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THE TREATMENT OF DYNAMICAL PROCESSES IN TWO-DIMENSIONAL MODELS OF THE TROPOSPHERE AND STRATOSPHERE

Donald J. Wuebbles

MASTER

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Lawrence
Livermore
Laboratory

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1. INTRODUCTION

The physical structure of the troposphere and stratosphere is the result of an intricate interplay among a large number of radiative, chemical, and dynamical processes. Because it is not possible to model the global environment in the laboratory, theoretical models must be relied on, subject to observational verification, to simulate atmospheric processes. Of particular concern in recent years has been the modeling of those processes affecting the structure of ozone and other trace species in the stratosphere and troposphere.

One-dimensional models have been the basic diagnostic and prognostic tools in theoretical studies of chemical processes in the troposphere and stratosphere. However, the usefulness of such models is limited due to their representation of transport processes by an empirically based globally averaged vertical diffusion approximation. In addition to the vertical variations which can be reproduced in a 1-D model, there are important variations in mixing ratios of trace species with latitude due to both radiative and dynamical processes. Therefore, as methodologies are developed, higher dimensional models will likely play an ever increasing role in future diagnostic and prognostic studies of the atmosphere because of their greater degrees of freedom in treating global dynamic and latitudinal effects.

Three-dimensional models have the potential to provide the closest simulation of trace species transport in the atmosphere. Such models determine transport fluxes through the solution, in three dimensions, of the appropriate conservation equations for momentum, energy, and mass. These models can, in principle, include all of the feedback mechanisms of the real world. However, currently developed three-dimensional model, are very demanding of computer time and storage, and so far have only been able to include highly simplified chemistry. Three-dimensional models capable of including all of the detailed chemistry necessary to model ozone variations are not foreseeable in the near future.

Zonally averaged two-dimensional models with spatial resolution in the vertical and meridional directions can provide a much more realistic representation of tracer transport than one-dimensional models, yet are capable of the detailed representation of chemical and radiative processes contained in the one-dimensional models. The purpose of this study is to describe and analyze existing approaches to representing global atmospheric transport processes in two-dimensional models and to discuss possible alternatives to these approaches. We will begin with a general description of the processes controlling the transport of trace constituents in the troposphere and stratosphere.

2. TRANSPORT OF TRACE SPECIES IN THE TROPOSPHERE AND STRATOSPHERE

One of the key early theories of tracer transport in the stratosphere centered around the model of meridional circulation suggested by Brewer (1949) and Dobson (1951, 1956) based on the distributions of water vapor and ozone. In this model, air particles ascend from the troposphere across the tropical tropopause and eventually move toward higher latitudes in the stratosphere where they descend and return to the troposphere.

Utilizing the heating rates derived by Murgatroyd and Goody (1958), Murgatroyd and Singleton (1961) estimated the magnitude of the meridional circulations in the stratosphere and mesosphere as motions to compensate for the net heating or cooling due to radiative processes. The circulation obtained by Murgatroyd and Singleton was similar to the Brewer-Dobson model. Murgatroyd and Singleton felt that this circulation was quite consistent with previous observations of tracer transport. However, they suggested that because of discrepancies in the angular momentum budget of this circulation, eddy transport processes, which they had neglected, were probably important.

As discussed by Mahlman and Moxim (1978), many other investigators proposed that zonally assymmetric motions (eddies) were important for the large-scale dispersion of tracers. The importance of vertical eddy fluxes of ozone was proposed by Reed and Julius (1951). Later Reed (1953) suggested that horizontal eddy fluxes might also be important. Similar suggestions were made in a number of other studies of the ozone transport proplem (Godson, 1960; Ramanathan and Kulkarni, 1960; Boville and Hare, 1961). The behavior of tungsten-185 following a series of low-latitude nuclear tests in 1958 led Feely and Spar (1960) and Newell (1961, 1963) to suggest that eddy processes dominated the poleward transpost in the stratosphere.

