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Long-term ozone trends derived from the 16-year combined Nimbus 7/Meteor 3 TOMS Version 7 record

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Abstract. Ozone measurements from the Nimbus 7 TOMS instrument, which operated from November 1978 through early May 1993, have been extended through December 1994 using data from the TOMS instrument on-board the Russian Meteor 3 satellite. Both TOMS data records have recently been recalibrated, and then reprocessed using the Version 7 retrieval algorithm. Long-term trend estimates obtained from a multiple regression analysis show ozone losses in the extended data record similar to those reported in previous studies using Version 6 TOMS and SBUV data, and ground-based Dobson data. Ozone continues to decline through the end of 1994, with the most significant ozone losses occurring in the high southern latitudes during October (–20% per decade) and in the northern mid- to high-latitudes during March/April (–6 to –8% per decade). There is no significant ozone trend in the tropics. Annual-average trends derived from the Nimbus 7 Version 7 data are 0–2.5% per decade less negative than those derived over the same time period using Version 6 data.

Introduction

The breakdown in the stratosphere of certain man-made chemicals containing chlorine and bromine are known to be responsible for the ozone depletion observed every year since the early 1980s over Antarctica during austral spring. These chemicals are also suspected as the source of ozone loss in the mid-latitudes of both hemispheres. Recent observations reported by Montzka *et al.* [1996] show that the concentrations of these chemicals have now begun to decline in the troposphere as a result of production restrictions. Models indicate that the rate of decline in stratospheric ozone should begin to slow as a result, but it is not known how long it will be before changes in the trend occur, or how the release of other lesser-restricted chemicals will affect future ozone loss. To detect expected changes in the ozone trend it is necessary to maintain a long-term record of calibrated global ozone data. The Nimbus 7 (N7) Total Ozone Mapping Spectrometer (TOMS) and Solar Backscatter Ultraviolet (SBUV) instruments functioned for over 14 years and 11 years, respectively, but now data from successive instruments must be used to continue the ozone time series. Hollandsworth *et al.* [1995] extended the N7 SBUV record using data from the NOAA 11 (N11) SBUV/2 instrument to create a global ozone time series through June 1994. In this study, a similar methodology is used to combine measurements from the N7 and Meteor 3 (M3)

TOMS instruments. A multiple regression analysis is then performed on the combined data set to assess the long-term trends. Data from recently launched TOMS instruments will be used to further extend this data record.

TOMS Data from Nimbus 7 and Meteor 3

The N7 and M3 TOMS data records have recently been reprocessed with an improved algorithm (Version 7 (V7)) and updated calibrations. The N7 record extends from 1 November 1978 through 6 May 1993, while the M3 record covers the period from 22 August 1991 through 27 December 1994. The important changes in the V7 algorithm are briefly discussed in a companion paper [McPeters and Labow, 1996]; full details of the V7 algorithm and the N7 TOMS calibration can be found in the N7 TOMS User's Guide [McPeters *et al.*, 1996].

For a data set to be usable for trend analysis it is important that the instrument calibration be maintained to high accuracy. TOMS uses the ratio of backscattered earth radiance to solar irradiance at specific wavelengths to infer column ozone amounts. In this ratio, all instrument-related changes except degradation of the diffuser plate, used to reflect diffuse solar light into the instrument optics, will cancel. It was shown by Cebula *et al.* [1988] that degradation of the diffuser plate is directly related to exposure to sunlight.

The N7 TOMS single diffuser plate suffered substantial degradation after 10 years of daily exposure to UV. Therefore, a non-diffuser-based technique termed spectral discrimination was developed to calibrate N7 TOMS [McPeters and Labow, 1996]. McPeters *et al.* [1996] estimate that the recalibrated N7 TOMS total ozone record is accurate to within 1% per decade (hereafter %/decade) over the length of the time series. Comparisons with an average of 30 Northern Hemisphere Dobson records [McPeters and Labow, 1996] show a N7 TOMS calibration drift relative to Dobson of less than 0.5%/decade. The V7 calibration is also verified through analysis of the long-term stability of reflectivity measurements over regions assumed to have roughly constant surface reflectivities, and through comparisons with N7 SBUV radiances.

