Conf-910143--4

UCRL-JC--106108

DE91 007132

SOLAR VARIATIONS AND THEIR INFLUENCE ON TRENDS IN UPPER STRATOSPHERIC OZONE AND TEMPERATURE

Donald J. Wuebles
Douglas E. Kinnison

This paper was prepared for submittal to
Second Symposium on Global Change Studies
AMS 71st Annual Meeting, January 13–18, 1991
New Orleans, Louisiana

October 1990

Lawrence Livermore National Laboratory

DISCLAIMER

SOLAR VARIATIONS AND THEIR INFLUENCE ON TRENDS IN UPPER STRATOSPHERIC OZONE AND TEMPERATURE

Donald J. Wuebbles and Douglas E. Kinnison

Atmospheric and Geophysical Sciences Division
Lawrence Livermore National Laboratory
Livermore, CA 94550

and

Judith L. Lean

E.O. Hulbert Center for Space Research
Naval Research Laboratory
Washington, D. C. 20375

1. INTRODUCTION

Over the past decade, knowledge of the magnitude and temporal structure of the variations in the sun's ultraviolet irradiance has increased steadily. A number of theoretical modeling studies (Penner and Chang, 1978; Callis and Nealy, 1978; Callis et al., 1979; Brasseur and Simon, 1981; Natarajan et al., 1981; Garcia et al., 1984; Brasseur et al., 1987) have shown that changes in the solar ultraviolet (UV) flux during the 11-year solar cycle can have a significant effect on stratospheric ozone concentrations. With the exception of Brasseur et al. (1987), who examined a very broad range of solar flux variations, all of these studies assumed much larger changes in the ultraviolet flux than measurements now indicate. These studies either calculated the steady-state effect at solar maximum and solar minimum or assumed sinusoidal variations in the solar flux changes with time. It is now possible to narrow the uncertainty range of the expected effects on upper stratospheric ozone and temperature resulting from the 11-year solar cycle. A more accurate representation of the solar flux changes with time is used in this analysis, as compared to previous published studies.

This study also evaluates the relative roles of solar flux variations and increasing concentrations of long-lived trace gases in determining the observed trends in upper stratospheric ozone and temperature. The LLNL two-dimensional chemical-radiative-transport model of the global atmosphere is used to evaluate the combined effects on the stratosphere from changes in solar ultraviolet irradiances and trace gas concentrations over the last several decades. Derived trends in upper stratospheric ozone concentrations and temperature are then compared with available analyses of ground-based and satellite measurements over this time period.

2. SOLAR UV IRRADIANCE VARIATIONS

The 11-year solar cycle variation has not yet been measured with sufficient accuracy over an entire cycle, primarily because of difficulties with satellite instrumentation (Rottman, 1988; Herman et al., 1990). Currently, the most reliable long term UV data are of the Lyman alpha (Lα) irradiance at 121.567 nm measured by the Solar Mesosphere Explorer (SME) satellite. These data, which extend from late 1981 until the measurements ended in 1989, are shown in Figure 1. This time series has been extended back to 1974, the beginning of solar cycle 21, by making use of the high correlation between variations in the Lα irradiance and in the Helium 1083 nm equivalent line width (Lean, 1990).

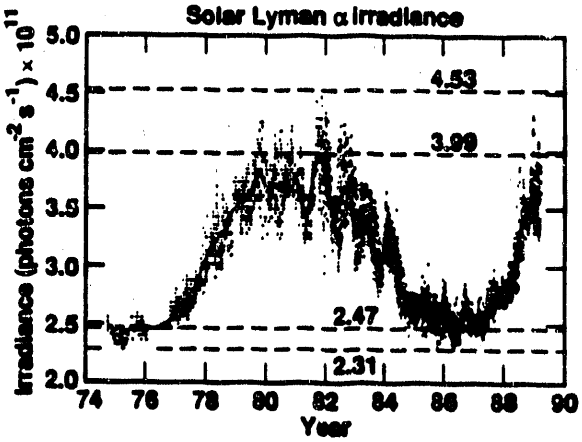

Fig. 1. Time series of Lyman alpha irradiance determined from SME measurements from 1981 to 1989, and extended back to 1974 by using high correlation with variations in the Helium 1083 nm ground-based measurements. Also shown are the maximum and minimum daily values over the entire time period, and the maximum and minimum values of a 180-day running mean (shown by the dark line) through the daily data.

