PAGEOPH, Vol. 121, 5/6 (1983) 0033–4553/83/011049–16$1.50+0.20/0

Transport and the Seasonal Variation of Ozone

RICHARD B. ROOD[1]

Abstract - The transport mechanisms responsible for the seasonal behavior of total ozone are deduced from the comparison of model results to stratospheric data. The seasonal transport is dominated by a combination of the diabatic circulation and transient planetary wave activity acting on a diffusively and photochemically determined background state. The seasonal variation is not correctly modeled as a diffusive process.

The buildup of total ozone at high latitudes during winter is dependent upon transient planetary wave activity of sufficient strength to cause the breakdown of the polar vortex. While midwinter warmings are responsible for enhanced ozone transport to high latitudes, the final warming marking the transition from zonal mean westerlies to zonal mean easterlies is the most important event leading to the spring maximum. The final warming is not followed by reacceleration of the mean flow; so that the ozone transport associated with this event is more pronounced than that associated with midwinter warmings.

Key words: Ozone; Ozone transport; Stratospheric warnings.

Introduction

Various stratospheric circulation systems have been postulated to explain how stratospheric ozone, water vapor, methane, and radioactive debris are distributed relative to their sources and sinks. Subsequent observations and theoretical developments have proven these proposed circulations to be more complex than originally postulated and in some cases incorrect. An excellent historical discussion of stratospheric transport studies is given in HSU (1980).

Perhaps the most controversial item in the study of stratospheric tracers has been the parameterization of constituent transport by planetary waves as a diffusive process. This parameterization has been used extensively in detailed photochemical models where computational

[1] NAS/NRC Research Associate, Code 616, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

limitations prohibit the use of detailed dynamics. The inability of diffusion models to simulate stratospheric transport, coupled with theoretical developments that show planetary waves' effects to be advective to a large extent, have left the validity of many chemistry and transport models in doubt.

This paper will briefly review the development of stratospheric transport models based either on the accurate representation of the dynamics or on the photochemistry. Then an attempt will be made to describe the advective and diffusive processes in the stratosphere, and to determine the appropriateness of advective and diffusive models based on results from these models and observations. It will be argued that the seasonal variation of ozone, the most-observed constituent, is dependent on advective, not diffusive, processes associated with transient planetary wave activity during winter. First, however, a simple thought experiment will be used to explore the relationship of advective and diffusive properties in a photochemically active atmosphere.

A simple model

The enigma of stratospheric transport is exemplified by the observed ozone distribution. Ozone is formed through photolysis of atomic oxygen in the middle and upper stratosphere. However, the maximum amounts of ozone are observed in the lower stratosphere, and the maximum column amounts are observed at polar latitudes in late winter and early spring. The fact that the bulk of the ozone is stored well away from its sources and sinks emphasizes the importance of transport in determining its distribution.

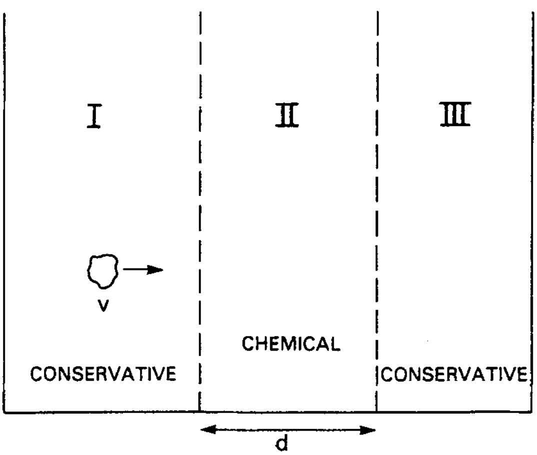

Figure 1. Simple model of a parcel moving from a conservative region, I; through a photochemical region, II; into another conservative region, III.

The rudiments of stratospheric transport can be demonstrated with the simple model in Figure 1, which shows a parcel moving with constant velocity v. In regions I and III the parcel constituent density is conserved, and in region II the parcel density obeys the relationship

$$\frac{dr}{dt} = -\lambda(r - r_e). \tag{1}$$

That is, the parcel constituent density r relaxes to the equilibrium density r_e with a time scale proportional to the inverse of λ. Assuming that the parcel enters region II (photochemical region) at time zero with zero initial constituent density, then the density of the parcel when it reaches region III is

$$r = r_e(1 - e^{-\lambda d/v}) \tag{2}$$

where d is the width of region II. The quantity d/v is the amount of time during which the parcel experiences the photochemistry. If $\lambda d/v \ll 1$, the time the parcel experiences the photochemistry is much smaller than the relaxation time of the photochemistry, and $r \sim 0$ in region III. If on the other hand $\lambda d/v \gg 1$, then the parcel density in region III is approximately r_e, the equilibrium density.