The M3 TOMS time-dependent calibration was maintained by using a series of three on-board diffuser plates. The cover diffuser is exposed continuously, while the working and reference diffusers are exposed for a period of minutes once every week and once every 15 weeks, respectively. The calibration can be directly maintained to high accuracy by analyzing the degradation of the cover diffuser relative to the working and reference diffusers [Jaross *et al.*, 1995]. The V7 time-dependent calibration is very similar to that derived in Version 6 (V6), which was maintained to within 1% over the lifetime of the instrument [Herman *et al.*, 1995]. Analysis of the long-term stability of M3 reflectivity measurements for assumed constant high-reflectivity scenes and comparison with the M3 calibration determined by using spectral discrimination are used to validate the V7 M3 calibration.

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During the 20-month overlap period there were small biases (1–2%) for N7 and M3 measurements made under very similar viewing conditions. A normalization was applied to the M3 calibration to bring the two instruments into absolute agreement. This adjustment was derived using a subset of the data records in which strict matchup criteria in space and time were met, and was implemented as an adjustment to the measured M3 backscattered radiances. After this normalization the M3 data are no longer independent, but it is believed that the M3 data are more useful as a consistent extension of the N7 data rather than as a totally independent data set. Details of the M3 calibration will be given in future publications.

Effects of Meteor 3 Orbital Precession

The N7 satellite was in a very stable polar sun-synchronous orbit, with a local equator crossing time (LECT) that only drifted from noon to approximately 10:45 AM in 14 years. The M3 satellite was also in a polar orbit, but one which precessed with a period of 212 days, leading to near-terminator observing conditions every 106 days. Measurements taken when the M3 orbit was parallel or nearly parallel to the terminator have increased uncertainty and are not included in our analysis. In this study, we use the publicly-released V7 gridded data product (1° latitude by 1.25° longitude data, available online and on CD-ROM from NASA/GSFC). Only measurements taken while the LECT of the satellite orbit was between the hours of 8 AM and 4 PM are included in the gridded data prod-

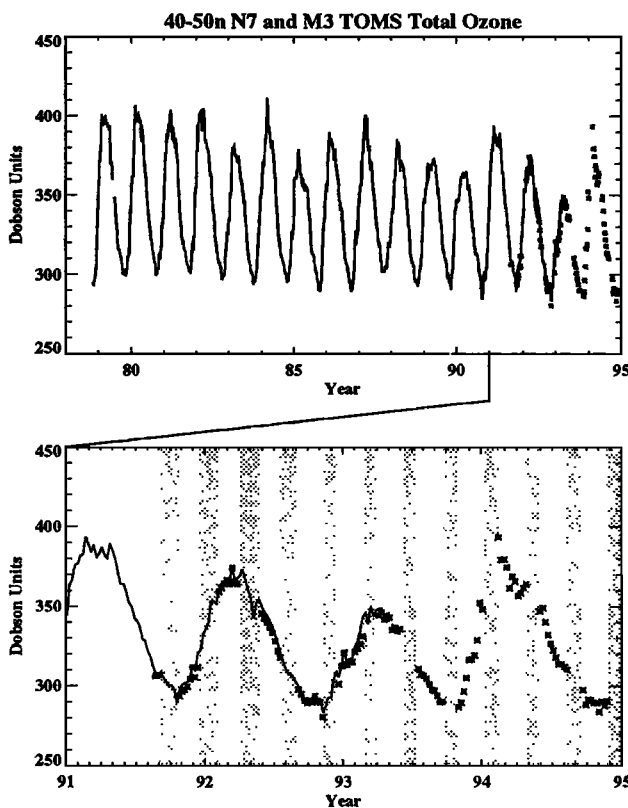


Figure 1. Top: N7 (solid line) and M3 (*) weekly-averaged total column ozone time series at 40°–50°N over the time period 11/78 to 12/94. Bottom: as above, but over the time period 1/91 to 12/94 only. The N7 time series (solid) ends in 5/93. The shaded regions indicate time periods in which the M3 data are not included due to bad observing conditions.

