	297	328	309	339	397	393	418	382	390
1986	347	304	294	294	327	378	398	428	410	437	391	0

Provisionally Revised Average Ozone Values at Hohenpeissenberg

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	360	364	360	372	345	347	326	320	296	274	269	310
1968	350	390	392	380	362	358	342	334	312	277	275	337
1969	337	412	373	400	356	365	331	332	293	282	306	341
1970	330	426	415	426	385	359	339	327	297	287	291	323
1971	356	373	407	374	359	359	329	308	309	263	288	294
1972	343	369	384	374	371	354	334	311	320	297	298	311
1973	329	389	378	459	355	344	343	317	292	292	276	308
1974	341	383	335	382	371	361	324	311	295	330	295	288
1975	310	342	376	371	360	353	324	319	287	279	302	292
1976	363	360	358	381	357	341	326	328	308	279	292	317
1977	374	403	364	383	378	361	343	329	310	278	294	308
1978	356	395	363	405	388	370	341	318	283	269	272	283
1979	363	376	378	406	373	345	339	317	289	283	286	316
1980	346	340	379	391	389	362	341	309	289	278	281	311
1981	337	374	362	372	368	337	330	313	297	297	281	329
1982	348	385	404	373	369	356	328	321	284	284	273	293
1983	298	339	340	355	343	339	319	319	291	273	271	310
1984	349	370	396	395	387	361	337	325	311	290	279	304
1985	361	359	369	360	354	350	325	309	286	281	300	295
1986	360	361	369	380	357	347	337	320	296	289	299	314

Provisionally Revised Average Ozone Values at Hradec Kralove

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1962	389	399	446	377	369	342	326	308	294	266	316	342
1963	384	431	404	395	386	377	330	311	293	295	299	318
1964	333	374	374	399	377	331	318	310	289	282	288	315
1965	373	413	414	399	375	347	336	324	303	283	311	330
1966	392	383	420	398	382	360	347	315	313	296	324	338
1967	404	401	411	364	348	349	327	316	293	282	289	347
1968	441	414	411	390	351	350	330	330	305	296	283	395
1969	410	464	411	428	375	373	338	338	297	291	319	358
1970	345	436	438	427	396	372	345	327	310	296	299	322
1971	356	392	413	389	374	363	336	314	320	287	292	295
1972	368	374	395	380	382	362	334	314	318	309	302	315
1973	352	441	391	448	382	364	354	328	293	301	314	329
1974	359	386	359	400	396	382	345	327	299	337	309	313
1975	330	351	397	395	365	360	344	326	298	300	317	309
1976	362	369	392	386	378	355	345	337	323	292	303	331
1977	390	411	383	406	378	369	356	336	312	287	307	317
1978	373	393	379	409	396	377	356	331	310	288	295	309
1979	385	389	412	423	384	386	330	299	294	290	331	289
1980	347	350	392	422	397	375	370	330	299	292	296	334
1981	366	391	370	388	395	349	353	332	306	304	306	344
1982	362	396	412	398	379	370	343	333	296	295	279	298
1983	312	359	357	375	359	352	330	328	301	279	285	319
1984	365	371	388	401	380	373	350	328	316	297	283	306
1985	373	391	376	373	365	366	330	308	296	280	307	318
1986	371	400	362	386	364	350	341	323	290	293	303	333

Provisionally Revised Average Ozone Values at Huancayo

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	0	261	257	253	252	248	248	253	264	261	259	259
1965	259	260	254	253	257	254	256	262	264	269	263	257
1966	253	249	256	252	249	253	259	267	268	264	260	261
1967	256	260	264	259	252	255	253	264	265	261	260	257
1968	252	256	259	253	251	253	254	258	267	263	256	260
1969	258	258	257	246	249	250	257	260	264	267	266	264
1970	255	255	255	252	252	254	259	264	266	270	263	267
1971	261	265	262	261	250	255	261	264	264	258	262	263
1972	260	259	259	254	259	255	255	258	259	258	257	255
1973	258	253	261	253	250	250	256	262	259	272	261	259
1974	259	260	246	246	258	259	260	262	267	268	263	261
1975	260	260	259	253	249	254	261	256	264	261	263	262
1976	261	266	262	257	258	262	260	265	270	267	265	259
1977	247	251	249	246	248	248	247	255	258	260	257	259
1978	258	257	257	251	256	259	259	262	262	263	264	255
1979	253	252	252	254	256	258	261	262	259	258	263	259
1980	259	255	252	246	247	252	252	259	265	261	260	258
1981	258	258	256	258	253	259	256	263	266	269	267	261
1982	253	257	259	251	253	251	257	261	260	271	262	254
1983	256	258	254	253	251	251	259	261	265	265	260	260
1984	259	258	250	252	249	242	248	255	259	259	258	254
1985	252	252	250	249	252	253	256	258	262	264	260	256
1986	255	252	252	244	246	250	0	0	0	0	0	0

Provisionally Revised Average Ozone Values at Kagoshima

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1961	0	0	0	307	299	283	274	267	260	260	267	278
1962	321	325	330	315	317	305	281	288	274	295	275	283
1963	320	318	336	338	320	314	296	275	264	289	252	268
1964	278	288	305	309	316	320	283	268	260	255	260	270
1965	301	300	331	324	333	317	283	290	286	284	264	273
1966	283	286	302	312	328	328	290	283	277	272	247	274
1967	272	283	308	306	315	304	276	273	278	264	256	294
1968	275	299	331	324	313	318	288	273	271	256	249	244
1969	265	268	307	308	315	315	288	281	267	269	262	260
1970	326	305	320	343	336	321	306	295	275	274	261	269
1971	283	276	315	314	331	305	295	287	282	275	259	275
1972	279	302	319	328	320	310	292	285	290	273	272	269
1973	296	283	306	315	324	329	305	291	288	281	282	307
1974	291	297	318	320	329	323	297	296	285	263	258	250
1975	284	302	314	326	328	331	296	287	281	264	274	276
1976	285	299	304	319	320	315	301	283	298	286	277	279
1977	281	294	304	324	321	321	293	287	274	271	261	254
1978	263	292	303	308	315	298	286	276	269	263	260	322
1979	292	322	323	332	341	328	297	290	291	273	268	275
1980	289	289	304	322	328	320	299	297	288	272	263	288
1981	295	302	327	339	329	311	301	295	285	273	267	281
1982	300	306	318	344	329	336	309	301	291	279	271	264
1983	274	301	318	305	332	323	300	290	278	271	276	292
1984	298	297	335	351	330	310	297	291	288	282	260	252
1985	269	272	274	310	316	310	293	283	274	272	272	276
1986	294	318	319	318	315	311	280	284	277	281	257	260

Provisionally Revised Average Ozone Values at Leningrad

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1968	0	0	0	0	0	0	0	322	298	293	288	323
1969	363	471	433	440	397	386	345	319	316	304	301	343
1970	343	426	447	427	394	378	361	320	331	314	315	333
1971	366	428	434	432	389	372	346	327	319	309	319	330
1972	349	378	425	421	399	367	321	311	303	316	305	343
1973	339	463	431	440	382	366	352	337	317	322	314	364
1974	356	384	350	416	405	368	333	332	312	320	324	369
1975	406	402	409	425	375	360	344	320	302	285	293	309
1976	393	351	429	449	401	384	344	326	306	299	289	338
1977	396	434	430	433	396	375	365	337	320	302	316	341
1978	362	394	393	427	388	368	355	334	321	305	316	340
1979	374	396	441	443	388	363	362	320	305	292	292	328
1980	358	366	408	419	421	375	356	340	313	310	314	339
1981	336	404	404	421	380	354	335	330	300	320	303	333
1982	347	416	414	405	401	390	347	351	321	302	286	300
1983	337	377	397	398	367	364	334	323	310	306	312	318
1984	360	372	400	404	374	376	355	322	315	318	296	315
1985	369	426	393	407	379	363	352	312	317	280	305	328

Provisionally Revised Average Ozone Values at Lerwick

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	330	430	395	375	400	363	344	322	308	278	280	300
1958	320	405	417	396	405	346	338	323	291	291	265	315
1959	330	341	411	418	368	352	326	303	283	281	300	305
1960	340	413	420	394	384	369	362	339	291	274	290	315
1961	350	390	376	414	388	369	355	328	294	300	274	280
1962	343	331	426	408	385	366	354	339	298	267	274	305
1963	328	407	416	428	414	377	358	348	318	287	290	284
1964	297	341	387	434	398	377	364	344	308	292	270	301
1965	327	326	392	416	405	372	357	338	314	285	300	335
1966	360	402	442	429	428	360	355	332	312	308	287	305
1967	345	365	410	405	395	365	350	337	322	292	280	330
1968	375	380	422	415	424	378	358	343	315	290	280	330
1969	355	413	402	438	416	388	364	329	319	288	304	320
1970	340	430	459	445	403	371	365	335	337	302	300	315
1971	365	409	408	407	402	381	349	335	308	295	280	320
1972	350	415	436	412	405	390	338	331	297	308	287	315
1973	325	381	379	447	401	380	351	332	306	298	280	310
1974	345	350	379	391	391	368	362	340	334	320	297	315
1975	345	360	409	439	400	379	359	326	323	309	300	305
1976	320	365	402	385	406	361	341	317	305	309	279	310
1977	350	394	434	451	411	396	369	340	331	299	295	305
1978	335	382	410	429	405	373	365	332	298	306	301	315
1979	330	385	445	442	440	364	371	341	315	296	317	325
1980	325	345	396	403	395	385	365	331	317	327	285	305
1981	320	380	410	422	396	371	357	325	310	303	277	315
1982	360	412	415	411	410	383	345	354	330	305	285	275
1983	290	303	381	415	380	352	335	313	311	300	290	310
1984	346	351	402	397	396	377	348	314	312	320	300	310
1985	320	366	380	400	380	384	357	341	310	284	282	300
1986	325	351	397	420	381	360	341	333	308	318	325	0

TOTAL COLUMN OZONE

Provisionally Revised Average Ozone Values at MacQuarie Isle

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1963	320	300	294	326	326	340	334	354	380	370	384	358
1964	328	299	323	321	330	330	337	384	413	415	391	322
1965	295	297	302	296	316	347	360	350	402	423	360	325
1966	331	295	279	324	329	344	329	326	322	344	359	327
1967	310	304	295	302	318	319	334	345	408	414	385	334
1968	315	308	298	316	322	325	330	344	422	443	394	332
1969	314	283	305	331	338	354	358	366	381	381	339	325
1970	286	309	290	319	318	322	370	374	445	428	352	329
1971	285	275	296	300	318	340	339	325	393	397	346	318
1972	309	271	287	314	327	343	363	382	421	410	364	356
1973	324	303	315	309	357	343	330	332	379	388	370	324
1974	294	277	277	276	313	313	338	391	360	393	356	329
1975	305	310	282	307	358	354	358	385	399	370	339	331
1976	304	289	282	294	347	348	350	325	337	402	360	326
1977	308	297	281	314	333	369	380	358	372	410	368	324
1978	312	280	282	279	327	336	368	383	379	412	394	336
1979	350	326	308	312	316	326	359	379	405	425	389	367
1980	336	320	326	304	337	339	353	366	405	406	389	339
1981	335	318	299	328	318	319	335	374	432	435	370	325
1982	320	303	293	303	327	316	329	371	378	406	359	327
1983	311	284	309	319	332	332	340	345	366	401	352	315
1984	281	285	270	307	317	368	364	361	390	403	389	336
1985	316	311	304	308	306	328	314	327	366	377	366	315
1986	294	287	292	316	324	369	357	383	411	403	390	331

Provisionally Revised Average Ozone Values at Mauna Loa

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	241	258	261	276	283	273	271	263	261	252	253	250
1965	259	278	278	286	284	280	269	267	265	262	246	243
1966	242	241	254	277	276	275	272	274	267	259	257	248
1967	260	270	274	300	289	278	267	274	268	262	267	263
1968	259	252	277	294	285	285	280	271	269	257	239	239
1969	240	252	263	278	287	285	277	278	273	267	263	257
1970	244	248	284	295	296	289	280	280	273	260	256	247
1971	243	255	263	284	288	284	281	281	274	266	265	272
1972	263	267	271	297	302	281	275	266	272	264	255	241
1973	240	241	275	278	289	283	280	274	269	266	268	264
1974	262	287	292	296	306	296	285	275	270	269	260	240
1975	240	259	267	279	289	286	286	278	274	270	262	266
1976	265	267	292	290	296	284	274	275	271	266	260	251
1977	245	251	276	296	298	298	279	272	259	251	238	233
1978	238	235	256	283	286	270	275	269	265	256	259	259
1979	260	260	282	300	298	287	279	274	269	257	257	241
1980	239	236	259	267	287	275	277	276	267	267	257	253
1981	244	256	274	296	289	281	277	277	278	271	259	258
1982	263	257	295	297	292	280	271	268	261	249	244	237
1983	225	236	248	280	279	282	271	269	263	261	255	254
1984	249	272	263	299	290	278	278	274	270	258	243	246
1985	230	234	252	276	284	280	267	266	266	256	260	250
1986	242	261	270	292	282	278	267	258	259	260	247	249

Provisionally Revised Average Ozone Values at Nashville

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1963	342	348	360	351	353	344	331	323	306	285	294	317
1964	324	360	343	332	335	331	333	312	300	309	293	309
1965	322	330	366	330	337	333	327	319	291	295	297	303
1966	337	356	365	370	363	352	331	327	314	297	301	312
1967	320	363	326	323	358	332	338	322	313	288	297	297
1968	336	380	366	342	363	339	342	334	314	300	292	309
1969	320	348	372	361	364	339	335	335	316	291	317	319
1970	342	357	393	361	361	343	359	349	309	311	316	292
1971	328	311	354	405	365	345	332	315	306	289	279	277
1972	305	339	355	344	365	345	330	331	304	302	298	293
1973	324	347	326	361	358	331	330	326	302	302	299	312
1974	316	348	345	353	344	356	339	326	304	310	291	308
1975	306	325	341	339	344	336	336	318	297	285	291	299
1976	324	309	328	319	339	337	325	312	303	302	306	302
1977	355	359	319	357	352	334	334	313	302	302	277	294
1978	314	329	322	331	351	331	316	312	293	286	274	286
1979	335	338	371	374	368	331	325	314	305	302	287	301
1980	316	360	343	372	355	335	320	313	303	306	286	313
1981	323	344	346	329	356	322	324	321	303	287	288	318
1982	318	339	357	365	347	338	325	321	315	289	273	293
1983	315	324	343	366	343	336	315	312	302	294	280	309
1984	325	352	371	374	349	328	328	314	296	280	296	268
1985	321	317	300	327	340	326	325	311	295	280	285	315
1986	332	331	337	340	339	320	314	310	287	295	304	302

Provisionally Revised Average Ozone Values at Quetta

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1969	0	0	0	0	0	0	0	288	286	289	281	285
1970	300	295	293	305	289	297	296	293	291	273	271	279
1971	285	287	290	295	298	283	270	279	289	280	281	282
1972	280	317	311	313	310	295	276	287	293	289	277	286
1973	291	308	314	289	287	283	281	284	278	282	280	289
1974	314	319	310	299	300	297	290	292	285	281	281	285
1975	296	299	316	313	286	292	286	280	267	264	271	260
1976	286	298	318	318	292	294	278	276	272	265	266	285
1977	304	297	308	320	312	297	283	279	276	267	277	283
1978	287	298	322	305	294	283	276	273	278	271	274	276
1979	308	309	318	300	310	294	291	290	288	273	270	278
1980	280	292	314	295	303	292	288	289	279	275	269	275
1981	290	289	303	304	292	295	289	284	278	276	280	289
1982	299	333	324	309	308	299	301	294	291	280	269	279
1983	280	289	283	304	297	288	289	285	274	265	264	276
1984	303	325	303	300	296	290	289	285	285	268	257	273
1985	267	258	263	273	289	282	281	280	276	276	281	279
1986	294	299	319	305	300	286	285	282	287	289	289	299

Provisionally Revised Average Ozone Values at Reykjavik

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975	0	0	0	0	0	0	0	0	0	0	0	290
1976	309	343	384	400	380	345	310	300	290	286	250	270
1977	348	375	390	385	375	356	340	330	311	301	324	336
1978	316	361	435	392	406	368	335	307	293	293	295	320
1979	340	408	457	432	423	360	350	341	330	293	313	350
1980	330	373	411	430	413	376	363	336	320	292	294	300
1981	320	409	462	392	394	375	352	333	297	288	278	320
1982	330	450	417	424	410	382	359	347	343	307	299	260
1983	285	301	406	397	375	364	342	328	298	292	286	298
1984	326	346	404	423	390	372	348	322	306	298	298	315
1985	333	367	380	384	382	368	360	334	317	279	286	270
1986	290	314	414	396	392	357	341	325	295	305	0	0

