Terannual Wave in the Ozone and Temperature in the Strato–Mesosphere as Deduced from Satellite Measurements

C. VAROTSOS,[@] N. DRIS,[*] AND D. ASIMAKOPOULOS[**]

[@]*University of Athens, Department of Applied Physics, Laboratory of Meteorology, Athens, Greece*
[*] *Hellenic National Meteorological Service*
[**] *Institute of Meteorology and Physics of the Atmospheric Environment of the National Observatory of Athens*

26 October 1990 and 9 July 1991

ABSTRACT

Two recent reference atmosphere models for ozone and temperature, which are deduced from satellite data, are employed to detect the existence and the behavior of a terannual wave both in ozone and temperature.

Through the photochemical and the radiative processes, physical considerations are given in an attempt to explain the cause of the formation of the terannual wave.

1. Introduction

In the middle atmosphere the photochemical and radiative processes result in the air relaxation to an equilibrium state. In this respect, it is important to know the temperature dependence on the equilibrium ozone concentration.

In general, the transition from dynamical to photochemical control is usually near about 40 km, well below the stratopause, although the height level changes with location and prevailing meteorological conditions.

It has long been realized (Barnett et al. 1975) that the ozone mixing ratio should be negatively correlated with temperature at the higher levels (i.e., 40 km) and positively correlated at the lower levels. Furthermore, the temperature-dependent chemical loss of ozone arises from reactions with odd nitrogen (NO, NO_2), odd chlorine (Cl, ClO), and odd hydrogen (H, OH, HO_2), as well as the direct reaction of O and O_3. The first two mechanisms are weakly temperature dependent, while the other two depend strongly on temperature. Thus, the ozone temperature sensitivity at any given height depends on the relative contribution of each of these four mechanisms to the total ozone loss rate (Nicolet 1975).

The thermal regime of the strato–mesosphere at high latitudes is mainly controlled by sudden stratospheric warmings, which are currently observed in the early winter stratosphere and are attributed to the upward propagation of planetary waves that originate in the troposphere (Labitzke 1977; Varotsos 1989).

Major warming events are always characterized by a local increase of temperature over a deep layer lower than the stratopause, with values of the order of 50 K at 10 mb, for a few days. These events lead to significant changes in the rate constants of several chemical reactions.

The purpose of this note is to indicate the existence of a 4-month time-period wave (terannual wave) in ozone at the strato–mesosphere for both hemispheres, using the Keating and Young (1985) reference ozone model. Furthermore, the behavior of the terannual wave in ozone and temperature is discussed combining the present knowledge of photochemical and radiative processes, in an attempt to propose a plausible physical explanation for its existence.

It is noted that a long-term variation in ozone or in temperature during the months of maxima of the terannual wave might cause changes on the regional climate system.

A possible physical mechanism for the changes can be the vertical flux of trace constituents across the tropopause. This transport across the tropopause can be caused by a number of processes, including:

(i) the large-scale mean diabatic circulation (Brewer-Dobson cell);

(ii) transverse secondary circulations related to subtropical and polar jetstreams;

(iii) tropopause folding; and

(iv) turbulent mixing associated with gravity-wave breaking. For instance, the tropopause-folding process considers the deformation field, which is associated with the development of a baroclinic wave, and tends to concentrate preexisting temperature gradients. This concentration is most intense near the ground and the tropopause (Andrews et al. 1987).

Corresponding author address: Dr. C. A. Varotsos, Laboratory of Meteorology, Department of Applied Physics, University of Athens, 33, Ippokratous Str. 106 80, Athens, Greece.

2. Data and analysis

A new reference atmosphere has recently been proposed by Barnett and Corney (1985) containing information on temperature fields in the stratosphere and mesosphere for latitudes ranging between 80°S and 80°N. This model was derived from radiance data collected by the *Nimbus 5* Selective Chopper Radiometer (SCR), *Nimbus 6* Pressure Modulator Radiometer (PMR), *Nimbus 7* Stratosphere and Mesosphere Sounder (SAMS), and Lidar Mesospheric Sounder (LIMS) radiometers. The temperature profiles were obtained by combining the satellite data above 30 mb with estimates produced by the Berlin-Free University at 30 mb and the climatology proposed by Oort (1983) for 50 mb and below.