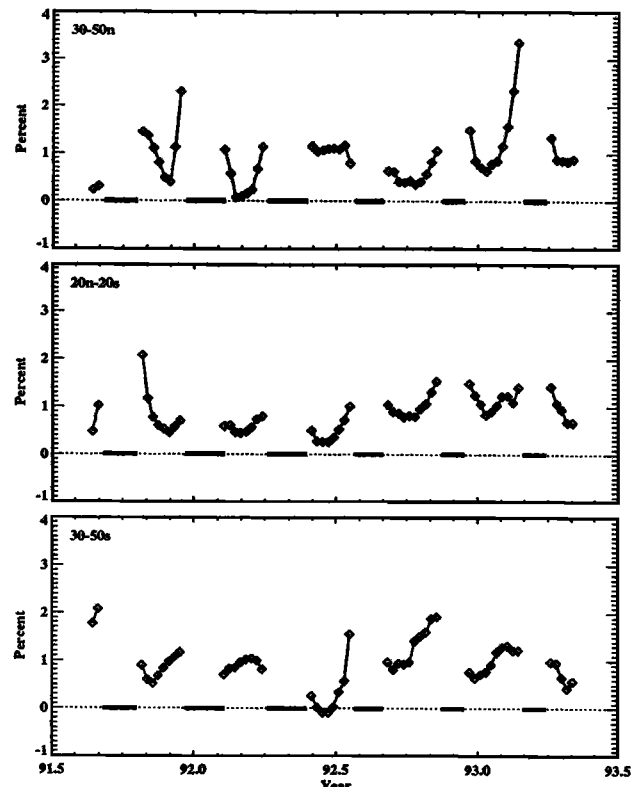


Figure 2. The percent difference $[(M3-N7)/N7]$ during the 20-month overlap period at 30°–50°N; 20°N–20°S; and 30°–50°S. The solid regions on the zero-line indicate periods of missing M3 data.

uct. During the first year, only data taken for 9 AM to 3 PM LECT are included, because the high levels of stratospheric aerosols after the eruption of Mt. Pinatubo introduce errors into the measurements taken at higher solar zenith angles [Torres *et al.*, 1995]. These aerosol-induced errors in zonally-averaged ozone diminished by late 1992.

The top panel of Figure 1 shows the N7 and M3 TOMS data in the 40°–50°N zone over the full time period, 11/78 through 12/94. The lower panel highlights the data from 1/91 to the end of the record. Periods when M3 data are omitted because the orbit is near the terminator are shaded. The missing periods are spaced as a function of season (data are never missing in a given season two years in a row) such that the missing data should not have a large effect on the trends.

The time-dependent differences between the N7 and M3 data during the 20 months of instrument overlap are shown in Figure 2 for three representative latitude bands: 30°–50°N, 20°N–20°S, and 30°–50°S. The agreement at these latitudes is generally to within 2%, with the N7 values generally being higher than the M3 values. There is an average bias of $1.0\% \pm 0.5\%$ (error is standard deviation of weekly differences) between the data sets at all latitudes except at the northern high latitudes where the average bias is $0.0\% \pm 1.5\%$. There is a consistent pattern in the time dependence of the differences, with the bias decreasing as the M3 satellite drifts from an afternoon towards a noon orbit, and then increasing again as the satellite drifts into a morning orbit. This dependence on LECT is most evident in the tropics, with a bias of $\sim 0.6\%$ at noon, increasing to 1.5–2% as M3 drifts away from a noon orbit. Systematic errors of 0.7 DU ($\sim 0.25\%$) are possible in the M3 retrieved ozone due to the precision of the radiance correction, and the

remaining bias may result from a combination of small algorithmic errors that depend on scan angle, solar zenith angle, and aerosol loading.

Trend Analysis Procedure

To derive the long-term ozone trend, the N7 and M3 data records are combined and fit with a standard linear multiple regression model. Despite the use of N7 to normalize the calibration of M3, there is a residual bias as the M3 orbit drifts with respect to the N7 orbit. For trend analysis we further adjust the M3 zonal averages by the average bias between N7 and M3 using all the available data from the gridded product. The M3 data are then averaged with the N7 data during the overlap period to form a consistent time series. The effect of this additional adjustment on the trends is 0.1–0.35%/decade.

The regression model used in this study is nearly identical to that used in *Hood et al.* [1993] and *Hollandsworth et al.* [1995], with terms for the seasonal cycle, linear trend, Quasi-Biennial Oscillation (QBO), and 11-year solar cycle. The trend, QBO, and solar cycle coefficients in the model vary as a function of season. The statistical trend error is estimated using bootstrap methods, as described in *Hood et al.* [1993]. Resampling of sequences of residuals (with an adjustment for M3 coverage) is used to estimate the uncertainty. Sixteen one-year blocks of model residuals over the N7 time period (i.e. no missing data) are chosen randomly with replacement and combined with the model time series to create a fictitious 16-year time series. The data in the last 17 months are then screened with the M3 LECT to provide the same time coverage as the real time series. Four hundred of these synthetic time series are created for each latitude. Linear regression is then used to estimate the parameters for the synthetic time series, and the variance of these parameters provides error estimates for the original parameters. The final error is the root mean square of the statistical error and the instrument uncertainty. The periods of missing data in the M3 data record introduce additional uncertainty into the trend analysis. To investigate the model's ability to accurately isolate signals in the time series despite the missing data periods, historical data variations are added to the model and then substituted for M3 data over the last 20 months of the time series, when only M3 data are available. Regression analysis of sample time series with full and with M3 sampling shows that the largest variations in the trend resulting from the M3 sampling occur in the high latitude winters of both hemispheres and in the southern hemisphere spring. These are regions where the sampling is affected by orbit drift and polar night, and where the unexplained variability is largest. In these regions the data loss due to the M3 orbit caused trend variations of 0.5–1%/decade. In the mid-latitudes of both hemispheres and in the equatorial region, the effect was on the order of 0.1%/decade, showing that the model trend estimates are only minimally affected by the M3 data loss.