Solar spectral irradiances at wavelengths greater than 180 nm are of importance to stratospheric ozone. However, in lieu of an accurate experimental determination of the solar cycle variations in the UV spectral irradiance at these wavelengths, it is possible to make use of the strong correlation between variations in the Lyman alpha irradiance and variations in the irradiance at higher UV wavelengths (Lean, 1987). There is an extremely high correlation for a number of solar rotations between the Lα irradiance measured by SME and the irradiance at 205 nm measured by the Solar Backscattered Ultraviolet (SBUV) spectrometer on the Nimbus-7 satellite. Assuming that this relationship holds over longer time scales, the long term Lyman alpha data can then be used to predict both the amplitude and temporal structure of longer wavelength UV irradiances throughout the solar cycle. A 0.5-year running mean of the detailed variations in Figure 1 was used to smooth the representation of the long term solar cycle variations for input into the model simulations (see solid line in Figure 1).

The magnitude of the solar irradiance changes from solar minimum to solar maximum at specific UV wavelengths remains uncertain. Because of this uncertainty, two different wavelength dependences, shown in Figure 2, were assumed in the model calculations. Recent analyses suggest that at 205 nm,the solar maximum irradiance is larger than than the solar minimum irradiance by six to nine percent. The larger value is consistent with analyses of the Mg index data from SBUV measurements (Heath and Schlesinger, 1984; Schlesinger et al., 1990). The most recent estimates from SME data indicate a solar cycle variation at 205 nm closer to 6 percent (Rottman, 1988; London and Rottman, 1990). In this study, the wavelength variations for the larger (9% at 205 nm), referred to as the normal, dependence were based on the earlier SBUV analysis. These values were scaled by a factor of two thirds to give the smaller, or reduced, dependence, based on the 205 nm analyses. There is some indication in the recent data analyses, however, that such a scaling to account for the uncertainty range may not be applicable evenly at all wavelengths; the most recent analyses of the SME data and the SBUV/Mg index data both suggest a solar cycle variation of about 4% at 250 nm.

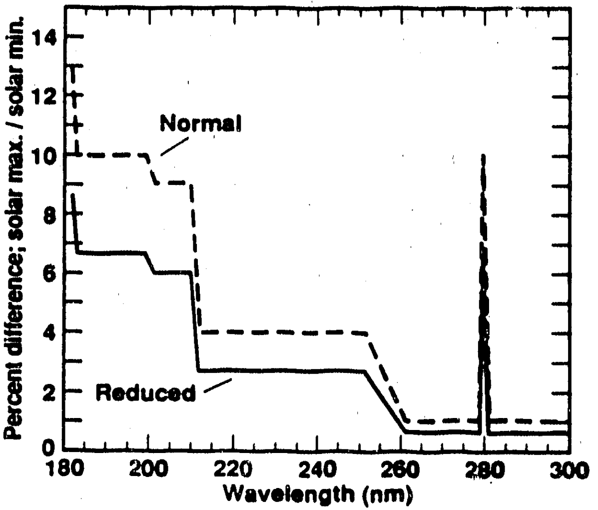

Fig. 2. Wavelength dependence of the solar cycle variations from solar minimum to solar maximum assumed in this study. Two different curves were assumed because of remaining uncertainties in this dependence.

