JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D15, PAGES 20,013–20,024, AUGUST 16, 2000

Analysis of residual mean transport in the stratosphere 2. Distributions of CO_2 and mean age

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Abstract. Distributions of CO_2 and the mean age of stratospheric air are examined using the interactive two-dimensional model described in the companion paper. It is shown that the model can explain the distribution of age in the lower stratosphere and reproduce the correlations between CO_2 and N_2O observed at midlatitudes in the lower stratosphere. Seasonal characteristics of the measured correlations are captured by the model. The model uses externally specified coefficients K_{yy} to account for large-scale isentropic mixing in the stratosphere. The sensitivity of calculated distributions of CO_2 to K_{yy} is be examined by comparing model runs using three different distributions of K_{yy}. It is shown that the CO_2 measurements require K_{yy} to exceed a threshold value of approximately 10^5 m^2 s^{-1} for most of the year. Once this threshold is exceeded, the slope of the CO_2/N_2 correlations depends only weakly on the magnitude and the structure of the distribution of K_{yy}.

1. Introduction

The existence of an air mass boundary in the subtropics of the stratosphere has been established by observations of aerosols [*Trepte and Hitchman*, 1992; *McCormick and Veiga*, 1992], N_2O and H_2O [*Randel et al.*, 1993] and NO_y and O_3 [*Murphy et al.*, 1993]. The isolation of the tropics from the midlatitudes and its implications for distributions of trace species have been described in the conceptual model of a "tropical pipe" [*Plumb*, 1996].

The subtropical barrier is not, however, an impermeable boundary. The rate of transport between the tropics and the midlatitudes of the stratosphere, sometimes referred to as the "leakiness of the tropical pipe," has an important influence on the distributions of tracers in the lower stratosphere. Transport across the subtropical barrier has been investigated using assimilated winds by *Chen et al.* [1994] and *Waugh* [1996]. In accordance with the above observations and the analyses of ozone data [*Leovy et al.*, 1985; *Manney et al.*, 1993], the assimilated winds give rise to transport out of the tropics during Rossby wave breaking events which result in filaments being drawn into midlatitudes. While the observational analyses mentioned above and the three-dimensional 3-D model calculations find for the most part transport out of the tropics at stratospheric levels, *Minschwaner et al.* [1996] have estimated that midlatitude air is entrained into the tropical upwelling region significantly at altitudes above 22 km. This study was based on measurements of N_2O and CCl_3F_3.

In the companion paper [*Schneider et al.*, this issue] (hereinafter referred to as part 1) we described an interactive two-dimensional (2-D) residual circulation model of the stratosphere and examined distributions of long-lived tracers at altitudes for which satellite data are available. The model was shown to produce tropical and midlatitude profiles of long-lived tracers in reasonable agreement with observations. In the following we will analyze exchange of mass between tropics and midlatitudes at stratospheric altitudes by comparing model calculations of mean age and CO_2 to observations.

As discussed in part 1, the most important factors that determine the rate of transport between tropics and midlatitudes in the model are (1) quasi-horizontal diffusion is acting in midlatitudes and high latitudes only. The magnitude of the diffusion coefficients decreases smoothly toward the subtropics. Transport within the tropics and across the subtropics is dominated by advection which is calculated to be consistent, within the framework of the transformed Eulerian mean theory, with the large-scale diffusion specified in the extratropics. (2) The nonlinear zonal mean momentum advection terms are included in the dynamics module and have a significant effect on the simulation of tracer gradients in the vicinity of the equator. (3) Mechanical damping in the lower stratosphere (15 to 25 km) is assumed to be small. Damping timescales are longer than a season. Gravity wave induced drag is assumed to act within the first 4 km above the tropopause with timescales between 30 and 90 days. We will show that the model reproduces the measured distribution of mean age in the lower stratosphere fairly well and that both the slope and seasonal behavior of measured cor-

Paper number 2000JD900212.
0148-0227/00/2000JD900212$09.00

relations between N_2O and CO_2 [*Boering et al.*, 1994] are well simulated by the model.

The sensitivity of calculated distributions of CO_2 to values assumed for extratropical Rossby wave mixing coefficients K_{yy} will be examined by comparing model runs using three different specifications of K_{yy} as described in part 1 of this paper. It will be shown that the CO_2 measurements require K_{yy} to exceed a threshold value of approximately 10^5 m^2 s^{-1} for most of the year. Once this threshold is exceeded, the slope of the CO_2/N_2O correlations depends only weakly on K_{yy}.

In addition, the sensitivity to the treatment of the troposphere in the model and to the meridional coupling provided by gravity wave drag in the lower stratosphere will be examined. In order to reproduce the measurements, the timescale for the mechanical damping due to gravity waves has to be larger than a season in the altitude range between 15 and 25 km. This sensitivity analysis is preliminary as the current vertical resolution does not allow for implemetations of detailed assumptions for the vertical structure of drag and vertical diffusion in the lower stratosphere.