Two extreme cases of the model should be discussed. In the case where the parcel goes through the photochemical region only once, the parcel constituent density in region I is always zero. If a normal diffusive scheme were used to model the dynamics in this extreme, then there would be nonzero constituent values in region I. This case is representative of advective motions that do not persist for a long enough time to mix the photochemical and conservative regions. Such motions are important in the atmosphere for determining the seasonal variations of a constituent.

The other extreme is represented either by having repeated regions where the photochemistry is nonzero or by making the model periodic with some length scale greater than d. This is analogous to a parcel moving into and out of a photochemical region over and over again. In this example, no matter how small λ is, the parcel eventually approaches the equilibrium density r_e. Therefore, the continual advection into and out of photochemical regions produces the same sort of result as diffusion: a constant density field. This extreme demonstrates the validity of diffusive parameterizations of advective processes in a well-mixed atmosphere with distinct photochemical and conservative regions.

This is not to say that all of the apparent diffusive transport in the stratosphere is in fact large-scale advection into and out of photochemical regions. There is, surely, what can be viewed as classically diffusive transport associated with planetary waves (e.g., STROBEL, 1981) as well as diffusion associated with smaller-scale waves. But the presence of photochemistry has the ability to disguise dynamically advective processes as diffusion.

Diffusion models (chemical)

Because of computational limitations detailed stratospheric chemistry models have relied on diffusive parameterizations to represent wave transport processes. The diffusion approximation is based on the concept that waves displace parcels from their equilibrium positions and then instantaneously mix them with the environment (REED and GERMAN, 1965). This approximation is accurate for turbulent fields, but is at best controversial for modeling planetary-scale wave (longitudinal wave numbers 1–3) transport.

The diffusion coefficients, originally derived from observations of neutral species, were found to do a poor job in modeling the two-dimensional structure of ozone. Therefore, they have been tuned to yield better results, which makes them unrepresentative of the dynamics of the stratosphere (NASA, 1979).

Subsequent observations and theoretical research have shown that the assumptions used in deriving the original diffusion parameterizations are incorrect. Perhaps the most important error is the assumption that the wave motion fields are independent of the mean motion fields. The diffusion scheme derived by REED and GERMAN (1965) was based on what is now termed the Eulerian decomposition of the waves: the waves are defined as deviations from a longitudinal (zonal) mean. As defined in this way, the waves force a secondary mean circulation that exactly counterbalances the wave transport (the nonacceleration theorem).[2] As a consequence of this compensating circulation, the assumption that the wave field is independent of the mean flow is incorrect.

As an alternative to the Eulerian description, ANDREWS and MCINTYRE (1978) introduced the Lagrangian mean formulation wherein the waves are defined as the deviation from a disturbance-free basic state: a coordinate system dependent on the fluid motion. One advantage of this system is that there is no compensating wave-induced mean flow. However, the definition of the Lagrangian mean coordinate system makes this formulation impractical for generalized transport studies.

With the Lagrangian mean formulation, it can be shown that idealized planetary waves are advective, and that the advection is directed opposite to the advection by the wave-induced mean field (e.g,

[2] The nonacceleration theorem states that for linear, steady (nontransient, *i.e.* no growth or decay of wave amplitude), nondissipating waves there is no acceleration of the mean zonal flow by the waves. Similarly, there is no net constituent transport by the waves (CHARNEY and DRAZIN, 1961; BOYD, 1976; ANDREWS and MCINTYRE, 1978).

MATSUNO, 1980). In Lagrangian mean theory the advective velocity of the planetary waves, the Stokes drift, is combined with the Eulerian mean velocity to form the Lagrangian mean velocity. The Lagrangian mean velocity is the velocity of the center of mass of a particular ensemble of parcels, and the wave-driven Lagrangian mean velocity is equal to zero given the premises for which the nonacceleration theorem is valid. Therefore, in order for constituent transport to occur in the absence of photochemistry, the waves must either be transient or dissipative. Since purely transient events (*i.e.*, advection) are time reversible, long-term changes ultimately depend upon irreversible processes such as dissipation and nonlinearity.

Using the Lagrangian mean concept a new generation of diffusion models has been developed. With the Lagrangian mean velocity as the advective field, diffusion can be incorporated to model subgrid and irreversible processes. Therefore some attempts have been made to estimate the Lagrangian mean velocity of the stratosphere. Of course, the dependence of the diffusion coefficients on the dynamics and photochemistry of the atmosphere (STROBEL, 1981) still presents formidable difficulties.

Based on arguments by DUNKERTON (1978) that the radiatively driven (diabatic) circulation should approximate the Lagrangian mean circulation to the first order, PYLE and ROGERS (1980) have studied ozone transport by the diabatic circulation with diffusively parameterized wave dynamics. The diabatic circulation in the upper stratosphere and mesosphere consists of rising motion at the summer pole, sinking motion at the winter pole, and a meridional transport from the summer to the winter pole. In the troposphere and lower stratosphere the circulation consists of rising motion in the tropics and sinking motion at the poles. As shown by Dunkerton this circulation is consistent with the Brewer-Dobson circulation proposed to explain the water vapor and ozone distribution (DUNKERTON, 1978; HSU, 1980). The Brewer-Dobson circulation proved to be inconsistent with Eulerian mean circulation patterns and was thought to be incorrect for much of the 1960s and 1970s.

