

# Interpretation of Ozone Temperature Correlations

## 1. Theory

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Correlations between ozone and temperature are commonly used to investigate the photochemical and dynamical aspects of satellite-derived ozone data. In this paper, the dynamical contributions to the ozone temperature correlations are examined using simple analytic and numerical models. It is shown that the phase differences between ozone and temperature waves caused by dynamical forcing can mimic the phase relationships predicted for photochemical equilibrium. Furthermore, the dynamical contribution to the phase relationship between ozone and temperature waves is routinely significant for chemistry time scales of  $\approx 0.5$  days and is potentially important for time scales as short as 2 hours during stratospheric warmings. The model results are highly relevant to the analysis of the limb infrared monitor of the stratosphere and solar backscatter ultraviolet data taken during the winter of 1979.

### INTRODUCTION

The relationship between ozone and temperature has been the subject of several investigations since the advent of satellite measurements. Early studies [e.g., Barnett *et al.*, 1975] focused on the comparison of the observed temperature dependence of the ozone mixing ratio to the temperature dependence predicted using different photochemical schemes. The relationship between ozone and temperature is also necessary to understanding the interaction of photochemical and radiative processes [e.g., Blake and Lindzen, 1973].

More recently, studies have focused not on testing chemical schemes, but on understanding dynamical and chemical effects through the correlation of ozone and temperature [Gille *et al.*, 1980; Wang *et al.*, 1983]. The ability to model the behavior of ozone in the dynamical and photochemical regimes, as well as in the transition region which separates these regimes, is vital to the development of the three-dimensional models which are necessary to predict the effects of pollutants such as chlorinated fluorocarbons on the ozone layer.

Hartmann and Garcia [1979] analyzed the coupling between chemistry and dynamics based on the linearized, eddy continuity equation on a  $\beta$  plane:

$$\left(\frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x}\right) \mu' + v' \frac{\partial \bar{\mu}}{\partial y} + w' \frac{\partial \bar{\mu}}{\partial z} = -\lambda \mu' - \theta T' \quad (1)$$

where  $\bar{\mu}$  is the zonal mean ozone mixing ratio,  $\mu'$  is the eddy ozone mixing ratio,  $\bar{u}$  is the mean zonal wind,  $v'$  and  $w'$  are the eddy meridional and vertical velocities,  $T'$  is the eddy temperature,  $t$  is time, and  $x$ ,  $y$ ,  $z$  are coordinates in the zonal, meridional, and vertical directions. The eddy terms (accented by primes) represent deviations from the zonal mean. The parameters  $\lambda$  and  $\theta$  describe the response of the ozone mixing ratio to dynamically induced perturbations in ozone and temperature. Hartmann and Garcia derived these parameters from a

simple Chapman scheme in which the rate coefficients are modified to account for the catalytic cycles that destroy ozone.

The main ideas concerning the interplay between dynamical and chemical effects can be understood by examining (1). Hartmann and Garcia showed that for time independent, zonally harmonic perturbations, the ozone perturbation should be  $90^\circ$  out of phase with the advective forcing of the perturbation in dynamical regions (where the terms involving  $\lambda$  and  $\theta$  can be neglected). In particular, they found that a zonal wave number 1 disturbance tended to force the ozone deviations to be in phase with the temperature deviations in the dynamical region. Hartmann and Garcia also found that for zonal wave number 5, the ozone and temperature perturbations were  $180^\circ$  out of phase at 25 km. This indicates that the ozone and temperature do not have to be in phase in the dynamical region as in the wave 1 case.

Regions where the terms on the right of (1) are much larger than those on the left are photochemically controlled, and dynamical effects are unimportant. When  $\lambda$  is large, local photochemical equilibrium is maintained; thus the ozone perturbations are  $180^\circ$  out of phase with the temperature perturbations and related according to

$$\mu' = -\frac{\theta}{\lambda} T' \quad (2)$$

This relationship provides, from  $T'$ , what is termed in this paper the "photochemical equilibrium estimate" of the ozone perturbation  $\mu'$ . The anticorrelation ( $180^\circ$  phase difference) between the ozone and temperature deviations has been taken to imply photochemical control of the ozone distribution by several authors [e.g., Gille *et al.*, 1980; Wang *et al.*, 1983; Nagatani and Miller, 1984]. For the wave number 1 results of Hartmann and Garcia [1979], the region in which the phase relation of the temperature and ozone perturbations shifts from in phase to  $180^\circ$  out of phase is considered the transition region where photochemical and dynamical effects are both important. Gille *et al.* [1980] and Wang *et al.* [1983] have observed phase shifts in the atmosphere similar to those observed in the Hartmann and Garcia calculations, and have identified the regions of phase shift as transition regions.

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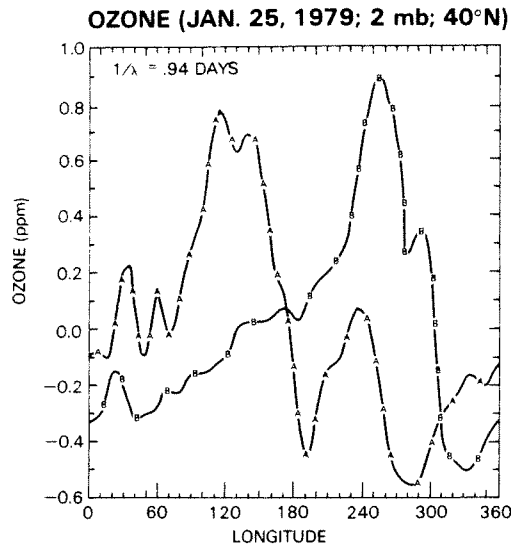


Fig. 1. Measured ozone (SBUV, see Heath *et al.* [1975]) (curve A) and that predicted by photochemical equilibrium (curve B) on January 25, 1979, 2 mbar, 40°N. The photochemical relaxation time is about 0.95 days at this height.

The motivation for this study rests largely on the comparison of measured zonal ozone distributions with distributions calculated using (2) from measured temperatures (Figures 1 and 2a) and evaluation of the individual terms in (1) (Figure 2b). The relaxation time scale for ozone perturbations is approximately 1 day for the latitude, height, and date of these figures. In Figure 1 the photochemical equilibrium estimate (2) is seen to be a poor approximation when compared to the observed ozone. In Figure 2a, the photochemical equilibrium estimate of the ozone is remarkably similar to the observed ozone; however, Figure 2b indicates that the dynamic terms are not dominated by the chemical terms. In this case, balance between the dynamical terms makes it appear that the region is in photochemical equilibrium, when in fact it is not. The relationship between ozone and temperature is evidently quite complex, and cannot be quickly analyzed by studying phase differences even at photochemical time scales on the order of 1 day.

The parameters  $\lambda$  and  $\theta$  used here are taken from Stolarski and Douglass [1985]. These parameters are derived in a manner similar to those derived by Hartmann and Garcia [1979]. However, the temperature and ozone dependencies of the catalytic cycles involving odd nitrogen, odd hydrogen and chlorine species, which dominate ozone destruction at different altitudes, have been included explicitly. Therefore the height dependence of the ozone response to dynamic perturbations in temperature and ozone is more accurately represented than with the Chapman chemistry alone. The responses calculated using these parameters have been found to be within 15% of the responses calculated using a 1-dimensional photochemical model, in the altitude range 35–60 km for ozone perturbations up to  $\pm 50\%$  and temperature perturbations of  $\pm 10$  K [Stolarski and Douglass, 1985].