Provisionally Revised Average Ozone Values at Rome

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	333	322	350	362	366	332	318	304	296	286	297	325
1958	358	365	405	410	352	351	325	307	302	293	310	327
1959	365	368	365	376	377	356	313	317	314	305	308	345
1960	352	390	401	414	373	345	333	314	320	307	296	346
1961	359	345	345	370	373	358	329	315	303	291	309	319
1962	354	379	409	384	357	347	320	296	297	279	303	329
1963	371	423	392	401	391	355	323	309	295	291	291	305
1964	323	344	354	378	364	327	319	309	301	305	287	332
1965	345	409	389	406	387	347	324	318	309	291	309	322
1966	369	338	413	383	369	349	343	315	311	291	320	326
1967	361	352	358	365	342	350	319	307	299	281	282	330
1968	387	381	400	374	350	348	327	331	318	299	298	346
1969	350	386	384	385	345	343	338	329	310	289	312	365
1970	361	385	408	417	392	350	332	318	307	299	297	320
1971	348	375	413	382	375	358	339	312	323	294	313	318
1972	358	368	384	381	375	353	346	327	323	311	304	331
1973	350	406	384	401	349	357	335	330	308	302	295	339
1974	354	388	368	409	376	350	325	315	303	320	309	311
1975	321	353	384	374	365	361	325	326	296	299	305	308
1976	334	361	372	383	356	361	334	327	314	289	301	324
1977	362	380	361	382	370	358	338	330	322	298	297	302
1978	355	349	365	400	382	354	337	328	305	290	298	288
1979	366	382	385	413	370	362	335	329	317	299	304	319
1980	347	336	377	399	390	359	341	317	309	317	299	316
1981	363	383	373	392	378	356	343	325	310	297	309	337
1982	347	389	394	381	370	354	326	325	306	306	294	321
1983	310	362	359	361	342	352	321	325	306	293	292	321
1984	359	398	407	396	379	359	327	333	319	294	292	317
1985	342	345	369	352	360	334	322	321	303	292	309	324
1986	353	373	379	386	366	350	333	309	300	294	304	319

Average ozone values at Samoa

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1976	264	262	261	255	261	267	263	268	264	276	269	263
1977	255	253	251	252	252	252	253	252	245	252	261	262
1978	256	260	260	257	259	265	267	263	269	266	261	264
1979	255	255	253	257	259	262	260	260	267	269	260	263
1980	259	254	244	243	247	245	241	255	258	261	258	256
1981	250	250	255	250	258	259	259	253	261	260	264	260
1982	252	252	253	250	245	245	244	246	253	253	257	264
1983	256	250	251	255	252	257	256	256	258	264	264	253
1984	246	246	243	245	250	254	252	252	256	258	262	264
1985	255	254	249	251	253	235	245	251	260	266	264	259
1986	246	247	249	246	250	253	253	254	261	269	250	246

Provisionally Revised Average Ozone Values at Sapporo

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958	410	427	467	420	408	376	324	309	292	319	326	390
1959	446	427	422	413	391	382	345	312	314	316	350	384
1960	441	460	441	414	397	376	331	288	299	288	325	367
1961	415	435	441	410	379	369	331	320	311	289	325	391
1962	429	449	454	390	388	342	311	287	290	296	323	371
1963	453	445	441	398	391	350	333	315	330	297	324	365
1964	398	442	436	383	390	366	325	291	312	315	339	366
1965	407	440	456	425	397	368	339	299	303	307	328	391
1966	448	433	447	429	401	386	347	297	309	325	336	410
1967	431	432	427	406	371	370	325	306	297	312	333	404
1968	435	471	463	401	406	374	344	315	312	318	325	354
1969	410	427	440	403	412	365	332	316	310	325	335	402
1970	431	449	496	426	390	374	330	310	301	317	338	392
1971	404	459	438	410	396	381	333	310	307	329	336	372
1972	381	416	415	406	386	370	327	305	306	312	351	378
1973	400	438	472	407	399	378	320	301	315	326	361	403
1974	437	414	437	405	408	356	338	302	295	313	347	371
1975	410	449	428	431	396	370	327	300	303	321	337	383
1976	408	411	406	420	376	349	317	315	301	306	335	382
1977	429	469	436	421	398	373	318	311	303	301	316	368
1978	413	444	438	434	390	344	305	298	309	313	327	386
1979	422	418	455	429	426	367	347	315	314	298	328	365
1980	423	464	437	430	401	370	349	330	310	313	338	403
1981	433	445	442	418	392	389	332	318	321	320	354	387
1982	442	466	439	419	403	380	357	304	312	317	335	355
1983	387	428	408	382	391	386	344	298	305	330	337	400
1984	438	463	470	428	408	364	323	297	312	317	332	380
1985	415	410	408	387	392	381	323	291	315	317	349	393
1986	437	456	419	421	397	364	335	296	304	325	355	362

Provisionally Revised Average Ozone Values at Srinigar

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	0	342	313	297	320	304	298	281	279	260	271	281
1965	301	322	325	304	306	299	287	283	280	270	272	276
1966	303	290	293	304	302	298	281	270	269	292	291	298
1967	307	299	317	321	313	294	284	286	275	281	290	303
1968	334	335	331	316	315	303	298	296	285	276	275	299
1969	306	296	288	309	297	290	280	274	284	288	287	291
1970	306	323	321	304	311	302	297	284	281	266	275	286
1971	301	307	297	292	302	290	292	285	283	272	276	280
1972	296	322	315	323	314	297	296	277	284	288	268	286
1973	310	302	305	291	301	290	284	278	276	276	285	295
1974	318	318	308	296	308	299	291	283	280	276	278	291
1975	306	317	319	326	320	308	296	283	276	272	285	285
1976	276	302	305	298	297	286	283	281	276	273	270	293
1977	314	319	300	313	322	310	286	281	283	277	269	298
1978	309	322	333	306	287	284	278	277	282	276	278	292
1979	325	363	345	296	315	297	287	280	289	277	269	305
1980	308	318	338	298	302	295	284	285	279	276	278	300
1981	309	313	337	316	299	301	286	279	278	275	281	311
1982	291	344	318	315	323	302	293	278	288	281	275	288
1983	292	303	311	316	309	306	295	280	276	277	282	296
1984	329	333	308	316	302	286	278	272	278	276	278	291
1985	288	287	285	291	302	286	275	269	271	269	284	277
1986	311	326	340	312	312	0	0	0	0	0	0	0

Provisionally Revised Average Ozone Values at Tateno

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	0	0	0	0	0	0	300	281	285	271	273	309
1958	320	335	385	357	351	339	308	294	279	281	274	309
1959	324	338	356	353	372	364	316	305	293	282	281	307
1960	343	376	389	378	371	347	321	297	290	275	292	290
1961	313	369	355	359	330	330	302	294	280	274	294	330
1962	378	379	399	386	362	341	322	295	287	285	288	339
1963	387	401	408	367	360	330	319	298	295	267	287	301
1964	325	350	373	344	359	347	307	282	279	274	287	300
1965	334	352	382	372	357	340	315	300	285	284	276	311
1966	345	346	358	348	356	350	316	298	287	290	276	318
1967	340	338	348	339	341	333	306	290	276	272	273	323
1968	337	378	397	360	367	353	330	302	291	285	276	291
1969	311	313	368	353	351	339	323	299	289	292	285	300
1970	352	349	376	370	355	341	323	301	289	283	282	310
1971	342	348	359	342	353	334	313	293	288	289	280	304
1972	315	349	369	358	340	338	306	294	297	278	293	306
1973	332	331	364	329	355	358	310	290	291	286	299	335
1974	355	353	375	345	344	338	317	291	292	275	279	281
1975	326	365	365	363	353	345	312	295	288	286	286	306
1976	309	331	327	337	337	322	309	295	288	280	279	303
1977	321	363	352	359	366	343	318	297	283	280	268	296
1978	317	350	371	358	340	313	301	290	286	280	283	328
1979	344	359	372	358	366	333	323	304	295	269	282	300
1980	326	346	349	347	350	327	318	304	285	270	287	332
1981	350	351	361	372	347	347	320	306	296	282	291	317
1982	354	368	365	379	346	350	333	307	298	281	280	289
1983	315	348	349	322	350	345	327	299	294	284	292	324
1984	350	368	397	373	362	335	306	295	292	279	277	292
1985	309	330	302	339	338	333	306	287	283	279	289	305
1986	341	387	374	363	349	341	310	291	286	295	280	297

Provisionally Revised Average Ozone Values at Toronto

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	393	428	477	401	390	369	351	328	313	310	320	371
1961	402	386	386	445	404	353	344	329	296	311	310	340
1962	372	429	453	437	369	360	354	334	328	315	315	365
1963	418	404	411	413	400	375	367	357	320	307	325	369
1964	372	399	429	392	365	354	343	333	309	317	308	341
1965	378	383	415	409	369	357	351	336	306	311	322	351
1966	386	417	424	422	421	368	353	340	340	330	319	358
1967	362	415	395	373	399	345	346	340	322	295	323	319
1968	381	430	397	371	403	359	346	328	309	305	323	364
1969	350	402	439	402	394	364	337	330	319	316	326	365
1970	416	417	418	394	365	353	350	331	312	308	327	333
1971	417	392	430	420	382	353	351	333	307	279	312	325
1972	356	406	426	392	430	372	348	333	303	322	339	333
1973	356	394	381	411	400	353	353	336	313	307	318	338
1974	358	417	414	402	388	376	347	340	321	316	331	363
1975	368	403	411	409	390	366	347	337	329	306	320	351
1976	382	368	386	384	402	358	353	335	330	324	350	350
1977	452	420	410	402	387	381	359	328	321	311	314	360
1978	366	394	403	383	375	360	335	322	308	310	295	325
1979	380	413	402	423	389	367	352	337	317	322	312	334
1980	361	432	406	412	373	377	340	327	323	317	319	346
1981	378	399	429	395	402	370	342	340	324	323	324	336
1982	379	391	408	412	374	378	344	336	326	291	305	325
1983	361	367	386	382	376	354	327	325	313	300	315	345
1984	378	385	429	416	402	350	338	329	316	293	321	300
1985	399	399	362	377	361	359	342	329	304	288	311	360

Provisionally Revised Average Ozone Values at Uccle

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1971	0	412	431	424	416	406	375	352	333	302	324	320
1972	376	397	418	414	411	385	355	344	338	315	306	321
1973	361	410	388	442	407	373	376	345	315	319	319	311
1974	374	386	378	404	395	384	354	335	314	348	335	301
1975	325	350	405	406	387	372	344	328	314	300	310	291
1976	357	354	376	392	372	354	341	340	327	291	289	335
1977	368	415	399	411	403	381	356	346	312	285	313	336
1978	373	387	378	419	395	380	369	349	291	291	290	310
1979	359	392	327	450	403	377	356	328	301	297	300	334
1980	340	353	393	415	416	386	363	324	320	307	297	327
1981	350	380	391	405	392	365	359	326	314	320	280	344
1982	370	402	433	393	389	376	351	348	302	301	275	288
1983	300	351	355	396	396	352	336	332	301	286	268	304
1984	362	350	403	391	421	380	350	336	319	308	289	312
1985	364	355	386	371	375	383	338	328	293	284	316	331
1986	378	396	388	427	371	349	343	337	286	292	307	316

Provisionally Revised Average Ozone Values at Wallops Is.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970	338	365	406	366	354	353	333	320	300	293	301	300
1971	328	325	360	383	358	341	319	315	302	277	293	293
1972	322	358	369	357	383	358	331	315	309	307	304	293
1973	321	360	341	363	366	329	332	324	302	298	296	308
1974	309	359	366	361	351	343	336	312	295	306	282	307
1975	306	323	349	368	353	343	328	319	301	289	293	307
1976	338	313	329	344	352	338	332	323	311	309	311	313
1977	395	386	345	371	387	363	336	319	309	304	287	308
1978	330	338	341	338	354	331	323	308	300	294	277	295
1979	350	355	370	374	347	341	323	314	290	295	284	305
1980	317	373	353	370	363	358	330	322	303	304	286	321
1981	341	350	375	351	370	324	328	321	307	296	305	322
1982	346	332	361	378	377	341	337	328	310	287	272	283
1983	324	329	353	370	350	340	327	315	303	299	286	290
1984	337	350	367	369	361	343	327	318	302	281	291	277
1985	328	323	316	333	336	335	325	315	304	282	288	321
1986	347	349	348	386	356	331	325	316	295	295	308	295

A. (ii) Latitudinal band averages prepared from provisionally revised data (Bojkov, private communication, 1987)

60°–80° North
53°–64° North
40°–52° North
30°–39° North

and M–83 regional averages (USSR), prepared by Bojkov (1988a)

European part
South Central Asia
Siberia
Far Eastern Asia

N.B. The latitudinal band averages are made up from the provisionally revised Dobson instrument records only, with the exception of the band between 30° and 39°N, which contains one M–83 filter instrument record.

Average Monthly Ozone Values for 60°N–80°N, Derived From the Provisionally Revised Data Sets; Dobson Only

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	346	456	411	397	403	377	333	318	309	297	289	310
1958	356	454	464	438	411	366	346	324	305	303	292	345
1959	376	383	441	448	400	371	332	318	299	292	300	289
1960	373	445	420	416	391	367	343	319	293	273	276	303
1961	351	392	443	425	390	361	338	318	287	288	292	296
1962	349	357	420	407	390	362	338	319	299	277	274	309
1963	350	430	444	434	406	371	347	324	314	294	295	295
1964	305	344	415	448	402	367	349	332	303	277	286	314
1965	351	372	415	425	408	361	343	323	305	292	292	355
1966	385	417	459	451	409	364	353	328	305	307	305	323
1967	358	394	417	409	392	360	346	320	302	299	295	322
1968	384	403	431	433	423	373	353	333	307	300	307	341
1969	368	422	443	444	414	388	354	322	311	301	313	336
1970	369	452	454	452	416	368	355	330	325	309	315	332
1971	377	424	442	431	396	367	345	323	310	311	312	333
1972	361	407	444	427	401	372	337	320	310	313	315	346
1973	349	435	438	449	391	362	339	318	311	315	303	338
1974	355	385	431	429	399	368	340	318	315	320	323	352
1975	381	393	438	435	390	362	334	317	303	295	305	316
1976	343	372	418	414	395	358	328	304	302	296	290	320
1977	371	407	444	432	394	370	347	326	308	308	325	338
1978	348	385	433	427	397	371	343	321	300	303	306	325
1979	358	410	457	443	409	368	349	327	313	302	318	346
1980	356	378	431	428	403	373	353	327	313	310	314	323
1981	333	405	434	427	392	367	342	321	303	302	301	340
1982	361	427	431	439	410	379	346	335	313	303	302	296
1983	322	344	409	413	392	357	334	315	305	297	301	322
1984	361	370	421	415	396	372	348	315	309	305	308	318
1985	355	401	430	426	393	371	350	329	312	290	303	304
1986	337	355	417	444	396	367	347	330	306	313	324	337

Average Monthly Ozone Values for 53°N–64°N, Derived From the Provisionally Revised Data Sets; Dobson Only

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	346	456	411	397	403	377	342	326	310	297	291	309
1958	345	426	442	420	403	365	350	330	309	305	299	350
1959	375	389	432	433	395	373	341	325	302	299	315	320
1960	371	448	424	404	394	378	360	350	307	295	309	326
1961	357	391	403	417	390	368	353	328	307	305	297	300
1962	358	389	423	409	381	366	345	326	305	281	281	323
1963	361	419	431	420	415	381	354	338	310	303	302	307
1964	331	370	417	426	400	371	349	335	319	295	297	326
1965	360	382	414	416	400	363	347	331	316	300	297	365
1966	392	418	438	427	410	369	356	332	313	317	313	339
1967	365	400	427	401	387	359	340	324	298	306	305	321
1968	397	403	422	416	400	369	353	335	307	305	314	351
1969	376	413	433	428	407	382	360	328	317	305	311	342
1970	385	444	449	438	406	361	353	331	329	313	316	337
1971	386	416	426	417	388	371	346	321	313	305	311	337
1972	368	410	430	414	395	363	343	321	320	314	324	355
1973	362	426	406	424	384	369	347	327	312	310	310	330
1974	363	401	427	413	396	364	346	329	313	311	328	351
1975	384	399	423	425	393	367	337	325	306	307	308	324
1976	344	382	414	399	389	363	334	314	301	301	298	327
1977	373	402	432	427	397	376	363	342	323	309	328	342
1978	353	389	428	420	398	371	351	330	309	304	305	326
1979	357	416	436	435	408	370	357	335	315	302	320	347
1980	362	388	423	412	402	379	362	335	319	310	317	325
1981	338	401	426	425	394	376	349	326	302	307	307	345
1982	374	428	423	431	409	382	356	347	320	304	306	308
1983	329	354	398	398	384	360	337	319	311	301	308	332
1984	361	379	410	405	394	373	348	318	316	310	317	330
1985	357	398	404	404	384	366	349	330	315	297	311	312
1986	356	379	415	414	381	365	348	328	312	312	327	329

Average Monthly Ozone Values for 40°N–52°N Derived From the Provisionally Revised Data Sets; Dobson Only