PYLE and ROGERS (1980) found that the diabatic circulation produced too large an ozone maximum at midlatitudes and did not transport enough ozone to northern high latitudes. Addition of diffusion to the model improved the results with the improvement resting largely on the fact that the large gradients produced by the diabatic circulation between the midlatitudes and the north pole were particularly susceptible to redistribution by diffusion. The polar total ozone maximum was not, however, modeled.

In another of the new generation of chemical models with transport, GARCIA and SOLOMON (1983) use the residual circulation as the advective field. The residual circulation is defined as the sum of the Eulerian mean circulation and the circulation driven by the north-south eddy heat flux. It has the same property as the Lagrangian mean circulation in that it equals the diabatic circulation in the absence of wave transience and dissipation. HOLTON (1981) has suggested that the residual circulation, which is easy to calculate, might be an appropriate approximation for the Lagrangian mean circulation, which is difficult to calculate.[3] Garcia and Solomon use the residual circulation forced by solar heating and include only the effects of the steady, nondissipating planetary waves. Therefore, their advective velocity is qualitatively the same as that used by PYLE and ROGERS (1980).

While steady, linear, nondissipating planetary waves cannot cause a change in the mean constituent field in the absence of photochemistry, the presence of a spatially varying photochemistry with the proper photochemical time scale can produce a transport effect (HARTMANN, 1981). Therefore, Garcia and Solomon model planetary wave effects where photochemical and dynamical time scales are the same order of magnitude. Furthermore, Garcia and Solomon avoid many of the problems of stratospheric transport by modeling only above 100 mb (~15 km). At high latitudes, 50 percent or more of the ozone is located at 100 mb or below but is approximately inert.

Using total ozone as a standard, Garcia and Solomon's model calculations combined with ozone climatology below 100 mb give excellent results. The implications from this study are that to study ozone photochemistry above about 40 km (where chlorine reduction would be most important, for instance), it may not be necessary to worry much about wave transience and dissipation. Perhaps the diabatic circulation and the stirring of parcels across regions of strong photochemical gradients are adequate dynamics. The required circulation need only transport ozone into the polar night, and no attempt need be made to model the lower stratosphere or troposphere. These results also emphasize that total ozone is not a good diagnostic to evaluate the chemical aspects of models, since most of the ozone is in the chemically conservative region of the atmosphere.

The approach used by Garcia and Solomon of modeling the atmosphere only above 100 mb is very valuable for studying chemical schemes but has serious limitations. Namely, lower boundary fluxes

[3] It has been shown in ROOD and SCHOEBERL (1983a) that there can be errors of 30% or more between the advection calculated with the residual circulation and with Lagrangian mean circulation for steady dissipative planetary waves. These errors would be much larger for the transport calculated using the transient wave dynamics in ROOD and SCHOEBERL (1983b). These errors suggest that the symmetric tensor neglected by HOLTON (1981) is indeed large for planetary wave dynamics. See TUNG (1982) concerning the development of diffusion models in isentropic coordinates.

must be measured or estimated in the free atmosphere, and it is not possible to study the transport of ground-generated species into the stratosphere. Also, constituents that are conservative above 100 mb will not be well represented, and some of these constituents may have a profound effect on ozone. Therefore, it is still desirable to represent transport processes throughout the atmosphere accurately. In general none of the diffusion models have been able to simulate transport related seasonal variations, and most of the models have difficulty in representing the observed profiles of ground-emitted tracers.

Dynamical studies (advective)

The studies described above emphasize accuracy in the chemical formulation as opposed to the dynamical formulation. An alternative to this approach is to model the dynamics accurately and to simplify the chemistry. This allows not only the study of dynamical mechanisms, but when dynamical parameterizations are derived from model data, this approach allows for the evaluation of the transport parameterizations themselves (MAHLMAN, 1975; TUCK, 1979).

Studies emphasizing realistic dynamics can be further subdivided into two types: those using general circulation models (GCMs), which attempt to model the entirety of the physics and dynamics of the atmosphere, and those using simplified mechanistic models, which model only specific phenomena. The simplified models are most useful in aiding the interpretation of complex GCMs and in evaluating different transport mechanisms.

Several ozone transport studies have used GCM dynamics (MAHLMAN *et al.*, 1980, and the references therein). These models vary in their formulation of both chemistry and dynamics, but all suffer from the problem that the complexity of the dynamics makes it difficult to isolate the causal process for a particular transport event. The important characteristics of the constituents transport in GCMs can be deduced from the inert tracer study by MAHLMAN and MOXIM (1978). In this experiment a distribution of an inert substance was placed in the winter atmosphere at a height of 65 mb ($\sim$18 km), and a tropospheric sink was modeled by rainout. Using the same dynamical model, MAHLMAN *et al.* (1980) have also performed two ozone transport experiments. There is a high degree of qualitative agreement in the lower stratosphere and upper troposphere between the inert tracer experiment (MAHLMAN and MOXIM, 1978) and the results of the ozone experiments in Mahlman *et al.* This supports the conclusion of Mahlman *et al.* that the details of the source chemistry are unimportant in determining the constituent distribution away from the source.