In this paper, (1) is analyzed to determine what types of phase relationships between ozone and temperature can be expected in dynamically dominated regions and on what time scales photochemistry might be expected to dominate. The results are generally presented as a comparison of the photochemical equilibrium estimate (2) to the exact model calculated ozone. Since the photochemical equilibrium estimates

are proportional to the temperature, such comparisons represent correlations between the ozone and temperature perturbations. Furthermore, since the model ozone is calculated exactly with the parameterized chemistry, the difference between the photochemical equilibrium estimate and the model ozone illustrates how far the dynamics drive the ozone from photochemical equilibrium. Although a complete analysis of the ozone and temperature data given in Figures 1 and 2 is deferred to a future paper [Douglass *et al.*, 1985], the pertinence of the theoretical results to data analysis will be discussed.

#### ANALYTIC MODEL

In order to see clearly the variety of possible phase relations between ozone and temperature waves derived from (1), it is useful to consider the following analytic form of the eddy

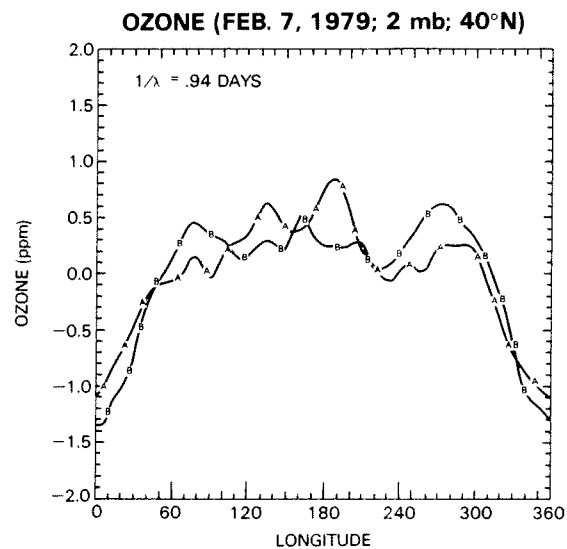


Fig. 2a

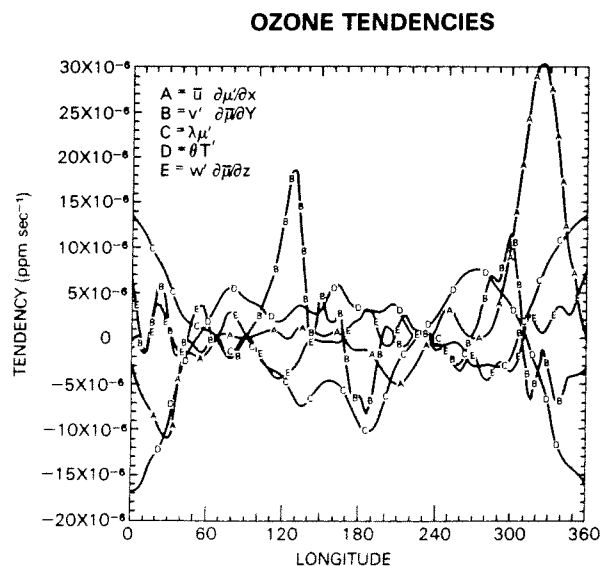


Fig. 2b

Fig. 2. (a) Same as Figure 1 but for February 7, 1979, (b) Individual terms (as calculated using NMC data, see, for instance, Hamilton [1982]) in the eddy continuity equation (1) for the time and location of Figure 2a.  $A = \bar{u}'\partial\mu'/\partial x$ ,  $B = \bar{v}'\partial\mu'/\partial y$ ,  $C = \lambda\mu'$ ,  $D = \theta T'$ ,  $E = \bar{w}'\partial\mu'/\partial z$ .

geopotential which is the solution to the quasigeostrophic potential vorticity equation [Holton, 1975] for constant zonal mean wind and constant Newtonian cooling and Rayleigh friction:

$$\phi' = \hat{\phi}(y) \exp [ikx + (\sigma - ikc)t + (r + 1/2H + i\gamma)z] \quad (3)$$

where  $k$  is the zonal wave number,  $\sigma$  is the growth rate of the wave amplitude,  $c$  is the phase velocity,  $r$  is a negative quantity proportional to Newtonian cooling and Rayleigh friction,  $H$  is the scale height, and  $\gamma$  is the vertical wave number. For quasigeostrophic dynamics,

$$v' = \frac{1}{f} \frac{\partial \phi'}{\partial x} = \frac{ik\phi'}{f} \quad (4)$$

and from the thermodynamic equation

$$\begin{aligned} w' &= -\frac{\Gamma}{N^2} \left( \frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x} + \alpha \right) T' \\ &= -\frac{\Gamma}{N^2} [\sigma + \alpha + ik(\bar{u} - c)] T' \end{aligned} \quad (5)$$

where  $f$  is the Coriolis parameter,  $N^2$  is the Brunt Väisälä frequency,  $\Gamma = R/H$ , where  $R$  is the gas constant for dry air, and  $\alpha$  represents constant Newtonian cooling and Rayleigh friction. The hydrostatic equation,

$$\frac{\partial \phi'}{\partial z} = \Gamma T'$$

can be used to rewrite  $v'$  in terms of  $T'$ , namely,

$$\begin{aligned} v' &= \frac{\Gamma T'}{f(\hat{r}^2 + \gamma^2)} (ik\hat{r} + k\gamma) \\ \hat{r} &= r + 1/2H \end{aligned} \quad (6)$$

Rewriting  $T'$  as

$$T' = \hat{T}(x, y, z)e^{(\sigma - ikc)t}$$

and using (5) and (6), (1) can be rewritten in the form

$$\frac{\partial \mu'}{\partial t} = -(\lambda + ik\bar{u})\mu' - C_0 \hat{T} e^{(\sigma - ikc)t}$$

under the assumption that the ozone perturbations are proportional to  $e^{ikx}$  ( $C_0$  is constant). This is a linear first-order differential equation with the integration factor  $\exp(\lambda + ik\bar{u}t)$ . Under the assumption that all the parameters in (1) and (3) are

TABLE 1. Ozone Temperature Phase for a Steady, Standing, Nondissipating Planetary Wave in a Photochemically Conservative Atmosphere

Background Gradient	Phase Difference Between Ozone and Temperature Waves, deg
$\partial \bar{\mu} / \partial z > 0$	0
$\partial \bar{\mu} / \partial z < 0$	180
$\partial \bar{\mu} / \partial y > 0$	90
$\partial \bar{\mu} / \partial y < 0$	270

PHASE DIFFERENCE (O<sub>3</sub> - T)

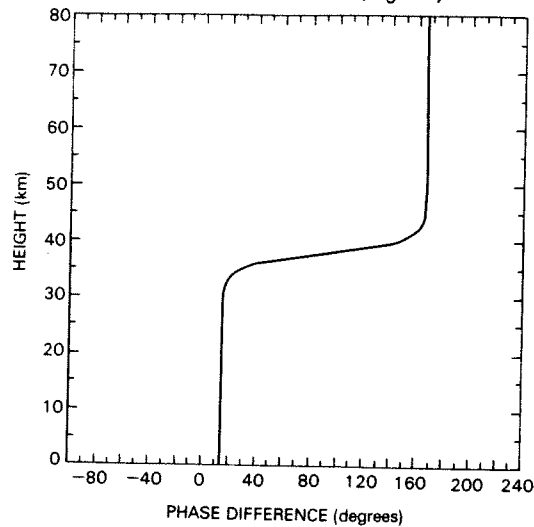


Fig. 3. Ozone temperature phase difference calculated for a steady, stationary, nondissipating planetary wave in a photochemically conservative atmosphere. The horizontal advection is 25% of the peak vertical advection.