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	344	348	350	358	374	345	320	309	295	277	290	323
1958	356	380	406	407	375	361	337	315	294	296	313	345
1959	382	392	403	396	378	353	333	311	306	300	318	341
1960	372	414	429	402	379	360	345	320	309	304	312	353
1961	386	370	374	399	383	358	338	323	301	298	311	330
1962	377	395	430	393	371	350	330	309	300	283	306	333
1963	388	423	406	397	388	365	336	324	301	290	306	324
1964	345	378	393	395	375	347	329	320	303	299	295	335
1965	361	395	408	398	380	353	340	323	311	294	310	342
1966	380	390	411	404	391	364	347	328	315	310	321	343
1967	373	390	385	379	366	356	331	321	302	288	299	337
1968	385	406	405	386	374	357	339	331	312	299	302	354
1969	359	412	408	399	377	368	341	332	309	301	314	353
1970	372	416	430	420	386	366	343	330	313	309	313	335
1971	371	392	411	393	378	365	341	320	318	292	306	323
1972	362	385	398	390	384	364	339	321	316	310	316	330
1973	353	396	389	422	380	361	347	326	308	306	309	330
1974	364	393	387	401	384	365	339	326	308	322	315	321
1975	342	372	398	398	379	362	335	325	307	300	310	318
1976	355	367	381	383	372	352	335	329	316	300	310	335
1977	390	403	392	399	385	369	346	329	310	294	304	329
1978	363	382	380	399	382	362	340	323	301	292	293	314
1979	371	393	397	419	389	360	342	323	305	301	310	326
1980	355	379	395	405	393	367	346	322	308	302	305	322
1981	358	385	390	390	387	357	338	323	309	309	307	340
1982	370	401	408	397	380	367	341	328	303	297	294	314
1983	326	362	368	381	369	350	327	318	301	292	293	331
1984	366	381	408	395	386	360	334	322	314	301	299	316
1985	367	372	374	368	360	356	327	314	299	291	318	333
1986	372	389	378	390	363	343	333	317	300	298	309	323

Average Monthly Ozone Values for 30°N–39°N, Derived From the Provisionally Revised Data Sets

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	317	309	320	335	342	319	298	291	291	286	289	299
1958	318	329	360	357	347	342	319	309	301	289	291	312
1959	316	328	338	343	348	335	310	303	295	289	286	306
1960	322	332	351	365	342	326	310	296	300	286	285	306
1961	319	333	334	337	330	324	305	297	291	284	296	309
1962	338	349	358	351	341	321	300	287	283	283	286	307
1963	338	355	350	354	349	327	312	298	291	286	282	293
1964	311	333	334	335	345	330	315	301	293	287	284	300
1965	323	341	356	351	348	334	312	308	299	297	290	301
1966	326	323	348	349	352	343	319	307	303	293	291	311
1967	325	333	335	337	339	329	311	305	297	288	289	313
1968	335	356	367	345	345	334	322	313	302	293	289	304
1969	315	325	343	346	340	334	317	310	305	299	299	316
1970	338	344	361	357	350	337	327	315	302	292	292	301
1971	322	329	349	349	344	326	311	304	301	292	291	298
1972	317	343	352	349	349	329	315	306	303	297	291	305
1973	328	337	344	339	338	325	313	305	300	297	299	318
1974	323	345	350	352	343	333	321	309	298	297	286	299
1975	312	334	347	340	343	337	317	307	295	287	290	301
1976	317	322	332	335	334	325	313	304	299	296	297	310
1977	341	347	333	351	354	335	317	308	300	295	285	301
1978	314	327	340	334	334	318	309	303	296	289	290	305
1979	336	349	358	348	352	328	312	308	303	291	287	307
1980	323	339	346	343	344	329	315	310	300	297	293	309
1981	326	335	356	344	342	325	317	309	300	292	294	310
1982	330	356	357	354	346	332	324	313	308	294	288	294
1983	308	324	337	340	337	328	316	306	297	291	289	308
1984	332	345	352	355	343	324	314	305	301	288	287	290
1985	300	306	306	322	331	318	307	303	295	288	296	307
1986	326	340	349	347	343	326	314	306	297	298	296	298

M–83 Average Monthly Ozone Measurements for the European Part of the USSR

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	339	368	414	414	397	367	317	315	318	323	310	336
1973	339	435	440	434	388	379	362	337	320	314	317	338
1974	359	384	364	411	402	367	344	335	315	313	311	342
1975	367	404	406	402	373	356	335	320	299	289	296	301
1976	370	371	428	423	396	378	345	332	315	302	297	343
1977	386	442	432	432	401	388	380	350	331	308	331	325
1978	367	399	399	430	401	377	363	343	331	306	302	334
1979	378	395	417	433	375	364	366	322	305	304	295	340
1980	370	378	416	423	408	377	356	343	316	305	306	334
1981	364	402	398	420	395	356	336	331	302	310	309	332
1982	357	417	411	396	388	384	353	342	308	299	284	299
1983	333	377	383	383	357	364	342	331	306	294	301	319
1984	361	368	399	393	372	368	349	333	315	312	293	319
1985	351	426	391	391	369	355	346	307	316	290	300	324

M–83 Average Monthly Ozone Measurements for the South Central Asian Part of the USSR

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	360	358	365	345	350	324	307	304	298	295	290	329
1973	349	346	352	327	345	313	313	301	305	305	321	344
1974	362	392	353	353	354	339	325	301	299	283	309	348
1975	359	387	378	362	352	321	303	283	293	296	315	323
1976	343	375	359	332	319	318	299	291	302	315	315	347
1977	388	384	361	357	358	325	313	307	304	312	306	333
1978	351	371	385	336	330	315	300	298	294	294	300	315
1979	368	379	383	333	355	323	303	301	302	292	288	325
1980	369	372	372	336	340	334	307	306	302	299	306	316
1981	349	366	378	355	328	318	309	302	295	294	296	318
1982	354	388	379	349	338	320	310	301	315	302	305	319
1983	324	338	367	352	328	319	302	287	294	288	299	322
1984	361	397	365	366	357	332	306	281	297	287	298	334
1985	325	335	350	317	344	320	298	311	297	302	312	323

M–83 Average Monthly Ozone Measurements for the Siberian Part of the USSR

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	359	377	422	423	406	376	338	327	322	332	341	349
1973	384	378	430	390	372	347	340	330	352	338	348	352
1974	373	392	369	421	391	368	333	329	325	308	322	341
1975	398	446	432	432	402	359	347	342	316	320	320	332
1976	365	394	396	413	387	364	349	317	325	329	304	321
1977	390	429	437	412	399	360	343	346	320	328	315	336
1978	382	400	389	414	401	353	344	333	321	312	319	327
1979	389	387	429	422	383	377	340	322	311	311	291	347
1980	394	378	435	406	382	379	349	339	321	311	303	337
1981	366	431	420	413	397	359	341	324	309	299	314	304
1982	415	436	435	382	388	361	348	334	309	299	291	295
1983	350	397	414	379	396	350	336	331	326	309	309	312
1984	381	374	428	438	401	369	340	311	332	326	299	322
1985	365	406	388	397	375	360	343	316	307	308	306	339

M–83 Average Monthly Ozone Measurements for the Far Eastern Part of the USSR

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	407	440	449	427	398	385	336	321	322	333	359	386
1973	403	445	478	421	411	383	317	314	339	345	371	412
1974	460	450	483	434	416	365	347	311	314	331	363	398
1975	423	457	441	451	413	382	344	318	322	336	366	405
1976	420	430	440	452	394	373	332	336	315	336	371	403
1977	445	484	477	454	414	390	340	331	325	338	343	371
1978	430	456	455	452	414	375	333	323	329	335	343	404
1979	433	444	466	433	424	384	352	322	327	326	362	371
1980	444	484	470	460	414	372	346	324	325	341	351	389
1981	437	471	463	439	402	388	335	322	336	339	371	399
1982	456	479	464	439	413	388	356	307	326	335	343	371
1983	407	455	436	403	393	388	352	303	306	337	351	411
1984	439	464	469	435	402	372	327	303	317	334	354	386
1985	419	424	433	410	396	375	330	301	318	328	366	404
1986	454	473	435	437	412	378	348	307	316	337	369	376

B. (i) Coefficients from individual station analyses

Part	Data Used	Trend Starts	Effects Allowed For		
			QBO	Solar Cycle	Nuclear Effect
(a)	1965–1986	1970	yes	yes	n/a
(b)	1965–1986	1976	yes	yes	n/a
(c)	1957–1986	1970	yes	yes	no
(d)	1957–1986	1976	yes	yes	no
(e)	1957–1986	1970	yes	yes	yes
(f)	1957–1986	1976	yes	yes	yes

For example, part (a) contains the results of analyses that used data from January 1965 to December 1986 and a model that allows for the quasi-biennial oscillation and the solar cycle, and that posits a trend that starts in January 1970.

Notes:

(1) If a station does not have a complete record for the whole time period, as much as possible is used—e.g., for Bismarck, whose record starts in January 1963, the last four analyses are performed on the complete Bismarck data set (1/63–12/86). The estimate of the nuclear bomb test parameter should be treated very carefully because the maximum predicted effect occurred as the ozone observations started.

(2) No data prior to January 1957 were analysed.

(3) The units of the QBO and solar cycle parameters are Dobson Unit per $m.s^{-1}$, and Dobson Units per 100 sunspots, respectively. To find the magnitude of these effects, see Figures 4.10 and 4.11.

(4) The nuclear bomb test parameter shows that the photochemical model prediction and the analysis agree when it has a value of -1. If it has a value of -0.5, the magnitude of the effect calculated from the data is one half that predicted by the LLNL model.

(5) The trend coefficients are all given in Dobson Units per year.

(6) The provisionally revised data (Bojkov, private communication, 1987) are used.

(a) Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	**Reykjavik**	**Lerwick**	**Leningrad**
Monthly calculation:			
January	−2.26 ± 1.66	−2.37 ± 0.86	−1.14 ± 1.30
February	−3.24 ± 3.04	−3.06 ± 1.53	−2.21 ± 2.10
March	−0.54 ± 1.72	−1.79 ± 0.98	−2.19 ± 1.51
April	+0.19 ± 1.51	−1.19 ± 0.91	−2.91 ± 0.93
May	−0.22 ± 1.57	−1.91 ± 0.75	−1.37 ± 0.85
June	+1.59 ± 0.91	−0.49 ± 0.59	−0.38 ± 0.62
July	+2.64 ± 1.11	−0.79 ± 0.54	+0.35 ± 0.74
August	+1.88 ± 0.94	−0.43 ± 0.51	+0.10 ± 0.65
September	+0.77 ± 1.31	−0.53 ± 0.63	−0.07 ± 0.56
October	+0.68 ± 0.69	+0.68 ± 0.68	−0.60 ± 0.76
November	+1.18 ± 1.69	+0.75 ± 0.69	−0.62 ± 0.74
December	−2.28 ± 2.04	−1.52 ± 0.58	−2.33 ± 1.07
Average	+0.03	−1.05	−1.11
QBO	−0.30 ± 0.11	−0.28 ± 0.080	−0.086 ± 0.096
Solar	+9.69 ± 2.88	+4.42 ± 2.12	+1.30 ± 2.61
Yearly calculation:			
Ramp	+0.86 ± 0.53	−0.80 ± 0.30	−0.66 ± 0.38

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	**Churchill**	**Edmonton**	**Goose**
Monthly calculation:			
January	−1.54 ± 1.07	−4.11 ± 1.42	−0.71 ± 1.51
February	−2.12 ± 1.14	−0.47 ± 0.98	−1.14 ± 1.01
March	−1.42 ± 1.02	−2.35 ± 0.97	−0.80 ± 0.96
April	−1.55 ± 0.94	−0.66 ± 0.86	−1.87 ± 1.13
May	−0.82 ± 0.82	−1.18 ± 0.65	−1.22 ± 0.99
June	+0.20 ± 0.80	−0.03 ± 0.69	+0.13 ± 0.54
July	−0.81 ± 0.51	+0.17 ± 0.51	−0.22 ± 0.56
August	−1.30 ± 0.78	+0.26 ± 0.64	−0.29 ± 0.53
September	−0.25 ± 0.71	+1.01 ± 0.76	−0.82 ± 0.58
October	−2.06 ± 0.60	−1.01 ± 0.59	+0.03 ± 0.41
November	+0.08 ± 0.83	+0.30 ± 0.91	+0.99 ± 0.67
December	−2.70 ± 1.05	−2.13 ± 1.49	+0.57 ± 1.11
Average	−1.19	−0.85	−0.45
QBO	−0.27 ± 0.080	−0.22 ± 0.080	−0.18 ± 0.073
Solar	+4.33 ± 2.10	+2.70 ± 2.06	+5.12 ± 2.01
Yearly calculation:			
Ramp	−1.13 ± 0.27	−0.46 ± 0.28	−0.17 ± 0.27

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Belsk	Bracknell	Uccle
Monthly calculation:			
January	−0.62 ± 1.23	−1.24 ± 1.14	−0.45 ± 1.27
February	−1.24 ± 1.35	−2.97 ± 1.16	−1.63 ± 1.47
March	−2.36 ± 1.14	−1.91 ± 1.16	−0.81 ± 1.52
April	−1.22 ± 0.91	−0.75 ± 1.19	−1.86 ± 1.15
May	−0.24 ± 0.74	−0.10 ± 0.62	−1.19 ± 0.90
June	−0.21 ± 0.65	−1.21 ± 0.63	−1.52 ± 0.84
July	+0.18 ± 0.55	−1.11 ± 0.49	−1.67 ± 0.71
August	−0.42 ± 0.49	−0.44 ± 0.50	−0.94 ± 0.55
September	−0.71 ± 0.58	−1.20 ± 0.70	−2.51 ± 0.85
October	−0.61 ± 0.63	−1.09 ± 0.70	−1.80 ± 0.97
November	−1.90 ± 0.73	−0.61 ± 0.70	−2.32 ± 1.07
December	−2.28 ± 1.06	+0.25 ± 0.75	+0.13 ± 0.95
Average	−0.97	−1.03	−1.38
QBO	−0.20 ± 0.082	−0.28 ± 0.081	−0.17 ± 0.106
Solar	+3.02 ± 2.21	+1.36 ± 2.03	+2.53 ± 2.58
Yearly calculation:			
Ramp	−0.73 ± 0.29	−0.82 ± 0.27	−1.35 ± 0.35

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Hradec Kralove	Hohenpeissenberg	Caribou
Monthly calculation:			
January	1.59 ± 1.42	+0.75 ± 1.01	−0.84 ± 1.45
February	2.16 ± 1.46	−2.20 ± 1.23	−2.70 ± 1.09
March	3.22 ± 1.21	−0.38 ± 1.10	−2.28 ± 1.12
April	1.30 ± 1.02	−1.96 ± 1.28	−1.34 ± 1.04
May	0.34 ± 0.70	+0.09 ± 0.74	−1.03 ± 0.68
June	+0.03 ± 0.71	−0.63 ± 0.49	−0.12 ± 0.59
July	+0.07 ± 0.63	−0.26 ± 0.41	−0.52 ± 0.43
August	+0.17 ± 0.56	−0.48 ± 0.42	+0.08 ± 0.43
September	0.74 ± 0.51	−0.89 ± 0.57	−0.79 ± 0.55
October	0.85 ± 0.69	−0.22 ± 0.74	−0.88 ± 0.53
November	1.11 ± 0.73	−0.40 ± 0.63	−0.54 ± 0.63
December	1.38 ± 1.17	−0.59 ± 0.83	−2.01 ± 0.89
Average	1.06 − 0.60	−1.08	
QBO	0.09 ± 0.09	−0.29 ± 0.069	−0.13 ± 0.076
Solar	+1.85 ± 2.52	+0.15 ± 1.80	+5.34 ± 2.14
Yearly calculation:			
Ramp	0.69 ± 0.34	−0.51 ± 0.23	−0.63 ± 0.29

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Bismarck	Arosa	Toronto
Monthly calculation:			
January	−1.94 ± 0.83	+0.25 ± 0.88	+0.47 ± 1.26
February	−1.02 ± 0.88	−0.86 ± 1.30	−1.45 ± 0.96
March	−2.11 ± 0.86	−1.70 ± 1.25	−1.67 ± 1.19
April	−1.37 ± 0.84	−1.62 ± 0.90	−0.46 ± 0.92
May	−1.45 ± 0.76	−0.55 ± 0.60	−2.17 ± 0.90
June	−1.13 ± 0.59	−1.34 ± 0.46	−0.38 ± 0.51
July	−0.73 ± 0.48	−0.89 ± 0.38	−1.28 ± 0.42
August	−0.55 ± 0.53	−0.96 ± 0.40	−0.47 ± 0.34
September	+0.20 ± 0.48	−1.31 ± 0.51	−0.54 ± 0.49
October	−0.34 ± 0.68	−0.49 ± 0.60	−1.09 ± 0.60
November	−0.75 ± 0.95	−0.47 ± 0.58	−0.99 ± 0.54
December	−1.10 ± 0.90	−1.55 ± 0.65	−1.69 ± 0.89
Average	−1.02	−0.96	−0.98
QBO	−0.19 ± 0.076	−0.13 ± 0.056	−0.11 ± 0.063
Solar	+4.39 ± 2.02	+2.10 ± 1.49	+0.36 ± 1.72
Yearly calculation:			
Ramp	−0.81 ± 0.27	−1.02 ± 0.19	−0.87 ± 0.24