Other studies have noted that while ar parcels in the troposphere which have been heated by radiative effects at low latitudes move poleward and upward, the poleward-moving air parcels in the lower stratosphere are sinking and equator-moving parcels are rising (Newell, 1969; Molla and Loisell, 1962; Oort, 1965).

A number of later observational studies showed the stratospheric meridional circulation to be quite different from the Brewer-Dobson model, particularly at higher latitude, (e.g. Reed et al., 1963; Julian and Labitzke, 1965; Murakami, 1965; Mahlman, 1966, 1969; Perry, 1967; Vincent, 1968). In particular, it was noted in Mahlman (1966, 1969) that the stratospheric heat balance is such that the heating effect of the meridional circulation acts in opposition to that produced by large-scale eddy flux convergence of heat. Mahlman (1966) hypothesized that the stratospheric dispersion of trace constituents is a rather complicated function of interactive mean cell and eddy transports. This was verified by Hunt and Manabe (1968) using a general circulation model. Theirs plus other more recent studies (e.g. Mahlman and Moxim, 1978, Mahlman et al., 1980) have shown a tendency for systematic cancellation between mean meridional and eddy effects in the dispersion of passive tracers most of the time interspersed with short periods during which the two processes reinforce each other.

The observational studies resulted in a new model for mean meridional transport in the stratosphere, with circulation depicted by the thermally direct Hadley cell in tropical latitudes, a thermally indirect cell (called the Ferrel cell) forced by the eddies (waves) at midlatitudes, accompanied by a direct polar cell.

Results of studies of the transport of tracers from the stratosphere into the troposphere appear to be as seemingly contradictory as the two models for mean stratospheric circulation discussed above. Reed and Sanders (1953) observed that significant amounts of stratospheric air can enter the troposphere in the intense baroclinic zone below the polar front jet stream associated with extratropical cyclones. These results were verified by later studies (Newton, 1954; Reed, 1955; Reed and Danielson, 1959; Danielson 1959; and Staley, 1960). Studies by Reiter (1963), Mahlman (1965, 1966), Reiter and Mahlman (1965), Danielson (1964, 1968) and Danielson et al. (1970) showed that the marked fallout of radioactive debris can be attributed to cyclonic activity, and that air of high radioactivity is inferred to originate in the lowest layer of the stratosphere. Kida (1977 a,b) in a Lagrangian analysis of a simplified general circulation model, indicated that the baroclinic process of cyclogenesis and its concommitant lowering of the center of mass leads to a systematic downward flux of stratospheric air in such regions. Further theoretical support is given by Hoskins (1971) and Mudrick (1974).

Meanwhile Stewart et al. (1957), Machta (1957) and others noted that latitudinal distributions of fallout of radioactive debris showed a marked maximum in mid-latitudes. Machta (1959) suggested that the most plausible explanation for appearance of the maximum is preferential return of stratospheric air to the troposphere in middle and high latitudes, and supported the Brewer-Dobson model. However, Martell and Dravinsky (1960) suggested that the transport of stratospheric debris to the troposphere presumably takes place near the subtropical jet. Also Feely (1960) claimed the transport of debris into the troposphere occurs at the tropopause gap. Studies with general circulation models by Hunt and Manabe (1968), Hunt (1969) and London and Park (1974) have supported the conclusion that the stratospheric-tropospheric exchange occurs principally in the vicinity of the tropopause gap in agreement with the indirect Ferrel cell model discussed earlier. However, it must be noted that their conclusions were arrived at from viewpoints of Eulerian motion and budget considerations, and that no direct evidences of the transport of stratospheric air into the troposphere were given (Kida, 1977 a,b).