For the current purposes, the results from Mahlman and Moxim and other GCMs can be summarized and generalized as follows. The atmosphere tends to distribute a substance such that it is in a quasi-steady equilibrium on which are superimposed seasonal variations. Initially, near sources, there are large fluxes due to the existence of gradients that are to some extent independent of the dynamics and therefore out of equilibrium with the dynamics. While a source that is a constant function of time would eventually reach a state in which such vigorous transport is minimal, constantly changing photochemical sources and major changes in the motion fields (seasonal variations) will continually cause large fluxes.

The background equilibrium state is characteristic of an atmosphere in which the dynamics have distributed the constituent in such a way that fluxes are minimized. This distribution should be largely representative of diffusive processes maintaining the constituent gradients between the constituent sources and sinks. The seasonal transport is particularly important during the wintertime due primarily to the constantly changing dynamics. Since the dynamics in the winter are strongly influenced by transient wave events, this aspect of the seasonal behavior cannot be properly modeled by a diffusive parameterization.

Mechanistic models have been very useful in evaluating the interaction of planetary wave dynamics with photochemistry (HARTMANN and GARCIA, 1979; KAWAHIRA, 1982 a, b). Assuming that the nature of the transport in GCMs is correct, then with the aid of mechanistic models it is now possible to derive a reasonable explanation of the seasonal variation of ozone transport. ROOD and SCHOEBERL (1983a, b) investigated the relative importance of transport by steady dissipative planetary waves, stirring of parcels across regions of strong photochemical gradients, the diabatic circulation, and transient planetary waves (sudden warmings).

In general it can be argued that the seasonal variation of ozone in the lower stratosphere, and therefore, of total ozone at extratropical latitudes, is driven largely by the diabatic circulation as suggested by DUNKERTON (1978). However, the diabatic circulation is not capable of causing the polar maximum, and the breakdown of the winter polar vortex is necessary for the intrusion of ozone into high latitudes. These breakdowns are associated with major midwinter warmings and the seasonal changeover of the stratospheric circulation in spring (final warming). While there can be large northward transport of ozone associated with midwinter warmings, in general, the springtime ozone maximum is associated with the final warming.

The stirring mechanism, which is related to the enhanced eddy transport discovered by HARTMANN and GARCIA (1979), is of relatively little importance in the buildup of high-latitude, lower stratospheric ozone but has potentially important local effects (see Figure 23 in GARCIA and SOLOMON, 1983). Steady dissipative planetary waves transport ozone poleward and downward in the same sense as the diabatic circulation, and in the lower stratosphere this mechanism could be more important than the diabatic circulation (SCHOEBERL, 1981). However, it is suggested in ROOD and SCHOEBERL (1983a) that ozone transport cannot be modeled simply by advection by steady dissipative waves, because these waves transport ozone from high altitudes into the lower polar stratosphere rather than northward from midlatitudes. Therefore, excessive hemispheric amounts of ozone are modeled, and the inadequacies of the diabatic circulation are compounded.

The most important augmentation to the diabatic circulation is transport during warmings or when the strong polar vortex breaks down. It was shown in ROOD and SCHOEBERL (1983b) that during the zonal mean deceleration phase of the warming there is strong poleward transport for a constituent with a negative meridional mixing ratio gradient. This transport mechanism is characterized by strong meridional eddy fluxes. The selectively meridional transport associated with warming events is the sort of mechanism required to correct the strong buildup of ozone in midlatitudes by the diabatic circulation.

The importance of subplanetary-scale waves must not be underemphasized. Baroclinic scale disturbances are required for the mixing of ozone in the lower stratosphere and for tropospheric-stratospheric interchange. These waves are probably instrumental in the maintenance of the typical poleward and downward isolines of ozone found by MAHLMAN *et al.* (1980) and play a similar role in the stratosphere. As with the general circulation these intermediate-scale waves are an important part of the time-averaged climatology.

If the most important transport mechanism on a seasonal scale is the diabatic circulation augmented by strong transient events that cause the breakdown of the polar vortex, then the following features should be observed in the ozone data:

1. There should be a strong poleward eddy flux of ozone during transient wave events (warmings). If nonlinear effects are small and the mean flow reaccelerates after the warming, then there should be a southward eddy flux after the warming.[4]

[4] If the warmings are completely time reversible, then there is no net transport of ozone to high latitudes. In ROOD and SCHOEBERL (1983b) there is net northward flux due to dissipative processes. In the atmosphere the warmings do not perfectly reverse themselves and there is net northward transport. Also wave-wave interaction can have significant consequences on the calculated transport.