3. HISTORICAL CHANGES IN THE TRACE GAS CONCENTRATIONS

The increasing tropospheric concentrations of several radiatively and chemically important trace constituents are represented in the model calculations. Historical trends in the surface concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), several chlorofluorocarbons (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115) and other halocarbons (CCl_4, CH_3CCl_3, Halon-1211 and Halon-1301) are included in the calculations. The assumed histories of these trace gas concentrations are based on WMO (1989). These historical records were based on trends derived from atmospheric measurements in concert with available estimates of pre-industrial concentrations from ice core data. Of particular importance in determining the effects on upper stratospheric ozone and temperature over the last twenty years is the increasing concentration of CFCs plus other halocarbons (4% per year for CFC-11 and CFC-12; 10% per year for CFC-113) and carbon dioxide (0.4% per year). Changes in surface emissions of NO_x, CO and other gases primarily affecting tropospheric chemistry were not included in this study.

4. THE LLNL TWO-DIMENSIONAL MODEL

The LLNL two-dimensional chemical-radiative-transport model determines the zonally-averaged composition and distribution of trace constituents in the troposphere, stratosphere, and lower mesophere. This model contains a numerical representation of the physical and chemical processes that control the concentrations of 35 chemically active constituents, based on more than 100 chemical and photochemical reactions. These concentrations are calculated as a function of altitude, latitude, and season within the model. The model domain extends from pole to pole, and from the ground to 60 km. Reaction rates, absorption cross sections, and quantum yields are based on the recommendations of the NASA Panel for Data Evaluation (Demore et al., 1987).

Essentially the two-dimensional model determines the atmospheric distribution of ozone and other important constituents based on the interactions of chemical, radiative, and dynamical processes thought to be operating in the global atmosphere. The diabatically-driven circulation is determined using net heating rates calculated in an internally consistent way with the derived species distributions for the reference (circa mid-1980s) atmosphere, with temperatures varying over the annual cycle based on the data analyses of Barnett and Corney (1984). The net heating rates are derived from solar and infrared radiative transfer submodels. A perturbation form of the thermodynamic equation is solved for the changes in stratospheric temperatures resulting from trends in ozone and other radiatively important trace constituents. In determining temperature changes, the diabatic circulation is assumed to be unchanged from that determined for the reference atmosphere.

5. SOLAR CYCLE EFFECTS

Figure 3 shows the derived change in total ozone from solar maximum (reached in 1981) to solar minimum (1987) due to solar variability only for the normal wavelength variation case. The model results indicate a global-average change in total ozone of about 1.7 percent from solar maximum to solar minimum, with minor variations in the change in total ozone as a function of season and latitude. The reduced wavelength variation gives a change in global-average total ozone of about 1.2% from solar maximum to solar minimum, with latitudinal and seasonal variations similar to the larger case. Although not presented here, concentrations of many other stratospheric constituents, such as the nitrogen oxide species, also have significant solar cycle variations.

Analyses of ground-based and satellite measurements of total ozone have determined solar cycle effects on total ozone comparable to those calculated here. However, the data analyses are not accurate enough to better define the solar cycle effect beyond the range determined in the model calculations. The most recent analyses, by Reinsel et al. (1988) and WMO (1989), have determined globally averaged changes in total ozone from solar maximum to solar minimum of 1.46 ± 0.92% and 1.2 ± 0.4%, respectively.

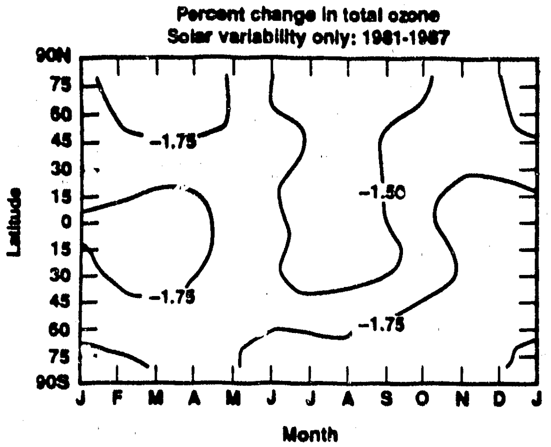

Fig. 3. Calculated percentage change in total ozone from solar maximum (in 1981) to solar minimum (1987) due to the effects of solar variability only, for the case with the larger assumed solar ultraviolet variations with wavelength.

