Analyzing Ultraviolet-B Radiation: Is There a Trend?

Kerr and McElroy state that "since 1989 . . . the intensity of [solar radiation] at wavelengths near 300 nanometers has increased by 35 percent per year in winter . . ." (1, p. 1032). We find that the purported trends depend entirely on the choice of time interval (that is, the first and last dates from which data are taken) and are therefore an artifact of the analysis. The purported winter trend is not statistically significant ($P = 0.05$) and is determined by four (out of 312) data points that lie at the extreme end of the record (March 1993) and that are associated with unusual meteorological conditions. Similarly, there is no statistically significant trend in the summer ultraviolet-B (UV-B) data when the analysis is run on the first 4 years of record; the reported trend is induced only when the data from 1993 is included.

We thus conclude that the unusual decline in total column ozone in 1992 and 1993 (2)—associated with, and likely caused by, a drop in the number of sunspots, a strong El Niño event, and the eruption of Mount Pinatubo—is not accompanied by a statistically significant upward trend in UV-B.

We performed a regression analysis using all of the winter data (provided to us by Kerr), including data (3) from March 1989 and February and March 1992 (Fig. 1). The slope of the assumed linear trend line now declines from $(165 \pm 75) \times 10^{-5}$ to $(92 \pm 67) \times 10^{-5}$ kilojoules m^{-2} nm^{-1} per year, which, using the method of Kerr and McElroy, would result in an annual increase of 21.1% ± 15.3% ($P = 0.05$), rather than 35% (no confidence limits were given in any figure in their report). However, the variance (R^2) explained by the 21% trend is only 2.4%. The putative upward trend in UV-B is completely determined by four data points at the extreme end of the record: 25, 26, 27, and 29 March 1993. Regression through the first 4 years of winter data (187 points) generates a slope not significantly different from zero, as does one ending on 24 March 1993. Thus any change on a "per year" basis calculated with the method used by Kerr and McElroy bears no relation to the first 4.95 (out of a possible 5.0) winters (4). The winter trend generated by their methodology thus results from a drastic overestimation of the number of degrees of freedom in the linear regression. A more appropriate analysis is an analysis of variance (ANOVA) between the years for each of the four winter months. In 3 of the 4 months (January, February, and March) only the 1993 data differs significantly ($P = 0.05$) from the mean in any other year. Of the 11 remaining combinations (not counting 1993), a significant difference appears only in one month, between December 1990 and December 1991.

We plotted (Fig. 2) the linear trend in irradiance (in percent per year) as a function of wavelength (i) all of the data [including those omitted by Kerr and McElroy (3)] and (ii) for the data without the four March observations. (Again we confined our study to the winter, for that is where the large changes were purported to occur in the UV-B.) When the four points from March 1993 were eliminated there was no UV-B trend significantly different from zero at any wavelength. Even when the four data points were included, the trends were approximately one-half of those in the report by Kerr and McElroy and were only significantly different from zero between 300 and 303 nm (5, 6). Thus, their "positive" result for a UV-B trend was determined by data selection that included large anomalies at the end of the record, which were associated with extreme meteorological conditions. In mid-March 1993, the deepest surface cyclone on record in the 20th century developed in the northeastern United States; surface pressure readings of less than 965 mb were common, and the core of the accompanying upper trough passed over Toronto.

Large, temporary UV variations are not unusual and do not indicate a trend. With the use of an instrument similar to the Toronto instrument, F. Mims (7) has described a strong, short-lived ozone decrease in South Texas around 23 June 1993, (associated with tropical storm Arlene) and a corresponding UV increase. Unlike Kerr and McElroy, he does not claim a "trend," but such a trend would appear statistically if this excursion was at the end of a record of inadequate length. Similarly, Correll *et al.* (8), using only "clear sky" days, found rapid and large changes of UV-B flux.

In conclusion, a careful analysis of the data used by Kerr and McElroy demonstrates the *lack* of any robust trend in the UV-B data over Toronto (9), and therefore the absence of an expected correlation between long-term trends in UV-B and total ozone. Even though such a

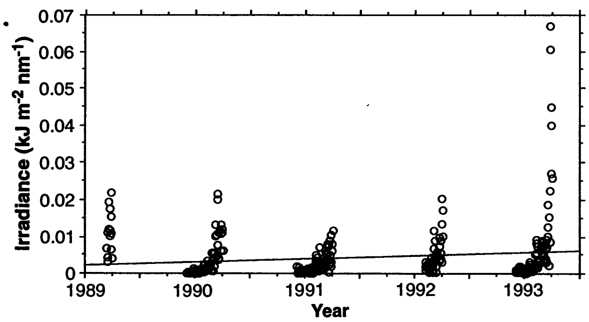

Fig. 1. Trend analysis, including winter UV-B (300 nm) data collected by Kerr and McElroy (*1*), which were omitted in their analysis (*3*).