Calculated distributions of CO_2 depend on the parameterization of the tropospheric heating rates and the matching of these rates with calculated rates for stratospheric heating. The treatment of the tropospheric lower boundary clearly affects the rate of upward mass flux in the lowest layers of the tropical stratosphere and therefore the speed at which tropospheric seasonal variations and the annual increase of CO_2 are propagated into the stratosphere. The vertical velocities also determine the rate of adiabatic cooling. The matching of the heating rates was implemented initially to ensure that the temperature at the tropical tropopause was within less than 2 K of observed zonal mean temperatures. Correlations of CO_2 and N_2O are not significantly affected so long as temperatures at the tropical tropopause are within a few degrees of observed values.

Because of the spacing of vertical layers in the model (2 km) no claim is made that the vertical structure of transport in the lower stratosphere is resolved. Parameters like the rate of mechanical dissipation are by necessity bulk values for fairly deep layers.

2. The Distribution of Mean Age

The concept of the mean age of stratospheric air has been introduced by *Hall and Plumb* [1994]. It is defined as the time required for a parcel of air to transit from its entry point into the stratosphere, the tropical tropopause, to a given location. The mean age and even more so the age spectra contain important information on the transport of mass in different models. Ages can be derived for the stratosphere by measuring the concentrations of tracers that are long-lived and linearly increasing in the troposphere. Mean ages have been derived for the lower stratosphere from observations of SF_6 and CO_2 [*Boering et al.*, 1996].

The mean age can also be thought of as the concentration of a tracer with a constant source in the stratosphere and a sink in the troposphere [*Boering et al.*, 1996]. This definition of age is equivalent to the transit time, except that it allows for influx of young, tropospheric air through the tropopause in mid and high latitudes. Upward transport in the extratropics can occur through vertical exchange processes in the troposphere that extend into the tropopause region. Therefore, the two definitions of mean age give different results in the vicinity of the extratropical tropopause. The differences diminish rapidly with vertical distance from the tropopause. Adding a tracer with a uniform stratospheric source to the set of transported species has the advantage that mean age distributions are calculated online in every model run and do not require a seperate integration for a δ function release of inert tracer at the tropical tropopause. The latter is, of course, necessary to generate age spectra. Model results for mean age, shown in the following, have been obtained by transporting a tracer with a uniform stratospheric source.

Viewed as a tracer with a stratospheric source, the calculated distribution of mean age in a model can give an indication of a model's capability to simulate the distribution of exhaust products from a planned fleet of stratospheric aircraft. Both age and aircraft NO_y have stratospheric sources. The source distributions of the two quantities differ spatially and temporally. In addition, NO_y has a photochemical sink in the upper stratosphere. In the lower stratosphere, however, both tracers should be affected similarly by errors in the rates of transport.

The distribution of mean age, calculated for the low K_{yy} case as defined in part 1 is shown in Figure 1 for the Northern Hemisphere fall and winter. Starting from the tropical tropopause, age increases rapidly with altitude for a few kilometers because vertical velocities are small. At altitudes above 25 km, vertical velocities increase and the vertical gradient in mean age diminishes accordingly. Above 40 km, horizontal zonal mean velocity components increase also. Above 50 km, horizontal velocities reach several meters per second. Speeds of the same order of magnitude are shown by *Eluszkiewicz et al.* [1996] for the residual circulation diagnosed from atmospheric observations. Strong meridional flow toward the winter pole is required to satisfy the momentum budget needed to decelerate the polar night jets in the mesosphere. As a consequence of the short (in relation to a season) advective timescales coupled with rapid mixing in the extratropics, the whole region above 40 km is characterized by weak gradients in age. In the model, age differences barely exceed a year.

We are not aware of direct measurements of mean age at mesospheric levels in the tropics. Calculated distributions of N_2O and CH_4, shown in part 1, agree reasonably well with UARS observations, lending confidence to the accuracy of calculated mean rates for upwelling in the tropics. The temperature structure of