Garcia et al. (1984) calculated large variations in total ozone as a function of latitude in their evaluation of the 11-year solar cycle. In their two-dimensional model calculations, they determined increased ozone from solar minimum to solar maximum in the tropics and mid-latitudes, with a decrease in ozone towards the poles. These large variations resulted from the downward transport to the stratosphere of nitrogen oxides produced by auroral particle precipitation at altitudes in the thermosphere (>90 km). The variation in the production of nitrogen oxides due to auroral particle precipitation was not included in the calculations presented here. However, analyses of the solar cycle effects in total ozone data do not indicate any apparent relationship in the solar-induced variations of ozone with latitude (WMO, 1989; Reinsel et al., 1988), suggesting that the variations in nitrogen oxide production in the thermosphere do not have a significant effect on stratospheric ozone.

The calculated change in ozone (for January) as a function of altitude and latitude due to the normal wavelength dependence in the solar variations is shown in Figure 4. The largest ozone decrease from solar maximum to solar minimum occurs near 40 km altitude, with a latitudinal-averaged change in ozone of about 3% at 40 km altitude. The smaller wavelength dependence gives a change in ozone of about 2%. Although the latitudinal and seasonal effects are small, the largest solar maximum to solar minimum effects on ozone were found during the late winter at mid-to-high latitudes. Recent analyses of Umkehr observations (WMO, 1989) suggest that the maximum effect of solar variability on ozone occurs in Umkehr layer 8, at altitudes near 40 km. The model-derived effects on ozone in Umkehr layer 8 for the two assumed wavelength dependences are well within the 2.2 ± 1.4% change in ozone from solar maximum to solar minimum determined from the measurements at 10 Umkehr stations in the Northern Hemisphere.

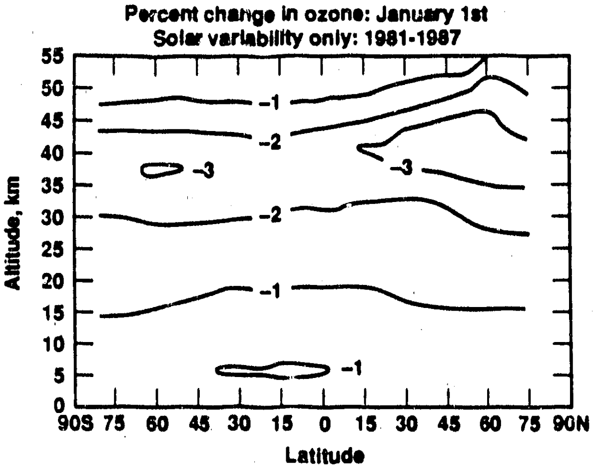

Fig. 4. Calculated percentage change in ozone (for January) as a function of altitude and latitude due to the effects of solar variability only, for the case with the larger assumed solar ultraviolet variations with wavelength.

Figures 5a and 5b show the model-calculated effects of solar variations (for the larger wavelength dependence) on ozone with altitude at a single latitude, 42°N, relative to the ozone concentrations in 1979. Note that seasonal variations in ozone have been removed. It is interesting to note that solar cycle effects are found well into the troposphere, with a change in ozone of about 0.7% determined from solar maximum to solar minimum in the middle troposphere. As shown in Figure 2, the solar variations were assumed to extend to 300 nm; it is the variations at the longer wavelengths that penetrate far enough into the troposphere to cause the derived effects on tropospheric ozone. Figure 5d shows, however, that increasing tropospheric ozone as a result of trace gas emissions, particularly from increasing methane concentrations, would make it difficult to determine a solar cycle effect in the troposphere from atmospheric measurements.