constant with time, the solution to (1) is written as

$$\begin{aligned} \mu' &= \left\{ -\frac{\theta}{D} \hat{T}(\sigma + \lambda) - \frac{\Gamma \hat{T}}{f(\hat{r}^2 + \gamma^2)D} \frac{\partial \bar{\mu}}{\partial y} [k\gamma(\sigma + \lambda) + k^2\hat{r}(\bar{u} - c)] \right. \\ &\quad + \frac{\Gamma \hat{T}}{DN^2} \frac{\partial \bar{\mu}}{\partial z} [(\sigma + \alpha)(\sigma + \lambda) + k^2(\bar{u} - c)^2] + i \frac{\theta}{D} \hat{T}k(\bar{u} - c) \\ &\quad - i \frac{\Gamma \hat{T}}{f(\hat{r}^2 + \gamma^2)D} \frac{\partial \bar{\mu}}{\partial y} [k\hat{r}(\sigma + \lambda) - k^2\gamma(\bar{u} - c)] \\ &\quad \left. + i \frac{\Gamma \hat{T}}{DN^2} \frac{\partial \bar{\mu}}{\partial z} [k(\bar{u} - c)(\sigma + \lambda) - k(\bar{u} - c)(\sigma + \alpha)] \right\} e^{(\sigma - ikc)t} \\ &\quad + \tilde{\mu} e^{-(\lambda + ik\bar{u})t} \end{aligned} \quad (7)$$

where  $D = [(\lambda + \sigma)^2 + k^2(\bar{u} - c)^2]$ .  $\tilde{\mu}$  is an arbitrary constant set by the initial condition. In the photochemical regions the term with  $\tilde{\mu}$  decays with time, while in conservative regions this term is responsible for a propagating term that is required to meet the initial condition. In the following discussion only the term without  $\tilde{\mu}$  is considered. This term represents the ozone perturbation associated with the continual action of the planetary waves on the background ozone gradients.

The first three terms on the right of (7) contribute to an ozone temperature phase difference of either 0° or 180°. The second three terms contribute to either a ±90° phase lag. It is seen in (7) that the ozone temperature phase relationship is a complicated function of wave growth, dissipation, velocities, photochemistry, and the background constituent gradients.

A simple, but meaningful, example is obtained when the geopotential wave is stationary ( $c = 0$ ), steady ( $\sigma = 0$ ), nondissipating ( $\alpha, r = 0$ ), in a photochemically conservative atmosphere ( $\lambda, \theta = 0$ ). On the further assumption that  $\partial \bar{\mu} / \partial y = 0$ , then (7) shows that ozone is in phase with temperature if  $\partial \bar{\mu} / \partial z > 0$ , and out of phase with temperature if  $\partial \bar{\mu} / \partial z < 0$ . If instead  $\partial \bar{\mu} / \partial z = 0$ , then (7) shows that the horizontal advection term would tend to generate ±90° phase lages depending upon the sign of the horizontal gradient of the mean state. These results are summarized in Table 1.

For the steady, stationary, nondissipating planetary wave

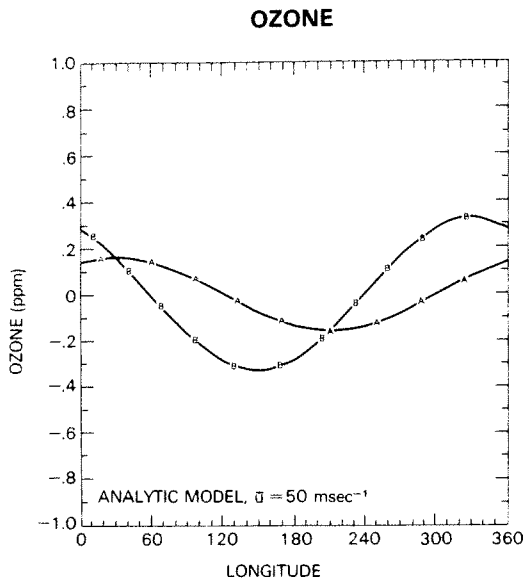


Fig. 4a

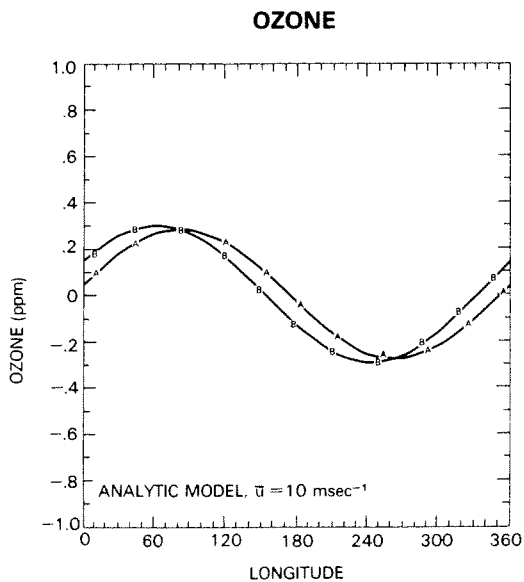


Fig. 4b

Fig. 4. Exact ozone (curve A) (7) and estimated ozone (curve B) (2) calculated for zero background gradients and (a)  $50 \text{ ms}^{-1}$  mean zonal wind and (b) for  $10 \text{ ms}^{-1}$  mean zonal wind.

described above, if it is assumed that ozone is dominated by its vertical stratification rather than its horizontal stratification, then even in a photochemically conservative atmosphere, there is a  $180^\circ$  phase change at the height of the ozone maximum (Figure 3). Below the ozone maximum ( $\partial \bar{\mu} / \partial z > 0$ ), ozone would be in phase with temperature, and above the ozone maximum ( $\partial \bar{\mu} / \partial z < 0$ ), ozone would be out of phase with temperature. In the region where  $\partial \bar{\mu} / \partial z \approx 0$ , the horizontal advection will dominate, causing the phase change to occur smoothly over a region centered at the height of the ozone maximum (also the expected height of the dynamical to photochemical transition region).

In the atmosphere the vertical ozone gradient is much larger than the horizontal gradient, but in general, the vertical advection term does not dominate the phase relationship. Both model studies and observations [Craig, 1950; Reed,

1950; Schoeberl and Krueger, 1983; Kurzeja, 1984] indicate that the horizontal and vertical advection terms are often of the same order of magnitude, and the phase relations are therefore more complicated than the previous example indicates. This example emphasizes that it is possible to generate a phase shift (without photochemical effects) between the ozone and temperature perturbations that has the same appearance of the shift due to photochemical processes calculated for wave number 1 by Hartmann and Garcia [1979].

Equation (7) shows that a wide range of correlations between ozone and temperature can be generated in the dynamical region. In order to investigate the phase relations within the transition region and to determine at what photochemical time scales photochemistry becomes dominant, it is useful to compare the "exact" ozone calculated with (7) to the photochemical equilibrium estimate defined by (2). Since the exact ozone is determined using the parameterized chemistry, differences between the estimated and exact solution must arise from dynamical sources. The results below are calculated only in regions where  $\lambda$  is large enough that the term with the arbitrary constant in (7) quickly decays to be much smaller than the forced term.

