"An empirical study of ozone-temperature correlations in the stratosphere"

by

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Abstract

The Microwave Sounding Unit (MSU) data are used in conjunction with Total Ozone Mapping Spectrometer (TOMS) data to study seasonal and interannual variability of ozone-temperature correlations between 1979 and 1991. The constant of proportionality between total ozone and lower stratospheric temperature changes varies significantly. Spatial patterns of changes in total ozone between 1979 and 1991 show remarkable agreement with lower stratospheric temperature changes. In addition to ozone variability correlated with observed temperature changes, there is a substantial non-linear decline in ozone related to the observed temperature change.

I. Introduction

Recent studies of the ozone layer have led to an increased appreciation of chemical and dynamical processes. The central importance of ozone is its ability to absorb ultraviolet radiation, which provides the heating that drives much of the circulation in the stratosphere (Biswas, 1979). The absorption also acts as a shield for lower levels against the harmful effects of ultraviolet radiation. The ozone concentration, however, is itself dependent on stratospheric circulation, because it is determined by a combination of photochemical and dynamical processes. The maintenance and variability of the ozone layer is thus dependant upon both chemistry and dynamics in the stratosphere.

Observations show that both total ozone and temperature at stratospheric levels are longitude-dependent. These longitude variations are, for the most part, the result of temperature and atmospheric circulation characteristics which, in turn, stem from the varying topography and nature (land/ocean, etc.) of the earth's
surface (Farrara and Mechoso, 1986). The Northern Hemisphere (NH) generally has a higher level of large-scale wave activity than the Southern Hemisphere (SH), due to the effect of the NH continents.

Year-to-year changes in the large-scale patterns of the general circulation of the atmosphere contribute to variations in the monthly means of ozone and temperature. Because ozone has its maximum mixing ratio in the stratosphere, upward transport brings ozone-poor air from the troposphere into ozone-rich air in the stratosphere which reduces total ozone.

Variations in local ozone concentration can be caused by either changes in chemical loss or production rates, or changes in atmospheric circulations, or both. For example, early debates concerning the Antarctic ozone hole focused on dynamical causes versus chemical causes. The chemical causes of Antarctic ozone depletion have since been analyzed. In terms of dynamically forced variability, the local ozone concentration is relatively sensitive to vertical motions, because ozone is strongly stratified in the stratosphere. Vertical motions in the atmosphere are also revealed in local temperature variations; upward motions result in adiabatically cooled air parcels. Thus ozone variations which are purely dynamical in origin will show spatial and temporal correlations with local temperatures (e.g. Newman and Randel, 1988).

Comparisons between temporal trends of ozone and temperature show that the longitudinal variability of ozone at high latitudes can be accounted for by transport due to waves. Hemispheric maps of monthly mean ozone and temperature over the ten-year data set display distinct waves. Moreover, there is a strong and statistically significant correlation between the monthly ozone perturbation and the temperature perturbation in the lower stratosphere.

Monthly anomalies of ozone and temperature are determined by subtracting long-term values from individual monthly averages. As mentioned before, the
Northern Hemisphere (NH) has more wave activity than the Southern Hemisphere (SH); therefore, there are distinctively large anomalies of ozone and temperature between 50° and 60° N. The strongest wave amplitudes during the thirteen-year analysis occurred in March and October of 1990 (50° to 60° N). In general, the anomalies of monthly mean ozone and temperature are fascinating and reveal nearly identical spatial patterns.

The purpose of this paper is to analyze the year-to-year changes of total ozone, together with the corresponding monthly mean temperature, to determine to what extent the ozone variability is coherent with temperature. The change in total ozone amount is nearly proportional to that of the lower stratospheric temperature. In this connection we can expect a high positive correlation between the stratospheric temperature and total ozone amount.

II. Data and Analysis

Total ozone amounts have been measured globally on a daily basis since 1978 by the Nimbus-7 Total Ozone Mapping Spectrometer (TOMS). The TOMS instrument provides a continuous series of global total ozone maps over the entire sunlit portions of the earth at horizontal resolutions varying between 50 km at nadir and 250 km at extreme off-nadir (Fleig, 1986). TOMS works on the principle of back-scattered ultraviolet radiation at several wavelength pairs in ultraviolet and visible portions of the spectrum and can provide a spatial resolution of better than 100 km (Isaksen, 1988). The data that are extracted from TOMS instrument are gridded monthly averages for a total of thirteen years (1979-91).

The lower stratospheric temperatures during 1979 and 1991 are intercalibrated from the Microwave Sounding Unit (MSU) channel 4 data from the
TIROS-N Series of NOAA satellites. A thirteen year record of temperature anomalies is time-averaged months on a 2.5 grid (Spencer, 1992).

Similar changes of total ozone and monthly mean temperature have been recognized since the work of Dobson (1928). Here we seek to quantify the observed associations between monthly mean anomalies in total ozone and lower stratospheric temperatures. The most important measure of degree of association between temperature and ozone is a quantity called the correlation coefficient (Chatfield, 1970). The spatial correlation between corresponding figures is defined as:

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R = \frac{[\Omega - \Omega][T - T]}{\sqrt{[\Omega - \Omega]^2[T - T]^2}}
\]

where \( R \) is the correlation coefficient. The square brackets represent an area average, \( \Omega \) is the total ozone, and \( T \) is the temperatures. The value of the correlation coefficient indicates the degree of linear dependence between two variables.