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Sapporo	Rome	Boulder
Monthly calculation:			
January	+0.62 ± 0.97	−0.89 ± 0.85	−0.99 ± 0.74
February	+0.55 ± 0.94	−0.07 ± 1.09	−1.65 ± 0.92
March	−1.77 ± 1.08	−0.81 ± 0.97	−1.77 ± 0.98
April	−0.47 ± 0.78	−1.02 ± 0.81	−2.01 ± 0.92
May	+0.31 ± 0.58	+0.15 ± 0.72	−1.16 ± 0.60
June	+0.44 ± 0.64	−0.20 ± 0.51	−1.97 ± 0.52
July	+0.42 ± 0.63	−0.43 ± 0.43	−1.27 ± 0.32
August	−0.65 ± 0.55	+0.03 ± 0.47	−1.49 ± 0.38
September	+0.66 ± 0.45	−0.39 ± 0.47	−1.35 ± 0.35
October	+0.33 ± 0.59	−0.11 ± 0.44	−1.13 ± 0.54
November	+0.68 ± 0.58	−0.38 ± 0.48	−0.59 ± 0.52
December	−0.72 ± 0.82	−0.72 ± 0.78	−1.05 ± 0.71
Average	+0.03	−0.40	−1.37
QBO	+0.069 ± 0.078	−0.079 ± 0.070	−0.053 ± 0.058
Solar	+4.63 ± 2.10	+2.84 ± 1.94	+0.64 ± 1.58
Yearly calculation:			
Ramp	+0.26 ± 0.27	−0.34 ± 0.25	−1.35 ± 0.21

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Cagliari	Wallops Is.	Nashville
Monthly calculation:			
January	−0.97 ± 0.87	+1.07 ± 1.23	−0.09 ± 0.60
February	−0.65 ± 1.11	−0.79 ± 1.20	−1.20 ± 0.91
March	−0.69 ± 0.83	−1.22 ± 1.20	−1.43 ± 1.08
April	−0.88 ± 0.84	+0.20 ± 0.89	−0.08 ± 1.06
May	−0.81 ± 0.75	−0.74 ± 0.79	−1.20 ± 0.52
June	−1.61 ± 0.48	−0.93 ± 0.65	−1.49 ± 0.44
July	−0.03 ± 0.44	−0.38 ± 0.31	−1.69 ± 0.49
August	−0.45 ± 0.43	−0.04 ± 0.29	−1.49 ± 0.50
September	−0.44 ± 0.57	−0.13 ± 0.35	−0.95 ± 0.39
October	−0.38 ± 0.45	−0.83 ± 0.56	−1.01 ± 0.47
November	+0.72 ± 0.52	−0.32 ± 0.65	−0.96 ± 0.59
December	−0.74 ± 0.66	−0.45 ± 0.78	−0.07 ± 0.68
Average	−0.58	−0.38	−0.97
QBO	+0.030 ± 0.092	+0.084 ± 0.075	+0.045 ± 0.079
Solar	+5.38 ± 2.43	+0.21 ± 1.62	+3.90 ± 1.98
Yearly calculation:			
Ramp	−0.48 ± 0.31	−0.27 ± 0.22	−1.12 ± 0.26

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Tateno	Srinigar	Kagoshima
Monthly calculation:			
January	−0.10 ± 0.94	−0.29 ± 0.66	−0.11 ± 0.79
February	+1.35 ± 0.96	+0.69 ± 0.87	+0.72 ± 0.72
March	−1.18 ± 1.04	+0.79 ± 0.80	−0.34 ± 0.72
April	+0.39 ± 0.74	+0.09 ± 0.55	+0.54 ± 0.67
May	−0.33 ± 0.54	−0.08 ± 0.48	−0.07 ± 0.45
June	−0.30 ± 0.52	−0.35 ± 0.45	−0.32 ± 0.58
July	−0.08 ± 0.52	−0.74 ± 0.40	+0.15 ± 0.45
August	−0.02 ± 0.34	−0.86 ± 0.36	+0.41 ± 0.44
September	+0.14 ± 0.29	−0.24 ± 0.28	+0.04 ± 0.49
October	−0.07 ± 0.35	−0.36 ± 0.42	+0.55 ± 0.48
November	+0.29 ± 0.37	+0.00 ± 0.40	+0.33 ± 0.43
December	−0.35 ± 0.73	+0.16 ± 0.57	−0.21 ± 0.85
Average	−0.02	−0.10	+0.14
QBO	+0.14 ± 0.074	+0.18 ± 0.058	+0.090 ± 0.088
Solar	+1.93 ± 1.82	+3.52 ± 1.40	−0.54 ± 2.45
Yearly calculation:			
Ramp	+0.09 ± 0.23	−0.26 ± 0.19	+0.33 ± 0.31

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Quetta	Cairo
Monthly calculation:		
January	0.25 ± 0.59	− 1.64 ± 1.38
February	0.43 ± 0.82	− 0.30 ± 1.48
March	0.86 ± 1.03	− 0.24 ± 1.18
April	0.92 ± 0.54	+ 0.41 ± 0.66
May	+ 0.08 ± 0.43	+ 0.75 ± 0.79
June	0.46 ± 0.34	− 1.49 ± 0.57
July	+ 0.49 ± 0.42	− 0.59 ± 0.38
August	0.08 ± 0.46	− 0.04 ± 0.23
September	0.13 ± 0.44	− 0.01 ± 0.25
October	0.14 ± 0.50	− 0.07 ± 0.24
November	0.21 ± 0.46	+ 0.81 ± 0.81
December	+ 0.28 ± 0.48	− 0.73 ± 0.51
Average	− 0.22	− 0.26
QBO	0.24 ± 0.08	+ 0.011 ± 0.054
Solar	+ 2.15 ± 1.92	+ 1.34 ± 1.11
Yearly calculation:		
Ramp	− 0.21 ± 0.25	− 0.06 ± 0.19

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Mauna Loa
Monthly calculation:	
January	− 0.85 ± 0.56
February	− 0.56 ± 0.79
March	− 0.81 ± 0.61
April	+ 0.23 ± 0.56
May	− 0.25 ± 0.31
June	− 0.05 ± 0.34
July	+ 0.16 ± 0.31
August	− 0.52 ± 0.27
September	− 0.39 ± 0.23
October	− 0.41 ± 0.29
November	− 0.67 ± 0.45
December	− 0.22 ± 0.52
Average	− 0.36
QBO	+ 0.147 ± 0.059
Solar	+ 1.13 ± 1.56
Yearly calculation:	
Ramp	− 0.36 ± 0.20

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Huancayo	Samoa
Monthly calculation:		
January	−0.24 ± 0.19	1.23 ± 0.44
February	−0.37 ± 0.22	1.21 ± 0.38
March	−0.59 ± 0.24	1.10 ± 0.43
April	−0.38 ± 0.22	0.80 ± 0.36
May	−0.30 ± 0.19	0.91 ± 0.39
June	−0.41 ± 0.23	1.71 ± 0.71
July	−0.31 ± 0.24	1.22 ± 0.61
August	−0.32 ± 0.20	1.13 ± 0.46
September	−0.32 ± 0.19	0.14 ± 0.50
October	−0.10 ± 0.26	0.17 ± 0.54
November	−0.11 ± 0.17	0.65 ± 0.38
December	−0.51 ± 0.19	0.98 ± 0.43
Average	−0.33	0.94
QBO	+0.066 ± 0.028	+0.12 ± 0.06
Solar	+0.90 ± 0.75	0.85 ± 1.40
Yearly calculation:		
Ramp	0.33 ± 0.10	−0.85 ± 0.25

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Aspendale	MacQuarie Isle
Monthly calculation:		
January	−0.80 ± 0.42	+0.25 ± 0.91
February	−1.20 ± 0.38	+0.55 ± 0.79
March	−1.48 ± 0.38	+0.47 ± 0.76
April	−0.80 ± 0.26	+0.50 ± 0.73
May	−1.17 ± 0.38	−1.05 ± 0.69
June	−0.79 ± 0.48	+0.50 ± 0.87
July	−1.10 ± 0.68	−0.63 ± 0.88
August	−1.34 ± 0.71	+0.58 ± 1.15
September	−1.57 ± 0.70	−0.05 ± 1.52
October	−0.80 ± 0.55	+0.17 ± 1.19
November	−1.33 ± 0.44	+1.66 ± 0.94
December	−1.15 ± 0.41	−0.25 ± 0.68
Average	−1.13	+0.22
QBO	−0.26 ± 0.066	−0.25 ± 0.12
Solar	+1.96 ± 1.59	+6.51 ± 3.13
Yearly calculation:		
Ramp	−1.01 ± 0.20	−0.01 ± 0.40

(b) Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Reykjavik	Lerwick	Leningrad
Monthly calculation:			
January	−2.26 ± 1.66	−1.86 ± 0.57	−0.27 ± 0.93
February	−3.24 ± 3.04	−2.12 ± 0.99	−2.69 ± 1.50
March	−0.54 ± 1.72	−1.25 ± 0.63	−2.02 ± 1.07
April	+0.19 ± 1.51	−0.68 ± 0.59	−1.87 ± 0.66
May	−0.22 ± 1.57	−1.21 ± 0.48	−0.88 ± 0.61
June	+1.59 ± 0.91	−0.20 ± 0.38	−0.44 ± 0.44
July	+2.64 ± 1.11	−0.38 ± 0.35	+0.27 ± 0.53
August	+1.88 ± 0.94	−0.32 ± 0.33	+0.32 ± 0.46
September	+0.77 ± 1.31	−0.29 ± 0.41	−0.28 ± 0.40
October	+0.68 ± 0.69	+0.75 ± 0.44	−0.45 ± 0.52
November	+1.18 ± 1.69	+0.50 ± 0.44	−0.38 ± 0.51
December	−2.28 ± 2.04	−1.13 ± 0.36	−1.36 ± 0.73
Average	+0.03	−0.68	−0.84
QBO	−0.30 ± 0.11	−0.28 ± 0.08	−0.09 ± 0.10
Solar	+9.69 ± 2.88	+4.14 ± 2.11	+0.87 ± 2.60
Yearly calculation:			
Ramp	+0.86 ± 0.53	−0.49 ± 0.19	−0.43 ± 0.26

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Churchill	Edmonton	Goose
Monthly calculation:			
January	−1.63 ± 0.71	−3.15 ± 0.94	−1.08 ± 1.01
February	−1.60 ± 0.74	−0.36 ± 0.64	−0.69 ± 0.66
March	−0.36 ± 0.66	−1.38 ± 0.64	−0.64 ± 0.63
April	−0.92 ± 0.61	−0.36 ± 0.56	−1.24 ± 0.74
May	−0.85 ± 0.53	−0.46 ± 0.42	−0.80 ± 0.65
June	+0.22 ± 0.51	+0.18 ± 0.45	+0.09 ± 0.35
July	−0.53 ± 0.33	+0.20 ± 0.33	−0.23 ± 0.37
August	−0.59 ± 0.50	+0.27 ± 0.42	−0.14 ± 0.35
September	−0.05 ± 0.46	+0.41 ± 0.50	−0.27 ± 0.38
October	−1.46 ± 0.39	−0.76 ± 0.38	+0.03 ± 0.27
November	+0.15 ± 0.54	+0.33 ± 0.59	+0.58 ± 0.42
December	−1.89 ± 0.68	−1.35 ± 0.94	−0.20 ± 0.70
Average	−0.79	−0.54	−0.38
QBO	−0.26 ± 0.08	−0.22 ± 0.08	−0.17 ± 0.07
Solar	+4.00 ± 2.10	+2.52 ± 2.06	+5.10 ± 2.01
Yearly calculation:			
Ramp	−0.73 ± 0.17	−0.24 ± 0.18	−0.11 ± 0.17

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986.Model: QS70

Station:	Belsk	Bracknell	Uccle
Monthly calculation:			
January	0.99 ± 0.82	− 1.48 ± 0.88	− 0.63 ± 1.09
February	1.22 ± 0.88	− 2.61 ± 0.84	− 1.72 ± 1.26
March	1.98 ± 0.74	− 1.73 ± 0.84	− 1.21 ± 1.23
April	0.51 ± 0.59	− 0.59 ± 0.86	− 1.65 ± 0.93
May	0.12 ± 0.48	− 0.06 ± 0.45	− 1.23 ± 0.73
June	0.00 ± 0.42	− 1.02 ± 0.46	− 1.53 ± 0.68
July	+ 0.36 ± 0.35	− 0.87 ± 0.36	− 1.55 ± 0.57
August	− 0.18 ± 0.32	− 0.55 ± 0.36	− 0.94 ± 0.44
September	0.42 ± 0.38	− 1.00 ± 0.51	− 2.27 ± 0.69
October	0.17 ± 0.41	− 0.63 ± 0.51	− 1.59 ± 0.78
November	1.06 ± 0.48	− 0.40 ± 0.50	− 2.13 ± 0.86
December	2.00 ± 0.68	+ 0.10 ± 0.55	+ 0.10 ± 0.77
Average	0.69	− 0.90	− 1.36
QBO	0.19 ± 0.08	− 0.28 ± 0.08	− 0.18 ± 0.10
Solar	+ 2.88 ± 2.19	+ 0.95 ± 1.94	+ 2.84 ± 2.41
Yearly calculation:			
Ramp	− 0.35 ± 0.19	− 0.68 ± 0.19	− 1.28 ± 0.26

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Hradec Kralove	Hohenpeissenberg	Caribou
Monthly calculation:			
January	− 1.84 ± 0.97	+ 0.57 ± 0.71	− 0.71 ± 0.96
February	− 2.28 ± 0.97	− 1.79 ± 0.84	− 2.04 ± 0.72
March	− 2.56 ± 0.80	− 0.69 ± 0.75	− 1.75 ± 0.72
April	− 0.61 ± 0.68	− 1.22 ± 0.87	− 0.92 ± 0.67
May	+ 0.14 ± 0.47	+ 0.30 ± 0.50	− 0.77 ± 0.44
June	+ 0.29 ± 0.47	− 0.46 ± 0.33	− 0.04 ± 0.38
July	+ 0.35 ± 0.42	− 0.17 ± 0.28	− 0.41 ± 0.28
August	+ 0.02 ± 0.37	− 0.43 ± 0.28	− 0.16 ± 0.28
September	− 0.38 ± 0.34	− 0.69 ± 0.39	− 0.44 ± 0.36
October	− 0.26 ± 0.46	+ 0.03 ± 0.50	− 0.49 ± 0.34
November	− 0.56 ± 0.48	− 0.18 ± 0.43	− 0.52 ± 0.41
December	− 1.56 ± 0.78	− 0.85 ± 0.56	− 1.44 ± 0.58
Average	− 0.77	− 0.46	− 0.81
QBO	− 0.08 ± 0.09	− 0.29 ± 0.07	− 0.12 ± 0.07
Solar	+ 1.67 ± 2.48	− 0.19 ± 1.80	+ 5.12 ± 2.07
Yearly calculation:			
Ramp	− 0.29 ± 0.22	− 0.36 ± 0.15	− 0.48 ± 0.18

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Bismarck	Arosa	Toronto
Monthly calculation:			
January	−1.24 ± 0.55	−0.12 ± 0.59	+0.31 ± 0.85
February	−1.06 ± 0.58	−0.88 ± 0.85	−1.30 ± 0.66
March	−1.43 ± 0.56	−1.49 ± 0.82	−1.28 ± 0.79
April	−0.71 ± 0.55	−0.83 ± 0.59	−0.18 ± 0.61
May	−0.81 ± 0.49	−0.21 ± 0.39	−1.32 ± 0.59
June	−0.72 ± 0.39	−0.73 ± 0.30	+0.05 ± 0.34
July	−0.46 ± 0.31	−0.46 ± 0.25	−0.70 ± 0.28
August	−0.19 ± 0.35	−0.64 ± 0.26	−0.28 ± 0.22
September	+0.13 ± 0.31	−0.87 ± 0.34	−0.18 ± 0.33
October	−0.28 ± 0.44	−0.04 ± 0.39	−0.50 ± 0.40
November	−0.49 ± 0.62	−0.29 ± 0.38	−0.60 ± 0.35
December	−0.87 ± 0.59	−1.35 ± 0.43	−1.00 ± 0.59
Average	−0.68	−0.66	−0.58
QBO	−0.18 ± 0.076	−0.11 ± 0.06	−0.10 ± 0.07
Solar	+4.14 ± 2.02	+1.85 ± 1.51	−0.26 ± 1.99
Yearly calculation:			
Ramp	−0.51 ± 0.17	−0.60 ± 0.12	−0.45 ± 0.17