Figure 4 illustrates a special case in which the background gradients are equal to zero, so that the only dynamical contribution to (7) is from advection by the mean zonal wind. The  $\phi$  has been chosen so that the temperature perturbations are approximately 10 K at the height of interest.  $\lambda$  and  $\theta$  are chosen to represent 2-mbar equinox conditions ( $1/\lambda \approx 0.7$  days,  $\theta = 1.19 \times 10^{-12} \text{ K}^{-1} \text{ s}^{-1}$ ). In Figure 4a the mean zonal wind is  $50 \text{ ms}^{-1}$ , and the difference between the exact and estimated solution is significant in both amplitude and phase. In Figure 4b the mean zonal wind has been reduced to  $10 \text{ ms}^{-1}$ , and the estimate and exact solution agree much more closely. It is seen therefore that realistic values of the mean zonal wind can force the ozone significantly away from photochemical equilibrium.

From the results in Table 1, the inclusion of the vertical derivative term above the ozone maximum would be expected to improve the phase relationship in Figure 4. This is seen to be true in Figure 5, where the results from (2) and (7) show

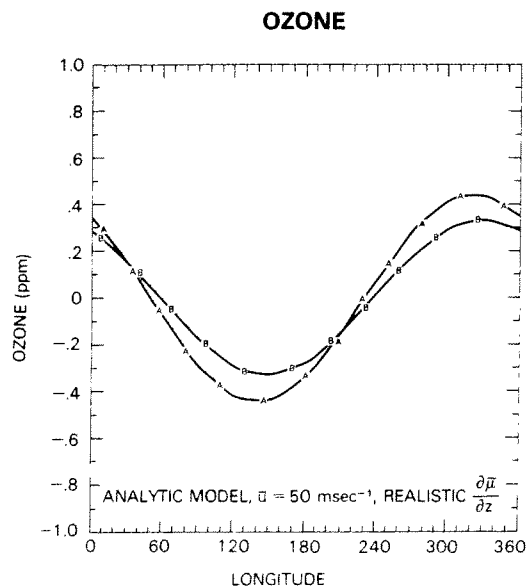


Fig. 5. Same as Figure 4a but with a realistic vertical background gradient.

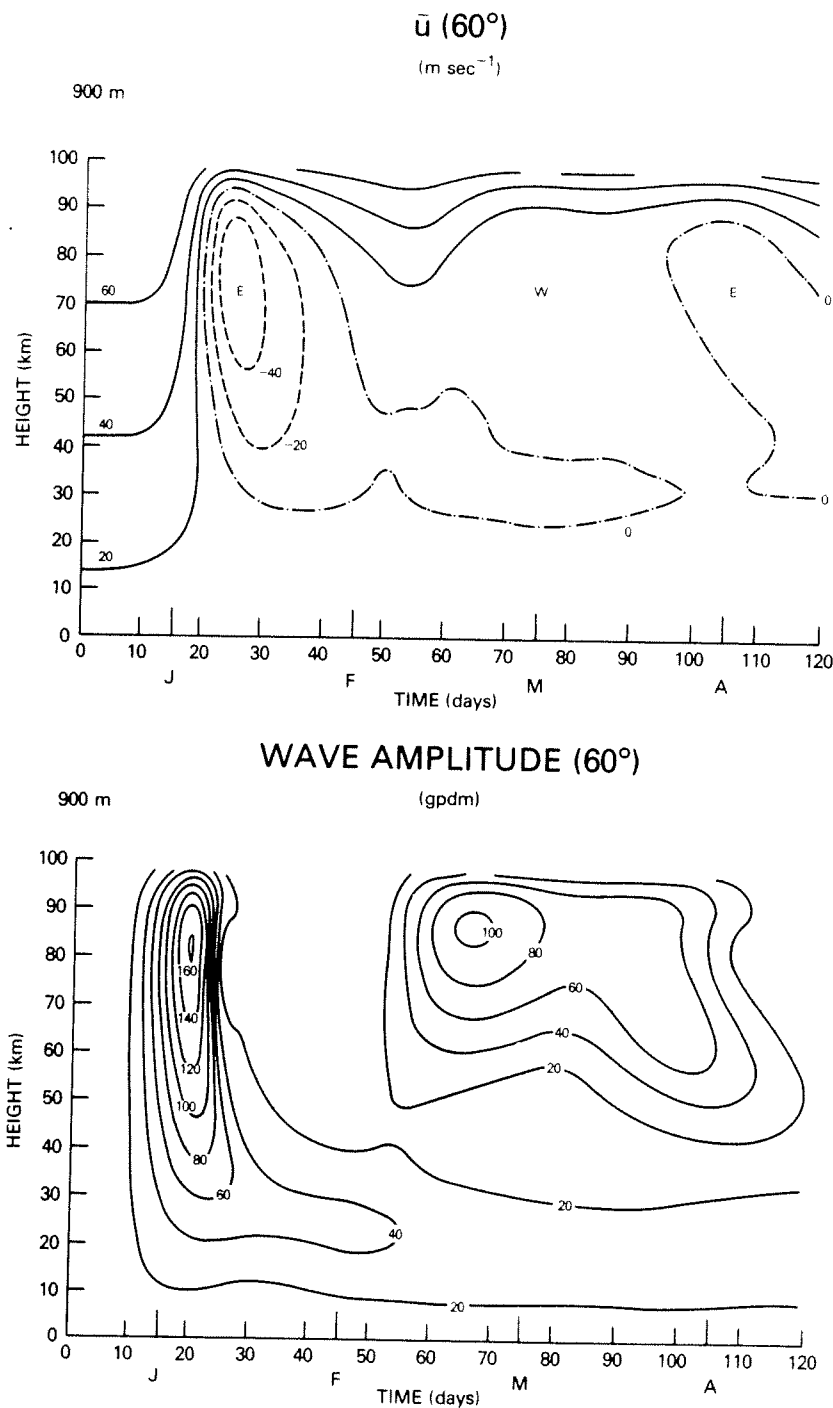


Fig. 6. Time-height series of (a) model mean zonal wind and (b) geopotential amplitude at  $60^\circ\text{N}$  [from Rood and Schoeberl, 1983].

excellent phase agreement. Under the conditions of this example, if the exact solution were satellite data, such a good phase estimate might indicate excellent photochemical agreement, when in fact both vertical and zonal transport are important. If it were assumed that the ozone was in photochemical equilibrium, then the ratio  $\theta/\lambda$  would be overestimated by approximately one third, and the temperature dependence of the ozone loss process would be assigned incorrectly.

Further analyses (not shown) indicate that Newtonian cooling and Rayleigh friction have small effects on the phase relationship at stratospheric altitudes.

#### NUMERICAL MODEL

The functional dependence of the wave growth as described by the analytic model (3) is only useful for the most primitive analysis of wave transience. Therefore a time dependent numerical model will be used to investigate the relationship between the ozone and temperature perturbations in the presence of a growing wave and a model stratospheric warming. The dynamical model is the same as that used in Rood and Schoeberl [1983]. Figure 6 shows the time development of the zonal mean wind and the wave amplitude at  $60^\circ$ . The chemical

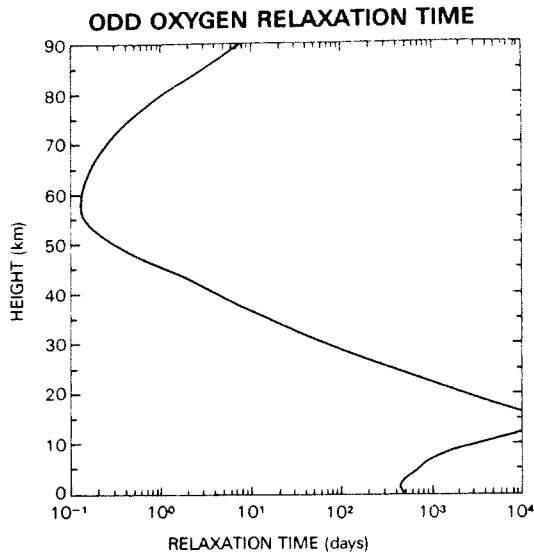


Fig. 7. Photochemical relaxation time,  $1/\lambda$ .

coefficients are from *Stolarski and Douglass [1985]* and are for February conditions, 60°N. Figure 7 shows the chemical coefficients as a function of height. For these simple experiments the chemistry coefficients are assumed to be independent of latitude and time. This assumption does not qualitatively affect the results.