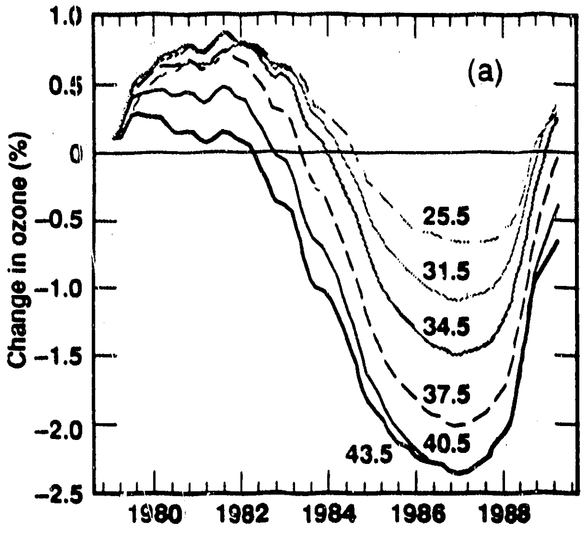

Fig. 5(a)

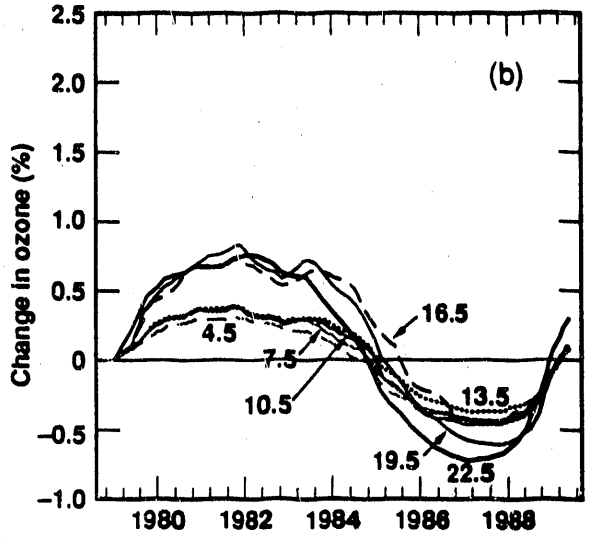

Fig. 5(b)

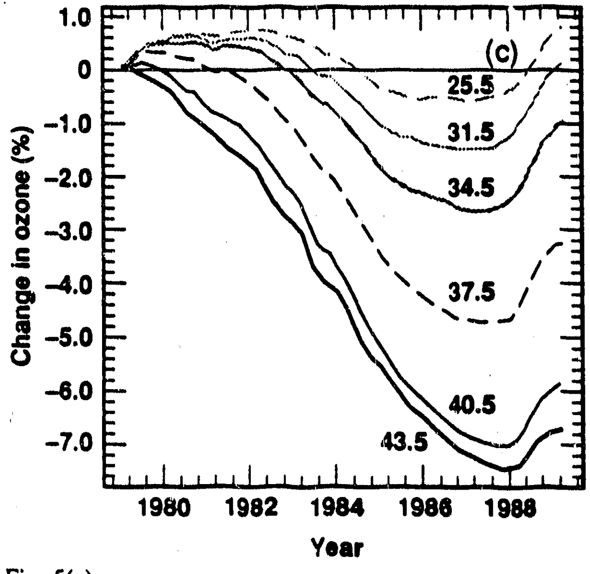

Fig. 5(c)

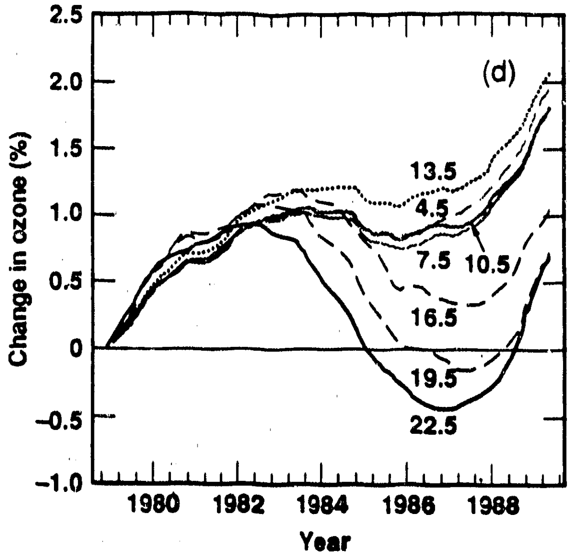

Fig. 5. Model-calculated effects of solar variations only (5a and 5b) and solar variations plus trace gas emissions (5c and 5d) on ozone with altitude at a single latitude, 42°N, relative to the ozone concentrations in 1979. Seasonal variations in ozone have been removed. The solar variations are based on the larger assumed wavelength dependence case.