Keating and Young (1985) have recently proposed a new reference ozone model. This model contains the monthly latitudinal variations of the vertical structure that are based on the ozone data from five satellite experiments:

(i) the *Nimbus 7* (SBUV);
(ii) the *Nimbus 7* (LIMS);
(iii) the Application Explorer Mission-2, Stratospheric Aerosol and Gas Experiment (SAGE);
(iv) the Solar Mesosphere Explorer 1.27 m Airglow (SME-IR); and
(v) the Solar Mesosphere Explorer UV Spectrometer (SME-UVS).

In this point, it is worth discussing the quality of the data used for the derivation of the reference ozone model.

(i) The nadir-viewing SBUV experiment determines the vertical structure of the ozone from absorption of ultraviolet backscattered radiation between 250 and 340 nm. The resolution of the ozone measurements is about 8 km in the vertical. From validation studies that were performed on the SBUV data employing balloon-, rocket-, and ground-based Umkehr measurements, the precision of the SBUV measurements was found to be better than 8% for pressures between 1 and 64 mb (Bhartia et al. 1984).

(ii) The LIMS ozone channel (cryogenically cooled radiometer) measures emission near 9.6 μm with a field-of-view 1.8 km in the vertical and 18 km in the horizontal.

From validation studies that were performed using balloon and rocket underflights, Umkehr soundings, and Dobson measurements, the correlative data showed mean differences of less than 10% at midlatitudes for balloonborne sensors and less than 16% up to 0.3 mb for rocket data (Remsberg et al. 1984).

(iii) The SAGE instrument is a sun photometer, which measures solar intensity at sunrise and sunset.

Comparisons were also made between balloon measurements and SAGE profiles from 18 to 28 km, and average differences were found to be less than 10%. Comparisons with rocketsondes up to 60 km yielded average differences of less than 14% (McCormick et al. 1984).

(iv) Two limb-scanning experiments (SME-UVS and SME-IR) were performed aboard the Solar Mesospheric Explorer (SME) spacecraft for the mesospheric ozone densities. The random errors were estimated to be less than 10% from 50 to 82 km, while the systematic errors were estimated to be about 15% (Thomas et al. 1984).

Note that for this ozone model, data contaminated by volcanic emissions after October 1980 (including El Chichón) have been removed. The mean monthly ozone and temperature values derived by the aforementioned models were Fourier analyzed in order to investigate the third harmonic (terannual wave) for all heights and latitudes of interest. Selective results from this analysis are presented in the following section.

3. The ozone and temperature terannual wave

Figures 1a and 1b show the amplitude and phase of the terannual wave in zonal mean ozone, respectively. The percentage contribution of the wave to the total variance at each latitude is presented in Fig. 1c. It is clearly shown in Figs. 1a,b that three main maxima of the terannual wave ozone are apparent:

(a) the tropical zone maximum, which is centered at the midstratosphere and occurs in January–June (or September–October) and
(b) the two high-latitude, almost symmetric maxima near the stratopause level, which appear during February–March (June–July, or October–November) in both hemispheres.

According to Fig. 1c, all three wave maxima have a significant percentage contribution to the total variance, with the tropical maximum being the strongest.

The amplitude and phase of the terannual wave in zonal mean temperature are shown in Figs. 2a and 2b. Figure 2c presents the percentage contribution of the wave to the total temperature variance at different latitudes. As seen from this figure, the amplitude in extratropical latitudes of the Southern Hemisphere is approximately equal to the amplitude in the symmetric location of the Northern Hemisphere, in agreement with previously published work (e.g., Nastrom and Belmont 1975).