Figure 8 shows the difference in phase as a function of height between the ozone and temperature waves on day 15. In the region below 40 km, where it is safe to assume that the photochemistry is negligible, there is a region where ozone leads the temperature perturbation by about 90° and a region where the ozone trails the temperature perturbation by about 90°. At this time, with a rapidly growing wave, there is no part of the dynamical region of the atmosphere where the ozone and temperature waves can be said to be in phase. The phase relationships at this time are indicative of domination by the meridional advective terms in the ozone continuity equation; the phase shift at 20 km occurs where  $\partial\bar{u}/\partial y$  changes sign. The ozone and temperature are in phase at 22 km, indicating the

dominance of the vertical advection at the height where  $\partial\bar{u}/\partial y$  is zero. At 40 km the difference in phase of the ozone and temperature waves changes abruptly to approximately 180°, indicating the increasing importance of photochemistry.

To determine at exactly what time scales the photochemistry becomes dominant, the photochemical equilibrium estimate (2) will be compared with the "exact" ozone calculated in the model. This comparison will be done at days 15 and 35 in the height range of  $\approx 36.5$ –54 km. In this height range the relaxation time varies from about 9.5 days at the lower altitude to 0.16 days at the upper altitude (see Figure 7).

On day 15, when the wave is growing rapidly and prior to the development of easterlies (before the warming, see Figure 6), at 36.5 km (Figure 9a) the size of the exact ozone perturbation is larger than the estimate, and the phase difference between the two is about 100°. At this altitude the vertical ozone gradient is small, and the most important terms in the continuity equation are the meridional eddy and zonal mean advection. The ozone amplitude the model generates can be either larger or smaller than the estimated value for time scales less than 10 days. At longer relaxation times, the ozone amplitude is usually larger than the estimate because the chemical coefficients are very small.

In Figure 9b the results are shown at 41.5 km where the ozone relaxation time is about 2.9 days. There are still major discrepancies between the exact ozone and the photochemical equilibrium estimate. At 46.5 km (Figure 9c), where the relaxation time is down to 0.71 days, the phase relationship is beginning to approach that predicted by the photochemical equilibrium estimate, but there are still significant amplitude errors. At this altitude the eddy vertical advection has a tendency to force the ozone and temperature to be anticorrelated and therefore mimic the phase relationship predicted by photochemical equilibrium. At 54 km (Figure 9d), where the photochemical time scale is 0.16 days, the exact ozone and the estimate show good agreement, but the amplitude is very small due to the rapid relaxation time.

The results from day 35, when the wave is decaying slowly, are shown in Figure 10. This is after the warming, and there are easterlies of smaller magnitude than the westerlies on day 15. In general, the estimated and exact ozone are seen to be in

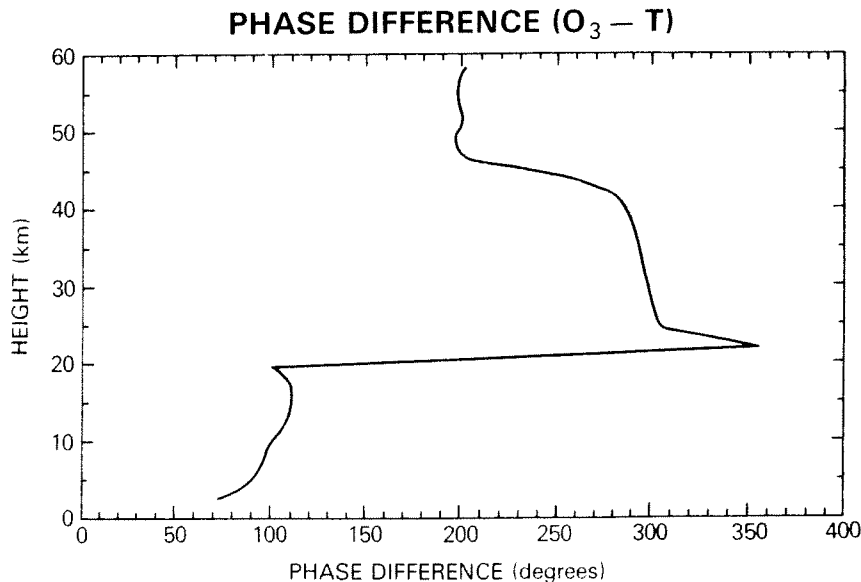


Fig. 8. Ozone and temperature wave phase differences at day 15 of the planetary wave model.

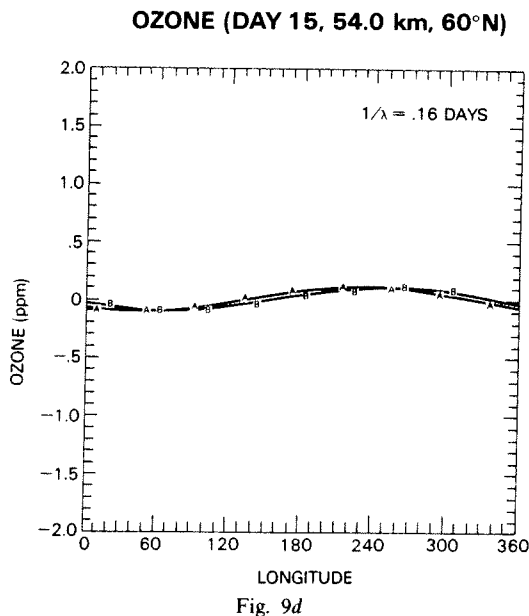
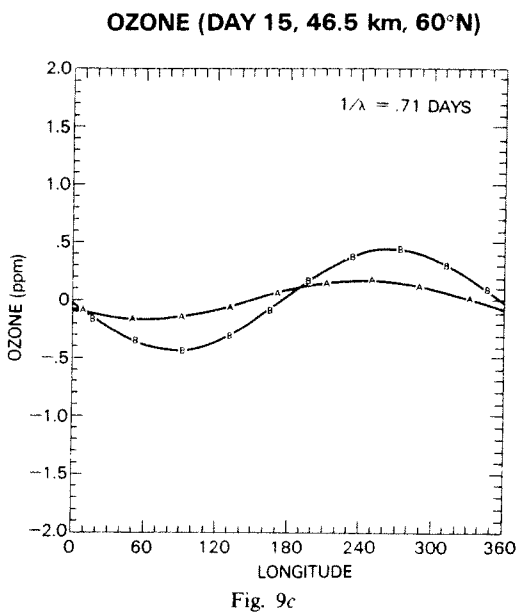
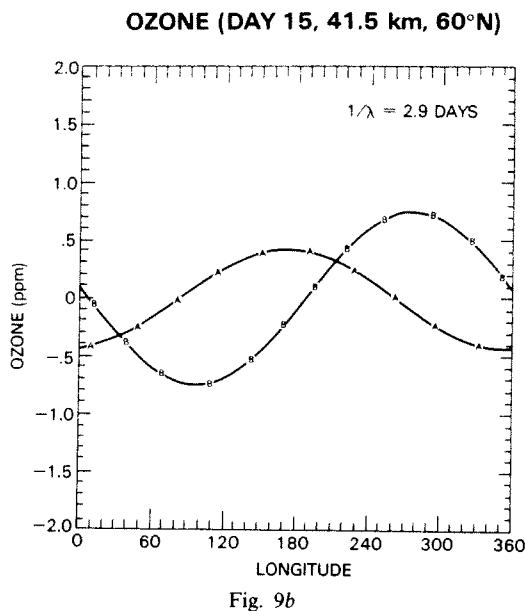
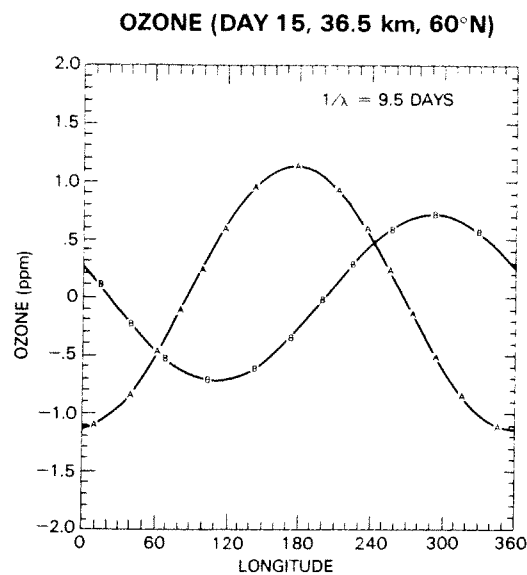


