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"Statistical Analysis and Interpretation of
Stratospheric Ozone and Temperature Trends"

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The overall objective of the research conducted under this contract was to reduce uncertainties concerning anthropogenic changes to the ozone distribution, their causes, and possible climatic interactions. Specific tasks were to (1) more completely determine the spatial (latitude, longitude, altitude) and seasonal dependences of trends in stratospheric and upper tropospheric (above 10 km) ozone; and (2) to evaluate the origin of midlatitude lower stratospheric ozone trends by analyzing physical relationships between these trends and stratospheric temperature trends. A major motivation for the research is the fact that observed negative column ozone trends at northern midlatitudes are significantly larger than predicted by current models that include known chemical losses in the presence of anthropogenic chlorine and bromine. An additional physical process was apparently causing additional decreases in column ozone. It was important to resolve this issue in order to quantify the relative importance of chemical and dynamical processes in producing midlatitude lower stratospheric ozone trends.

The single most important accomplishment that resulted from this research project was the conclusion that "dynamical forcing" associated with tropospheric climate change is an important contributor to midlatitude total ozone trends as derived from temporally limited satellite data sets, both for the zonally asymmetric trend component [Hood and Zaff, 1995] and for the zonal mean trend in winter [Hood et al., 1997]. One specific symptom of the existence of a dynamical component of column ozone trends is an observed long-term increase in the frequency and sizes of short-term total ozone reductions (e.g., mini-hole events) in winter and spring whose occurrence depends on climatic conditions [McCormack and Hood, 1997b]. While the dynamical transport processes associated with these reductions act mainly to redistribute ozone molecules over time scales of a few days rather than to destroy them, their influence on the total column amount is significant. Our initial conclusion has been supported by several independent studies [Fortuin and Kelder, 1996; Peters and Entzian, 1996; Chandra et al., 1996; Ziemke et al., 1997; Fusco and Salby, 1997].

Our most recent work (completed after the termination of our DOE grant with support from the NASA ACMAP) has obtained evidence that the mean meridional wind shear in the lower stratosphere at northern midlatitudes has tended to become less cyclonic with time over the period from 1979 to 1998. In other words, the zonal wind has tended to increase in strength near 55° - 60°N and has decreased in strength near 35° - 40°N. This finding is consistent with previous reports of increases in the strength of the polar vortex near 60°N, for example. The latter zonal wind trends and associated polar cooling are qualitatively similar to the predictions of climate models that include the radiative effects

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of increasing concentrations of combined greenhouse gases.

Because the wind shear has tended to become less cyclonic at midlatitudes, conditions have become more favorable for the occurrence of anticyclonic, poleward Rossby wave breaking events that transport low PV, ozone-poor air from the subtropical upper troposphere to the midlatitude lower stratosphere. The increased occurrence of these wave-breaking events (the most extreme example of which is an ozone mini-hole) has led to decreases in the mean winter/spring column ozone abundance at northern midlatitudes that are independent of those being caused by chemical loss processes. Using regression relationships between 330 K PV and total ozone derived from monthly mean measurements, we estimate that as much as 40% of the zonal mean total ozone decline at midlatitudes in February is caused by trends in wave-breaking behavior; as much as 25% of the zonal mean trend in March is caused by the same process. In some regions, e.g. the eastern Atlantic and western Europe, this dynamical mechanism has dominated over chemical processes in producing observed ozone reductions in late winter. In other areas (e.g., over the southern tip of Greenland), zonal wind trends are opposite to the zonal mean tendency so that column ozone amounts have actually increased with time.

Our specific progress toward the research objectives stated above is given below in the form of summaries of research publications that resulted from the proposed work.

First, we collaborated with others at GSFC to obtain an initial statistical estimate of the trend in stratospheric ozone as a function of altitude. In a resulting paper, (*Hood et al., Altitude dependence of stratospheric ozone trends based on Nimbus 7 SBUV data, GRL, v. 20, 2667-2670, 1993*), a multiple regression statistical model was applied to estimate the altitude, latitude, and seasonal dependences of stratospheric ozone trends using 11.5 years of Nimbus 7 SBUV data for the period November 1978 to June 1990. In the upper stratosphere, the derived trends agreed in both latitude dependence and approximate amplitude with published predictions from stratospheric models that consider gas-phase chemical processes together with the observed ~ 0.1 ppbV per year increase in tropospheric chlorine. The dominant contribution to column ozone trends occurred in the lower stratosphere where significant negative trends were present at latitudes $> 20^\circ$ in both hemispheres. The observed latitude dependence was qualitatively consistent with model predictions that include the effects of heterogeneous chemical ozone losses on lower stratospheric aerosols.