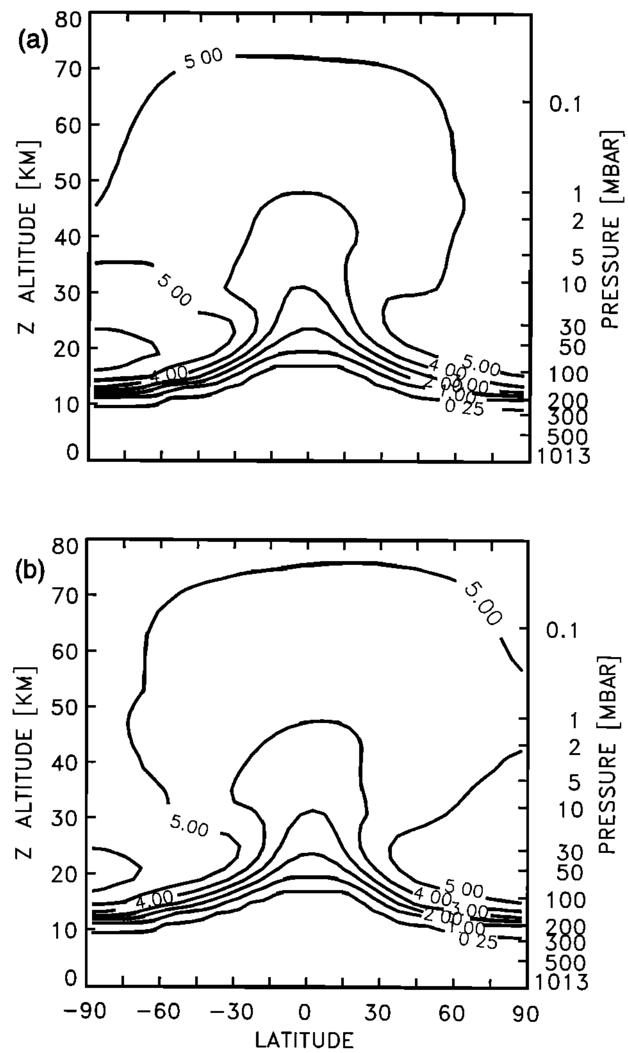

Figure 1. Calculated distributions of mean age for (a) October, 1993 and (b) January, 1994. Units are years.

the mesosphere is captured by the model. Our current understanding is that it is determined by adiabatic processes. Downwelling over the winter pole results in some of the warmest temperatures in the stratosphere and upwelling in the summer polar regions leads to temperatures that are anomalously cold. To satisfy mass continuity, strong horizontal motions are required, which do not allow large gradients in age to persist between the tropics and high latitudes.

Once an air parcel has reached the descending branch of the Brewer-Dobson circulation, its age increases with decreasing altitude. However, the parcel is mixed with younger air that has been transported out of the tropical region at lower altitudes and has been distributed across midlatitudes by large-scale mixing. The rate of outflow from the tropics varies with altitude. In the model we obtain moderate outflow at low stratospheric altitudes and strong outflow at altitudes over 30 km with reduced rates in between. This leads to a reversal in the vertical gradient of age in high latitudes. A maximum in age appears in the annual mean at about 25 km in the polar regions. The altitude at which age becomes younger varies seasonally, as can be seen in Figure 1. Data shown by *Harnisch et al.* [1996] indicate that such a reversal may occur at some altitude. However, we do not intend to read too much into this reversal in the model since it is affected by the profile of gravity wave drag above 25 km which is not well constrained and because no particular attention has been given to the dynamics of the polar vortex.

The calculated distribution of mean age at 20 km is compared with ages derived from measurements of SF_6 in Figure 2. SF_6 concentrations were measured by an instrument flown on the ER-2 aircraft. The ages inferred were provided by J. Elkins (personal communication, 1997). The curves display calculated age for all four seasons. Seasonal variations of mean age at this altitude are generally of the order of half a year. The latitudinal gradient of age at low latitudes and midlatitudes appears to be represented well in the model. The data at high altitudes indicate a large amount of scatter.

The dependence of calculated mean age on Rossby wave diffusion coefficients in the extratropics is similar to that of other long-lived tracers such as N_2O as described in part 1 of this paper. Increasing K_{yy} leads to a stronger overturning rate which causes the slopes of tracer isolines to become steeper. At the same time, the increased quasi-horizontal diffusion in the tracer transport equation counteracts the steepening [*Holton*, 1986], with the net effect consisting in only slightly increased slopes. Ages obtained for the low and high K_{yy} case are compared in Figure 3. The distribution at the altitude of 20 km for the high K_{yy} case is compared to