III. Results

The total ozone and lower stratospheric temperature data are averaged monthly over a ten-year period (1981-1991). This monthly average is essential to the study of ozone-temperature variability. Figure 1a displays the long-term mean of January total ozone from 1981 to 1991. This polar stenographic color map of the NH total column values of ozone. In the lower latitudes and around the equator are low values of ozone. As latitude increases, there are high values of ozone. Directly over the pole, there are missing data. The data can not be analyzed over the pole because of polar night periods.

Variations in ozone at different latitude are due to wave activity. Wave activity is produced by topography and heating contrasts of the ocean. As the air
heats up, it causes general circulation of the stratosphere which tends to effect the overall ozone column.

Figure 1b shows the long-term mean of January temperature (1979-1991). In the lower latitudes and around the equator, there are low temperatures. Towards the pole there is a distinct warming effect. These variations in temperature are also affected by wave activity.

The relationship of wave activity in the long-term mean of January ozone-temperature is nearly identical. Such a positive coherence can be readily explained by evoking adiabatic vertical air motion. Figure 2 shows how vertical motion does contributes to changes of total ozone. Moreover, lower stratospheric temperatures are also affected by vertical motion. In conjunction, ozone and temperature decrease with vertical motions, which reveals the highly significant positive correlation between total ozone and temperature.

Figure 3 shows the January 1983 total ozone. In lower latitudes and around the equator, low values of ozone appear. Towards the pole there are high values of ozone. Directly over the pole, there are missing data. To determine the differences of every month over a thirteen-year analysis, total ozone and the long-term mean are needed. The long-term mean of January ozone is subtracted from total ozone. These differences are called anomalies. The same procedure is used for lower stratospheric temperatures. Figure 4a and Figure 4b clearly indicate a nearly identical spatial pattern. The January 1983 ozone and temperature anomalies display low values at low latitudes and high values at the pole. The patterns and magnitude are in good overall agreement. Another example of ozone-temperature anomalies is Figure 5a and Figure 5b, which also establish similar spatial patterns.
Figure 1a. Long-term mean of January total ozone
Figure 1b. Long-term mean of January temperature
Figure 2. The adiabatic upward air motion at the tropopause level pushes ozone-poor air in the lower stratosphere which leads to the net decrease of total ozone. The stippled area represents the atmospheric column. The heavy arrows indicate a (temporary) upward displacement of lower stratospheric air within the column.
Figure 3. January, 1983 total ozone.
Figure 4a. January, 1983 ozone anomaly
Figure 4b. January, 1983 temperature anomaly
Figure 5a. January, 1982 ozone anomaly
Figure 5b. January, 1982 temperature anomaly
To demonstrate and quantify the high spatial correlations that are found between ozone and temperature anomalies (1979-1991), the year-to-year changes of these quantities are analyzed in detail.

Figure 6a shows the January ozone-temperature correlation from 1979 to 1991. In the SH at 50° to 60° latitude there is a high correlation. Over the tropics there tends to be low correlation because of small amplitude waves. In addition, the NH at 50° to 60° latitude has high correlation. (There is some variability within the correlations.) Figure 6b shows the October ozone-temperature correlation from 1979 to 1991. It also indicates the high correlation at high latitudes and low correlation over the tropics. However, the October 1987 ozone-temperature anomalies are not very well correlated in the SH at 50° to 60° latitude. Figure 7a and Figure 7b indicate this low correlation. The October 1987 ozone anomaly at low latitudes has negative values, and the October 1987 temperature anomaly at low latitudes has positive values; therefore, the correlation between ozone and temperature is low.

The evolution of the flow in individual years departs significantly from its mean as events of wave, mean-flow interaction develop at different times in different years. The time evolution of temperature and ozone is averaged between 50° to 60° S and between 50° to 60° N. Figure 8a shows the seasonal evolution (50° to 60° S) from 1981 to 1991. The largest interannual differences appear in October and early November. Figure 8b shows the seasonal evolution (50° to 60° N) from 1981 to 1991. The largest interannual differences appear in February and March.

Figure 9a displays a thirteen-year (1979-1991) analysis of ozone and temperature anomalies in the SH. The shaded areas and dashed lines represent negative anomalies. The solid lines represent positive anomalies. From 1979 to 1984, there are positive anomalies; however, from 1985 to 1991, negative
Figure 6a. January ozone-temperature correlations, 1979-1991
Figure 6b. October ozone-temperature correlations, 1979-1991
Figure 7a. October, 1987 ozone anomaly
Figure 7b. October, 1987 temperature anomaly
Figure 8a. Seasonal Evolution in the SH
Figure 8b. Seasonal Evolution in the NH
Figure 9a. Ozone and Temperature anomalies in the SH, 1979-1991
Temperature anomaly 50-60,NH Ozone anomaly

1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991

Figure 9b. Ozone and Temperature anomalies in the NH, 1979-1991
anomalies are distinctly displayed. Figure 9b shows a thirteen-year (1979-1991) analysis of ozone and temperature anomalies in the NH. The shaded areas and dashed lines represent negative anomalies. The solid lines represent positive anomalies. In addition, more negative anomalies appear in the NH than in the SH. As pointed out before, it is well known that very small shifts, in the atmospheric waves and large circulation patterns, can result in dramatic changes in ozone and temperature; therefore, interannual variations of total ozone are found to be coherent with lower stratospheric temperatures.

IV. Summary and Discussion

Calculations of the long-term averaged annual ozone variation from the thirteen-year data set have shown significant correlations with lower stratospheric temperatures. The observed ozone-temperature changes are consistent with those predicted for air parcels which are displaced vertically from constant-pressure surfaces as the parcels move adiabatically in the lower stratosphere (Newman and Randel, 1988). The interannual variability of total ozone and lower stratospheric temperatures indicates an intimate interaction of transport and dynamics.

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BIBLIOGRAPHY