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A New Approach to the Characterization of Long-Term Changes in Total
Atmospheric Ozone: Applications of Frequency and Extreme Value
Statistics

by

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Abstract

This paper sets forth a new approach for describing long-term changes in total ozone by using extreme value statistics and frequency distributions. We applied this methodology to the database of column ozone provided by the Total Ozone Mapping Spectrometer aboard Nimbus 7. We examined a geographic region measuring 7.0 degrees in latitude by 6.25 degrees in longitude in the midwestern United States from 1979-1991. On any given spring day, individual ozone measurements in this region show a large variability, where the differences between noontime maximum and minimum values sometimes exceed 100 Dobson units. During spring, the frequency of extremely low ozone values decreased over the period 1980-1991, while the opposite situation prevailed during fall.

Introduction

In this paper, we establish a new approach for characterizing changes in total ozone (TOZ). Our approach is based upon the frequency distribution of TOZ and the application of extreme value statistics to the database obtained by the Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7. Standard practice is to describe long-term changes in TOZ by linear trends in monthly mean amounts. The trends are usually computed over a large geographic area, often a zonal band measuring several degrees in latitude. Such studies have firmly established a decline in TOZ over middle and high latitudes during the 1980s (Stolarski et al., 1991; World Meteorological Organization, 1991; Niu et al., 1992).

The present work examines changes in TOZ from a new perspective. Our rationale for studies of total ozone concerns the effect of solar ultraviolet radiation on human health and biota. Because health-related statistics refer to specific geographic regions like metropolitan areas, it is reasonable to focus on the behavior of ozone over spatial scales that are much smaller than a zonal average.

Long-term changes in ozone are not necessarily described in full by linear trends in monthly averaged quantities. Long-term variations in ozone may manifest themselves as changes in the frequency distribution of TOZ values, especially in the distribution of extremely small values over a season. One can characterize TOZ behavior in a region over any time period by stating the probability of observing a particular TOZ value. Changes in the behavior of ozone are then characterized by a change in the probability (or frequency) distribution function, usually over time scales of years. While a shift in the frequency of occurrence of the TOZ value in a region affects the monthly averaged ozone, the averaged values do not necessarily show the large variability of day-to-day TOZ values or the very small TOZ values that occur from time to time. We believe a consideration of these daily variations and the low TOZ values is potentially important to a full understanding of the impact of TOZ on human health and biota.

Variability in Daily Total Column Ozone

We have chosen a region of the midwestern United States in which 35 values of TOZ per day are available on TOMS CD-ROM version 6. This region extends from 35.0°N to 42.0°N and from 81.25°W to 87.50°W and includes much of Indiana, Ohio, Kentucky, Tennessee and the western portion of West Virginia. Seven metropolitan areas with populations greater than 0.8 million lie in the region, as do agricultural areas that produce soybeans, corn and wheat. Figure 1 shows the maximum and minimum daily TOZ values, in Dobson units (DU), during the spring and fall seasons.

(insert Figure 1)

Fig. 1(a) Daily maximum and minimum values of TOZ in the spring for an area 7.0° in latitude by 6.25° in longitude. Red represents daily maximum TOZ, and blue represents daily minimum. (b) Analogous data for fall.

Within the geographic region under study, the difference between the daily maximum and daily minimum TOZ value at day i , δ_i , can vary greatly (Figure 2). In addition, the largest change between consecutive daily differences, Δ , ($\Delta = \delta_{i+1} - \delta_i$, where $\delta_i = [\text{largest}$

TOZ on day i] - [smallest TOZ on day i], etc.) can also be substantial, for example, 137 DU for spring and 69 DU for fall. Here δ_i measures change in the TOZ field within a given day and Δ measures change in δ_i from day to day.

(insert Figure 2)

Fig. 2(a) Difference, δ_i , between the daily maximum and minimum values of TOZ (in DU) in the spring for the 7.0° latitude by 6.25° longitude region under study. (b) Analogous data for fall.

Analysis of the seasonal trend¹ in *daily variability*, δ_i , shows a negative trend during spring in 12 of the 13 years and a positive trend during all fall seasons. These trends are probably attributable to differences in seasonal transport processes (Chandra and Stolarski, 1991).