2. Since the final warming is not followed by a reacceleration of the mean flow, the time of the total ozone maximum should occur at the time of the final warming.
3. If irreversible processes in conjunction with transient events are in fact important in the northward transport of ozone, then years with major warmings should exhibit more ozone at high latitudes than years without major warnings.
4. If the ozone maximum occurs with the final warming, then the Southern Hemisphere maximum should occur later relative to the spring equinox than the Northern Hemisphere maximum. This conclusion is based on the assumption that the stronger planetary wave activity in the Northern Hemisphere causes the spring changeover to occur earlier than would be the case with diabatic forcing alone.

Figure 2 shows that horizontal eddy flux of ozone at 30 mb (~24 km) during January and February of 1979 (positive is poleward). During this year there was a strong minor midwinter warming in late January and a major wave number two warming in late February. Coincident with both

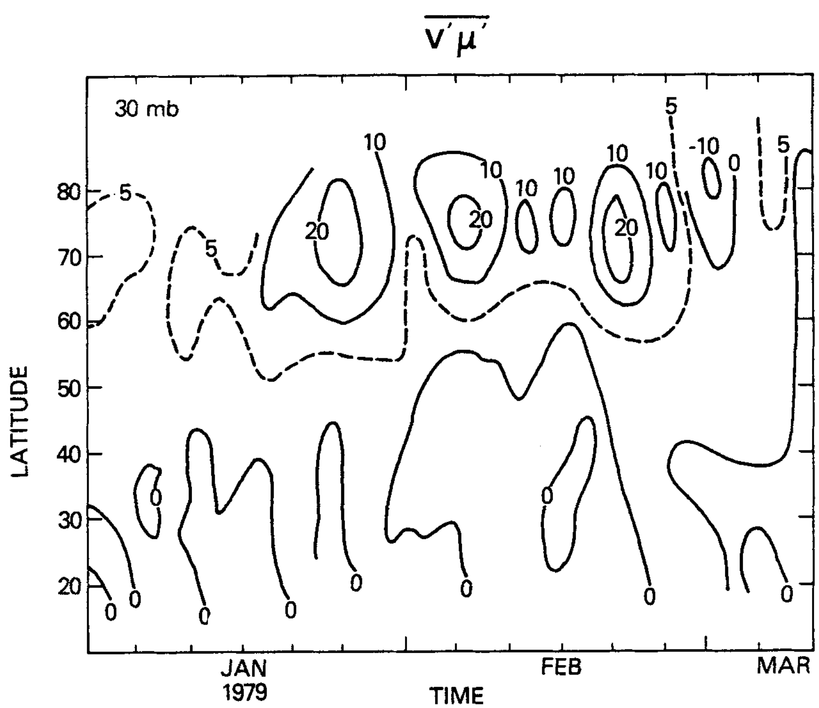

Figure 2. Horizontal eddy flux of ozone at 30 mb in ppm m sec^{-1} from SBUV data (courtesy of R. M. Nagatani and A. J. Miller).