The calculated effects of the solar variations on temperature are largest in the upper stratosphere, with a maximum effect near the stratopause, at approximately 50 km altitude. The maximum change in temperature calculated from solar maximum to solar minimum is 0.75 K to 1 K, depending on the wavelength dependence assumed for the solar variations. There are not any published estimates of the solar cycle effect on stratospheric temperatures from available observations, although Angell (1987) found that the upper stratospheric temperatures did vary in phase with the solar cycle.

6. TRENDS IN OZONE AND TEMPERATURE

The effects of the Antarctic ozone hole and its dilution effects have not been included in the calculations presented here. Because these and other possible effects on trends in lower stratospheric ozone have not been considered, this study will not compare the calculated trends in total ozone with available observations other than to note that the model calculations including solar variability and trace gas emissions clearly underestimates the ozone decrease found in the ground-based total ozone data since 1970 (WMO, 1989). As satellite data is only available after late 1978, with trend analyses determined through 1986, the model calculations presented will focus primarily on the time period from 1979 through 1986.

Figure 6 shows the model-calculated change in ozone from 1979 to 1986 for January due to the effects of solar variability (for the larger wavelength dependence) and trace gas emissions. Although ozone decreased throughout most of the stratosphere over this period, the largest calculated decrease occurs between 40 and 45 km, reaching a maximum 8% decrease at the winter high latitudes. This is significantly larger than the -3 to -5% change in ozone over this period found in the difference between the SAGE I and SAGE II satellite data, although the altitudes and latitudes of the maximum effects are in good agreement between the model and observed ozone trends (WMO, 1989). The model results compare much better with the ground-based

Umkehr measurements. Using data from five northern mid-latitude Umkehr sites, with preliminary corrections for stratospheric aerosol effects, Deluisi et al.(1989) found a decrease in ozone of 8.8 ± 1% from 1979 through 1986 in Umkehr layer 8, in good agreement with the model-determined trend. In general, as shown in Figure 7, the model results for layer 8 compare well with the time trend of the Umkehr data; however, the model does not represent the variability found in the ozone data expected as a result of temperature and dynamical effects.

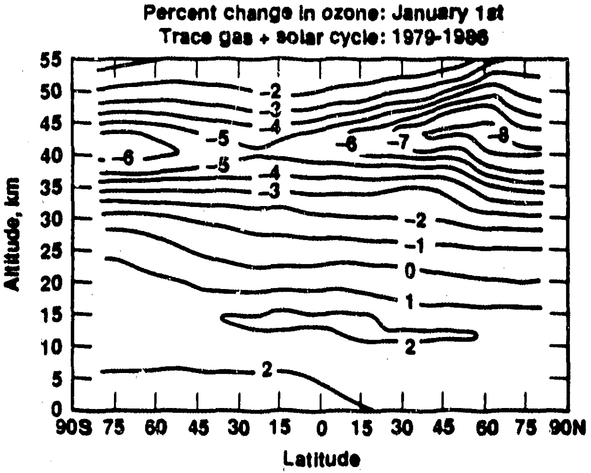

Fig. 6. Calculated percentage change in ozone from 1979 to 1986 for January due to the effects of solar variability and trace gas emissions.

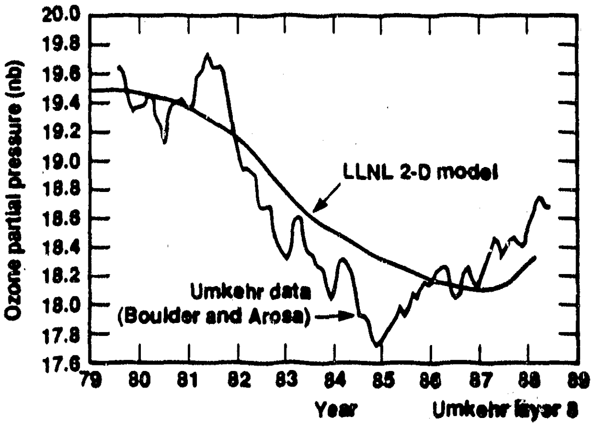

Fig. 7. Comparison of calculated time trend of ozone in Umkehr level 8 (2-4 mb) with observed trends since 1979 at Boulder and Arosa. The data is an extension of that presented by Deluisi et al. (1989) through private communication with J. Deluisi (1990).