Furthermore, the amplitude of the terannual wave in the middle mesosphere shows two maxima, one relatively weaker at the northern latitudes and a second stronger one at the high latitudes of the Southern Hemisphere. Also from Fig. 2b it appears that the main maxima at the mesosphere occur during December (April or August) and February (June or October) for

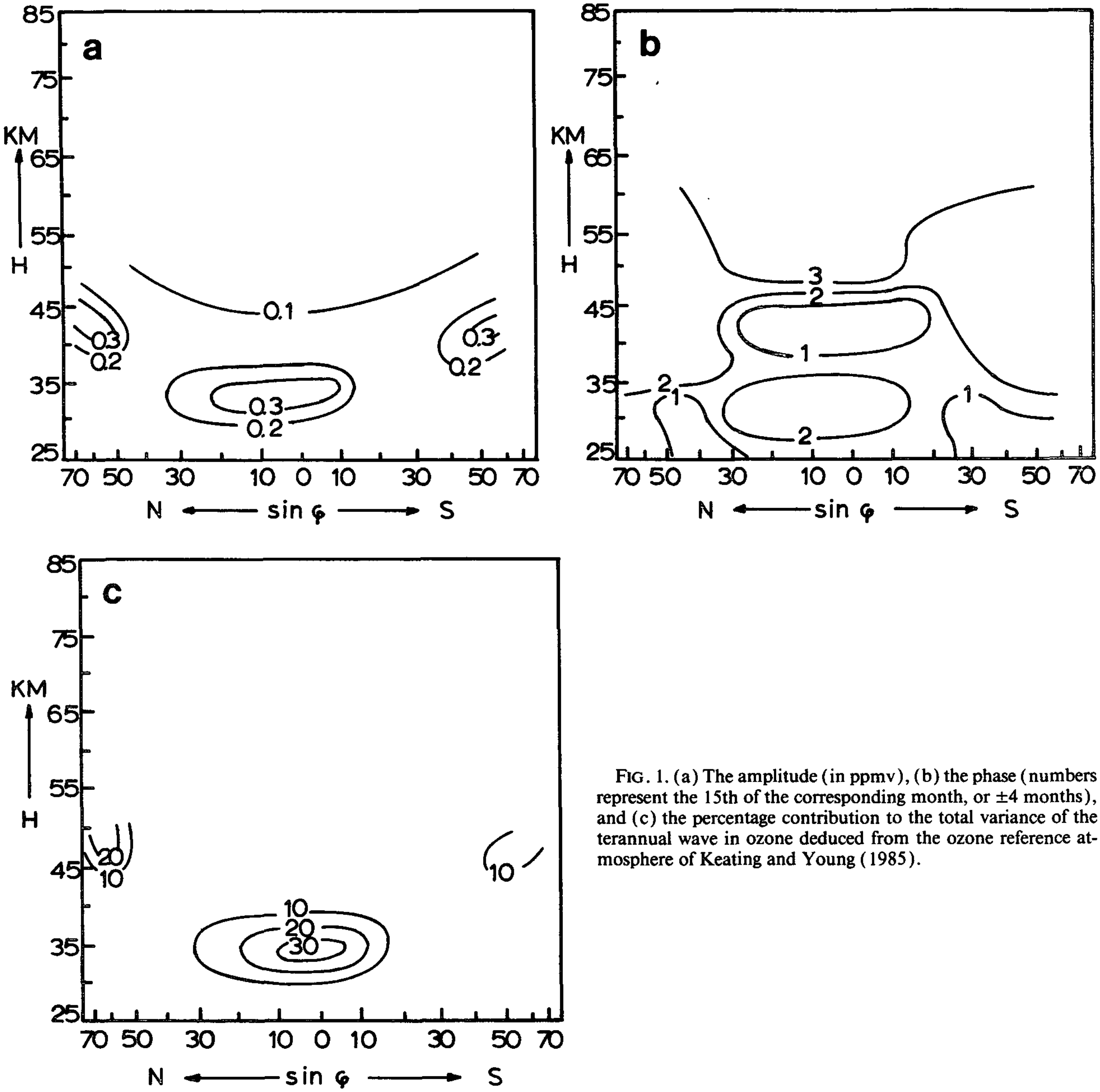

FIG. 1. (a) The amplitude (in ppmv), (b) the phase (numbers represent the 15th of the corresponding month, or ±4 months), and (c) the percentage contribution to the total variance of the terannual wave in ozone deduced from the ozone reference atmosphere of Keating and Young (1985).