Trend Results: 1979–1994

Figure 3 shows the seasonally-varying trend as a function of month and latitude for the 16-year period 11/78–10/94. The pattern of ozone loss in latitude and season is similar to that reported in previous studies using satellite [*Stolarski et al.*, 1991; *Hood et al.*, 1993; *Hollandsworth et al.*, 1995] and ground-based [*Bojkov et al.*, 1995] data, with maximum loss in the high latitude winter season, and little significant loss in

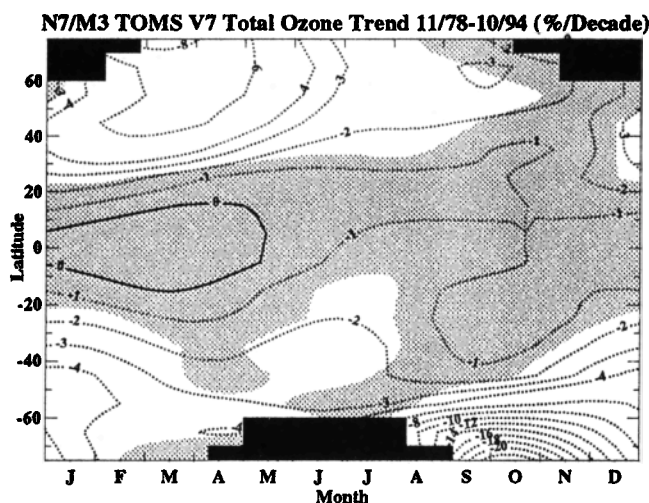


Figure 3. Trend in total ozone in % per decade as a function of latitude and season based on the combined TOMS data set over the 16-year period from 11/78 to 10/94. The shaded region indicates trends which are not significant at the 2σ level. The solid black regions indicate polar night.

either hemisphere equatorward of 20° latitude. Loss rates in the southern hemisphere polar regions are largest (-24% /decade) in early October, in association with the antarctic ozone hole. In the northern mid-latitudes, the maximum negative trends of $6\text{--}8\%$ /decade during late winter and early spring occur as far south as 40° latitude. The mechanism for this loss is not fully understood, though work by *Hofmann and Solomon* [1989] and *Solomon et al.* [1996] suggests that these losses result from a combination of enhanced chlorine levels in the stratosphere and enhanced levels of background aerosols after volcanic eruptions on which heterogeneous reactions can take place, particularly in the presence of cold stratospheric temperatures. In this study a linear function is assumed for the trend, so the results represent the average loss rate over the full period.

Figure 4(a) shows the comparison of annual-average total ozone trends as a function of latitude derived from three sources: the V7 N7/M3 TOMS data from 11/78–10/94; the SBUV(2) data from 11/78–12/94 [*Hollandsworth et al.*, 1995]; and the average Dobson data from 1/79–2/94 [*WMO*, 1995]. The V7 trends in the equatorial region are near zero, but trends in the southern high latitudes approach -9% /decade, and trends in the northern high latitudes reach -5% /decade. The error bars on the TOMS combined trend estimates are 2σ reliability estimates, including both statistical and instrument error. The N7/M3 trends are in good agreement, generally within $\pm 1\%$ /decade, with trends derived from ground-based Dobson data (taken from [*WMO*, 1995]). The trend estimates derived from the SBUV(2) record are $1\text{--}2\%$ /decade more negative in most latitude bands. However, both the SBUV and SBUV/2 data are processed with the V6 algorithm. The SBUV(2) trends may also be affected by data loss due to drift in the N11 satellite and uncertainties in the long-term calibration, which has been extrapolated since 1/93 (see *Hollandsworth et al.*, 1995).