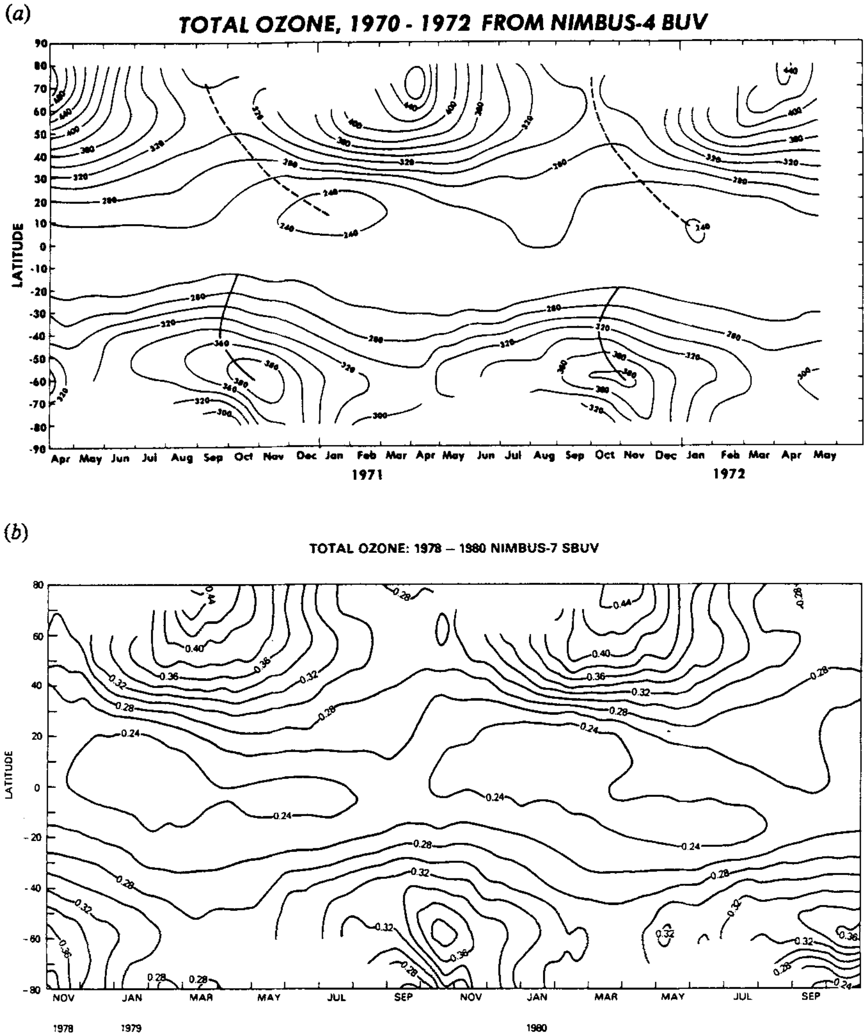

Figure 3. Total ozone time series from BUV and SBUV data (courtesy of E. Hilsenrath (a) in Dobson Units (D.U.) (b) in 10^3 D.U.

warmings is a strong burst of northward flux. After the wave number two warming there is some southward flux associated with the partial restoration of the mean zonal flow. The wave number one warming in late January is followed by a complex series of nonlinear events rather than the restoration of the mean flow.

The southward flux after the late February warming is not large enough to counterbalance the northward flux, because the mean zonal wind does not re-establish a prewarming state. In fact the westerlies never really reform after this warming, and it can be viewed as the final warming. The ozone maximum is associated with this event, supporting the proposition that the final warming fixes the time of the ozone maximum (see Figure 3).

The total ozone time series for several years (Figure 3) shows interannual variation of the time of the total ozone maximum. The maximum generally occurs in late March or early April and is associated with the seasonal changeover in the mean circulation (DÜTSCH, 1974). The planetary waves cause the circulation reversal to occur somewhat earlier than if the diabatic forcing alone governed the circulation. In a wave-free atmosphere the seasonal reversal would occur in late April or early May (LABITZKE and GORETZKI, 1982; HOLTON and WEHRBEIN, 1980, 1981). If there is a major warming just prior to the equinox, the westerly circulation may not recover and the final warming and the corresponding ozone maximum will occur especially early in the year as in 1979.

Figure 4 shows the integrated total ozone north of 40° for three winters. It is seen that the total integrated ozone is significantly larger in the two winters during which major warmings occurred. While this amount of data may not be statistically significant, the data do support the idea that warmings are responsible for enhanced northward transport of ozone.

In the Southern Hemisphere (Figure 3) the well-known interhemispheric asymmetries are seen. The ozone buildup occurs more at

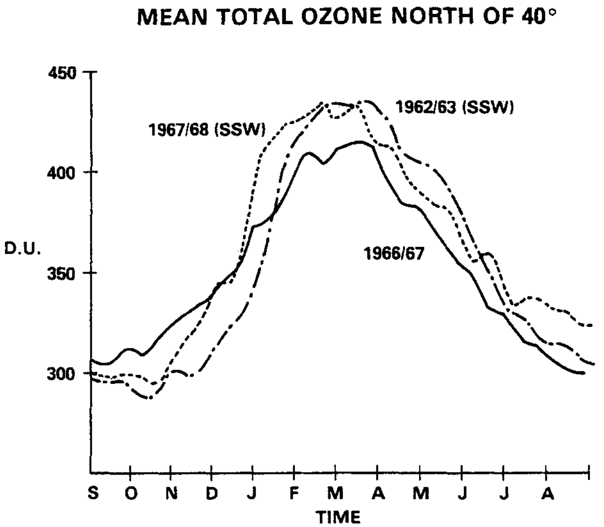

Figure 4. Integrated total ozone in D.U. north of 40° for three winters. (From Zullig, 1973).

midlatitudes and is characteristic of a regime dominated more by the diabatic circulation than by planetary waves. This is consistent with the weaker planetary wave activity and the more stable polar vortex observed in the Southern Hemisphere. There is, however, a late spring excursion of ozone into high latitudes associated with the collapse of the wave field during the diabatically driven reversal of the polar vortex. This ozone maximum occurs one month later relative to the spring equinox than the maximum in the Northern Hemisphere

Summary and discussion

Modeling of stratospheric transport with chemistry has been approached from two different, often conflicting ways. One emphasizes chemistry, the other dynamics. It has been seen that models that emphasize chemistry work well away from dynamically controlled regions, and that models that emphasize dynamics work well away from chemically controlled regions.

The comments thus far have been biased towards ozone. Modeling of other constituents is not as well understood and will prove to be a difficult undertaking. The described transport mechanisms have been verified only on the basis of ozone data, and very limited amounts of data at that. The transport mechanisms, however, are not derived based on any assumptions about ozone and should ultimately be applicable to other constituents. The most complex problems will be presented by constituents with lifetimes of a few days.