Seasonal Frequency Distributions of Total Ozone

The frequency distributions for TOZ in four-year intervals for the spring and fall seasons appear in Figure 3(a) and (b) respectively.

(insert Figure 3)

Fig. 3(a) Plot of the number of observed TOZ values in the 7.0° latitude by 6.25° longitude region under study versus TOZ (in DU) and the Gaussian curve fit for spring (data taken four years at a time, except for the most recent plot [1989-1991 (at top)] which includes only three years of data). (b) Analogous plot for the fall season.

The frequency distributions are readily fit by a Gaussian function, with resulting correlation coefficients, R , in the range 0.96-0.99. It is reasonable to assume the pattern of events leading to this Gaussian form was generated by a large set of random interactions of many small causes of comparable magnitude, acting independently of each other (Kaye, 1993). The means for the Gaussian frequency distributions for spring demonstrate a significant temporal decrease from 362 to 339 DU between 1979-1982 and 1989-1991,

¹Here the spring season is defined as March 1 to May 31 and the fall season is defined as September 1 to November 30 for each year.

respectively. This observation agrees with the well-established trend in the monthly means of TOZ (Stolarski et al., 1991).

Also interesting is the digression from the Gaussian behavior in the wings of these distribution functions. On the high-ozone side of the distribution, a positive deviation from the Gaussian fit occurs. It is possibly the result of large tropospheric ozone amounts generated in urban or industrial areas. This positive deviation is much more pronounced in the spring than in the fall, probably due to increased concentrations of tropospheric ozone during the spring (Guicherit, 1988). On the low-ozone side, the observed negative deviation from Gaussian behavior, would be expected to result from stratospheric ozone depletion. The negative trend in TOZ is known to be more pronounced in the spring than fall (Stolarski et al., 1991). We postulate that the total curve is the sum of two curves: a highly peaked Gaussian representing the ozone distribution for the stratosphere and a second curve, possibly Gaussian, representing the distribution for the troposphere. In future research we intend to examine this postulate in order to separate tropospheric and stratospheric ozone contributions to these total distributions.

Extreme Value Statistics: Analysis of the Wings of the Frequency Distribution Function

As Figure 2 shows, the daily variability in TOZ can be substantial. This, in turn, implies a variability in surface ultraviolet-B radiation (UV-B). Extremely low-TOZ events, although limited in geographic area and duration, may be associated with elevated surface UV-B and may affect health (e.g., by increasing the risk of skin cancer) and biota (Scientific Committee on Problems of the Environment, 1992). A complete understanding of the effects of changing regional TOZ, requires a description of these extreme events and their trends in addition to studies of the means.

To illustrate extreme events, Figure 4 shows the 100 lowest values of TOZ in the spring and fall over the full data set. These low values occurred in separate events of varying location and temporal duration.

(insert Figure 4)

Fig. 4(a) The two separate low-ozone events containing the 100 lowest spring TOZ values in the 13 years of the TOMS data set for a region 7.0° in latitude by 6.25° in longitude. Both events occurred in 1985. (b) The nine low-ozone events containing the 100 lowest fall TOZ values.

The 100 lowest values for spring occurred in two events during 1985. The first event began on March 3 and persisted until March 8; the second lasted from March 29 until March 31. The large negative anomaly in 1985 is well documented and is considered to be related mainly to the quasi-biennial oscillation in the northern mid latitudes (Bojkov, 1987).

The 100 lowest values for fall occurred in nine separate events between 1982 and 1991 and ranged in duration from one to four days, mainly in the month of November. The majority of low fall TOZ (and the lowest in magnitude) occurred in 1990; this has been previously discussed by Stolarski et al. (1991).

As seen in Figure 3, the frequency distribution function for the full data set is well approximated by a Gaussian curve, except in the wings which contain the extreme regions. For our purposes, we define the extreme regions as the TOZ values falling farther than two standard deviations from the mean of the Gaussian curve fitted to the frequency distribution. Extreme value theory postulates that these extremes follow a *probability* distribution function of the form $\exp\{-\exp[-f(x)]\}$ (where x is TOZ) (Gumbel, 1958; Gerstengarbe and Werner, 1990). Functions yielding the probable return times of extreme TOZ events are, theoretically, derivable from this distribution function and will be studied in further analyses.