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Sapporo	Rome	Boulder
Monthly calculation:			
January	+0.13 ± 0.65	−0.97 ± 0.56	−0.57 ± 0.49
February	+0.22 ± 0.62	−0.02 ± 0.72	−1.28 ± 0.60
March	−1.40 ± 0.71	−0.89 ± 0.63	−1.14 ± 0.64
April	−0.06 ± 0.51	−0.42 ± 0.52	−1.12 ± 0.60
May	+0.21 ± 0.38	+0.25 ± 0.47	−0.70 ± 0.39
June	+0.05 ± 0.42	+0.14 ± 0.33	−1.39 ± 0.34
July	+0.04 ± 0.41	−0.18 ± 0.28	−0.77 ± 0.21
August	−0.31 ± 0.36	+0.19 ± 0.30	−0.98 ± 0.25
September	+0.40 ± 0.29	−0.23 ± 0.31	−0.90 ± 0.23
October	+0.04 ± 0.38	+0.18 ± 0.29	−0.76 ± 0.35
November	+0.45 ± 0.38	−0.27 ± 0.31	−0.41 ± 0.34
December	−0.67 ± 0.54	−0.93 ± 0.51	−0.86 ± 0.46
Average	−0.075	−0.26	−0.91
QBO	+0.00 ± 0.08	−0.07 ± 0.07	−0.04 ± 0.06
Solar	+4.66 ± 2.12	+2.76 ± 1.94	+0.27 ± 1.59
Yearly calculation:			
Ramp	+0.10 ± 0.17	−0.12 ± 0.16	−0.87 ± 0.13

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Cagliari	Wallops Is.	Nashville
Monthly calculation:			
January	−0.92 ± 0.52	+1.03 ± 1.03	−0.19 ± 0.39
February	−0.31 ± 0.74	−0.63 ± 0.94	−1.19 ± 0.59
March	−0.38 ± 0.54	−1.43 ± 0.94	−1.44 ± 0.69
April	−0.41 ± 0.55	−0.03 ± 0.70	−0.13 ± 0.68
May	−0.34 ± 0.49	−0.54 ± 0.62	−0.86 ± 0.33
June	−1.03 ± 0.31	−0.76 ± 0.51	−0.92 ± 0.28
July	−0.26 ± 0.29	−0.23 ± 0.24	−1.16 ± 0.31
August	−0.28 ± 0.28	−0.02 ± 0.23	−1.14 ± 0.32
September	−0.53 ± 0.37	−0.07 ± 0.27	−0.71 ± 0.25
October	−0.41 ± 0.29	−0.44 ± 0.44	−0.53 ± 0.30
November	+0.22 ± 0.34	−0.41 ± 0.51	−0.89 ± 0.38
December	−0.95 ± 0.43	−0.16 ± 0.61	−0.13 ± 0.43
Average	−0.47	−0.31	−0.77
QBO	+0.027 ± 0.091	+0.082 ± 0.075	+0.044 ± 0.075
Solar	+5.11 ± 2.42	+0.16 ± 1.62	+3.65 ± 1.85
Yearly calculation:			
Ramp	−0.38 ± 0.20	−0.18 ± 0.17	−0.78 ± 0.16

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Tateno	Srinigar	Kagoshima
Monthly calculation:			
January	−0.21 ± 0.63	−0.26 ± 0.44	+0.05 ± 0.53
February	+0.96 ± 0.64	+0.64 ± 0.58	+0.74 ± 0.48
March	−0.93 ± 0.68	+0.64 ± 0.52	−0.25 ± 0.47
April	+0.18 ± 0.48	+0.01 ± 0.36	+0.48 ± 0.43
May	−0.27 ± 0.35	−0.01 ± 0.32	+0.06 ± 0.29
June	−0.33 ± 0.34	−0.15 ± 0.29	−0.05 ± 0.37
July	−0.12 ± 0.34	−0.38 ± 0.25	+0.34 ± 0.29
August	−0.03 ± 0.22	−0.47 ± 0.23	+0.41 ± 0.28
September	+0.17 ± 0.19	−0.08 ± 0.18	+0.25 ± 0.32
October	−0.18 ± 0.23	−0.29 ± 0.27	+0.37 ± 0.31
November	+0.28 ± 0.24	−0.15 ± 0.25	+0.50 ± 0.28
December	−0.20 ± 0.47	+0.18 ± 0.36	+0.17 ± 0.53
Average	−0.057	−0.027	+0.26
QBO	+0.142 ± 0.074	+0.182 ± 0.058	+0.086 ± 0.086
Solar	+1.99 ± 1.82	+3.32 ± 1.41	−0.21 ± 2.39
Yearly calculation:			
Ramp	+0.72 ± 0.14	−0.15 ± 0.12	+0.35 ± 0.19

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Quetta	Cairo
Monthly calculation:		
January	−0.13 ± 0.46	−1.68 ± 1.39
February	−0.25 ± 0.65	−0.35 ± 1.49
March	−0.27 ± 0.81	−0.27 ± 1.19
April	−0.51 ± 0.43	+0.40 ± 0.66
May	+0.11 ± 0.33	+0.74 ± 0.79
June	−0.29 ± 0.27	−1.49 ± 0.57
July	+0.39 ± 0.33	−0.59 ± 0.38
August	−0.16 ± 0.36	−0.04 ± 0.23
September	−0.34 ± 0.33	+0.01 ± 0.25
October	−0.37 ± 0.37	+0.07 ± 0.24
November	−0.27 ± 0.34	+0.79 ± 0.81
December	−0.27 ± 0.34	−0.75 ± 0.51
Average	−0.20	−0.26
QBO	+0.242 ± 0.078	+0.011 ± 0.054
Solar	+2.04 ± 1.92	+1.34 ± 1.11
Yearly calculation:		
Ramp	−0.18 ± 0.19	−0.06 ± 0.18

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Mauna Loa
Monthly calculation:	
January	−0.53 ± 0.38
February	−0.34 ± 0.53
March	−0.39 ± 0.40
April	+0.06 ± 0.37
May	−0.03 ± 0.20
June	+0.02 ± 0.22
July	+0.12 ± 0.20
August	−0.38 ± 0.18
September	−0.34 ± 0.15
October	−0.28 ± 0.19
November	−0.40 ± 0.29
December	−0.19 ± 0.34
Average	−0.22
QBO	+0.147 ± 0.059
Solar	+1.01 ± 1.57
Yearly calculation:	
Ramp	−0.24 ± 0.13

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Huancayo
Monthly calculation:	
January	−0.10 ± 0.13
February	−0.19 ± 0.15
March	−0.39 ± 0.16
April	−0.24 ± 0.15
May	−0.13 ± 0.13
June	−0.17 ± 0.15
July	−0.15 ± 0.15
August	−0.24 ± 0.13
September	−0.22 ± 0.12
October	−0.08 ± 0.17
November	−0.02 ± 0.11
December	−0.31 ± 0.12
Average	−0.19
QBO	+0.066 ± 0.029
Solar	+0.80 ± 0.77
Yearly calculation:	
Ramp	−0.18 ± 0.065

Not using data prior to 1/65
Coefficients for individual stations
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Aspendale	MacQuarie Isle
Monthly calculation:		
January	−0.48 ± 0.29	+0.27 ± 0.62
February	−0.70 ± 0.27	+0.37 ± 0.52
March	−0.74 ± 0.26	+0.15 ± 0.50
April	−0.39 ± 0.18	−0.02 ± 0.48
May	−0.69 ± 0.26	−0.27 ± 0.45
June	−0.30 ± 0.33	+0.40 ± 0.57
July	−0.61 ± 0.46	−0.10 ± 0.58
August	−0.60 ± 0.49	+0.81 ± 0.76
September	−0.92 ± 0.48	−0.35 ± 1.00
October	−0.26 ± 0.38	+0.07 ± 0.78
November	−0.75 ± 0.30	+0.99 ± 0.62
December	−0.83 ± 0.28	−0.20 ± 0.45
Average	−0.61	+0.18
QBO	−0.24 ± 0.072	−0.26 ± 0.12
Solar	+1.51 ± 1.80	+6.65 ± 3.11
Yearly calculation:		
Ramp	−0.57 ± 0.15	−0.12 ± 0.25

(c) Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Reykjavik	Lerwick	Leningrad
Monthly calculation:			
January	No Data	−0.85 ± 0.54	No Data
February		−1.71 ± 0.97	
March		−0.71 ± 0.61	
April		−0.02 ± 0.57	
May		−0.43 ± 0.47	
June		+0.24 ± 0.37	
July		−0.11 ± 0.34	
August		−0.18 ± 0.32	
September		+0.41 ± 0.40	
October		+1.26 ± 0.43	
November		+0.81 ± 0.43	
December		−0.24 ± 0.35	
Average		−0.13	
QBO		−0.24 ± 0.08	
Solar		−1.66 ± 1.94	
Yearly calculation:			
Ramp		+0.02 ± 0.20	

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Churchill	Edmonton	Goose
Monthly calculation:			
January	No Data	−1.45 ± 0.83	−1.07 ± 0.93
February		−0.81 ± 0.59	−0.93 ± 0.61
March		−1.47 ± 0.58	−0.98 ± 0.58
April		−0.62 ± 0.51	−1.36 ± 0.69
May		−0.56 ± 0.39	−0.74 ± 0.60
June		+0.30 ± 0.41	−0.11 ± 0.33
July		+0.52 ± 0.34	−0.01 ± 0.34
August		+0.23 ± 0.38	−0.02 ± 0.32
September		+0.34 ± 0.45	−0.27 ± 0.36
October		−0.31 ± 0.35	+0.01 ± 0.25
November		+0.72 ± 0.54	+0.62 ± 0.39
December		−0.19 ± 0.84	−0.37 ± 0.65
Average		−0.28	0.44
QBO		−0.12 ± 0.08	−0.15 ± 0.07
Solar		+1.42 ± 1.93	+4.65 ± 1.91
Yearly calculation:			
Ramp		−0.06 ± 0.19	−0.13 ± 0.16

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Belsk	Bracknell	Uccle
Monthly calculation:			
January	−0.51 ± 0.77	No Data	No Data
February	−1.22 ± 0.83		
March	−1.75 ± 0.70		
April	−0.39 ± 0.56		
May	−0.09 ± 0.46		
June	+0.03 ± 0.40		
July	+0.43 ± 0.34		
August	−0.22 ± 0.30		
September	−0.33 ± 0.36		
October	−0.17 ± 0.39		
November	−0.78 ± 0.45		
December	−1.76 ± 0.65		
Average	−0.56		
QBO	−0.22 ± 0.08		
Solar	+3.59 ± 2.09		
Yearly calculation:			
Ramp	−0.30 ± .18		

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Hradec Kralove	Hohenpeissenberg	Caribou
Monthly calculation:			
January	No Data	No Data	−0.78 ± 0.86
February			−1.90 ± 0.64
March			−1.76 ± 0.67
April			−0.96 ± 0.62
May			−0.88 ± 0.41
June			−0.16 ± 0.36
July			−0.34 ± 0.26
August			−0.28 ± 0.25
September			−0.39 ± 0.32
October			−0.40 ± 0.31
November			−0.48 ± 0.37
December			−1.63 ± 0.52
Average			−0.83
QBO			−0.11 ± 0.07
Solar			+4.48 ± 1.90
Yearly calculation:			
Ramp	−0.07 ± 0.21		−0.50 ± 0.16

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Bismarck	Arosa	Toronto
Monthly calculation:			
January	−1.10 ± 0.51	−0.33 ± 0.49	−0.05 ± 0.77
February	−0.98 ± 0.54	+0.01 ± 0.73	−0.98 ± 0.58
March	−1.51 ± 0.53	−1.24 ± 0.70	−1.65 ± 0.72
April	−0.72 ± 0.51	−0.56 ± 0.51	−0.65 ± 0.56
May	−0.79 ± 0.46	−0.36 ± 0.34	−0.92 ± 0.54
June	−0.59 ± 0.36	−0.40 ± 0.26	+0.06 ± 0.31
July	−0.41 ± 0.29	−0.34 ± 0.22	−0.74 ± 0.25
August	−0.14 ± 0.32	−0.28 ± 0.23	−0.32 ± 0.20
September	+0.23 ± 0.29	−0.51 ± 0.29	−0.04 ± 0.30
October	−0.09 ± 0.41	−0.03 ± 0.34	−0.51 ± 0.37
November	−0.31 ± 0.58	−0.26 ± 0.33	−0.32 ± 0.32
December	−0.71 ± 0.55	−1.16 ± 0.37	−1.27 ± 0.54
Average	−0.59	−0.46	−0.62
QBO	−0.17 ± 0.07	−0.13 ± 0.05	−0.15 ± 0.06
Solar	+4.93 ± 1.93	+2.42 ± 1.18	−0.19 ± 1.72
Yearly calculation:			
Ramp	−0.42 ± 0.16	−0.42 ± .11	−0.43 ± .13

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Sapporo	Rome	Boulder
Monthly calculation:			
January	−0.22 ± 0.56	−0.70 ± 0.50	−0.53 ± 0.48
February	+0.18 ± 0.54	−0.30 ± 0.63	−1.37 ± 0.59
March	−1.14 ± 0.62	−0.50 ± 0.57	−1.36 ± 0.62
April	+0.40 ± 0.45	−0.34 ± 0.47	−1.21 ± 0.59
May	+0.36 ± 0.34	+0.11 ± 0.43	−0.68 ± 0.38
June	+0.24 ± 0.37	+0.37 ± 0.30	−1.41 ± 0.33
July	+0.19 ± 0.37	+0.28 ± 0.25	−0.64 ± 0.21
August	−0.10 ± 0.32	+0.70 ± 0.27	−1.00 ± 0.24
September	+0.34 ± 0.26	+0.10 ± 0.28	−0.84 ± 0.22
October	+0.56 ± 0.34	+0.24 ± 0.26	−0.68 ± 0.34
November	+0.62 ± 0.33	−0.12 ± 0.28	−0.30 ± 0.33
December	−0.22 ± 0.47	−0.89 ± 0.46	−1.06 ± 0.45
Average	+0.10	−0.09	−0.92
QBO	+0.08 ± 0.07	−0.08 ± 0.07	−0.06 ± 0.06
Solar	+4.54 ± 1.70	+1.26 ± 1.68	+0.88 ± 1.53
Yearly calculation:			
Ramp	+0.26 ± 0.15	+0.16 ± 0.17	−0.83 ± 0.13

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Cagliari	Wallops Is.	Nashville
Monthly calculation:			
January	−0.46 ± 0.53	No Data	−0.17 ± 0.36
February	−0.02 ± 0.66		−1.12 ± 0.55
March	−0.00 ± 0.50		−1.30 ± 0.65
April	−1.14 ± 0.50		+0.06 ± 0.63
May	−0.23 ± 0.45		−0.65 ± 0.31
June	−0.77 ± 0.29		−0.87 ± 0.26
July	+0.26 ± 0.27		−1.10 ± 0.29
August	+0.31 ± 0.26		−1.00 ± 0.30
September	−0.05 ± 0.34		−0.66 ± 0.24
October	+0.03 ± 0.27		−0.53 ± 0.28
November	+0.55 ± 0.31		−0.84 ± 0.35
December	−0.56 ± 0.40		−0.34 ± 0.41
Average	−0.17		−0.71
QBO	−0.01 ± 0.08		−0.02 ± 0.07
Solar	+1.98 ± 2.07		+4.31 ± 1.74
Yearly calculation:			
Ramp	+0.04 ± 0.20		−0.75 ± 0.13

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986.Model: QS70

Station:	Tateno	Srinigar	Kagoshima
Monthly calculation:			
January	−0.50 ± 0.56	−0.19 ± 0.43	−0.56 ± 0.51
February	+0.14 ± 0.57	+0.68 ± 0.59	+0.20 ± 0.46
March	−1.40 ± 0.63	+0.71 ± 0.51	−0.51 ± 0.46
April	−0.24 ± 0.45	+0.12 ± 0.35	+0.40 ± 0.43
May	−0.45 ± 0.32	−0.12 ± 0.31	+0.19 ± 0.29
June	−0.37 ± 0.32	−0.21 ± 0.28	+0.16 ± 0.37
July	−0.01 ± 0.32	−0.46 ± 0.24	0.48 ± 0.29
August	+0.05 ± 0.20	−0.46 ± 0.22	+0.63 ± 0.28
September	+0.22 ± 0.17	−0.07 ± 0.17	+0.62 ± 0.31
October	+0.07 ± 0.21	−0.11 ± 0.26	+0.21 ± 0.30
November	+0.10 ± 0.22	−0.07 ± 0.25	+0.41 ± 0.27
December	−0.30 ± 0.43	+0.28 ± 0.35	+0.08 ± 0.53
Average	−0.22	+0.01	+0.19
QBO	+0.06 ± 0.07	−0.17 ± 0.06	−0.05 ± 0.08
Solar	+1.27 ± 1.57	+3.58 ± 1.38	+0.24 ± 2.47
Yearly calculation:			
Ramp	+0.10 ± 0.15	−0.13 ± 0.12	+0.42 ± 0.20