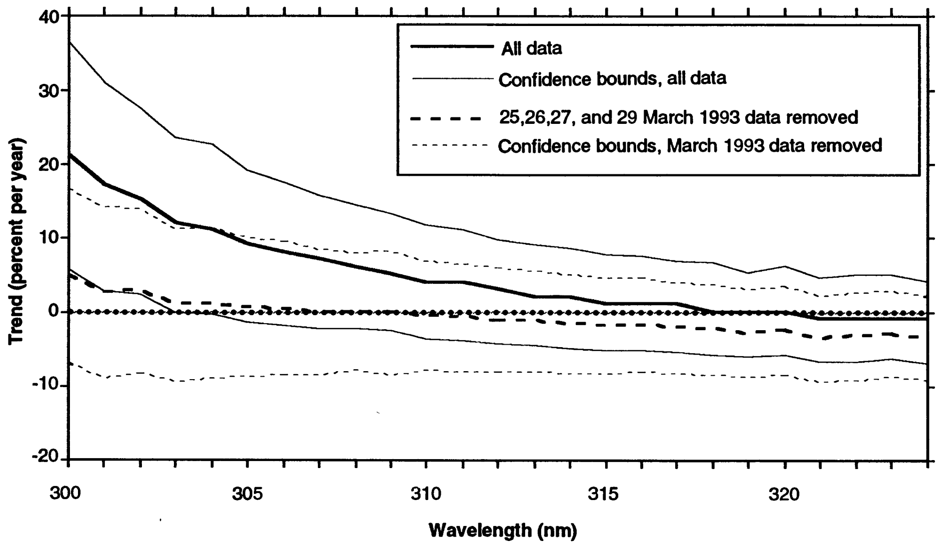

Fig. 2. Changes in irradiance, with confidence limits ($P \leq 0.05$) calculated from all of the winter data collected by Kerr and McElroy (*1, 3*) and also with the data from 25, 26, 27, and 29 March 1993 removed.

correlation is expected, the report by Kerr and McElroy provides no direct support for that hypothesis.

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REFERENCES AND NOTES

1. J. B. Kerr and C. T. McElroy, *Science* 262, 1032 (1993).
2. W. Komhyr *et al.*, *Geophys. Res. Lett.* 21, 201 (1994).
3. Kerr and McElroy state that data for the winter of 1991–92 (1 December to 31 March) are absent "because the instrument was out of service for a calibration trip" (*1*, p. 1033). [In figure 2B of their report, "winter" data are labeled with orange circles and spring (April) data with black crosses.] However, data for 1 February to 31 March 1992 appear to be present, but to have been labeled as spring data, and are not included in subsequent regression analyses. Data for 15 to 31 March 1989 also appear to have been mislabeled and not included in subsequent analysis.
4. If one only uses the winter data analyzed in the report by Kerr and McElroy (*1*) exclusion of data from the last week of March 1993 reduces the trend from the original value of 0.00165 to 0.00041 ± 0.00038, that is, by a factor of 4.
5. The argument could be made that it was inappropriate for us to include the "partial" winter data, because of seasonal trends, but Kerr and McElroy state that they removed annual cycles from the data before performing their analysis (*1*, p. 1032). Inspection of the column ozone and UV irradiances (*1*) show that this analysis was not done in a satisfactory fashion, for the annual cycles are obvious. We passed a sinusoidal filter through their ozone data and removed the annual trend. A slight downward trend in the residual total ozone remained corresponding to 2.3% per year. But because there was no significant increase in winter UV-B, there is therefore no trend correlation between departures from the average in ozone and in UV-B.
6. The reported trend results [figure 4 of (*1*)] show no confidence limits; hence the purported "striking similarity" to the ozone absorption spectrum [figure 3 of (*1*)] is problematic.
7. F. M. Mims, unpublished data.
8. D. L. Correll *et al.*, *J. Geophys. Res.* 97, 7579 (1992).
9. Because of very few degrees of freedom in the original winter data, the statistically significant results were created by four (out of 312) data points lying at the end of the record. ANOVA demonstrates that (with one exception) only monthly data from 1993 differs from that of any other year. The summer "trend" is similarly induced by the last year in the 5-year record.