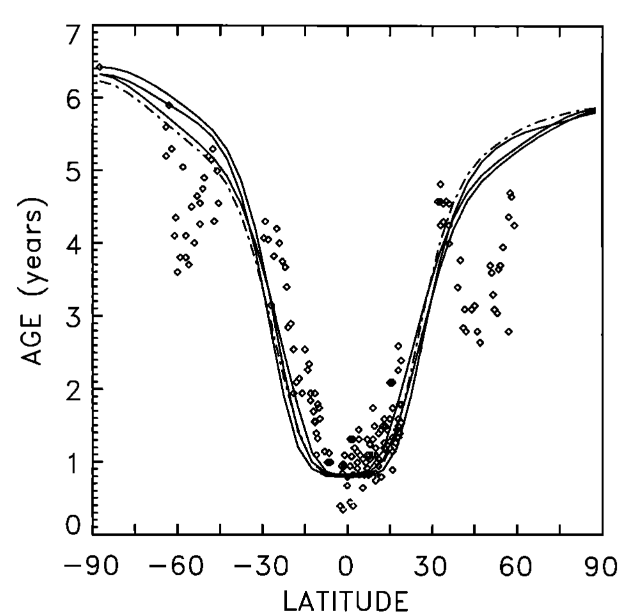

Figure 2. Latitudinal distribution of mean age at 20 km for four seasons. The diamonds represent ages determined from measurements of SF_6.

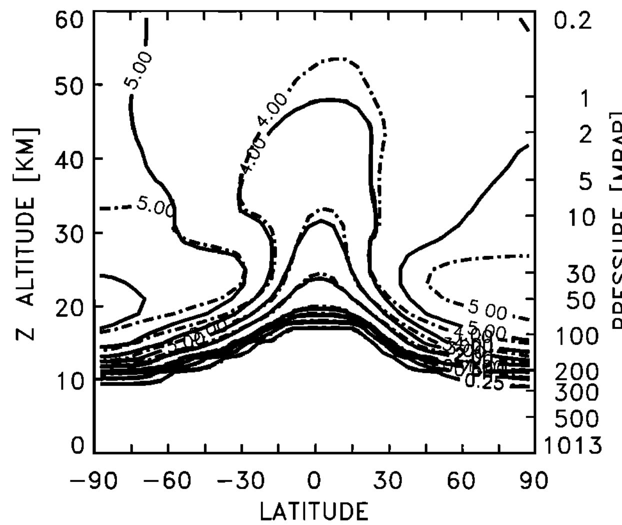

Figure 3. Calculated mean age for January 1992 for the low K_{yy} case (solid lines) and the large-K_{yy} case (dotted lines).

the measurements in Figure 4. Increasing extratropical diffusion causes air parcels in midlatitutdes and high latitudes to undergo more north-south excursions on a given isentropic surface with the effect that horizontal age gradients are reduced and the mean age increases [*Neu and Plumb*, 1999]. In a model with consistent transport, however, the mean meridional circulation is intensified simultaneously, resulting in a faster rate of overturning of the stratosphere and and an increased supply of younger air from the tropics to the midlatitudes. The change in overturning rates is somewhat diminished again by altered ozone distributions. The net effect of the competition between the slope flattening and slope steepening effect of K_{yy} [*Holton*, 1986] is that the air becomes slightly younger for higher diffusion. Differences between the low- and high-K_{yy} case exceed half a year only in small regions of the high-latitude lower stratosphere. For comparison, the uncertainty of age derived from SF_6 is also about half a year due to difficulties in determining the age which are associated with latitudinal gradients of SF_6 at the tropical tropopause.

Although differences in age of half a year may seem insignificant, the change in overturning rates associated with a doubling of extratropical large-scale diffusion coefficients results in substantial differences in the vertical velocity at 100 mbar as shown in Figure 5a. Percent differences for the Northern midlatitudes and high latitudes are shown in Figure 5b. The changes amount to about 30%, comparable to uncertainties associated with attempts to use observations to determine the flux of mass through the 100 mbar level [*Rosenlof*, 1996; *Eluszkiewicz et al.*, 1996]. Temperature changes associated with the change in overturning rates, averaged between 50 and 100 mbar, are between 1 and 2 K in the model. It seems therefore that age needs to be known to a fairly high precision in order to reduce current uncertainties in estimates of the mass exchange between stratosphere and troposphere.

Calculated correlations between age and N_2O are shown in Figure 6. N_2O is long-lived in the lower stratosphere only. Therefore the relation between the two tracers is not globally compact. The symbols in Figure 6 indicate correlations for different latitude regions. Compactness is lost with altitude (low N_2O) first in the tropics. Correlations between 40° and 60°N remain fairly compact to high altitudes. This pattern is consistent with the observed downward slope of the isolines of N_2O between the tropics and high latitudes and the distribution of photochemical loss rates for N_2O in the stratosphere. Ages on N_2O surfaces derived from measurements of CO_2 have been presented by *Boering et al.* [1996]. The lower envelope of the calculated correlations agrees with these observations to within half a year.

3. Simulation of CO_2 in the Stratosphere

Comparison of model-generated CO_2 distributions with the measurements in the stratosphere provides a stringent test for the accuracy of the circulation as simulated by the model for the lower stratosphere. CO_2 is controlled by processes at the Earth surface. Its concentrations exhibit a long-term trend, on which a seasonal signal is superimposed. A maximum is observed in late spring at the midlatitudes and high latitudes of the Northern Hemisphere. The seasonal variation observed in the tropics and in the Southern Hemisphere is much smaller.