Fig. 9. (a) Exact model ozone (curve A) and estimated ozone (curve B) (2), at 36.5 km ( $1/\lambda \approx 9.5$  days) on day 15. (b) Same as Figure 9a, but for 41.5 km ( $1/\lambda \approx 2.9$  days). (c) Same as Figure 9a, but for 46.5 km ( $1/\lambda \approx 0.71$  days). (d) Same as Figure 9a, but for 54 km ( $1/\lambda \approx 0.16$  days).

better agreement on day 35 than on day 15. At 36.5 km (9.5 days relaxation, Figure 10a), the estimated solution is greater than the exact solution in contrast to the same altitude on day 15 (Figure 9a). At 46.5 and 54 km (Figures 10b and 10c) there is close agreement between the exact ozone and the photochemical equilibrium estimate. This demonstrates the smaller role of advection by both the wave and mean fields at this time.

The ultimate strength of the dynamical effects in the transition region is indicated in Figure 11, which shows the exact ozone and the estimated solution at day 25 at 54 km (0.16 days' relaxation). This is near the time of maximum easterlies, large wave amplitude, and rapid wave decay. The dynamical forcing produces differences between the exact and photochemically estimated solution even at this short relaxation time.

Another aspect of the difficulties in interpreting the phase relationships between ozone and temperature perturbations is exhibited in Figure 12. At this height,  $\approx 32$  km, the temperature and relaxation parameters are quite small, but ozone and temperature perturbations are  $180^\circ$  out of phase as expected if the photochemistry were dominant. At the bottom of the transition region this signature could easily be misinterpreted as a photochemical effect.

#### DISCUSSION AND SUMMARY

The relationship between ozone and temperature perturbations has been investigated both directly and by using the photochemical equilibrium estimate given by (2) to see how well it predicts the exact model calculated ozone. Model results indicate that the phase difference between ozone and temperature waves, and therefore the size and sign of the cor-

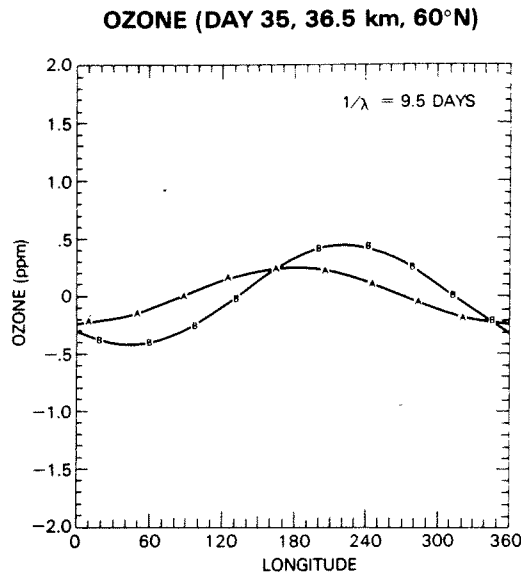


Fig. 10a

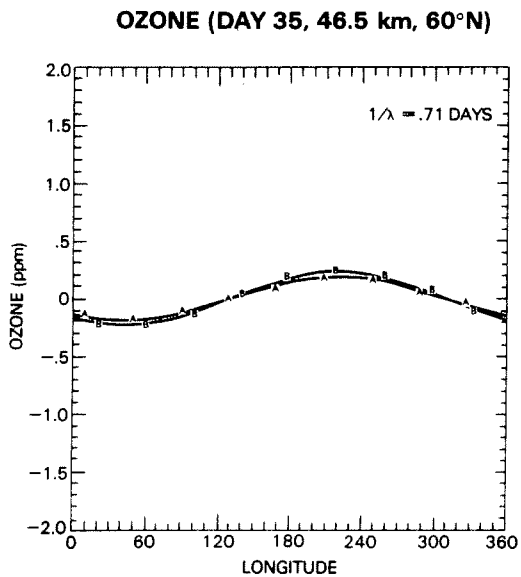


Fig. 10b

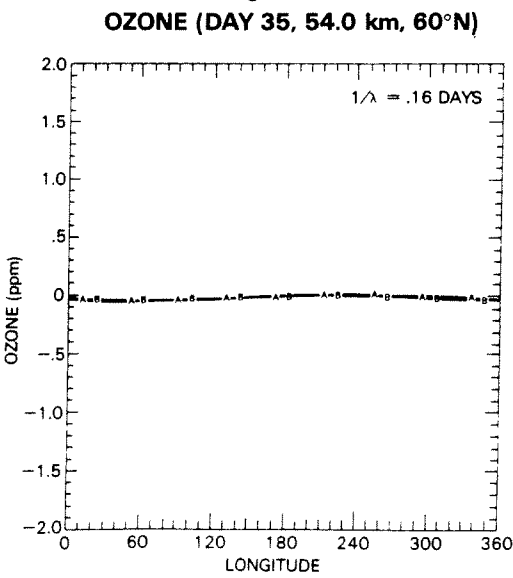


Fig. 10c

relation between ozone and temperature deviations, can assume a wide variety of values based on a realistic range of dynamical variables. Even for time scales as short as 12 hours, the dynamical contributions to the ozone temperature correlations are routinely as large as the photochemical contributions. There are times, for example, during model warmings, when there are significant dynamical contributions on time scales of 2 hours or less. It should be stressed that the model dynamics may be more vigorous than actual atmospheric processes during warmings, so that the most extreme dynamical time scales (2 hours) may be unrepresentative of atmospheric processes.