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Response: We reported (*1*) measurements of spectral UV-B radiation from 1989 to 1993. We compared changes in ozone and UV-B (seasonally corrected linear trends) over the period, and we compared UV-B during 1992–93 (a year of low ozone measurements) with that during 1989–90 (a year of higher ozone measurements). Both comparisons quantified significant year-to-year changes in spectral UV-B in summer and winter months. We reported our results as evidence for trends in UV-B radiation.

We considered seasonal variations for both the ozone and UV-B radiation time series because the large differences from one time of year to another influence trend determinations and their uncertainty estimates. As stated in our report, the linear regressions for ozone [figure 1 of (*1*)] and for UV-B radiation [figure 2 of (*1*)] were derived from data with the annual cycles removed (*2*). We subtracted annual mean curves from the data points and fitted trend lines to the resulting differences which were, therefore, distributed around zero at all times of the year. This process maintains the weighting of the measured variable (ozone or UV-B energy) and does not result in a seasonal sampling bias in the determination of slopes or in an over-estimation of their errors as a result of seasonal variability. We determined the annual mean curve by smoothing the data with a 60-day full-width at half-maximum (FWHM) triangular filter (*3*).

We addressed the question of nonrandomness of the data variability with an autocorrelation analysis of adjacent data points when determining uncertainty estimates; this increased the uncertainty estimates for the slopes from a data set with random and uniform point-to-point variability (*4*). We have calculated the statistical significance (≤0.05) of the data in figure 4 of our report (*1*) based on the variance of the data points and the discussion above (Fig. 1).

Michaels *et al.* present results from data sets that include partial seasons (March 1989 and February through March 1992). These data were not included in our analysis because they might introduce a seasonal bias which is not removed when the annual cycle is removed. For example, an ozone trend with monthly dependence [as has been observed and reported (*5*)] would influence the results if partial seasons were included (*6*).

Perhaps the most serious bias in the analysis by Michaels *et al.* comes from the removal of data points without an apparent physical basis for doing so. The average ozone amount is low in the spring of 1993 precisely because there are several very low ozone values. The ozone mean could be adjusted to almost any value by arbitrarily removing data points from the analysis.

Surface and 500-mb weather maps and the Total Ozone Mapping Spectrometer maps for the period between 10 and 31 March 1993 show that the record low ozone values (and corresponding high amounts of UV-B) recorded near the end of March are not associated with a cyclone. Low surface pressure values are associated with high ozone values at midlatitudes (*7*), as was evident during the passage of the storm—a relatively high

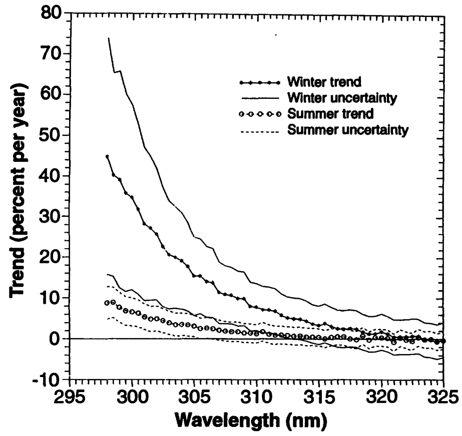

Fig. 1. Data from figure 4 of our report (*1*) with uncertainty estimates based on the variance of the data during the sample period. The uncertainty estimates ($P \leq 0.05$) include considerations with regard to the removal of seasonal variations and the correlation between adjacent data points.

ozone measurement of 400 DU was observed on 14 March, the day "the core of the accompanying upper trough passed over Toronto," as pointed out by Michaels *et al.* The unusually low ozone values (near 260 DU) at Toronto after 25 March were associated with a ridge of high pressure that had passed over western Canada a few days earlier. Removal of these critical data points is inappropriate.

The data points in question are influential because they occur at the end of March when energy readings are significantly higher than those earlier in the winter as a result of the higher solar elevation. Those data points at the end of March, although few in number, constitute about 40% of the entire winter accumulation of energy. A month-by-month analysis (Fig. 2) shows the trend.

The "uncertainty" and "significance" tests presented by Michaels *et al.* are appropriate for data at individual wavelengths considered in isolation. If data were available from one wavelength only (say 300 nm), then the error at 300 nm would be indicative of statistical significance (error bars shown in Fig. 1). However, our data set consists of 51 times the number of data points (for wavelengths between 300 and 325 nm) that should be considered together to extract conclusions and information regarding "statistical significance." (Actually, the amount of independent information is slightly less because the slit functions of adjacent wavelength samples overlap.)