CO_2 concentrations have been measured with high precision using ER-2 aircraft based instruments during

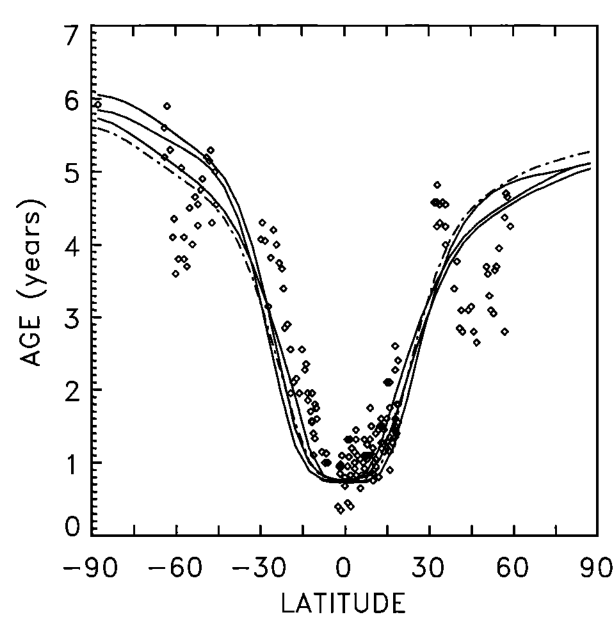

Figure 4. As in Figure 2, but for the large-K_{yy} case.

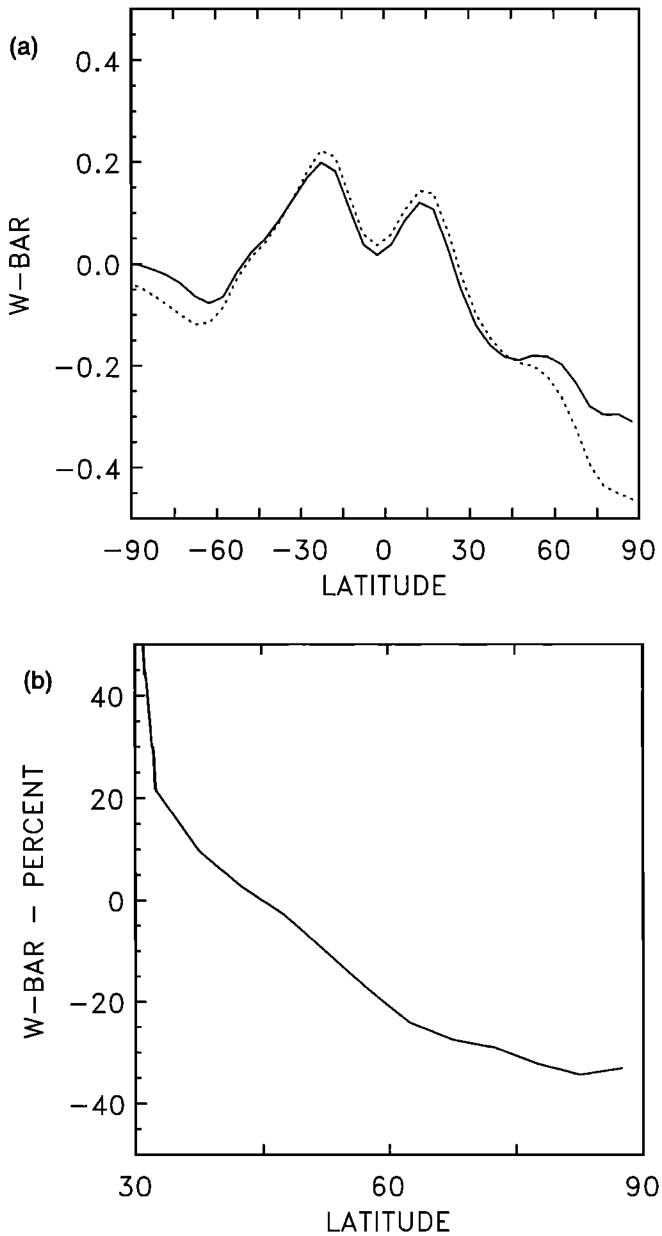

Figure 5. (a) Calculated vertical velocity at 100 mbar for the low-K_{yy} case (solid line) and for the large-K_{yy} case (dotted line). (b) Percent difference between vertical velocities, shown in (5a) for northern midlatitudes and high latitudes. Variable z = 15 and 17 for Figures 5a and 5b.

the Stratospheric Photochemistry Aerosol and Dynamics Experiment (SPADE) and the Airborne Southern Hemisphere Ozone Experiment and Measurement for Assessing the Effects of Stratospheric Aircraft (ASHOE/MAESA) [*Boering et al.*, 1994]. Additional data have been gathered since. In this paper we will concentrate on the SPADE ASHOE/MAESA measurements in order to analyze the seasonality of mass exchange between tropics and midlatitudes. SPADE data are available for fall 1992 and for spring and fall 1993. The ASHOE/MAESA data were taken in the spring and fall of 1994.