the Northern and the Southern hemispheres, respectively. Inspection of Fig. 2c indicates that two maxima have a significant percentage contribution to the total variance in contrast with those of the stratosphere, where the existence of the annual and semiannual wave possibly causes the elimination of the percentage contribution to the total variance.

A first comparison between Figs. 1a and 2a indicates that the high-latitude maxima of the terannual wave in ozone lie between the maxima of the terannual wave in temperature.

4. Discussion

a. *Terannual wave in temperature*

According to Nastrom and Belmont (1975), the terannual wave in temperature arises from the square-wave character of the seasonal temperature changes, especially at high latitudes. It is known that the mean monthly temperature shows small changes during the summer and winter seasons as well as large gradients during spring and autumn. In a pure square wave the

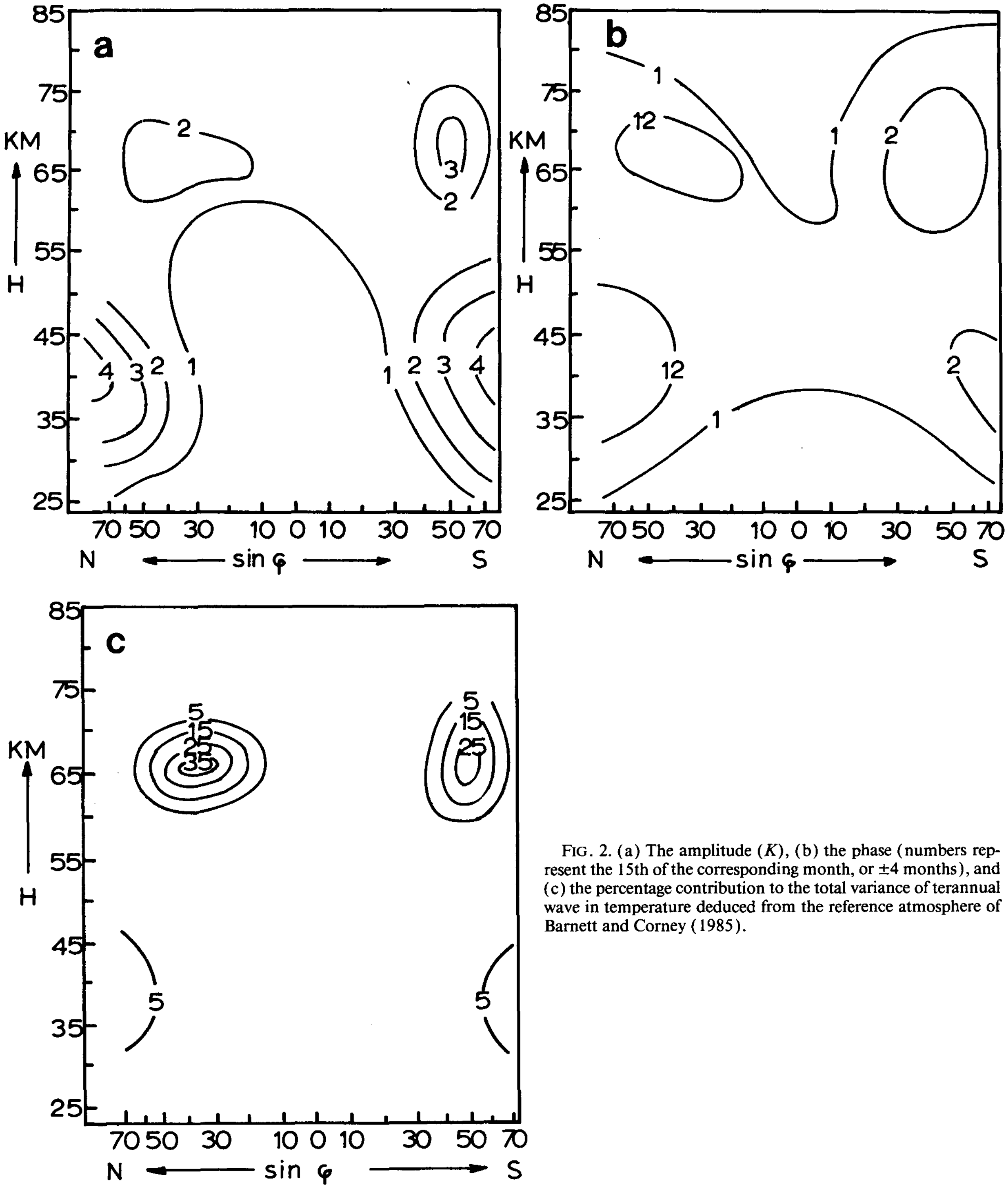

FIG. 2. (a) The amplitude (*K*), (b) the phase (numbers represent the 15th of the corresponding month, or ±4 months), and (c) the percentage contribution to the total variance of terannual wave in temperature deduced from the reference atmosphere of Barnett and Corney (1985).

phase of the third harmonic lags that of the first harmonic by one-sixth the period of the first harmonic. From Figs. 2a and 2b it can be seen that where the amplitude of the terannual wave in temperature is large, the phase data is December (April or August) for the Northern Hemisphere, which lags the phase of the corresponding annual component by 2 months (see Nastrom and Belmont 1975).

The above described consideration for the terannual wave in temperature is valid for both the stratosphere and the mesosphere.

b. Terannual wave in ozone

It is known that in the upper stratosphere, the ozone mixing ratio is essentially under photochemical control, whereas in the lower stratosphere it is under dynamic influence.

Considering the photochemical theory, the connection between ozone and temperature is described by the following well-known chemical reactions (Barnett et al. 1975):