Figure 4(b) compares the TOMS V7 trends for the period 11/78–6/91 with the TOMS V6 trends (similar to the trends published previously by *Stolarski et al.* [1991] for 11/78–5/90), and with trends from the combined SAGE I/II data record [*Wang et al.*, 1996]. The V7 trends are about 0.1% /decade more negative than the V6 trends in the equatorial region, but are $1\text{--}2\%$ /decade less negative above 45° latitude in each hemi-

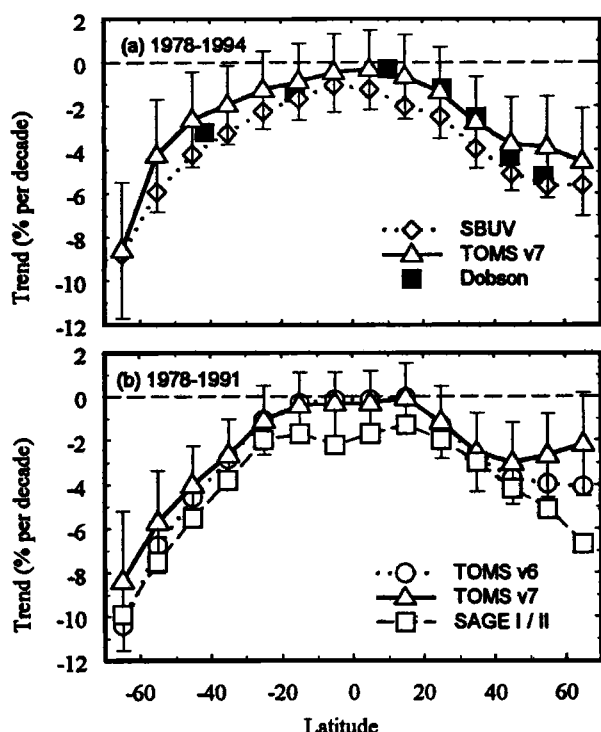


Figure 4. Annual-average total column ozone trend estimates as a function of latitude (% per decade). The top plot compares TOMS V7 trends for the period 11/78 to 12/94 (triangles), SBUV (2) trends (diamonds); and ground-based Dobson (squares). The error bars represent the 2σ error for the combined TOMS V7 trend estimates. The bottom plot compares TOMS V7 trends for the period 11/78 to 6/91 (triangles) with V6 trends (circles) and with SAGE I/II trends reported by Wang et al. [1996] (squares).

sphere. The SAGE trends shown were derived using a corrected SAGE I data set with the corrected reference height [Wang et al., 1996]. The data plotted, taken from Fig. 18a of their paper, consist of the trends from the SAGE column integrated upward from 3.5 km above the tropopause for the period 2/79–5/91. The SAGE trends are about 2%/decade and 2.5%/decade more negative than the TOMS V7 trends at high and equatorial latitudes, respectively. These trend differences may be due in part to the fact that TOMS measures tropospheric ozone and SAGE does not, so a positive trend in tropospheric ozone could be offsetting lower stratosphere ozone decrease measured by SAGE. Wang et al. [1996] note that uncertainties in the SAGE aerosol correction could also be responsible. The discrepancy, especially for the points above 50° latitude, could be enhanced by the fact that matched data are not used here and that SAGE sampling in the 50° – 75° zone is not uniform through the year.

Conclusions

Data from the N7 and M3 instruments processed with the V7 algorithm have been combined to create a 16-year record of global total column ozone. The stability of each instrument was maintained to within 1% over each data record. Precession of the M3 orbit led to periods of lower quality data when the orbit was near the terminator, but we estimate that the effect of this missing data on the derived trends is minimal.

The long-term trends as a function of latitude and season for the period 11/78–10/94 are estimated using a standard linear regression trend model. The V7 trends are near zero in the equatorial region, but are 1–2%/decade smaller than V6 trends at mid and high latitudes. In the northern hemisphere, the maximum negative trend occurs in March/April at 40° – 70° N. The maximum trend of more than –20%/decade in the southern hemisphere is associated with the antarctic ozone hole.

Comparison of SAGE I/II trends with TOMS V7 trends in the equatorial zone suggest that ozone in the mid to lower stratosphere is depleting at the rate of about 2%/decade, but is being compensated by a tropospheric ozone increase to produce the 0.3%/decade decrease observed in the TOMS V7 data record. Alternatively, there could be errors in the trends from one or both instruments. Data from other instruments are needed to resolve this question.

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