Available satellite and rocketsonde data from 1979 to 1985 indicate that upper stratospheric (at about 48 km) temperatures cooled by 1.75 ± 1 K at equatorial latitudes and about 1.5 ± 1 K globally (WMO, 1989). Smaller trends were found at lower altitudes. The model calculated temperature trend from 1979 to 1986 for January is shown in Figure 8. The calculated trend agrees both with the altitude and magnitude of the maximum cooling seen in the observed temperature trend for the upper stratosphere. About half of the temperature change over this time period is due to solar effects, while the other half is due to cooling from increased concentrations of carbon dioxide and decreased concentrations of ozone as a result of increasing CFCs and other trace gases.

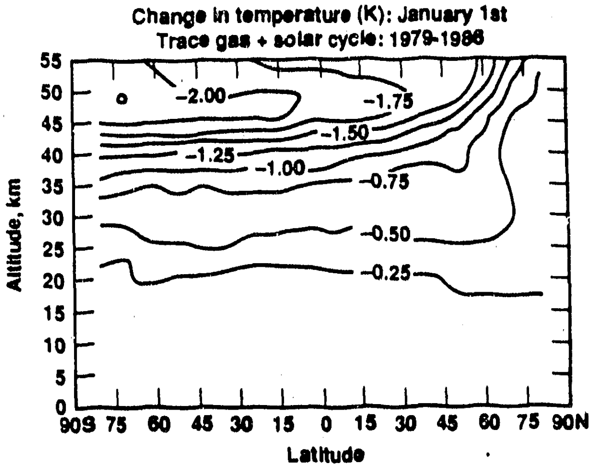

Fig. 8. Calculated change in temperature, in degrees Kelvin, from 1979 to 1986 for January due to the effects of solar variability and trace gas emissions.

7. CONCLUSIONS

The use of Lyman alpha and He 1083 nm data provide a useful surrogate for UV-solar cycle variations. The model-calculated effect on total ozone ranged from 1.2 to 1.7%, depending on remaining uncertainties in the wavelength dependence from solar maximum to solar minimum. This agrees well with available observational trend analyses. Model calculated solar effects on upper stratospheric ozone and temperature are within the uncertainty range of observational data analyses. The model calculations including both solar variability and the effects of changing trace gas emissions adequately explain the observed trends in upper stratospheric ozone and temperature from 1979 to 1986.

The model calculations examining the solar cycle UV irradiance variations indicate that current knowledge of these variations is inadequate. Improvements are needed in the measured UV irradiances in order to get an accurate measure of the solar cycle influence on stratospheric ozone and temperature. Accurate information about the true solar UV irradiance variations now await the observations from the SUSIM and SOLSTICE measurements aboard the Upper Atmospheric Research Satellite (UARS) scheduled to be launched in 1991.

ACKNOWLEDGEMENTS

Work at Lawrence Livermore National Laboratory was performed under the auspices of the U.S. Department of Energy under Contract W-7405-ENG-48 and was supported in part by DOE's Carbon Dioxide Research Program and by NASA's Upper Atmospheric Research Program.

REFERENCES

Angell, J.K., 1987: Rocketsonde evidence for a stratospheric temperature decrease in the western hemisphere during 1973-85, *Monthly Weath. Rev.*, **115**, 2569-2577.

Barnett, J.J., and M. Corney, 1984: A middle atmosphere temperature reference model from satellite measurements, *Adv. Space Res.*, **5**, 125-134.

Brasseur, G., and P.C. Simon, 1981: Stratospheric chemical and thermal response to long-term variability in solar UV irradiance, *J. Geophys. Res.*, **86**, 7343-6362.