All of the apparent incompatibility of the two models discussed above disappears when one considers the difference in viewpoints of atmospheric motion. The indirect Ferrel cell structure is deduced by zonally averaging instantaneous motions, while the Brewer-Dobson circulation is equivalent to the net displacement of air particles for a long period (Kida, 1977 a,b). In short, the former is Eulerian mean motion, but the latter is Lagrangian mean motion. Implicit within the Lagrangian mean motions are the contribution by the eddy motions, which are predominant in mid-latitudes (Andrews and McIntyre, 1978 a,b; McIntyre, 1980; Dunkerton, 1978). As discussed by Wallace (1978), the mean circulation (called Stokes drift) induced by the eddy motions in mid-latitude, when added to the Eulerian mean circulation, acts to counteract the effect of the indirect Ferrel cell. The Brewer-Dobson model of the mean meridional circulation was not widely accepted until recently because it was mistakenly interpreted as an Eulerian model.

Using a simplified Lagrangian general circulation model, Kida (1977 a,b) describes the travel of an air particle around the atmosphere as follows. Consider an air particle starting at the tropical tropopause. It ascends directly across the tropopause into the stratosphere in the upward branch of the Hadley cell, and then gradually moves towards higher latitudes. When it gets through the subtropics and comes to middle or high latitudes, it begins to descend slowly enough for compressional heating to balance radiative cooling there. After a long-period of residence in the stratosphere, it arrives at the lowest layer of the stratosphere where intermittent intense downward motions can occur, and then intrudes directly across the mid-latitude tropopause to merge in the troposphere when cyclone activity exists. Also within the troposphere, it tends to descend but with much horizontal dispersion. In the course of time, it flows out through a route in the lowest troposphere in the subtropics to the tropics and finally back to its original position. Kida notes, however, that this general circulation of the air particle should be understood as a representation of statistical measurements of a large number of air particles for a long period.

Likewise, recent studies of Mahlman and Moxim (1978) and Mahlman et al. (1980) in tracer experiments with a general circulation model have indicated that trace species such as ozone produced in the upper stratosphere move downward and poleward. Their results show the zonal-mean diabatic circulation to be a systematic contribution to the model's rapid evolution to poleward-downward slopes. Eddy diabatic processes were found to be important for allowing systematic poleward-downward and equatorward-upward flux of air particles across zonal mean isentropic surfaces. In addition, the model produces the largest transport to the troposphere in association with growing midlatitude cyclones in agreement with the previously discussed results of Kida (1977 a,b).

3. EXISTING TWO-DIMENSIONAL MODELS

All of the current two-dimensional models of the chemistry and transport of trace species in the global troposphere and stratosphere use time and zonal averages of the continuity equation to split atmospheric transport processes into mean and eddy components. Advection by the mean meridional circulation is represented in terms of a horizontal mean velocity, v, and a vertical mean velocity, w. Eddy terms, which result from the deviations from the mean, are generally represented by the derivative of a diffusive flux. Eulerian representation of the transport terms is used in current models. Eulerian signifies that the averaging is performed along latitude circles, at fixed latitude and vertical coordinates. Existing two-dimensional models can be classified into two approaches for determining the transport coefficients necessary as inputs to the mean and eddy terms of the continuity equation.

The majority of the two-dimensional models (Brasseur, 1980; Clough, 1980; Crutzen and Gidel, 1980; Miller et al., 1980; Whitten et al, 1977) parameterize transport processes phenomenologically by prescribing the mean meridional and vertical wind velocities and the eddy-diffusion coefficients for the horizontal (K_{yy}, K_{yz}) and vertical (K_{zy}, K_{zz}) eddy fluxes. Such models specify as a function of month or season (as well as altitude and latitude) the air temperature transport parameters.

These models take the values of the transport parameters as external variables supplied to the program as suitable tables from estimates based on observations (e.g., Gudiksen et al., 1968; Louis, 1974; Luther, 1973) or three-dimensional models (e.g., COMESA, 1975). However, recognizing that these transport parameters are poorly known, several investigators adjust these parameters to produce a good agreement between modelled and observed trace species (e.g., ozone, radioactive debris) concentrations. Although adjustments to obtain a better agreement with observations of chemically active species such as ozone, nitrous oxide, and methane may be necessary because of inadequate knowledge of the transport parameters, there are obvious dangers in the practice. In particular, one may be attempting to use the transports to correct for what is really a deficiency in the chemical scheme (Harwood, 1980).