$$O_2 + h\nu \rightarrow O + O \quad \lambda > 2450\text{ Å} \quad J_2 \quad (1)$$

$$O + O_2 + M \rightarrow O_3 + M \quad K_2 \quad (2)$$

$$O_3 + h\nu \rightarrow O_2 + O \quad \lambda < 10\,800\text{ Å} \quad J_3 \quad (3)$$

$$O_3 + O \rightarrow 2O_2 \quad (4)$$

$$O + O + M \rightarrow O_2 + M \quad K_3, \quad (5)$$

where J_i and K_i are dissociation and reaction rates, respectively. These reactions lead to the equation

$$[O_3]/[O_2] = [(J_2K_2[M])/(J_3K_3)]^{1/2}, \quad (6)$$

where the brackets indicate concentration. In the pure oxygen photochemical scheme, the main temperature quantity $(K_2/K_3)^{1/2}$ may be expected to lie between $\exp(1675/T)$ and $\exp(1330/T)$ (Barnett et al. 1975).

Although the quantity J_2/J_3 depends on the total ozone content above the level in question (a function of the temperature profile), its variation at a given level is due to variations of K_2/K_3.

By the pure oxygen photochemistry and by the scheme involving nitrogen oxides, a temperature dependence of about $1200/T$ to $1400/T$ is given for $1n[O_3]$. If the reactions that involve the hydrogen compounds dominate, a much smaller temperature dependence (i.e., $500/T$ to $330/T$) for $1n[O_3]$ is expected.

The temperature sensitivity of ozone at any given pressure depends on the relative contribution of each of these mechanisms to the total loss rate.

Using these physical aspects for the high-latitude maxima of the terannual wave in ozone near the stratopause, the following explanations can be considered.

(i) In the 35–45-km region (where both polar maxima of the terannual wave in temperature are located), the odd nitrogen (very temperature sensitive) reactions dominate the ozone loss, whereas in the region above the stratopause (where the corresponding maxima of the terannual wave in temperature are located), the pure oxygen reactions dominate. It is worth noting here that the high-latitude terannual wave center is located in the region of the rapid change shift of the annual wave.