Estimates of the normal dynamical time scales in winter are given in Table 2. One estimate of the eddy time scale is given by  $(k\bar{u})^{-1}$  [Hartmann and Garcia, 1979]. It was argued by Wang et al. [1983] that the transition region moved to lower levels in the stratosphere as the dynamical time scale became longer due to the decrease of  $\bar{u}$  during the sudden warming of February 1979. The current model (and preliminary data analysis) shows significant dynamical contributions to the ozone deviation field even during warmings, suggesting that during stratospheric warmings more useful time scales are perhaps given by

$$\left(\frac{|v'|}{|\mu'|} \frac{\partial \bar{\mu}}{\partial y}\right)^{-1} \quad \left(\frac{|w'|}{|\mu'|} \frac{\partial \bar{\mu}}{\partial z}\right)^{-1}$$

which are eddy advection time scales in the meridional and vertical directions. It is seen from Table 2 that at 60° the  $k\bar{u}$  time scales are typically significantly less than 1 day for wave numbers 2 and 3 and can be as small as 0.5 days for wave 1 if the mean zonal wind is greater than 60  $\text{ms}^{-1}$ . The time scale of the meridional eddy advection is typically on the order of 1 day and can become smaller than 0.5 days during strong wave events. The eddy vertical time scale is typically much longer than the meridional time scale.

In view of the time scales given in Table 2 and the photochemical relaxation times in Figure 8, it is concluded that the only region of the atmosphere in which ozone can be considered to be in photochemical equilibrium with the temperature at high latitudes during winter is the region between approximately 50 and 65 km. Above this altitude, where the photochemical lifetime of odd oxygen is increasing (see Figure

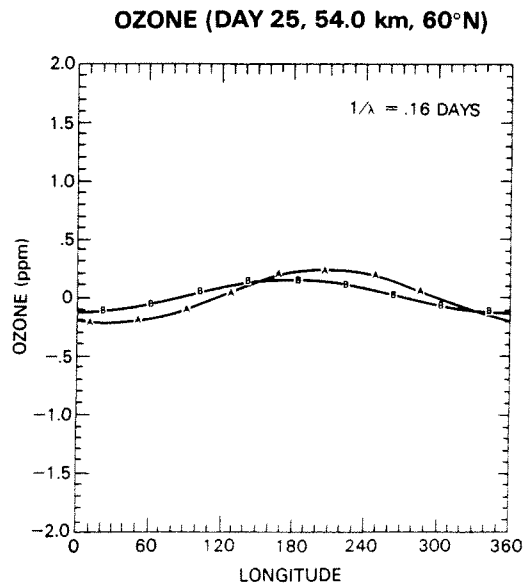


Fig. 11. Same as Figure 9d, but on day 25.

Fig. 10. (a) Same as Figure 9a, but on day 35. (b) Same as Figure 9c, but on day 35. (c) Same as Figure 9d, but on day 35.



7), the effects of gravity waves are potentially important. This conclusion has significant implications for studies like those of *Barnett et al.* [1975] and *Nagatani and Miller* [1984], in which ozone temperature correlations were examined by estimating the photochemical response to a temperature perturbation without regard to the dynamical contribution to the correlation. The planetary wave models used here suggest that only at the highest level reported by the National Meteorological Center (0.4 mbar) should the photochemistry consistently dominate the ozone in winter.

Eddy and zonal mean advection, and to a lesser extent wave transience, play an important role in determining the dynamical contribution to the phase relationship. In the model results, the meridional eddy term is usually the largest dynamical term, consistent with the scale analysis of *Barnett et al.* [1975], but all the dynamical terms can be significant. Preliminary results using solar backscatter ultraviolet (SBUV) ozone data indicate that during warmings the nonlinear advection terms must be included in the continuity equation in order to explain the ozone data successfully. The inclusion of these terms severely complicates the analysis of the response of ozone to dynamically driven temperature perturbations.

It has been shown that a change of  $180^\circ$  in the phase difference between the ozone and temperature waves is not a unique signature of the transition from dynamical to photochemical control of ozone. The use of this phase change to identify the transition region [*Gille et al.*, 1980; *Wang et al.*, 1983; *Nagatani and Miller*, 1984] may be erroneous. As an extreme case, it has been shown that it is possible to generate a change of  $180^\circ$  in the phase difference between ozone and temperature waves by dynamical effects alone (Figure 3). However, this feature is dependent largely on the domination of the vertical advection term over the horizontal advection term which does not generally occur. Even so, this extreme demonstrates that in regions where the horizontal gradient is small, the dynamical contribution to an observed  $180^\circ$  phase change between the ozone and temperature waves might be large. The data of Figure 2 further illustrate this point. Although the ozone and temperature deviations are  $180^\circ$  out of phase, this should be considered part of the transition region because the dynamical and photochemical terms are of comparable size. Also the use of a  $90^\circ$  phase difference (zero corre-

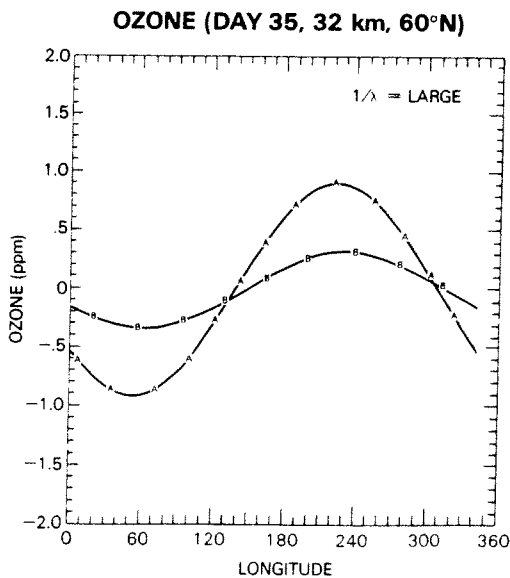


Fig. 12. Same as Figure 9a, but at 32 km, day 35 ( $\approx$  conservative).

TABLE 2. Representative Dynamical Time Scales in Winter

Quantity	Value, days	Comment
$(k\bar{u})^{-1}$	1.2	$60^\circ$ , $\bar{u} \approx 30 \text{ ms}^{-1}$ , wave 1
	0.6	$60^\circ$ , $\bar{u} \approx 30 \text{ ms}^{-1}$ , wave 2
	0.4	$60^\circ$ , $\bar{u} \approx 30 \text{ ms}^{-1}$ , wave 3
	0.6	$60^\circ$ , $\bar{u} \approx 60 \text{ ms}^{-1}$ , wave 1
	0.3	$75^\circ$ , $\bar{u} \approx 60 \text{ ms}^{-1}$ , wave 1
$\left(\frac{ v' }{ \mu' } \frac{\partial \bar{\mu}}{\partial y}\right)^{-1}$	0.5	$ v'  \approx 35 \text{ ms}^{-1}$
$\left(\frac{ w' }{ \mu' } \frac{\partial \bar{\mu}}{\partial z}\right)^{-1}$	1.5	$ w'  \approx 2 \text{ cms}^{-1}$

Here  $u'$  is often as large or larger than  $\bar{u}$  during winter. Therefore the time scales  $ku'$  and  $k(\bar{u} + u')$  are also appropriate.

lation) between the ozone and temperature deviations to identify the center of the transition region [*Nagatani and Miller*, 1984] is probably incorrect. A zero correlation between ozone and temperature is indicative of dominance by the meridional advection when the mean vertical ozone gradient is small, and can rise under a wide variety of circumstances, as indicated by (7).

This study also emphasizes that the phase difference between ozone and temperature waves does not necessarily change between a photochemical and dynamical region, because dynamical terms can generate any phase pattern in the dynamical region. *Hartmann and Garcia* [1979] show no change in the phase difference in the transition region for wave 3, which does not propagate to high altitudes. The current numerical model shows times after the warming when there is no change in the phase difference across the transition region associated with wave 1.