Parameterized models, due to the uncoupling of the chemistry and transport, cannot consider feedback effects on calculated ozone (or other species) from any change in background temperature and dynamics which could result from changes in both the absorption of solar radiation and emission of infrared radiation induced by calculated changes in ozone densities. Such feedbacks could be important for the large changes in ozone currently predicted to occur due to potentially large emissions of chlorofluoromethanes. Parameterized models, therefore, are designed to investigate small changes in the chemical structure of the atmosphere, which are, in turn, implicitly assumed to have a negligible effect on the transport and temperature distributions (Hudson, 1977).

A fundamental problem in the two-dimensional description of atmospheric dynamics is the formulation of the eddy transports of chemical species. The diffusive approximation was originally based on the mixing length hypothesis developed by Reed and German (1965). This generally assumes that projections of particle trajectories in the meridional plane are straight lines (Hudson and Reed, 1979). Mahlman (1975) demonstrated that such a parameterization can fail. His tracer experiments with a 3-D general circulation model showed that the eddy-flux tensor can locally often become totally negative. Matsuno (1979) showed that for a simple analytical model of a steady, weakly dissipated, stratospheric planetary wave, the projections of the particle paths in the meridional plane are ellipses, and that the tensor relating eddy fluxes to mean gradients is strongly antisymmetric, representing an advective, rather than a diffusive process (Hudson and Reed, 1979).

The above arguments indicate only that eddy parameterizations by the Reed and German (1965) hypothesis can be inconsistent. However, no existing two-dimensional model has yet demonstrated a more fundamentally correct representation of the eddy processes than the diffusive approximation suggested by the Reed and German (1965) mixing length hypothesis. Many of the current models, although still using the diffusive representation of eddy processes, are considered by their developers to be entirely empirical. These models have achieved varying degrees of success when applied to species other than those for which the original model was calibrated. This points out the necessity for such models to be very carefully validated against observations for a number of trace species.

In the second classification of two-dimensional models an atmospheric radiation model is included, and the temperature and mean circulation are calculated as part of the solution. Eddy diffusivities are still prescribed, however. The models of Pyle (1980) and Vupputuri (1980) fall into this second category. This type of model shows the promise of a more coupled and consistant evaluation of the changes in atmospheric properties expected due to anthropogenic perturbations, since the mean circulation and temperature are coupled with the chemistry. However, the coupling is not complete since the eddy transport is still prescribed.

Difficulties also remain in the parameterization of the eddy momentum flux (Harwood, 1980), a necessary input for calculating the mean circulation explicitly. However, the calculated mean meridional circulation and modelled meridional distribution of ozone determined by Pyle (1976) agrees sufficiently well with the observation of Vincent (1968) and Dutsch (1971), respectively, to lend confidence in this approach.

An interesting discussion on the cancellation between mean circulation and eddy processes mentioned in section (2) as related to 2-D models occurs in Harwood (1980) and will be restated here: although it is often claimed that adoption of mean velocities and eddy coefficients deduced from different data sets will lead to a gross disturbance of the near cancellation between mean and eddy flux convergence, in practice the near cancellation is found. Harwood and Pyle (1977) contend that this is to be expected, because in K-theory the eddies are a diffusive system which, since K_{yy} is typically 10^6 m^2 s^{-1}, has a diffusive timescale of only 10 days for distances of 1000 Km. Consequently, transient effects are very rapidly damped out, leaving a quasi-stationary state in which the near cancellation is found. The resulting tracer distribution may not be very realistic, of course, but the cancellation is unavoidable.

This cancellation effect would, therefore, be expected in both those models that parameterize the mean circulation and those that calculate the mean circulation internally. Likewise, the potential for unrealistic results from not using self-consistent mean velocities and eddy diffusion coefficients is also possible in both types of models. Since the total transport represents a small difference between two large numbers (because of the cancellation effect), one would have to specify the mean velocities and eddy transports with a high degree of accuracy in order to get the total transport correct.