(ii) Furthermore, the tropical center of the terannual wave in ozone can be contributed to the fact that during sudden warmings a slight increase in ozone (south of 30°N) occurs, which is probably due to the temperature decrease, which in turn leads to a somewhat lower O_3 destruction rate. The above process justifies partially the genesis of the tropical center of the terannual wave, although at these altitudes the dynamical processes dominate.

According to these dynamical processes at these low altitudes, the simplest plausible model that can explain the gross features of the meridional distributions of various tracers consists of advection by a single mean meridional cell with rising motion across the tropical tropopause, a poleward drift in the stratosphere, and a return flow into the troposphere in the extratropics. This type of mean circulation is qualitatively consistent with the observed high concentration of ozone in the lower polar stratosphere, far from the region of photochemical production. In that sense, the existence of the terannual wave in temperature will influence the poleward drift and hence the transport of ozone in the lower polar stratosphere.

REFERENCES

Andrews, D. G., J. R. Holton, and C. B. Leovy, 1987: *Middle Atmosphere Dynamics*. Academic Press, 372 pp.

Barnett, J. J., and M. Corney, 1985: Middle atmosphere reference derived from satellite data. *Handbook for M.A.P.*, Univ. of Illinois, **16**, 47–85.

——, J. T. Houghton, and J. A. Pyle, 1975: The temperature dependence of the ozone concentration near the stratopause. *Quart. J. Roy. Meteor. Soc.*, **101**, 245–257.

Bhartia, P. K., K. F. Klenk, A. J. Fleig, C. G. Wellemeyer, and G. Gordon, 1984: Intercomparison of *Nimbus 7* solar backscattered ultraviolet ozone profiles with rocket, balloon, and Umkehr profiles. *J. Geophys. Res.*, **89**, 5227–5238.

Keating, G. M., and D. F. Young, 1985: Interim reference ozone model for the middle atmosphere. *Handbook for M.A.P.*, **16**, University of Illinois, 205–229.

Labitzke, K., 1977: Interannual variability of the winter stratosphere in the Northern Hemisphere. *Mon. Wea. Rev.*, **105**, 762–770.

McCormick, M. P., T. J. Swissler, E. Hilsenrath, A. J. Kruger, and M. T. Osborn, 1984: Satellite and correlative measurements of stratospheric ozone: Comparison of measurements made by SAGE, ECC balloons, chemiluminescent and optical rocketsondes. *J. Geophys. Res.*, **89**, 5315–5320.

Nastrom, G. D., and A. D. Belmont, 1975: Periodic variations in stratospheric–mesospheric temperature, from 20–65 km at 80°N to 30°S. *J. Atmos. Sci.*, **32**, 1715–1722.

Nicolet, M., 1975: Stratospheric ozone: An introduction to its study. *Rev. Geophys. Space Phys.*, **14**, 593–636.

Oort, A. H., 1983: Global Atmosphere Circulation Statistics, 1958–1973. NOAA Prof. Paper 14, U.S. Govt. Printing Office, Washington, D.C., 180 pp.

Remsberg, E. F., J. M. Russel, J. C. Gille, L. L. Gordley, P. L. Bailey, W. G. Planet, and J. E. Harries, 1984: The validation of *Nimbus 7* LIMS measurements of ozone. *J. Geophys. Res.*, **89**, 5161–5178.

Thomas, R. J., C. A. Barth, D. W. Rusch, and B. W. Sanders, 1984: Solar mesosphere Explorer near-infrared spectrometer: Measurements of 1.27 radiances and the inference of mesospheric ozone. *J. Geophys. Res.*, **89**, 9569–9580.

Varotsos, C., 1989: Comments on the connections between the 11-year solar cycle, the Q.B.O. and the total ozone. *J. Atmos. Terr. Phys.*, **51**, 5, 367–370.