The seasonal signal has been detected at low altitudes in midlatitudes of the stratosphere about 4 months after it occurs at the surface. This time lag is too short for the signal to have propagated to high altitudes first and then have been advected subsequently downward by the diabatic circulation. After being transported up through the tropical tropopause, some material is advected into midlatitudes at low stratospheric altitudes. Whatever passes through the subtropical barrier is distributed latitudinally by planetary wave mixing on a timescale of weeks to months. At higher altitudes, the seasonal signal is washed out, but the annual increase can be identified.

For model runs, variations of CO_2 at the surface were specified using the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory (NOAA CMDL) data (T. Conway, personal communication, 1997) from 1980 onward. Integrations were done for 15 years, until the end of 1994. At the start of the model integration the initial condition for CO_2 was taken as the global average value appropriate for the surface in 1980, constant in latitude and height. It takes at least 5 years of integration for the high-latitude distribution of a stratospheric tracer to equilibrate to surface values. Given the annual increase of CO_2, an integration period longer than 15 years would have been preferable. However, the number of stations reporting CO_2 before 1980 is small, and thus it is difficult to derive monthly mean concentrations as a function of time and latitude.

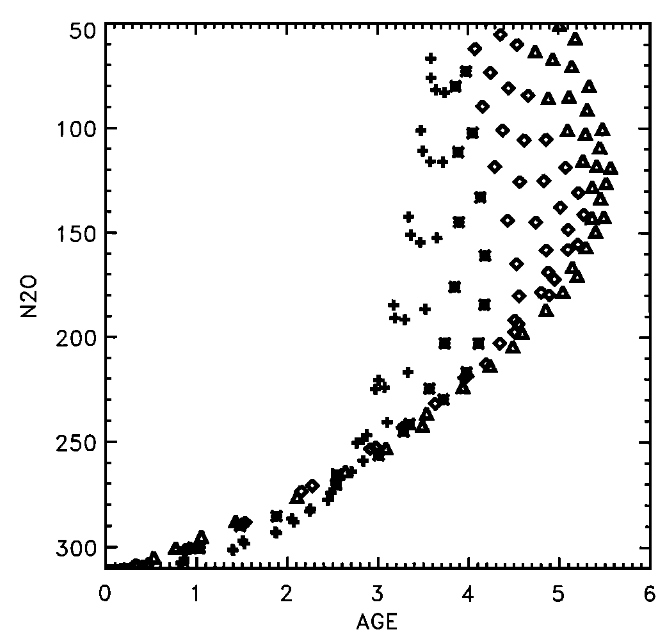

Figure 6. Calculated correlations between N_2O and mean age. Points have been sampled between the altitudes of 10 and 40 km. Plus signs are points obtained for the latitude region between −10° and 10°, asterisks are for 10° to 20°, diamonds are for 20° to 40°, and triangles are for 40° to 60°.

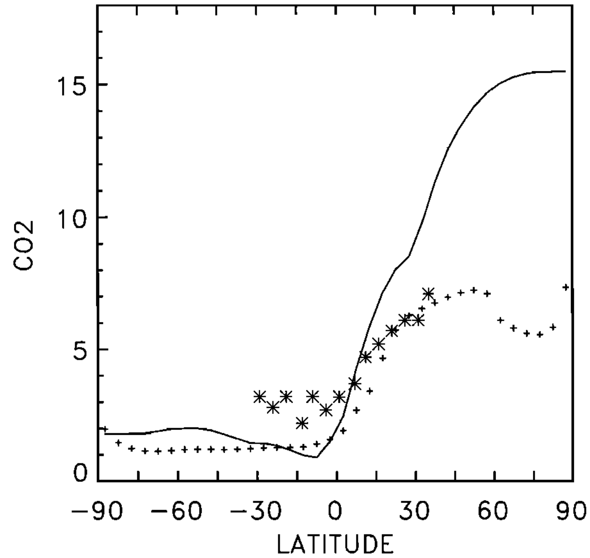

Figure 7. Peak to peak differences in CO_2 concentrations during the year 1993. The solid line represents values at the surface and the dotted line is the seasonal amplitude at 300 mbar. Measurements by *Nakazawa et al.* [1991] are indicated by asterisks. Units are ppm.