4. NEW DIRECTIONS

As indicated in the previous section, major difficulties still exist in current treatments of processes important to transport of trace species in zonally averaged two-dimensional models.

One of the major problems with the models that calculate the mean circulation internally could be eliminated if a relation could be found to relate the eddy terms to the calculated mean circulation. Although several groups are pursuing this possibility, (e.g., Harwood and Pyle) a successful solution has yet to be reported.

According to Hidalgo (1978), Mahlman and Lee at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey are considering a two-dimensional statistical-dynamical formulation of the eddy fluxes. Eddy fluxes would be computed internally by using the equations of motion to generate specific prognostic equations for the eddy flux themselves. Required input parameters are self-consistent sets of zonally averaged meteorological statistics composed of individual variables, variances, and covariances (of $[v^{*2}R^{*}]$, for example, where v^{*} and R^{*} are the deviation from the mean for the meridional velocity and tracer density respectively). In this approach, they assume closure at the level of triple-eddy products. The degree of sensitivity to higher-order closure uncertainties remain unclear. The three-dimensional general circulation model at GFDL would be used to generate the necessary parameters.

The discussion in section (2) suggests that, rather than the existing Eulerian approaches, a Lagrangian averaging approach might provide a more natural way of describing the transport of trace species in two-dimensional models. Perhaps the most promising approach for the treatment of tracer transport processes in future 2-D models is that suggested by the generalized Lagrangian-mean theory for wave, mean-flow interactions developed by Andrews and McIntyre (1978b). Significant advances in our understanding of fluid motions in the presence of waves have already occurred due to this theory. However, outstanding questions remain to be answered before this theory can be fully applied to zonally averaged models of the global atmosphere. Nonetheless, it may be feasible in the interim (before the Lagrangian theory is acceptably refined) to develop parameterized transport parameters for two-dimensional models that would provide many of the advantages of the Lagrangian approach.

Before proceeding, I will discuss some of the concepts important to the Lagrangian theory. Rather than the classical idea of Lagrangian averaging of taking the time mean following a single air parcel, we wish to examine the Lagrangian-mean velocity at a given point in space. As discussed in Andrews and McIntyre (1978b) and McIntyre (1980), any exact theory of the Lagrangian-mean velocity field must abandon the simple concept of the mean following a single air parcel. The result will be neither a pure Lagrangian nor a pure Eulerian description but, rather, a hybrid Eulerian-Lagrangian description of the motion. In practice this means that the grid structure of existing two-dimensional models could still be utilized if Lagrangian transport parameters were substituted for the existing Eulerian parameters.

According to the generalized Lagrangian-mean theory, the Lagrangian mean of any quantity is the sum of the Eulerian mean of the quantity plus its corresponding Stokes correction. When the quantity is velocity, the Stokes correction is referred to as Stokes drift (Andrews and McIntyre, 1978b; Wallace, 1978; McIntyre, 1980). The Stokes drift effect is shown by examining an air parcel in a steady, periodic, small-amplitude wave. Although the Eulerian-mean velocity is zero, there results an induced Stokes drift velocity of the parcel that is nonzero (see McIntyre, 1980 or Wallace, 1978).

Since the eddy motions in the lower stratosphere are more wavelike than like a random, turbulent flow, it is not at all clear that large scale eddy transports can be described using a diffusive process. In the Lagrangian interpretation, the poleward eddy transports are attributed, not to the slopes of the trajectories of the eddies (as in the diffusive approach developed by Reed and German (1965)), but to the vertical component of the Stokes drift in the presence of a strong vertical gradient of concentration of the tracer in question (Wallace, 1978).

The Lagrangian formulation provides a simple interpretation of the tendency for cancellation between the mean circulation and eddy transport. Exact cancellation is only possible if the Stokes drift exactly cancels the Eulerian mean meridional motion.