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Mauna Loa
Monthly calculation:	
January	−0.62 ± 0.37
February	−0.56 ± 0.52
March	−0.39 ± 0.39
April	+0.07 ± 0.36
May	−0.02 ± 0.20
June	+0.05 ± 0.22
July	+0.12 ± 0.20
August	−0.31 ± 0.18
September	−0.29 ± 0.15
October	−0.20 ± 0.18
November	−0.37 ± 0.29
December	−0.20 ± 0.33
Average	−0.23
QBO	+0.13 ± 0.06
Solar	+1.69 ± 1.55
Yearly calculation:	
Ramp	−0.19 ± 0.13

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Huancayo
Monthly calculation:	
January	−0.12 ± 0.12
February	−0.19 ± 0.15
March	−0.37 ± 0.15
April	−0.23 ± 0.14
May	−0.12 ± 0.13
June	−0.13 ± 0.16
July	−0.07 ± 0.15
August	−0.15 ± 0.13
September	−0.22 ± 0.12
October	−0.04 ± 0.17
November	−0.00 ± 0.11
December	−0.29 ± 0.12
Average	−0.16
QBO	+0.05 ± 0.03
Solar	+1.12 ± 0.78
Yearly calculation:	
Ramp	−0.16 ± 0.07

(d) Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QS70

Station:	Aspendale	MacQuarie Isle
Monthly calculation:		
January	−0.53 ± 0.26	0.15 ± 0.59
February	−0.77 ± 0.24	0.32 ± 0.50
March	−0.64 ± 0.24	−0.09 ± 0.48
April	−0.20 ± 0.16	−0.28 ± 0.46
May	−0.60 ± 0.24	−0.28 ± 0.44
June	−0.49 ± 0.31	0.38 ± 0.55
July	−0.67 ± 0.43	0.06 ± 0.56
August	−0.67 ± 0.45	0.50 ± 0.73
September	−0.90 ± 0.44	−0.49 ± 0.96
October	−0.32 ± 0.35	0.15 ± 0.75
November	−0.50 ± 0.28	0.48 ± 0.59
December	−0.75 ± 0.26	−0.26 ± 0.43
Average	−0.59	+0.05
QBO	−0.22 ± 0.06	−0.19 ± 0.12
Solar	−0.30 ± 1.50	−4.97 ± 3.05
Yearly calculation:		
Ramp	−0.45 ± 0.14	−0.02 ± 0.25

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Reykjavik	Lerwick	Leningrad
Monthly calculation:	No Data		No Data
January		−1.44 ± 0.90	
February		−2.83 ± 1.62	
March		−1.28 ± 1.03	
April		−0.43 ± 0.96	
May		−1.08 ± 0.79	
June		+0.63 ± 0.63	
July		−0.46 ± 0.57	
August		−0.29 ± 0.54	
September		+0.31 ± 0.67	
October		+1.46 ± 0.72	
November		+1.18 ± 0.72	
December		−0.57 ± 0.61	
Average		−0.45	
QBO		−0.24 ± 0.08	
Solar		−1.74 ± 1.94	
Yearly calculation:			
Ramp		−0.19 ± 0.33	

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Churchill	Edmonton	Goose
Monthly calculation:			
January		-2.64 ± 1.38	-0.82 ± 1.47
February		-1.07 ± 0.97	-1.43 ± 0.98
March		-2.58 ± 0.96	-1.23 ± 0.93
April		-1.00 ± 0.85	-2.08 ± 1.10
May		-1.28 ± 0.64	-1.20 ± 0.97
June		$+0.18 \pm 0.68$	-0.08 ± 0.53
July		$+0.59 \pm 0.50$	$+0.01 \pm 0.55$
August		$+0.27 \pm 0.63$	-0.16 ± 0.52
September		$+0.93 \pm 0.75$	-0.80 ± 0.57
October	No Data	-0.57 ± 0.58	$+0.01 \pm 0.40$
November		$+0.84 \pm 0.89$	$+1.07 \pm 0.66$
December		-0.94 ± 1.47	$+0.30 \pm 1.09$
Average		-0.61	-0.53
QBO		-0.12 ± 0.08	-0.15 ± 0.07
Solar		$+1.46 \pm 1.91$	$+4.59 \pm 1.92$
Yearly calculation:			
Ramp		-0.24 ± 0.32	-0.19 ± 0.26

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Belsk	Bracknell	Uccle
Monthly calculation:			
January	-0.22 ± 1.20		
February	-1.32 ± 1.32		
March	-2.23 ± 1.11		
April	-1.09 ± 0.89		
May	-0.44 ± 0.72		
June	-0.16 ± 0.63		
July	$+0.28 \pm 0.53$		
August	-0.46 ± 0.48		
September	-0.62 ± 0.57		
October	-0.60 ± 0.61	No Data	No Data
November	-1.64 ± 0.72		
December	-2.14 ± 1.03		
Average	-0.89		
QBO	-0.22 ± 0.08		
Solar	$+3.65 \pm 2.08$		
Yearly calculation:	-0.67 ± 0.28		
Ramp	+		

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Hradec Kralove	Hohenpeissenberg	Caribou
Monthly calculation:			
January	No Data	No Data	-0.97 ± 1.37
February			-2.70 ± 1.03
March			-2.39 ± 1.07
April			-1.42 ± 0.99
May			-1.19 ± 0.65
June			-0.24 ± 0.57
July			-0.46 ± 0.41
August			-0.09 ± 0.41
September			-0.75 ± 0.52
October			-0.80 ± 0.50
November			-0.54 ± 0.60
December			-2.30 ± 0.84
Average			-1.15
QBO			-0.12 ± 0.07
Solar			$+4.76 \pm 1.98$
Yearly calculation:			
Ramp	0.46 ± 0.35		-0.68 ± 0.27

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Bismarck	Arosa	Toronto
Monthly calculation:			
January	-1.85 ± 0.79	-0.07 ± 0.81	$+0.13 \pm 1.23$
February	-1.01 ± 0.85	$+0.04 \pm 1.21$	-1.51 ± 0.94
March	-2.27 ± 0.83	-1.65 ± 1.17	-2.30 ± 1.17
April	-1.40 ± 0.81	-1.34 ± 0.84	-1.04 ± 0.90
May	-1.46 ± 0.73	-0.72 ± 0.56	-1.81 ± 0.88
June	-1.01 ± 0.57	-1.00 ± 0.43	-0.33 ± 0.50
July	-0.70 ± 0.46	-0.77 ± 0.36	-1.36 ± 0.41
August	-0.48 ± 0.51	-0.62 ± 0.37	-0.53 ± 0.33
September	$+0.32 \pm 0.46$	-0.99 ± 0.48	-0.36 ± 0.48
October	-0.16 ± 0.65	-0.42 ± 0.56	-1.12 ± 0.59
November	-0.58 ± 0.92	-0.47 ± 0.54	-0.72 ± 0.52
December	-0.97 ± 0.87	-1.55 ± 0.61	-2.08 ± 0.87
Average	-0.96	-0.80	-1.09
QBO	-0.17 ± 0.07	-0.14 ± 0.05	-0.15 ± 0.06
Solar	$+4.97 \pm 1.93$	$+2.56 \pm 1.14$	-0.11 ± 1.67
Yearly calculation:			
Ramp	-0.73 ± 0.27	-0.85 ± 0.19	-0.89 ± 0.22

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Sapporo	Rome	Boulder
Monthly calculation:			
January	+0.15 ± 0.92	−0.77 ± 0.83	−0.97 ± 0.73
February	+0.48 ± 0.90	−0.37 ± 1.06	−1.80 ± 0.91
March	−1.68 ± 1.03	−0.51 ± 0.96	−2.02 ± 0.97
April	+0.11 ± 0.75	−0.91 ± 0.80	−2.12 ± 0.92
May	+0.51 ± 0.56	+0.05 ± 0.72	−1.15 ± 0.60
June	+0.62 ± 0.61	+0.16 ± 0.51	−2.02 ± 0.51
July	+0.56 ± 0.60	+0.12 ± 0.43	−1.15 ± 0.32
August	−0.40 ± 0.52	+0.70 ± 0.46	−1.52 ± 0.38
September	+0.64 ± 0.43	−0.02 ± 0.47	−1.31 ± 0.35
October	+0.93 ± 0.56	+0.04 ± 0.44	−1.07 ± 0.53
November	+0.95 ± 0.55	−0.23 ± 0.47	−0.49 ± 0.52
December	−0.29 ± 0.79	−0.88 ± 0.78	−1.29 ± 0.71
Average	+0.22	−0.22	−1.41
QBO	+0.09 ± 0.07	−0.08 ± 0.07	−0.06 ± 0.06
Solar	+4.45 ± 1.69	+1.03 ± 1.70	+0.98 ± 1.52
Yearly calculation:			
Ramp	+0.46 ± 0.26	−0.01 ± 0.28	−1.34 ± 0.20

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Cagliari	Wallops Is.	Nashville
Monthly calculation:			
January	−0.59 ± 0.86		−0.22 ± 0.57
February	−0.29 ± 1.09		−1.23 ± 0.87
March	−0.24 ± 0.83		−1.37 ± 1.04
April	−0.54 ± 0.84		+0.12 ± 1.02
May	−0.65 ± 0.75		−1.01 ± 0.50
June	−1.40 ± 0.48		−1.47 ± 0.42
July	+0.32 ± 0.45		−1.67 ± 0.47
August	+0.24 ± 0.43		−1.39 ± 0.48
September	+0.02 ± 0.57	No Data	−0.92 ± 0.38
October	+0.07 ± 0.46		−1.02 ± 0.45
November	+1.09 ± 0.52		−0.97 ± 0.57
December	−0.49 ± 0.66		−0.30 ± 0.65
Average	−0.20		−0.94
QBO	+0.02 ± 0.08		+0.02 ± 0.07
Solar	+2.02 ± 2.04		+4.21 ± 1.82
Yearly calculation:			
Ramp	0.00 ± 0.34		−1.10 ± 0.24

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Tateno	Srinigar	Kagoshima
Monthly calculation:			
January	−0.50 ± 0.93	−0.23 ± 0.65	−0.77 ± 0.82
February	+0.51 ± 0.95	+0.71 ± 0.89	+0.21 ± 0.75
March	−1.87 ± 1.05	+0.87 ± 0.80	−0.64 ± 0.75
April	−0.09 ± 0.75	+0.20 ± 0.54	+0.50 ± 0.70
May	−0.58 ± 0.54	−0.19 ± 0.48	+0.08 ± 0.47
June	−0.40 ± 0.53	−0.42 ± 0.45	−0.07 ± 0.60
July	+0.04 ± 0.53	−0.84 ± 0.40	+0.37 ± 0.47
August	+0.08 ± 0.34	−0.86 ± 0.36	+0.71 ± 0.46
September	+0.25 ± 0.29	−0.23 ± 0.28	+0.50 ± 0.51
October	+0.18 ± 0.35	−0.19 ± 0.42	+0.40 ± 0.50
November	+0.12 ± 0.37	+0.07 ± 0.40	+0.29 ± 0.45
December	−0.49 ± 0.73	+0.27 ± 0.57	−0.27 ± 0.88
Average	−0.23	−0.07	+0.11
QBO	+0.06 ± 0.07	+0.17 ± 0.06	+0.05 ± 0.08
Solar	+1.27 ± 1.57	+3.73 ± 1.36	+0.41 ± 2.53
Yearly calculation:			
Ramp	+0.15 ± 0.25	−0.25 ± 0.20	+0.44 ± 0.33

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Mauna Loa
Monthly calculation:	
January	−1.01 ± 0.55
February	−0.83 ± 0.77
March	−0.88 ± 0.59
April	+0.17 ± 0.55
May	−0.34 ± 0.31
June	−0.13 ± 0.33
July	+0.06 ± 0.30
August	−0.56 ± 0.27
September	−0.45 ± 0.23
October	−0.43 ± 0.28
November	−0.73 ± 0.43
December	−0.31 ± 0.50
Average	−0.43
QBO	+0.16 ± 0.06
Nuclear	−2.28 ± 1.16
Solar	+0.60 ± 1.57
Yearly calculation:	−0.42 ± 0.20

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Huancayo
Monthly calculation:	
January	−0.26+0.19
February	−0.38+0.22
March	−0.58+0.24
April	−0.37+0.22
May	−0.29+0.20
June	−0.42+0.26
July	−0.25+0.25
August	−0.25+0.21
September	−0.32+0.19
October	−0.07+0.27
November	−0.08+0.17
December	−0.50+0.19
Average	−0.31
QBO	+0.05+0.03
Solar	+1.22±0.76
Yearly calculation:	−0.31±0.10

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QS76

Station:	Aspendale	MacQuarie Isle
Monthly calculation:		
January	−0.88+0.42	+0.15+0.90
February	−1.35+0.38	+0.52+0.78
March	−1.39+0.39	+0.20+0.76
April	−0.57+0.26	+0.20+0.73
May	−1.12+0.39	−1.03+0.68
June	−0.99+0.50	+0.52+0.86
July	−1.21+0.69	−0.43+0.87
August	−1.41+0.73	+0.33+1.15
September	−1.62+0.72	−0.22+1.51
October	−0.83+0.56	+0.27+1.18
November	−1.08+0.45	+1.15+0.93
December	−1.17+0.41	−0.49+0.68
Average	−1.14	+0.10
QBO	−0.23+0.06	−0.19+0.12
Solar	+0.01+1.39	+4.96±3.07
Yearly calculation:	−0.98±0.22	−0.16±0.40

(e) Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Reykjavik	Lerwick	Leningrad
Monthly calculation:			
January		−1.09 + 0.54	
February		−1.94 + 0.95	
March		−0.92 + 0.61	
April		−0.22 + 0.57	
May		−0.60 + 0.47	
June		+0.10 + 0.37	
July		−0.24 + 0.34	
August		−0.35 + 0.32	
September		+0.23 + 0.40	
October	No Data	+1.04 + 0.43	No Data
November		+0.55 + 0.43	
December		−0.50 + 0.36	
Average		−0.33	
QBO		−0.28 + 0.08	
Solar		−3.57 ± 2.00	
Nuclear		−0.71 + 0.27	
Yearly calculation:		−0.18 ± 0.20	

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Churchill	Edmonton	Goose
Monthly calculation:			
January		−1.64 + 0.83	−1.08 + 0.93
February		−1.00 + 0.59	−0.94 + 0.62
March		−1.65 + 0.58	−1.00 + 0.59
April		−0.79 + 0.51	−1.38 + 0.69
May		−0.71 + 0.39	−0.75 + 0.61
June		+0.17 + 0.41	−0.12 + 0.33
July		+0.41 + 0.30	−0.02 + 0.34
August		+0.09 + 0.38	−0.04 + 0.33
September		+0.18 + 0.45	−0.29 + 0.36
October	No Data	−0.50 + 0.35	−0.01 + 0.26
November		+0.50 + 0.54	+0.61 + 0.40
December		−0.39 + 0.84	−0.39 + 0.65
Average		−0.44	−0.46
QBO		−0.16 + 0.08	−0.15 + 0.07
Nuclear		−0.62 + 0.27	−0.04 + 0.21
Solar		−0.20 ± 1.95	+4.54 ± 1.98
Yearly calculation:		−0.20 ± 0.19	−0.14 ± 0.17

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Belsk	Bracknell	Uccle
Monthly calculation:			
January	−0.58+0.77		
February	−1.32+0.84		
March	−1.85+0.71		
April	−0.48+0.57		
May	−0.17+0.47		
June	−0.04+0.41		
July	+0.37+0.34		
August	−0.27+0.31		
September	−0.39+0.36		
October	−0.23+0.39	No Data	No Data
November	−0.85+0.46		
December	−1.83+0.65		
Average	−0.64		
QBO	−0.22+0.08		
Nuclear	−0.37+0.43		
Solar	+3.02±2.18		
Yearly calculation:	−0.35±0.19		

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Hradec Kralove	Hohenpeissenberg	Caribou
Monthly calculation:			
January			−0.76+0.86
February			−1.87+0.65
March			−1.74+0.67
April			−0.93+0.62
May			−0.86+0.41
June			−0.15+0.36
July			−0.33+0.26
August			−0.27+0.26
September			−0.37+0.33
October	No Data	No Data	−0.37+0.32
November			−0.45+0.38
December			−1.60+0.53
Average			−0.81
QBO			−0.11+0.07
Nuclear			+0.09+0.32
Solar			+5.05±1.98
Yearly calculation:	−0.20+.023		−0.47±0.18