It is clear from our analysis (Fig. 1) and from that of Michaels *et al.* (their figure 1) that the slopes of energy values increase from near zero (or slightly negative) at 324 nm to more positive values at 300 nm and

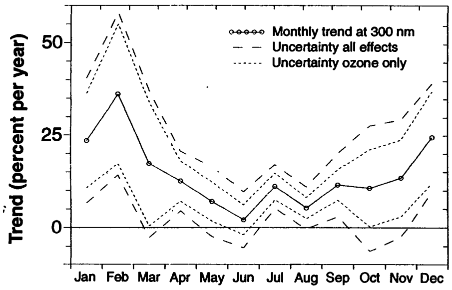

Fig. 2. Month-by-month trend measurements at 300 nm with the use of all available data between March 1989 and August 1993. Uncertainty estimates ($P \leq 0.05$) are based on the variance of the data from all sources (dashed lines).

that the variance increases in magnitude over the same wavelength range. This occurs for all months and even in the most severely biased example presented by Michaels *et al.* The wavelength dependence of the trends and variance matches the ozone absorption spectrum.

Calculating the correlation coefficient between the trends in UV-B and the ozone absorption coefficient spectrum yields values greater than 0.96 in most monthly and seasonal cases, including the examples provided by Michaels *et al.* This means that about 92% of the observed, long-term change in the UV spectrum relative to 324 nm can be accounted for by change in the amount of ozone. We are unaware of any candidate species, other than ozone, in the atmosphere that could account for this observation.

The variance contribution in the UV data resulting from ozone and from other causes at all wavelengths can be estimated by the use of the correlation coefficients calculated from data taken at 324 nm and at other wavelengths. The wavelength dependence of the variance is a result of ozone absorption, and the variance resulting from ozone at 324 nm is essentially zero because of the small value of the ozone coefficient at that wavelength (Fig. 2).

The rates of change for UV-B radiation and ozone (expressed as trends in percent per year) are those observed over the time period and seasons as defined in our report. We stated that the ozone trend at Toronto over our sample period does not represent past trends over longer periods at Toronto or other comparable sites and that the reported rates of change were very unlikely to continue into the future (*1*, p. 1034).

Michaels *et al.* refer to data collected by F. Mims "using an instrument similar to . . ." the one we used. The instrument used by Mims is a multi-wavelength, interference filter photometer. The data presented in our study were collected with a Brewer Ozone Spectrophotometer. The Brewer is an environmentally hardened, precision diffraction-grating spectrophotometer. It is a critically important element in the global ozone observing system and provides a highly accurate (<1%) and traceable total ozone measurement in addition to UV spectra of the quality used in our study.

In summary, Michaels *et al.* carry out statistical analyses to determine the strength of our evidence, but they use only the winter data, and they arbitrarily reject some of the data points. Our conclusion remains that the causal relationship between decreasing ozone and increasing UV-B radiation was demonstrated during the period of our study (*1*), and that this provides evidence that there has been a long-term change in UV-B associated with the documented decline in ozone since 1980.

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REFERENCES AND NOTES

1. J. B. Kerr and C. T. McElroy, *Science* **262**, 1032 (1993).
2. In figures 2 and 5 of our report (*1*, pp. 1033–1034) the *y*-axis was incorrectly labeled. The units in both cases should have read kJ m^{-2} nm^{-1}.
3. The annually averaged curves were subtracted from the data points shown in figures 1 and 2 of our report (*1*) before fitting the linear trends. The colored lines shown on those figures have the same slope as the trend lines, but are offset by the annual averages to show their relationship to the original data, which are also shown.
4. Use of the autocorrelation procedure to increase the uncertainty estimates takes into account the comment by Michaels *et al.* with regard to the "overestimation of the number of degrees of freedom in the linear regression." Error estimates and their effects on trend results based on calibration records were given in our report; uncertainty estimates based on data variance were not included in our report to avoid a lengthy discussion of their derivation and significance [note (*6*) of the comment by Michaels *et al.*].
5. R. Stolarski *et al.*, *Science* **256**, 342 (1992).
6. Data from figures 1 and 2 in our report (*1*) were not "mislabeled" [note (*3*) of the comment by Michaels *et al.*]. The orange data points labeled "winter" are the data points used for the regression of the orange winter line. Data points labeled "other" are other data points that were not used in the regressions because they fall in other seasons or are part of an incomplete season of data.
7. G. M. B. Dobson and D. N. Harrison, *Proc. R. Soc. London* **A110**, 660 (1926).
8. We thank R. D. McPeters, P. T. Guimaraes, and A. J. Kreuger of the NASA Goddard Space Flight Center, and the Goddard Ozone Processing Team, for providing the TOMS data through the World Data Center A for Rockets and Satellites, Goddard Space Flight Center, Greenbelt, MD.

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