Kida (1977b) and Dunkerton (1978) have shown the Stokes drift induced by the eddies to be sufficiently strong that it overwhelms the effect of the Ferrel cell at mid-latitudes, so that the Lagrangian mean circulation looks like that postulated by Brewer and Dobson (see section 2).

The discussions of Andrews and McIntyre (1978b) and Dunkerton (1978) suggest that the Lagrangian mean circulation can entirely describe the mass transport in the atmosphere (i.e., eddy flux terms are not important). However, McIntyre (1980) points out that the effects of wave or eddy motion on net heat and tracer transport are necessarily bound up with departures from conservation motion, and not necessarily with wave activity per se. Therefore, although a net cancellation occurs between the Eulerian motion from the wave activity and the induced Stokes drift, there nonetheless, could be terms describing departures from conservative motion representing effects of small-scale turbulence.

Using a simplified system of equations, Dunkerton (1978) calculated a Lagrangian representation of the mean meridional mass circulation of the stratosphere and mesosphere that compares very well with the circulation determined by Murgatroyd and Singleton (1961) (see section 2). These results immediately suggested to me that an improved representation of transport in two-dimensional models that would better account for the cancellation effects could be accomplished by using the velocities derived by Murgatroyd and Singleton. However, there is remaining uncertainty about the treatment of the eddy term. Because the magnitude of these terms should be much less than in the Eulerian representation, a serious error is probably not made by continuing to use a diffusive approximation. By using the Murgatroyd and Singleton velocities, however, there is no way of estimating the values for the various K's that is internally self-consistent.

Perhaps a better approach would be to use the equations developed by Dunkerton (1978) directly to derive the velocities from measured data (or from data provided by a three-dimensional general circulation model). Using these equations, the only data needed would be the Eulerian mean diabatic heating and the static stability. In this approach, more recent data than that used by Murgatroyd and

Singleton (1961) could be used, resulting in hopefully better accuracy. In addition, by using temperature (or tracer) data measured at the same time as the heating rates and static stability, an internally self-consistent evaluation of the magnitude of the eddy terms could also be done (by subtracting out the known effect of the mean circulation from the continuity equation) and K's could be estimated.

Several approximations and assumptions were made by Dunkerton (1978) in developing his simple equations for the Lagrangian velocities. First of all, the zonal average of $\frac{\partial T}{\partial t}$ was assumed to be negligible; (t is time, T is temperature) secondly, the zonal average of $\frac{v}{a} \cdot \frac{\partial T}{\partial \theta}$ was assumed to be negligible; (where a is the radius of the earth and θ is latitude); thirdly, the vertical eddy flux is assumed to be negligible; and, fourth, waves were assumed to be steady, periodic and small-amplitude. Probably the most important of these is the time derivative of temperature which at other than solstice conditions may not be small. The effect this term would have is uncertain. Transient waves should primarily contribute to the eddy terms. Therefore, assuming standing waves in the Lagrangian development should not greatly affect the results.

It would also be desirable to use Lagrangian diabatic heating rates if possible. However, such rates would likely have to be provided by a three-dimensional general circulation model. Mahlman et al. (1980) have shown that using Lagrangian versus Eulerian heating rates could be significant in the lower stratosphere.

McIntyre (1980) points out some additional problems with the Lagrangian approach. In general, the Lagrangian velocities are divergent (i.e., $\nabla \cdot \overline{V}^L \neq 0$). However, I don't see this being a particular difficulty because it may simply mean that eddy terms must also be included for the flow to be incompressible in the Lagrangian representation. McIntyre also discusses some refinements that could be made to Dunkerton's analysis to make it more accurate quantitatively. However, these refinements would also make Dunkerton's approach more difficult to use.

Although transport parameters based on the analyses of Dunkerton do not accurately reflect a well defined theory for Lagrangian motions, such a representation should, nonetheless, eliminate many of the problems with current Eulerian approaches and should, therefore, be given further consideration and study.

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