———, A. De Rudder, G.M. Keating, and M.C. Pitts, 1987: Response of middle atmosphere to short-term solar ultraviolet variations: 2. Theory, *J. Geophys. Res.*, **92**, 903-914.

Callis, L.B., and J.E. Nealy, 1978: Solar UV variability and its effect on stratospheric thermal structure and trace constituents, *Geophys. Res. Lett.*, **5**, 249-252.

———, M. Natarajan, and J.E. Nealy, 1979: Ozone and temperature trends associated with the 11-year solar cycle, *Science*, **204**, 1303-1306.

Demore, W.B., J.J. Margitan, M.J. Kurylo, C.J. Howard, and A.R. Ravishankara, 1987: Chemical kinetics and photochemical data for use in stratospheric modeling. Evaluation number 8, JPL Publication 87-41, 196 pp., Jet Propulsion Laboratory, Pasadena, CA.

Deluisi, J.J., D.U. Longenecker, C.L. Mateer, and D.J. Wuebbles, 1989: An analysis of northern mid-latitude Umkehr measurements corrected for stratospheric aerosols for 1979-1986, *J. Geophys. Res.*, **94**, 9837-9845.

Garcia, R.R., S. Solomon, R.G. Roble and D.W. Rusch, 1984: A numerical response of the middle atmosphere to the 11-year solar cycle, *Planet. Space Sci.*, **32**, 411-423.

Heath, D.F., and B.M. Schlesinger, 1984: Temporal variability of UV solar spectral irradiance from 160-400 nm over periods of the evolution and rotation of active regions from maximum to minimum phase of the sunspot cycle, in IRS '84: Current Problems in Atmospheric Radiation, Proceedings of the International Radiation Symposium, edited by G. Fiocco, A. Deerpak Publishing, Hampton, VA.

Herman, J.R., R.D. Hudson, and G. Serafino, 1990: Analysis of the eight-year trend in ozone depletion from empirical models of solar backscattered ultraviolet instrument degradation, *J. Geophys. Res.*, **95**, 7403-7416.

Lean, J., 1987: Solar ultraviolet irradiance variations: a review, *J. Geophys. Rev.*, **92**, 839-868.

———, 1990: A comparison of models of the sun's extreme ultraviolet irradiance variations, *J. Geophys. Rev.*, in press.

London, J., and G.J. Rottman, 1990: Wavelength dependence of solar rotation and solar cycle UV irradiance variations, in *Proceedings of NASA Conference on the Climatic Impact of Solar Variability*, NASA/GSFC.

Natarajan, M., L.B. Callis, and J.E. Nealy, 1981: Solar UV variability: effects on stratospheric ozone, trace constituents and thermal structure, *Pure Appl. Geophys.*, **119**, 750-779.

Penner, J.E., and J.S. Chang, 1978: Possible variations in atmospheric ozone related to the eleven-year solar cycle, *Geophys. Res. Lett.*, **5**, 817-820.

Reinsel, G.C., G.C. Tiao, S.K. Ahn, M. Pugh, S. Basu, J.J. Deluisi, C.L. Mateer, A.J. Miller, P.S. Connell, and D.J. Wuebbles, 1988: An analysis of the 7-year record of SBUV satellite ozone data: Global profile features and trends in total ozone, *J. Geophys. Res.*, **93**, 1689-1703.

Rottman, G.J., 1988: Observations of solar UV and EUV variability, *Adv. Space Res.*, **8**, 53-66.

Shesinger, B.M., R.P. Cepula, D.F. Heath, M.T. Deland, and R.D. Hudson, 1990: Ten years of solar change as monitored by SBUV and SBUV/2, in *Proceedings of NASA Conference on the Climatic Impact of Solar Variability*, NASA/GSFC.

World Meteorological Organization (WMO), 1989: Scientific Assessment of Stratospheric Ozone: 1989, Global Ozone Research and Monitoring Project–Report No. 20.

DISCLAIMER

END

DATE FILMED

02 / 19 / 91