The most important direct dynamical effect on ozone photochemistry is the stirring of parcels across regions of strong photochemical gradients. The importance of the stirring term is exhibited in GARCIA and SOLOMON (1983) and ROOD and SCHOEBERL (1983a) where changes on the order of 1 ppm are seen on the edge of the photochemically controlled region of ozone. This effect should not be ignored as unimportant just because it causes little change in the total ozone field.

Dynamics can also cause large changes in the local ozone distribution in the middle atmosphere through temperature-dependent photochemistry. The importance of the temperature effects depends largely on the temporal scales of interest in a particular problem. The temperature perturbations associated with the quasi-steady planetary waves force certain regions of the atmosphere away from their radiative equilibrium temperature and will have to be considered in any accurate chemical study. Transient planetary waves force the high latitudes in the Northern Hemisphere to be warmer than radiative considerations alone, and this temperature effect may have to be considered. Systematic temperature perturbations associated with breaking gravity waves may be important in the mesophere.

General circulation studies and observations indicate that atmospheric motions tend to force a constituent, away from it sources, to be in a quasi-steady climatological mean state. In this state the constituent gradients can be thought of as being in equilibrium with the climatological dynamics.

Superimposed on this mean state, particularly in the Northern Hemisphere winter are very large seasonal variations. The major mechanisms for these variations seem to be the diabatic circulation, which is rather simple to model, and transport by transient planetary waves. The wintertime onset of wave activity and the large changes of the photochemistry associated with the polar night are both events that cause large constituent fluxes. The advection associated with transient waves is on the time scale of days and is highly variable. This strong transient transport is not efficiently or correctly modeled as diffusion.[5] Any parameterization of this process requires rapid movement of ozone from middle to high latitudes.

The transport processes described here and represented in more detail in Rood and Schoeberl (1983b) show periods of strong horizontal transport that appear on latitude-longitude grids as rapidly moving tongues of ozone-rich and ozone-poor air. The amount of ozone that is irreversibly transported depends on the dissipation in the model or on transient wave events that are not time reversible (like the final warming). Nonlinear and other effects in the atmosphere make atmospheric warmings less symmetric than the ones in the model. Therefore there is a general tendency for planetary waves to build up ozone in the northern reaches of their domain and likewise transport potential vorticity to the southern reaches of their domain. The mechanisms described in Rood and Schoeberl (1983b) are adequate for explaining the gross features of the ozone and potential vorticity distribution and do not require the esoteric concept of planetary wave breaking as recently postulated by McIntyre and Palmer (1983).

The ultimate goal of several research groups is to produce a general circulation model that accurately represents the chemistry and dynamics of ozone. One possible approach to this model might include a chemistry model with parameterized dynamics at high altitudes on top of a transport model with reasonable dynamics and parameterized photochemistry. Modeling of ozone in the transition region is complex and will require detailed representation of both transport and chemistry.

[5] Time dependent diffusion can be derived at least for simple dynamics (Strobel, 1981). However, to implement such a scheme on the time scales appropriate to transient planetary waves would be more expensive than calculating the transport directly.

Acknowledgements

Contribution Number 11 of the Stratospheric General Circulation with Chemistry Modeling Project of NASA/GSFC. The author expresses gratitude to M. R. Schoeberl for many helpful discussions and reviewing the manuscript. The authors also acknowledges helpful conversations with H. R. Schneider, S. Solomon, and R. A. Plumb. Finally thanks are extended to M. A. Geller, C. Jackman, R. S. Stolarski, and an anonymous referee for reviewing the manuscript.

REFERENCES

ANDREWS, D. G., and MCINTYRE, M. E. (1978), *An Exact Theory of Nonlinear Waves on a Lagrangian-mean Flow*, J. Fluid Mech. *89*, 609–646.

BOYD, J. P. (1976), *The Noninteraction of Waves with the Zonally Averaged Flow on a Spherical Earth and the Interrelations of Eddy Fluxes of Energy, Heat, and Momentum*, J. Atmos. Sci. *33*, 2285–2291.

CHARNEY, J. G., and DRAZIN, P. G. (1961), *Propagation of Planetary-scale Disturbances from the Lower into the Upper Stratosphere*, J. Geophys. Res. *66*, 83–109.

DUNKERTON, T. (1978), *On the Mean Meridional Mass Motions of the Stratosphere and Mesosphere*, J. Atmos. Sci. *35*, 2325–2333.

DÜTSCH, H. U. (1974), *The Ozone Distribution in the Atmosphere*, Can. J. Chem. *52*, 1491–1504.

GRACIA, R. R., and SOLOMON, S. (1983), *A Numerical Model of the Zonally Averaged Dynamical and Chemical Structure of the Middle Atmosphere*, J. Geophys. Res. *88*, 1379–1400.

HARTMANN, D. L. (1981), *Some Aspects of the Coupling between Radiation, Chemistry, and Dynamics in the Stratosphere*, J. Geophys. Res. *86*, 9631–9640.