The oversimplified treatment of the troposphere in our 2-D model presents a problem for simulating tracers with gradients at the surface. Vertical diffusion coefficients are specified in the model troposphere to guarantee a timescale for vertical exchange of about 1 month for the troposphere. Therefore existing latitudinal surface gradients near the equator are maintained throughout the troposphere in the model. The gradients can be reduced by adding large horizontal diffusion in the troposphere. However, it is a difficult and not very rewarding exercise to adjust these parameters in such a manner that, for example, observed surface gradients of SF_6 [*Elkins et al.*, 1996] can be reproduced when specifying SF_6 emissions in the model and that gradients of CO_2 in the upper troposphere agree with observations [*Nakazawa et al.*, 1991] at the same time.

Differences between the seasonal maximum and minimum of CO_2 at the surface and in the upper tropopause are shown for 2 years in Figure 7. The structure of the peak to peak gradients seen by *Nakazawa et al.* [1991] is indicated in the figure. Because the boundary condition for CO_2 is set at the surface in the model, concentrations at the tropopause are, in general, different from actual measurements at that altitude. Therefore direct comparisons of the stratospheric CO_2 signal with measurements are not always possible. However, correlations between CO_2 and N_2O at midlatitudes, discussed in the next section, are not significantly affected by the ambiguity in specifying CO_2 at the lower boundary of the stratosphere. This was verified by making a control run with CO_2 specified at the surface independent of latitude. The concentration was taken as the average of measurements at Mouna Loa and Samoa.

The coarse vertical resolution of the model (2 km) is cause for concern about the accuracy of the numerical solution for the upward propagation of the seasonal cycle of CO_2 through the lowermost tropical stratosphere. Age increases by several years within the first few kilometers above the tropical tropopause. A finite amount of vertical diffusion will therefore critically affect the attenuation of seasonally varying tracer signals with height. The propagation of time-dependent tracer signals is discussed in detail by *Kogan-LeFlore* [1999]. It is shown there that an adequate numerical solution is obtained in the model with the 2 km vertical resolution in conjunction with the profile specified for the vertical diffusion coefficients.

A time sequence for calculated CO_2 concentrations is shown in Figure 8 The first panel shows concentrations for late spring in the Northern Hemisphere, corresponding to the seasonal maximum at the surface. About 4 months later, tropospheric values have decreased and the high concentrations in the lower tropical stratosphere can be seen to extend into midlatitudes at low levels. During the course of a year the concentrations increase by about 1 ppm (the annual rate of increase) throughout the model domain. However, the increase is not uniform.

The seasonal behavior of CO_2 and age is illustrated further in Figure 9 The figure shows time series for the two quantities in the tropics and for midlatitudes and high latitudes at altitudes of 17, 21, 31, and 41 km. At the lowest altitude in the tropics the seasonal variation of CO_2 shows no correlation with age and is determined mainly by variations imposed at the lower boundary. At higher altitudes in the tropics, CO_2 increases more or less steadily and age remains constant. Large seasonal variations can be seen at 31 km at midlatitudes. Here fluctuations of CO_2 and age are anticorrelated and caused by seasonally varying rates of outflow of younger, CO_2 enriched air from the tropics. Low levels at midlatitudes show a combination of seasonality induced by changing rates of tropical outflow and changes in the boundary condition imposed for CO_2. The seasonality at low altitudes is not symmetric with respect to the equator because the minima and maxima of CO_2 are not centered at the equator in the model.

4. Correlations of N_2O and CO_2

Some aspects of the transport of CO_2 into the midlatitudes and high latitudes of the lower stratosphere can be checked against observations. Correlations of CO_2 and N_2O have been measured at ER-2 flight altitudes (20 km and below) for different seasons [*Boering et al.*, 1994]. CO_2 and N_2O are both long-lived tracers (N_2O only for the lower stratosphere) with tropospheric sources. Concentrations of long-lived tracers with similar source regions are proportional to each other in steady state (see the discussion by *Plumb and Ko* [1992]). However, the seasonal variations of CO_2