In a second effort, we completed a quantitative investigation of the hypothesis that lower stratospheric temperature trends, including latitude, longitude, and seasonal dependences, can be explained as due to radiative equilibrium temperature changes associated with anthropogenic ozone declines. For this purpose, we applied a one-dimensional radiative transfer model with fixed dynamical heating to calculate the approximate latitude and seasonal dependences of lower stratospheric temperature changes associated with observed ozone trends (*McCormack and Hood, Relationship between ozone and temperature trends in the lower stratosphere: Latitude and seasonal dependences, Geophys. Res. Lett., v. 21, p. 1615, 1994*) The model employed was the radiative code from NCAR's Community Climate Model Version 2 (CCM2). The calculated temperature trends agreed roughly with those derived by W. Randel in 1994 from MSU Channel 4 data. This result therefore

supported the above hypothesis. However, only zonal mean quantities were considered and no demonstration of cause and effect was possible. Also, since ozone trends were regarded as given, no explanation was possible for the discrepancy between observed and modeled ozone trends at northern middle latitudes in winter.

In a third effort, an investigation of the origin of the observed strong longitude dependence of northern hemisphere winter ozone trends was conducted. For this purpose (*Hood and Zaff, Lower stratospheric stationary waves and the longitude dependence of ozone trends in winter, J. Geophys. Res., v. 100, p. 25791, 1995*), we first applied a standard multiple regression statistical model to determine trends in total ozone and lower stratospheric temperature as a function of geographic position in the northern hemisphere. Trends and associated errors were estimated for the period 1979 to 1991 for which Version 6 TOMS data were available. During the northern winter when ozone trends are largest at middle latitudes, it was found (following earlier work by Stolarski et al., *Science*, 1992) that a strong longitude dependence for the observed trends existed. Moreover, as found also by Randel and Cobb (*J. Geophys. Res.*, 1994), there was a close correlation between the geographic dependences of total ozone trends and those of lower stratospheric temperature trends for any given month. (A later analysis showed that trends in lower stratospheric geopotential heights were inversely correlated with total ozone trends.)

Briefly, in the paper by Hood and Zaff, we constructed mean geopotential height fields (using NMC data) for the early 1980's and the late 1980's, averaging over three years of equal QBO phase to minimize effects of the QBO. We then used a mechanistic dynamical forcing model previously applied, for example, by Kurzeja (*J. Atmos. Sci.*, 1984) to calculate the corresponding mean geographic distributions of total ozone for January for each of these two periods. We then subtracted one from the other to obtain a model ozone anomaly. The resulting ozone anomaly field closely resembled that obtained directly from the TOMS data and was also similar to the distribution of linear trends. This showed that the longitude dependence of the trends was caused primarily by changes in the amplitudes and phases of quasi-stationary waves between the early 1980's and the late 1980's. In support of this conclusion, lower stratospheric geopotential height differences or anomalies between the early and late 1980's were inversely correlated with the geographic distribution of total ozone trends. We therefore concluded that the observed longitude dependence of winter total ozone trends during the 1980's is most probably a consequence of decadal climate variability in the troposphere (which determines the changes in quasi-stationary wave structure).

During 1996, as part of John McCormack's dissertation work, we undertook a study similar to that of Hood and Zaff but directed toward modeling interannual variability of the distribution of total ozone (*McCormack and Hood, J. Geophys. Res., v. 102, p. 13711, 1997a*). In this paper, a form of the linearized steady state ozone continuity equation was applied to model deviations from the zonal mean of total ozone at a series of northern latitudes in winter. Lower stratospheric (MSU Channel 4) temperatures, Berlin geopotential heights, and climatological ozone mixing ratios were used to calculate mixing ratio perturbations for a given location at several pressure levels in the lower stratosphere. These values were then summed to obtain an estimate of the total ozone perturbation at a series of northern

latitudes during January and February. Much of the observed year-to-year variability in the spatial distribution of total ozone was approximately simulated in this way. A significant decrease of the wave-induced variance in the wintertime total ozone distribution over the 1979-1991 period was indicated, consistent with the observed longitude dependences of total ozone trends in NH winter.