HARTMANN, D. L., and GARCIA, R. (1979), *A Mechanistic Model of Ozone Transport by Planetary Waves in the Stratosphere*, J. Atmos. Sci. *36*, 350–364.

HOLTON, J. R. (1981), *An Advective Model for Two Dimensional Transport of Stratospheric Trace Species*, J. Geophys. Res. *86*, 11989–11994.

HOLTON, J. R., and WEHRBEIN, W. M. (1980), *The Role of Forced Planetary Waves in the Annual Cycle of the Zonal Mean Circulation of the Middle Atmosphere*, J. Atmos. Sci. *37*, 1968–1983.

HOLTON, J. R., and WEHRBEIN, W. M. (1981), *A Further Study of the Annual Cycle of the Zonal Mean Circulation in the Middle Atmosphere*, J. Atmos, Sci. *38*, 1504–1509.

HSU, C. P. F. (1980), *Air Parcel Motions During a Numerically Simulated Sudden Stratospheric Warming*, J. Atmos. Sci. *37*, 2768–2792.

KAWAHIRA, K. (1982a), *A Quasi-one-dimensional Model of the Ozone Transport by Planetary Waves in the Winter Stratosphere*, J. Met. Soc. Japan *60*, 831–849.

KAWAHIRA, K. (1982b), *A Two-dimensional Model for Ozone Changes by Planetary Waves in the Stratosphere I. Formulation and the Effect of Temparature Waves on the Zonal Mean Ozone Concentration*, J. Met. Soc. Japan *60*, 1058–1062.

LABITZKE, K., and GORETZKI, B., *Handbook for MAP*, *5* (Sechrist, C. F. ed.) (SCOSTEP, U of Illinois, Urbana, Il., 1982).

MAHLMAN, J. D., *Some Fundamental Limitations of Simplified Transport Models as Implied by Results from a Three-dimensional General-circulation/tracer Model*, in *Proceedings of the Fourth Conference on the Climatic Impact Assessment Program* (ed. Hard, T. M., and Broderick, A. J.) (DOT-TSC-OST-75-38, U.S. Dept. of Trans., Washington, D.C., 1975), pp. 132–146.

MAHLMAN, J. D., and MOXIM, W. M. (1978), *Tracer Simulation Using a Global General Circulation Model: Results from a Midlatitude Instantaneous Source Experiment*, J. Atmos. Sci. *35*, 1340–1374.

MAHLMAN, J. D., LEVY, H., II, and MOXIM, W. J. (1980), *Three-dimensional Tracer Structure and Behavior as Simulated in Two Ozone Precursor Experiments*, J. Atmos. Sci. *37*, 655–685.

MATSUNO, T. (1980), *Lagrangian Motion of Air Parcels in the Stratosphere in the Presence of Planetary Waves*, Pure Appl. Geophys. *118*, 189–216.

MCINTYRE, M. E., and PALMER, T. N. (1983), *Breaking Planetary Waves in the Stratosphere*, Nature *305*, 593–600.

NASA, *The Stratosphere Present and Future* (NASA RP 1049, Washington, D.C., 1979).

PYLE, J. A., and ROGERS, C. F. (1980), *A Modified Diabatic Circulation Model for Stratospheric Tracer Transport*, Nature *287*, 711–714.

REED, R. J., and GERMAN, K. E. (1965), *A Contribution to the Problem of Stratospheric Diffusion by Large-scale Mixing*, Mon. Wea. Rev. *93*, 313–321.

ROOD, R. B., and SCHOEBERL, M. R. (1983a), *A Mechanistic Model of Eulerian, Lagrangian Mean, and Lagrangian Ozone Transport by Steady Planetary Waves*, J. Geophys. Res. *88*, 5208–5218.

ROOD, R. B., and SCHOEBERL, M. R. (1983b), *Ozone Transport by Diabatic and Planetary Wave Circulations on a Beta-plane*, J. Geophys. Res. *88*, 8491–8504.

SCHOEBERL, M. R. (1981), *A Simple Model of the Lagrangian-mean Flow Produced by Dissipating Planetary Waves*, J. Atmos. Sci. *38*, 1841–1855.

STROBEL, D. F. (1981), *Parameterization of Linear Wave Chemical Transport in Planetary Atmospheres by Eddy Diffusion*, J. Geophys. Res. *86*, 9806–9810.

TUCK, A. F. (1979), *A Comparision of One- Two- Three- Dimensional Model Representations of Stratospheric Gases*, Phil. Trans. Roy. Soc. Lon. *A290*, 477–495.

TUNG, K. K. (1982), *On the Two-dimensional Transport of Stratospheric Trace Gases in Isentropic Coordinates*, J. Atmos. Sci. *39*, 2330–2355.

ZULLIG, W. (1973), *Relation between the Intensity of the Stratospheric Circumpolar Vortex and the Accumulation of Ozone in the Winter Hemisphere*, Pure Appl. Geophys. *106–108*, 1544–1552.

(Received 21st March 1984, accepted 21st March 1984)