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Bismarck	Arosa	Toronto
Monthly calculation:			
January	−1.25 ± 0.51	−0.49 ± 0.49	+0.06 ± 0.77
February	−1.20 ± 0.54	−0.14 ± 0.73	−0.88 ± 0.59
March	−1.73 ± 0.53	−1.38 ± 0.70	−1.55 ± 0.72
April	−0.92 ± 0.52	−0.69 ± 0.50	−0.56 ± 0.56
May	−0.96 ± 0.46	−0.48 ± 0.34	−0.84 ± 0.54
June	−0.73 ± 0.36	−0.51 ± 0.26	+0.12 ± 0.31
July	−0.53 ± 0.29	−0.44 ± 0.22	−0.69 ± 0.26
August	−0.25 ± 0.32	−0.39 ± 0.23	−0.25 ± 0.21
September	+0.12 ± 0.30	−0.62 ± 0.29	+0.03 ± 0.30
October	−0.22 ± 0.41	−0.16 ± 0.34	−0.43 ± 0.37
November	−0.46 ± 0.58	−0.42 ± 0.33	−0.22 ± 0.33
December	−0.86 ± 0.55	−1.32 ± 0.37	−1.16 ± 0.54
Average	−0.75	−0.59	−0.53
QBO	−0.18 ± 0.07	−0.15 ± 0.05	−0.13 ± 0.06
Nuclear	−0.80 ± 0.38	−0.60 ± 0.25	+0.38 ± 0.29
Solar	+3.69 ± 1.98	+1.25 ± 1.24	+0.59 ± 1.79
Yearly calculation:	−0.54 ± 0.18	−0.53 ± 0.12	−0.35 ± 0.14

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Sapporo	Rome	Boulder
Monthly calculation:			
January	−0.26 ± 0.57	−0.85 ± 0.50	−0.66 ± 0.48
February	+0.13 ± 0.55	−0.44 ± 0.63	−1.55 ± 0.59
March	−1.19 ± 0.63	−0.64 ± 0.57	−1.54 ± 0.63
April	+0.36 ± 0.43	−0.47 ± 0.47	−1.38 ± 0.59
May	+0.32 ± 0.34	+0.00 ± 0.43	−0.82 ± 0.39
June	+0.21 ± 0.37	+0.28 ± 0.30	−1.52 ± 0.33
July	+0.16 ± 0.37	+0.19 ± 0.26	−0.74 ± 0.21
August	−0.13 ± 0.32	+0.61 ± 0.28	−1.09 ± 0.25
September	+0.30 ± 0.26	−0.01 ± 0.28	−0.93 ± 0.23
October	+0.52 ± 0.35	+0.12 ± 0.27	−0.78 ± 0.35
November	+0.58 ± 0.34	−0.26 ± 0.29	−0.41 ± 0.34
December	−0.27 ± 0.48	−1.04 ± 0.46	−1.18 ± 0.46
Average	−0.06	−0.21	−1.05
QBO	+0.08 ± 0.07	−0.10 ± 0.07	−0.05 ± 0.06
Nuclear	−0.18 ± 0.31	−0.55 ± 0.33	−1.14 ± 0.67
Solar	+4.16 ± 1.82	+0.17 ± 1.75	−0.06 ± 1.61
Yearly calculation:	+0.22 ± 0.16	+0.06 ± 0.17	−0.92 ± 0.14

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Cagliari	Wallops Is.	Nashville
Monthly calculation:			
January	−0.53 ± 0.54	No Data	−0.25 ± 0.37
February	−0.10 ± 0.67		−1.20 ± 0.56
March	−0.07 ± 0.51		−1.40 ± 0.65
April	−0.21 ± 0.52		−0.03 ± 0.64
May	−0.29 ± 0.46		−0.74 ± 0.32
June	−0.82 ± 0.30		−0.95 ± 0.27
July	+0.21 ± 0.28		−1.16 ± 0.30
August	+0.27 ± 0.27		−1.06 ± 0.30
September	−0.10 ± 0.35		−0.71 ± 0.24
October	−0.02 ± 0.29		−0.60 ± 0.29
November	+0.49 ± 0.33		−0.91 ± 0.36
December	−0.63 ± 0.41		−0.42 ± 0.41
Average	−0.15		−0.78
QBO	−0.00 ± 0.08		+0.01 ± 0.07
Nuclear	−0.38 ± 0.63		−0.54 ± 0.49
Solar	+1.46 ± 2.24		+3.68 ± 1.82
Yearly calculation:	0.00 ± 0.21	.	−0.81 ± 0.14

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Mauna Loa
Monthly calculation:	
January	−0.69 ± 0.36
February	−0.62 ± 0.50
March	−0.48 ± 0.38
April	−0.02 ± 0.35
May	−0.14 ± 0.20
June	−0.09 ± 0.22
July	−0.00 ± 0.20
August	−0.44 ± 0.18
September	−0.41 ± 0.15
October	−0.30 ± 0.18
November	−0.47 ± 0.28
December	−0.29 ± 0.32
Average	−0.33
QBO	+0.16 ± 0.06
Nuclear	−2.73 ± 1.21
Solar	+0.33 ± 1.57
Yearly calculation:	−0.31 ± 0.13

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1970 through 1986. Model: QNS70

Station:	Tateno	Srinigar	Kagoshima
Monthly calculation:			
January	−0.37 ± 0.56	−0.25 ± 0.43	−0.46 ± 0.52
February	+0.27 ± 0.57	+0.62 ± 0.59	+0.30 ± 0.47
March	−1.27 ± 0.63	+0.63 ± 0.52	−0.40 ± 0.48
April	−0.12 ± 0.45	+0.04 ± 0.36	+0.50 ± 0.44
May	−0.35 ± 0.33	−0.19 ± 0.32	+0.27 ± 0.30
June	−0.29 ± 0.32	−0.27 ± 0.29	+0.23 ± 0.37
July	+0.06 ± 0.32	−0.51 ± 0.25	+0.54 ± 0.29
August	+0.12 ± 0.21	−0.51 ± 0.23	+0.68 ± 0.28
September	+0.30 ± 0.18	−0.11 ± 0.18	+0.67 ± 0.31
October	+0.16 ± 0.21	−0.16 ± 0.27	+0.28 ± 0.31
November	+0.20 ± 0.23	−0.12 ± 0.25	+0.49 ± 0.29
December	−0.17 ± 0.44	+0.22 ± 0.36	+0.18 ± 0.54
Average	−0.12	−0.05	+0.27
QBO	+0.07 ± 0.07	+0.18 ± 0.06	+0.06 ± 0.08
Nuclear	+0.65 ± 0.46	−0.72 ± 0.75	+0.46 ± 0.56
Solar	+2.23 ± 1.64	+3.13 ± 1.45	+0.96 ± 2.55
Yearly calculation:	+0.18 ± 0.15	−0.19 ± 0.13	+0.50 ± 0.21

(f) Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Reykjavik	Lerwick	Leningrad
Monthly calculation:			
January		−1.71 ± 0.89	
February		−3.08 ± 1.59	
March		−1.15 ± 1.01	
April		−0.65 ± 0.94	
May		−1.27 ± 0.77	
June		−0.11 ± 0.62	
July		−0.61 ± 0.57	
August		−0.49 ± 0.53	
September	No Data	+0.09 ± 0.66	No Data
October		+1.19 ± 0.71	
November		+0.88 ± 0.72	
December		−0.87 ± 0.61	
Average		−0.68	
QBO		−0.28 ± 0.08	
Solar		−3.49 ± 1.97	
Nuclear		−0.70 ± 0.25	
Yearly calculation:			
Ramp		−0.43 ± 0.33	

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Churchill	Edmonton	Goose
Monthly calculation:			
January	No Data	−2.75 ± 1.36	−0.82 ± 1.47
February		−1.24 ± 0.96	−1.43 ± 0.99
March		−2.76 ± 0.95	−1.23 ± 0.94
April		−1.17 ± 0.84	−2.08 ± 1.10
May		−1.44 ± 0.64	−1.20 ± 0.97
June		+0.05 ± 0.67	−0.09 ± 0.53
July		+0.47 ± 0.50	+0.01 ± 0.55
August		+0.15 ± 0.62	−0.16 ± 0.52
September		+0.76 ± 0.74	−0.80 ± 0.57
October		−0.79 ± 0.58	+0.01 ± 0.41
November		+0.59 ± 0.89	+1.06 ± 0.66
December		−1.01 ± 1.45	+0.30 ± 1.09
Average		−0.76	−0.54
QBO		−0.17 ± 0.07	−0.15 ± 0.07
Solar		−0.21 ± 1.73	+4.57 ± 2.00
Nuclear		−0.60	−0.01 ± 0.21
Yearly calculation:			
Ramp		−0.41 ± 0.31	−0.20 ± 0.27

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Belsk	Bracknell	Uccle
Monthly calculation:			
January	−0.27 ± 1.20	No Data	No Data
February	−1.40 ± 1.32		
March	−2.31 ± 1.11		
April	−1.16 ± 0.89		
May	−0.50 ± 0.73		
June	−0.22 ± 0.64		
July	+0.23 ± 0.54		
August	−0.51 ± 0.48		
September	−0.66 ± 0.57		
October	−0.65 ± 0.62		
November	−1.69 ± 0.72		
December	−2.19 ± 1.03		
Average	−0.94		
QBO	−0.23 ± 0.08		
Solar	+3.20 ± 2.18		
Nuclear	−0.28 ± 0.41		
Yearly calculation:			
Ramp	−0.72 ± 0.29		

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Hradec Kralove	Hohenpeissenberg	Caribou
Monthly calculation:			
January	No Data	No Data	−0.88 ± 1.37
February			−2.62 ± 1.03
March			−2.31 ± 1.07
April			−1.35 ± 0.99
May			−1.13 ± 0.65
June			−0.19 ± 0.57
July			−0.42 ± 0.41
August			−0.03 ± 0.41
September			−0.68 ± 0.52
October			−0.71 ± 0.51
November			−0.44 ± 0.60
December			−2.21 ± 0.85
Average			−1.08
QBO			−0.10 ± 0.07
Solar			+5.30 ± 2.04
Nuclear			+0.29 ± 0.31
Yearly calculation:			
Ramp	−0.61 ± 0.35		−0.61 ± 0.28

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Bismarck	Arosa	Toronto
Monthly calculation:			
January	−1.95 ± 0.79	−0.21 ± 0.81	+0.26 ± 1.22
February	−1.16 ± 0.85	−0.09 ± 1.21	−1.38 ± 0.94
March	−2.42 ± 0.83	−1.78 ± 1.16	−2.18 ± 1.16
April	−1.54 ± 0.81	−1.46 ± 0.83	−0.93 ± 0.90
May	−1.58 ± 0.73	−0.83 ± 0.56	−1.72 ± 0.87
June	−1.11 ± 0.57	−1.09 ± 0.43	−0.25 ± 0.50
July	−0.78 ± 0.46	−0.86 ± 0.36	−1.30 ± 0.41
August	−0.57 ± 0.51	−0.71 ± 0.37	−0.46 ± 0.33
September	+0.23 ± 0.46	−1.09 ± 0.48	−0.27 ± 0.48
October	−0.25 ± 0.65	−0.54 ± 0.56	−1.01 ± 0.59
November	−0.68 ± 0.91	−0.61 ± 0.54	−0.59 ± 0.53
December	−1.08 ± 0.87	−1.70 ± 0.61	−1.94 ± 0.87
Average	−1.07	−0.91	−0.98
QBO	−0.18 ± 0.07	−0.16 ± 0.05	−0.14 ± 0.06
Solar	+4.09 ± 2.00	+1.71 ± 1.20	+0.77 ± 1.73
Nuclear	−0.54 ± 0.37	−0.47 ± 0.23	+0.42 ± 0.27
Yearly calculation:			
Ramp	−0.82 ± 0.27	−0.96 ± 0.19	−0.79 ± 0.22

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Sapporo	Rome	Boulder
Monthly calculation:			
January	+0.09±0.92	−0.95±0.83	−1.00±0.74
February	+0.41±0.90	−0.55±1.06	−1.84±0.92
March	−1.74±1.03	−0.68±0.96	−2.07±0.98
April	+0.05±0.75	−1.06±0.79	−2.16±0.92
May	+0.46±0.56	−0.09±0.71	−1.19±0.60
June	+0.58±0.61	+0.04±0.51	−2.05±0.52
July	+0.52±0.60	+0.01±0.43	−1.18±0.33
August	−0.44±0.53	+0.58±0.46	−1.55±0.38
September	+0.59±0.43	−0.16±0.47	−1.34±0.35
October	+0.87±0.57	−0.11±0.44	−1.10±0.54
November	+0.87±0.56	−0.42±0.48	−0.52±0.53
December	−0.37±0.79	−1.07±0.78	−1.32±0.71
Average	+0.16	−0.37	−1.44
QBO	+0.08±0.07	−0.10±0.07	−0.06±0.06
Solar	+4.00±1.78	−0.03±1.75	+0.76±1.61
Nuclear	−0.22±0.30	−0.58±0.32	−0.27±0.62
Yearly calculation:			
Ramp	+0.40±0.27	−0.15±0.28	−1.35±0.21

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Cagliari	Wallops Is.	Nashville
Monthly calculation:		No Data	
January	−0.66±0.87		−0.04±0.58
February	−0.36±1.10		−1.24±0.88
March	−0.31±0.84		−1.39±1.04
April	−0.61±0.84		+0.10±1.02
May	−0.70±0.76		−1.02±0.51
June	−1.45±0.49		−1.49±0.43
July	+0.28±0.45		−1.68±0.48
August	+0.20±0.44		−1.40±0.48
September	−0.02±0.58		−0.93±0.38
October	+0.02±0.47		−1.03±0.46
November	+1.03±0.53		−0.98±0.57
December	−0.56±0.67		−0.32±0.66
Average	−0.26		−0.95
QBO	+0.01±0.08		+0.02±0.07
Solar	+1.59±2.18		+4.08±1.92
Nuclear	−0.33±0.60		−0.10±0.49
Yearly calculation:			
Ramp	−0.05±0.35		−1.11±0.25

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Tateno	Srinigar	Kagoshima
Monthly calculation:			
January	−0.37 ± 0.92	−0.27 ± 0.65	−0.73 ± 0.82
February	+0.65 ± 0.94	+0.67 ± 0.89	+0.25 ± 0.76
March	−1.74 ± 1.04	+0.81 ± 0.80	−0.59 ± 0.76
April	+0.03 ± 0.74	+0.14 ± 0.55	+0.53 ± 0.71
May	−0.48 ± 0.54	−0.24 ± 0.49	+0.12 ± 0.48
June	−0.32 ± 0.52	−0.47 ± 0.46	−0.05 ± 0.61
July	+0.11 ± 0.52	−0.87 ± 0.40	+0.39 ± 0.48
August	+0.15 ± 0.34	−0.89 ± 0.37	+0.73 ± 0.46
September	+0.32 ± 0.29	−0.26 ± 0.29	+0.52 ± 0.51
October	+0.27 ± 0.35	−0.22 ± 0.43	+0.43 ± 0.51
November	+0.23 ± 0.37	+0.04 ± 0.40	+0.33 ± 0.46
December	−0.36 ± 0.73	+0.22 ± 0.58	+0.23 ± 0.89
Average	−0.13	−0.11	+0.14
QBO	+0.08 ± 0.066	+0.18 ± 0.06	+0.06 ± 0.08
Solar	+2.02 ± 1.62	+3.39 ± 1.44	+0.68 ± 2.66
Nuclear	+0.58 ± 0.44	−0.53 ± 0.69	+0.17 ± 0.55
Yearly calculation:			
Ramp	+0.23 ± 0.25	−0.29 ± 0.20	+0.48 ± 0.34

Using all data
Coefficients for individual stations.
Dobson Units per year change for 1976 through 1986. Model: QNS76

Station:	Mauna Loa
Monthly calculation:	
January	−1.01 ± 0.55
February	−0.83 ± 0.77
March	−0.88 ± 0.59
April	+0.17 ± 0.55
May	−0.34 ± 0.31
June	−0.13 ± 0.33
July	+0.06 ± 0.30
August	−0.56 ± 0.27
September	−0.45 ± 0.23
October	−0.43 ± 0.28
November	−0.73 ± 0.43
December	−0.31 ± 0.50
Average	−0.43
QBO	+0.16 ± 0.06
Nuclear	−2.28 ± 1.16
Solar	+0.60 ± 1.57
Yearly calculation:	−0.42 ± 0.20

B. (ii) Coefficients from latitudinal band averages prepared from the provisionally revised data (Bojkov, private communication, 1987)

60°–80°North
53°–64°North
40°–52°North
30°–39°North

and M–83 USSR regional averages (Bojkov, 1988a)

European part
South Central Asia
Siberia
Far Eastern Asia.