The results detailed above are most relevant to data sampled at a particular time. Figure 13 shows the averaged linear correlation coefficient between ozone and temperature for time periods for a model run which produced a single minor warming. The warming is classified as minor because the zero wind contour remained above 10 mbar ( $\approx 32 \text{ km}$ ).

In Figure 13a is a 2-week time average during the prewarming (wave growth) stage. Above 40 km the correlation is seen to be consistently large and negative. In Figure 13b is the 2-week time average taken during the minor warming. The effect of the zero wind line (critical line), which descends to 48 km and remains quasistationary, is obvious as the correlations are forced toward zero. A 6-week average encompassing both prewarming and post warming times is presented in Figure 4c. The major deviations from a  $-1$  correlation caused by the warming are lessened, but the correlation above 40 km is still significantly removed from  $-1$ . Finally, in Figure 13d a 10-week average is shown. While the correlations are moved more toward  $-1$  than in Figure 13c, the integrated effects of the dynamics are important.

All of the frames in Figure 13 show the same basic pattern. The ozone is negatively correlated with temperature above 40 km and positively correlated with temperature between 20 and 40 km. The effect of time averaging does seem to lessen the strongly varying signal of the planetary waves, but the choice of the averaging period is critical. The winter stratosphere experiences one planetary wave event after another. Averaging over time scales on the same order as the time scale of a planetary wave event will show the effects of that particular event. For averaging time scales much longer than the time scale of a single wave event, the averaged effects of the dynam-

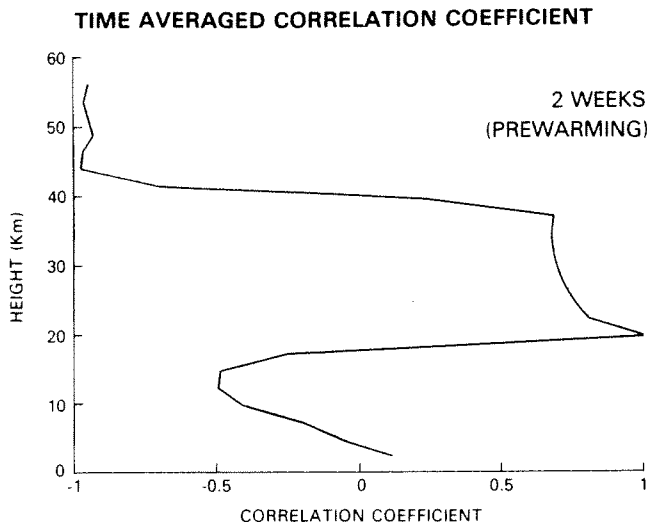


Fig. 13a

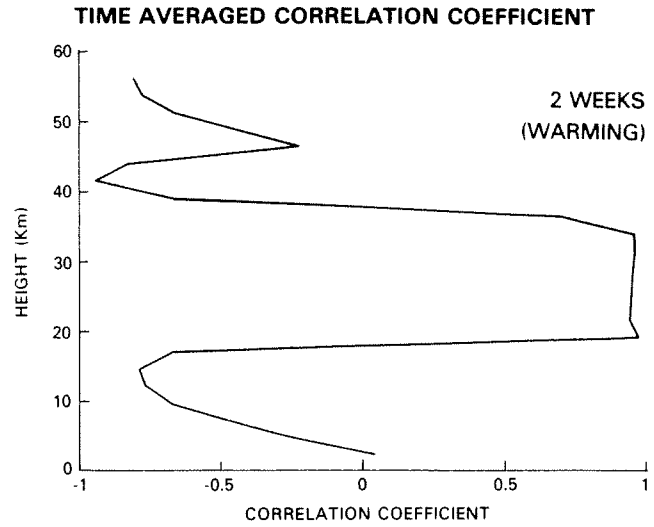


Fig. 13b

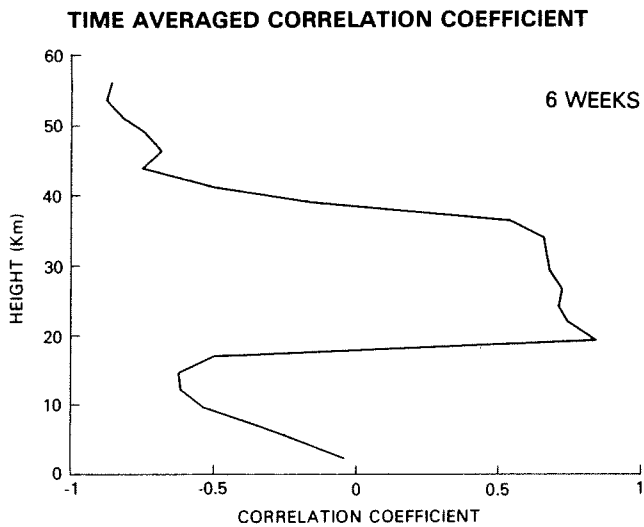


Fig. 13c

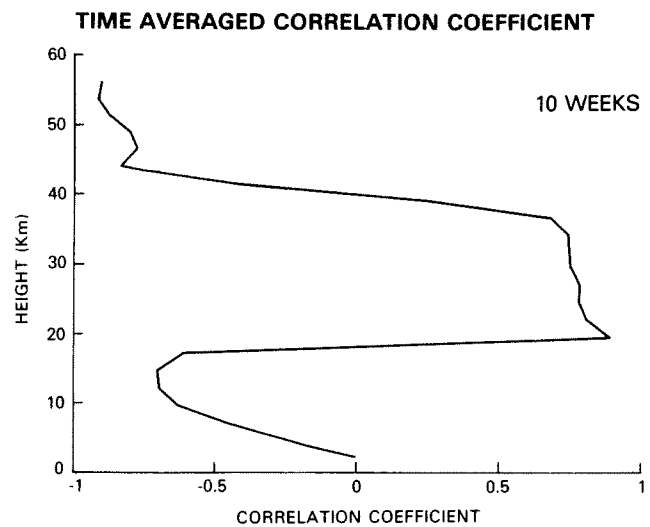


Fig. 13d

Fig. 13. Model calculated linear correlations between ozone and temperature perturbations. (a) Two-week average (prewarming), (b) 2-week average (during warming), (c) 6-week average, and (d) 10-week average.

ics will not be negligible, and the correlation between ozone and temperature above 40 km will be significantly different from  $-1$ .

In conclusion, extreme care must be taken in analyzing either the correlation between ozone temperature deviations, or the phase relationship of ozone and temperature waves. In order to analyze the ozone data from any single day properly, the contribution of the dynamical terms should be calculated explicitly. In an analysis that involves time averaging, for short-term averaging ( $< 2$  weeks) the dynamics can dominate the photochemistry, and for long-term averaging the ozone and temperature will be negatively correlated, but the effects of the dynamics should not be negligible. Therefore even in the time-averaged analysis, the effects of the dynamics must be carefully considered.

*Acknowledgments.* The authors wish to acknowledge the Space Plasma Computer Analysis Network (SCAN), centered at NASA/Marshall Space Flight Center, for the use of computation facilities. Some of this work was performed while one of the authors (R.B.R.) was an NAS/NRC Research Associate at NASA/GSFC. Thanks is also expressed to two anonymous reviewers for their comments.

Stratospheric General Circulation With Chemistry Modeling Project (NASA/Goddard Space Flight Center) contribution 17.

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(Received July 2, 1984;  
revised December 19, 1984;  
accepted January 3, 1985.)