For the extreme lows, we have looked at these distribution functions for the first and second halves of the data set, 1980-1985 and 1986-1991, respectively, for spring and fall. The functions $f(x)$ and their linear fits are shown in Figure 5(a)-(d) and are related to the number of times each value of TOZ occurred in the respective six-year period. From Figure 5(a) and (b), it can be seen that the ordinate intercept of the fall 1980-1985

distribution is lower than that of fall 1986-1991 and the slope is 1.45 times greater.

Together, these observations imply the frequency of low-TOZ events is increasing with time. For example, in the fall data the lowest TOZ values over 13 years were between 225 and 230 DU and occurred 12 times during the second six-year period. There were no occurrences in this magnitude range during the first six years. The lowest TOZ values for the first half of the data set fall in the range 230-235 DU. Events of this magnitude occurred 5 times in 1980-1985 and 11 times in 1986-1991.

(insert Figure 5)

Fig. 5(a) and (b) Plots of the functions $f(x)$, which are related to the number of times a given range of minimal TOZ values occurred during the fall seasons of 1980-1985 and 1986-1991, for an area 7.0° in latitude by 6.25° in longitude, respectively. Fig. 5(c) and (d) Analogous plots for spring 1980-1985 and 1986-1991. Linear fits are included in each.

The opposite trend is observed in the spring, as seen in Figure 5(c) and (d). The ordinate intercept of the 1980-1985 distribution is higher than that for 1986-1991, and the slope is 0.41 times that for 1986-1991. That is, the frequency of low-TOZ events decreased with time for the spring. Again, this is clearly observed in the absolute number of occurrences in the data set. The first half of the data set contained 82 occurrences of extreme TOZ values between 240 and 260 DU. However, no TOZ between 240 and 260 DU were observed during the spring in 1986-1991, which is quite surprising. The lowest TOZ value for spring during the second six-year period is between 260 and 265 DU with only 1 occurrence, versus 28 occurrences for spring 1980-1985 in this magnitude range.

In summary, our analysis of the extremes for fall and spring demonstrated that over time the frequency of low-TOZ events has increased during the fall season, while the frequency of low-TOZ events has decreased during the spring season. Future work will use this approach to examine all seasons in depth, to allow long-term predictions about seasonal extremes.

Conclusions

A detailed understanding of TOZ is required to understand the harmful effects increased UV-B may have on human health and biota. Characterization of TOZ on smaller geographic scales is also essential. In addition to trend studies of average TOZ, analyses of the daily variability of TOZ, the frequency distribution of TOZ and the probability distribution function of the extremes are necessary. We have analyzed daily TOZ data for a region of the midwestern United States from 1979 through 1991. The daily variability in total column ozone was shown to be greater in the spring than in the fall. The difference between daily maximum and minimum TOZ values decreased during the spring and increased during the fall. Both findings are thought to be a consequence of the difference in seasonal dynamics.

The frequency distributions are well approximated by Gaussian curves, except in the wings which contain the extreme regions. Means for the spring season decreased from 1979 to 1991.

The probability distribution functions in the extreme regions can be used to predict the probable return times of extremely low-ozone events. From these distribution functions, it was shown that the frequency of low- TOZ in the fall events increased over the time of the data set, while the frequency of low-TOZ events in the spring decreased.

We believe these initial results demonstrate that this approach can illuminate the detailed behavior of TOZ within each season. In future research, we will analyze data for the summer and winter seasons to understand the seasonal dependence of the probability (frequency) distributions.

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Figure 1a (top); Figure 1b (bottom)

Figure 1a (top); Figure 1b (bottom)

Figure 2a (top); Figure 2b (bottom)

Figure 3

(a)

(b)

Figure 4a (top); Figure 4b (bottom)

Figure 5a (top); Figure 5b (bottom)

Figure 5c (top); Figure 5d (bottom)