Dobson Only: Latitudes 60–80 Degrees North

Model **Time Period**	**QS70** **1/65–12/86**	**QS76** **1/65–12/86**
January	-1.60 ± 0.51	-2.09 ± 0.77
February	-2.16 ± 0.90	-3.03 ± 1.38
March	-0.83 ± 0.42	-1.41 ± 0.65
April	-0.45 ± 0.40	-0.59 ± 0.62
May	-0.69 ± 0.25	-0.69 ± 0.39
June	$+0.05 \pm 0.18$	$+0.17 \pm 0.28$
July	-0.15 ± 0.20	$+0.13 \pm 0.32$
August	$+0.02 \pm 0.18$	$+0.29 \pm 0.28$
September	-0.06 ± 0.20	-0.08 ± 0.31
October	-0.11 ± 0.32	-0.36 ± 0.49
November	$+0.23 \pm 0.37$	$+0.18 \pm 0.57$
December	-1.06 ± 0.56	-1.72 ± 0.87
Average	-0.56	-0.77
QBO	-0.20 ± 0.057	-0.20 ± 0.57
Solar	$+4.78 \pm 1.55$	$+4.84 \pm 1.56$
Yearly coefficient	-0.12 ± 0.14	-0.05 ± 0.22

Dobson Only: Latitudes 60–80 Degrees North

Model **Time Period**	**QS70** **1/57–12/86**	**QS76** **1/57–12/86**
January	−0.82 ± 0.51	−1.42 ± .84
February	−1.92 ± 0.91	−3.06 ± 1.53
March	−0.51 ± 0.43	−1.10 ± 0.72
April	−0.08 ± 0.41	−0.21 ± 0.69
May	−0.39 ± 0.26	−0.46 ± 0.44
June	+0.09 ± 0.19	+0.22 ± 0.32
July	+0.09 ± 0.21	+0.36 ± 0.35
August	+0.10 ± 0.19	+0.36 ± 0.31
September	+0.28 ± 0.21	+0.33 ± 0.35
October	+0.60 ± 0.33	+0.53 ± 0.55
November	+1.00 ± 0.38	+1.16 ± 0.63
December	+0.17 ± 0.57	−0.35 ± 0.96
Average	−0.12	−0.30
QBO	−0.12 ± 0.060	−0.11 ± 0.060
Solar	+2.73 ± 1.43	+2.69 ± 1.43
Yearly coefficient	+0.12 ± 0.14	+0.22 ± 0.25

Dobson Only: Latitudes 60–80 Degrees North

Model **Time Period**	**QS70** **1/57–12/86**	**QS76** **1/57–12/86**
January	−0.91 ± 0.51	−1.53 ± 0.84
February	−2.01 ± 0.91	−3.16 ± 1.51
March	−0.58 ± 0.43	−1.19 ± 0.71
April	−0.15 ± 0.41	−0.29 ± 0.68
May	−0.45 ± 0.26	−0.53 ± 0.43
June	+0.04 ± 0.19	+0.16 ± 0.32
July	+0.04 ± 0.21	+0.31 ± 0.35
August	+0.03 ± 0.19	+0.28 ± 0.32
September	+0.21 ± 0.21	+0.24 ± 0.35
October	+0.52 ± 0.33	+0.42 ± 0.55
November	+0.91 ± 0.38	+1.04 ± 0.63
December	+0.08 ± 0.57	−0.46 ± 0.96
Average	−0.19	−0.39
QBO	−0.13 ± .060	−0.13 ± .060
Solar	+2.12 ± 1.47	+2.11 ± 1.45
Nuclear	−0.22 ± 0.17	−0.22 ± .16
Yearly coefficient	+0.05 ± 0.15	+0.15 ± 0.25

Dobson Only: Latitudes 53–64 Degrees North

Model Time Period	QS70 1/65–12/86	QS76 1/65–12/86
January	−1.84 ± 0.50	−2.31 ± 0.75
February	−1.79 ± 0.71	−2.33 ± 1.05
March	−1.07 ± 0.36	−1.57 ± 0.54
April	−0.52 ± 0.34	−0.84 ± 0.51
May	−0.52 ± 0.27	−0.72 ± 0.42
June	+0.22 ± 0.20	+0.28 ± 0.30
July	0.00 ± 0.22	+0.10 ± 0.34
August	+0.03 ± 0.24	+0.05 ± 0.36
September	+0.03 ± 0.21	+0.07 ± 0.32
October	−0.19 ± 0.21	−0.34 ± 0.32
November	+0.27 ± 0.32	+0.29 ± 0.50
December	−1.17 ± 0.46	−1.77 ± 0.70
Average	−0.55	−0.73
QBO	−0.16 ± 0.059	−0.19 ± 0.056
Solar	+3.92 ± 1.75	+4.4 ± 1.5
Yearly coefficient	−0.14 ± 0.13	−0.24 ± 0.21

Dobson Only: Latitudes 53–64 Degrees North

Model Time Period	QS70 1/57–12/86	QS76 1/57–12/86
January	−0.95 ± 0.48	−1.56 ± 0.79
February	−1.55 ± 0.67	−2.49 ± 1.11
March	−0.69 ± 0.34	−1.29 ± 0.57
April	−0.23 ± 0.33	−0.57 ± 0.55
May	−0.40 ± 0.26	−0.66 ± 0.44
June	+0.06 ± 0.19	+0.12 ± 0.32
July	+0.02 ± 0.21	+0.11 ± 0.36
August	−0.11 ± 0.23	−0.11 ± 0.38
September	+0.21 ± 0.20	+0.30 ± 0.34
October	+0.25 ± 0.21	+0.18 ± 0.34
November	+0.77 ± 0.32	+0.94 ± 0.53
December	−0.21 ± 0.45	−0.76 ± 0.75
Average	−0.24	−0.48
QBO	−0.14 ± 0.054	−0.14 ± 0.054
Solar	+1.99 ± 1.30	+1.96 ± 1.29
Yearly coefficient	+0.03 ± 0.13	−0.03 ± 0.22

Dobson Only: Latitudes 53–64 Degrees North

Model Time Period	QS70 1/57–12/86	QS76 1/57–12/86
January	−1.10 ± 0.47	−1.73 ± 0.78
February	−1.70 ± 0.66	−2.65 ± 1.10
March	−0.83 ± 0.34	−1.44 ± 0.57
April	−0.35 ± 0.33	−0.71 ± 0.54
May	−0.51 ± 0.26	−0.78 ± 0.44
June	−0.04 ± 0.19	+0.07 ± 0.32
July	−0.06 ± 0.21	+0.01 ± 0.35
August	−0.22 ± 0.23	−0.24 ± 0.38
September	+0.09 ± 0.20	+0.15 ± 0.34
October	+0.10 ± 0.21	+0.01 ± 0.34
November	+0.61 ± 0.32	+0.74 ± 0.52
December	−0.38 ± 0.44	−0.96 ± 0.74
Average	−0.37	−0.63
QBO	−0.17 ± 0.054	−0.17 ± 0.054
Solar	+0.82 ± 1.35	+0.90 ± 1.32
Nuclear	−0.48 ± 0.19	−0.47 ± 0.18
Yearly coefficient	−0.09 ± 0.14	−0.18 ± 0.22

Dobson Only: Latitudes 40–52 Degrees North

Model Time Period	QS70 1/65–12/86	QS76 1/65–12/86
January	−0.56 ± 0.45	−0.40 ± 0.67
February	−1.18 ± 0.51	−1.33 ± 0.77
March	−1.33 ± 0.55	−1.61 ± 0.83
April	−0.58 ± 0.41	−1.18 ± 0.62
May	−0.30 ± 0.24	−0.72 ± 0.37
June	−0.39 ± 0.21	−0.77 ± 0.32
July	−0.43 ± 0.20	−0.78 ± 0.30
August	−0.46 ± 0.18	−0.78 ± 0.28
September	−0.53 ± 0.19	−0.86 ± 0.29
October	−0.27 ± 0.26	−0.61 ± 0.40
November	−0.44 ± 0.25	−0.64 ± 0.37
December	−1.08 ± 0.33	−1.10 ± 0.51
Average	−0.63	−0.90
QBO	−0.11 ± 0.057	−0.12 ± 0.056
Solar	+1.76 ± 1.65	+2.04 ± 1.61
Yearly coefficient	−0.47 ± 0.13	−0.83 ± 0.21

Dobson Only: Latitudes 40–52 Degrees North

Model Time Period	QS70 1/57–12/86	QS76 1/57–12/86
January	-0.68 ± 0.43	-0.65 ± 0.70
February	-1.02 ± 0.49	-1.33 ± 0.80
March	-1.23 ± 0.54	-1.69 ± 0.89
April	-0.37 ± 0.40	-0.93 ± 0.66
May	-0.18 ± 0.24	-0.55 ± 0.39
June	-0.09 ± 0.21	-0.41 ± 0.34
July	-0.12 ± 0.19	-0.43 ± 0.32
August	-0.04 ± 0.18	-0.30 ± 0.30
September	-0.11 ± 0.19	-0.40 ± 0.31
October	$+0.06 \pm 0.26$	-0.21 ± 0.43
November	-0.31 ± 0.24	-0.53 ± 0.40
December	-1.01 ± 0.32	-1.20 ± 0.54
Average	-0.42	-0.72
QBO	-0.12 ± 0.057	-0.13 ± 0.057
Solar	-0.75 ± 1.50	-0.79 ± 1.48
Yearly coefficient	-0.15 ± 0.15	-0.47 ± 0.25

Dobson Only: Latitudes 40–52 Degrees North

Model Time Period	QS70 1/57–12/86	QS76 1/57–12/86
January	-0.81 ± 0.43	-0.79 ± 0.69
February	-1.15 ± 0.49	-1.47 ± 0.80
March	-1.35 ± 0.53	-1.82 ± 0.88
April	-0.48 ± 0.39	-1.05 ± 0.65
May	-0.28 ± 0.24	-0.66 ± 0.39
June	-0.17 ± 0.21	-0.51 ± 0.34
July	-0.20 ± 0.20	-0.52 ± 0.32
August	-0.12 ± 0.18	-0.40 ± 0.30
September	-0.21 ± 0.19	-0.51 ± 0.31
October	-0.05 ± 0.26	-0.33 ± 0.43
November	-0.44 ± 0.25	-0.67 ± 0.40
December	-1.14 ± 0.33	-1.35 ± 0.54
Average	-0.53	-0.84
QBO	-0.14 ± 0.057	-0.14 ± 0.057
Solar	-1.68 ± 1.55	-1.57 ± 1.51
Nuclear	-0.50 ± 0.30	-0.46 ± 0.29
Yearly coefficient	-0.24 ± 0.15	-0.58 ± 0.25

Dobson Only: Latitudes 30–39 Degrees North

Model Time Period	QS70 1/65–12/86	QS76 1/65–12/86
January	−0.42 ± 0.30	−0.55 ± 0.44
February	−0.25 ± 0.37	−0.43 ± 0.56
March	−0.72 ± 0.38	−0.95 ± 0.58
April	−0.35 ± 0.27	−0.44 ± 0.41
May	−0.35 ± 0.18	−0.50 ± 0.28
June	−0.64 ± 0.19	−0.91 ± 0.30
July	−0.23 ± 0.18	−0.34 ± 0.29
August	−0.18 ± 0.18	−0.22 ± 0.28
September	−0.17 ± 0.15	−0.20 ± 0.24
October	−0.15 ± 0.14	−0.23 ± 0.21
November	−0.02 ± 0.13	+0.04 ± 0.21
December	−0.38 ± 0.20	−0.54 ± 0.31
Average	−0.32	−0.44
QBO	+0.15 ± 0.050	+0.15 ± 0.051
Solar	+0.22 ± 1.33	+0.27 ± 1.34
Yearly coefficient	−0.16 ± 0.11	−0.21 ± 0.17

Dobson Only: Latitudes 30–39 Degrees North

Model Time Period	QS70 1/57–12/86	QS76 1/57–12/86
January	−0.29 ± 0.28	−0.46 ± 0.46
February	−0.10 ± 0.36	−0.27 ± 0.59
March	−0.42 ± 0.37	−0.69 ± 0.62
April	−0.36 ± 0.26	−0.51 ± 0.43
May	−0.26 ± 0.18	−0.45 ± 0.29
June	−0.43 ± 0.19	−0.74 ± 0.31
July	+0.09 ± 0.18	+0.02 ± 0.30
August	+0.24 ± 0.18	+0.26 ± 0.30
September	+0.14 ± 0.15	+0.14 ± 0.25
October	+0.16 ± 0.13	+0.12 ± 0.22
November	+0.14 ± 0.13	+0.22 ± 0.22
December	−0.24 ± 0.19	−0.43 ± 0.32
Average	−0.11	−0.23
QBO	+0.13 ± 0.046	+0.14 ± 0.046
Solar	+0.76 ± 1.13	+0.73 ± 1.13
Yearly coefficient	+0.05 ± 0.11	+0.03 ± 0.19

Dobson Only: Latitudes 30–39 Degrees North

Model Time Period	QS70 1/57–12/86	QS76 1/57–12/86
January	−0.31±0.29	−0.48±0.46
February	−0.11±0.36	−0.29±0.59
March	−0.43±0.37	−0.71±0.62
April	−0.38±0.27	−0.53±0.44
May	−0.28±0.18	−0.46±0.30
June	−0.44±0.19	−0.75±0.32
July	+0.08±0.18	+0.01±0.30
August	+0.23±0.18	+0.25±0.30
September	+0.13±0.15	+0.13±0.25
October	+0.14±0.14	+0.11±0.23
November	+0.12±0.14	+0.20±0.23
December	−0.26±0.20	−0.45±0.33
Average	−0.13	−0.25
QBO	+0.13±0.047	+0.13±0.047
Solar	+0.64±1.22	+0.61±1.20
Nuclear	−0.09±0.32	−0.09±0.31
Yearly coefficient	+0.05±0.12	+0.02±0.19

European M–83 Regional Average.

Model	QS70	QS76
January	−0.60±0.97	−0.95±1.06
February	−0.95±1.60	−0.67±1.74
March	−2.01±1.21	−2.15±1.38
April	−2.73±1.02	−3.19±1.18
May	−2.12±0.90	−2.45±1.04
June	−0.77±0.63	−0.93±0.72
July	+0.36±0.91	+0.08±1.05
August	−0.25±0.70	−0.52±0.81
September	−0.54±0.56	−0.57±0.65
October	−1.13±0.56	−1.03±0.65
November	−1.26±0.68	−1.33±0.78
December	−1.29±0.82	−1.30±0.95
Average	−1.11	−1.25
QBO	−0.22±0.11	−0.22±0.11
Solar	+2.09±3.17	+2.03±3.11
Yearly coefficient	−0.99±0.40	−1.19±0.46

Far Eastern M–83 Regional Average.

Model	QS70	QS76
January	+0.62±1.09	+0.59±1.17
February	+0.95±1.02	+0.92±1.15
March	−1.49±0.92	−1.73±1.04
April	−0.91±0.89	−1.47±1.01
May	−0.43±0.51	−0.63±0.58
June	−0.05±0.41	−0.03±0.47
July	+0.56±0.59	+0.49±0.66
August	−1.40±0.57	−1.80±0.65
September	−0.64±0.46	−0.72±0.52
October	−0.21±0.26	−0.23±0.29
November	−0.33±0.57	−0.28±0.65
December	−0.76±0.80	−0.84±0.91
Average	−0.34	−0.48
QBO	+0.13±0.079	+0.13±0.078
Solar	+2.36±1.58	+2.35±1.56
Yearly coefficient	−0.30±0.19	−0.40±0.22

Siberian M–83 Regional Average.

Model	QS70	QS76
January	−0.70±1.16	−0.80±1.28
February	−0.70±1.16	+0.04±1.68
March	+0.20±1.28	+0.28±1.51
April	−1.24±1.05	−1.61±1.23
May	−0.37±0.64	−0.46±0.75
June	−0.15±0.58	−0.13±0.68
July	+0.14±0.29	+0.04±0.34
August	−0.87±0.59	−1.17±0.70
September	−1.21±0.69	−1.21±0.81
October	−1.75±0.73	−1.86±0.86
November	−2.94±0.98	−2.99±1.15
December	−2.31±1.01	−2.43±1.19
Average	−0.89	−1.02
QBO	−0.046±0.083	−0.046±0.084
Solar	+0.40±1.78	+0.41±1.82
Yearly coefficient	−0.39±0.25	−0.55±0.29

South Central Asian M–83 Regional Average.

Model	QS70	QS76
January	−1.66 ± 1.15	−1.89 ± 1.25
February	−0.69 ± 1.26	−1.19 ± 1.44
March	+0.43 ± 0.74	+0.29 ± 0.86
April	+0.01 ± 0.89	−0.11 ± 1.04
May	−0.59 ± 0.78	−0.56 ± 0.90
June	+0.00 ± 0.46	+0.00 ± 0.54
July	−0.71 ± 0.45	−0.76 ± 0.52
August	−0.17 ± 0.57	−0.07 ± 0.66
September	−0.06 ± 0.37	−0.06 ± 0.43
October	−0.38 ± 0.56	−0.54 ± 0.65
November	−0.53 ± 0.61	−0.71 ± 0.71
December	−1.41 ± 0.71	−1.53 ± 0.82
Average	−0.48	−0.59
QBO	−0.01 ± 0.09	−0.01 ± 0.09
Solar	+0.29 ± 2.04	+0.26 ± 2.02
Yearly coefficient	−0.28 ± 0.26	−0.36 ± 0.31