In view of the importance of quasi-stationary wave variability in producing the observed longitude dependence of total ozone trends in winter, a major focus of our research during the last 3 years has been the development of a method for estimating possible dynamical contributions to zonal mean total ozone trends. It has been our hypothesis that these contributions could account for the large differences between observed total ozone trends in winter and those that are predicted by models that account primarily for chemically induced ozone losses. In a recent paper (Hood, McCormack, and Labitzke, *An investigation of dynamical contributions to midlatitude ozone trends in winter*, *J. Geophys. Res.*, 102, p. 13079, 1997), we have reported the results of this effort. First, empirical relationships were determined between total ozone, 100 hPa temperature, and 100 hPa geopotential height as a function of latitude in the NH on the basis of a single year of daily global measurements. These relationships are approximately valid for advective forcing of the lower stratosphere occurring on timescales shorter than the odd oxygen lifetime and the radiative lifetime, that is ≤ 1 month. Monthly anomalies (i.e., deviations from monthly climatological means) of 100 hPa temperature and height were also calculated at northern midlatitudes where the correlation with total ozone variations is largest. The derived linear regression relationships between total ozone and 100 hPa temperature and height were then applied together with the observed monthly temperature and height anomalies to estimate the component of total ozone variability at northern midlatitudes that results from month-to-month differences in advective transport. At 45°N, this empirical method successfully simulated a large part of the observed zonal mean total ozone variability over the period 1979-1991. In order to estimate the advective transport contribution to total ozone trends, we applied a multiple regression statistical model to empirical model time series for latitudes of 10°N to 60°N. The resulting model trend component at northern midlatitudes in February had a longitude dependence consistent with that of the observed ozone trends and had a latitude dependence that also agreed with that of the observed trends, peaking at midlatitudes and decreasing at higher latitudes. Subtracting the estimated advective contribution from the observed trends yielded a residual meridional trend profile that agreed more closely in latitude dependence and amplitude with two-dimensional stratospheric model estimates.

The empirical analysis of Hood et al. (1997) provided evidence that interannual changes in the transport of ozone occurring on time scales of one month or less may have contributed substantially to northern midlatitude total ozone trends in winter. In an effort to identify more specifically the dynamical processes that are involved, we completed a study of the frequency and size of ozone "mini-hole" events at northern midlatitudes in winter (McCormack and Hood, *Geophys. Res. Lett.*, v. 24, 2647-2650, 1997b). Briefly, ozone mini-hole events represent localized regions of low total ozone values (< 300 Dobson Units) that persist for several days over extratropical latitudes in winter. These events are usually associated with breaking Rossby waves in the upper troposphere that allow

poleward injections of ozone-poor, low potential vorticity (PV) tropospheric air into the lower stratosphere. Using daily TOMS total ozone data together with daily PV maps derived from reanalyzed NCEP data, the interannual variability of ozone mini-hole events in the northern hemisphere was investigated for the month of February during the 1979–1993 time period. For this purpose, the total area of anomalously low total ozone and PV between 40°N and 60°N and between 90°W and 90°E was computed for February of each year. The values of low total ozone and low PV areas both peak during February of 1988, 1989, and 1990, coincident with the lowest monthly zonal mean total ozone values observed at northern midlatitudes prior to the Pinatubo eruption. The frequency of intense anti-cyclones that lead to mini-hole events over Europe is a function of climatic conditions as monitored specifically by the North Atlantic Oscillation (NAO) index. The NAO index has been increasing generally since the 1970's and reached maximum values during the same years (1988–90) when zonal mean ozone values were lowest. We have therefore drawn a preliminary conclusion that tropospheric climate change is ultimately responsible for part of midlatitude ozone trends. The causes of tropospheric climate change (anthropogenic or natural) remain controversial and are continuing to be studied by a large number of researchers. If the observed changes are anthropogenic (associated with CO₂ increases, for example), then these results would represent evidence for an additional, unanticipated anthropogenic source of total ozone trends in winter.