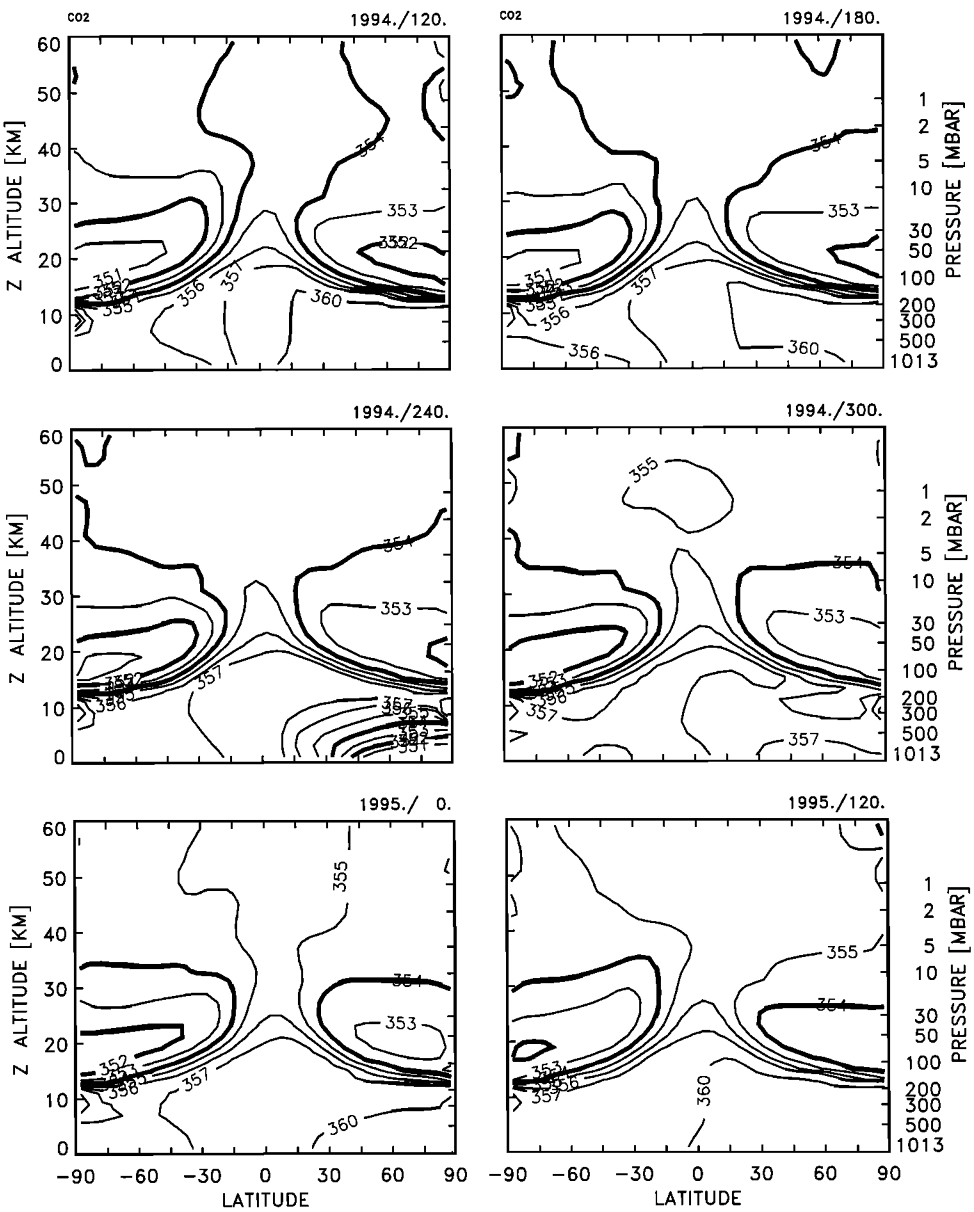

Figure 8. Calculated concentrations of CO_2 for the years 1994/1995. Panels show the distribution every 2 months, starting from late spring. The Julian day is indicated in the panels. Units are ppm.

occur on a timescale that is much faster than the increase in N_2O at the surface and also smaller than the average age of stratospheric air. Therefore the slope of the correlations changes with season and is sensitive to the rate of transport of CO_2 through the subtropical barrier.

Calculated CO_2/N_2O correlations are compared with the SPADE observations in Figures 10 and 11 for the low-K_{yy} case. Correlations are shown for fall 1992, spring 1993, and fall 1993. The seasonal behavior of the correlations in the Northern Hemisphere follows the observed changes in slopes fairly well. The appearance of the seasonal minimum of CO_2 in Fall at low altitudes is evident in the data and qualitatively captured by the model. The data also show that the annual increase of CO_2 appears at low values of N_2O, or higher altitudes, between fall and spring (Figure 10). The correlations remain almost unchanged between spring and fall (Figure 11). The seasonal variations of the correlations are a composite of the seasonal behavior of CO_2, shown in Figure 9, and the seasonal changes in the isolines of N_2O.

Correlations of CO_2 and N_2O, calculated with the model, are compared with the ASHOE/MEASA data in Figures 12 and 13. The figures show correlations for the Southern Hemisphere, tropics, and Northern Hemisphere for spring (Figure 12a) and fall (Figure 12b) of 1994. Agreement with the Southern Hemisphere data is good for all seasons. In the Northern Hemisphere, concentrations calculated for CO_2 are about 1 ppm higher

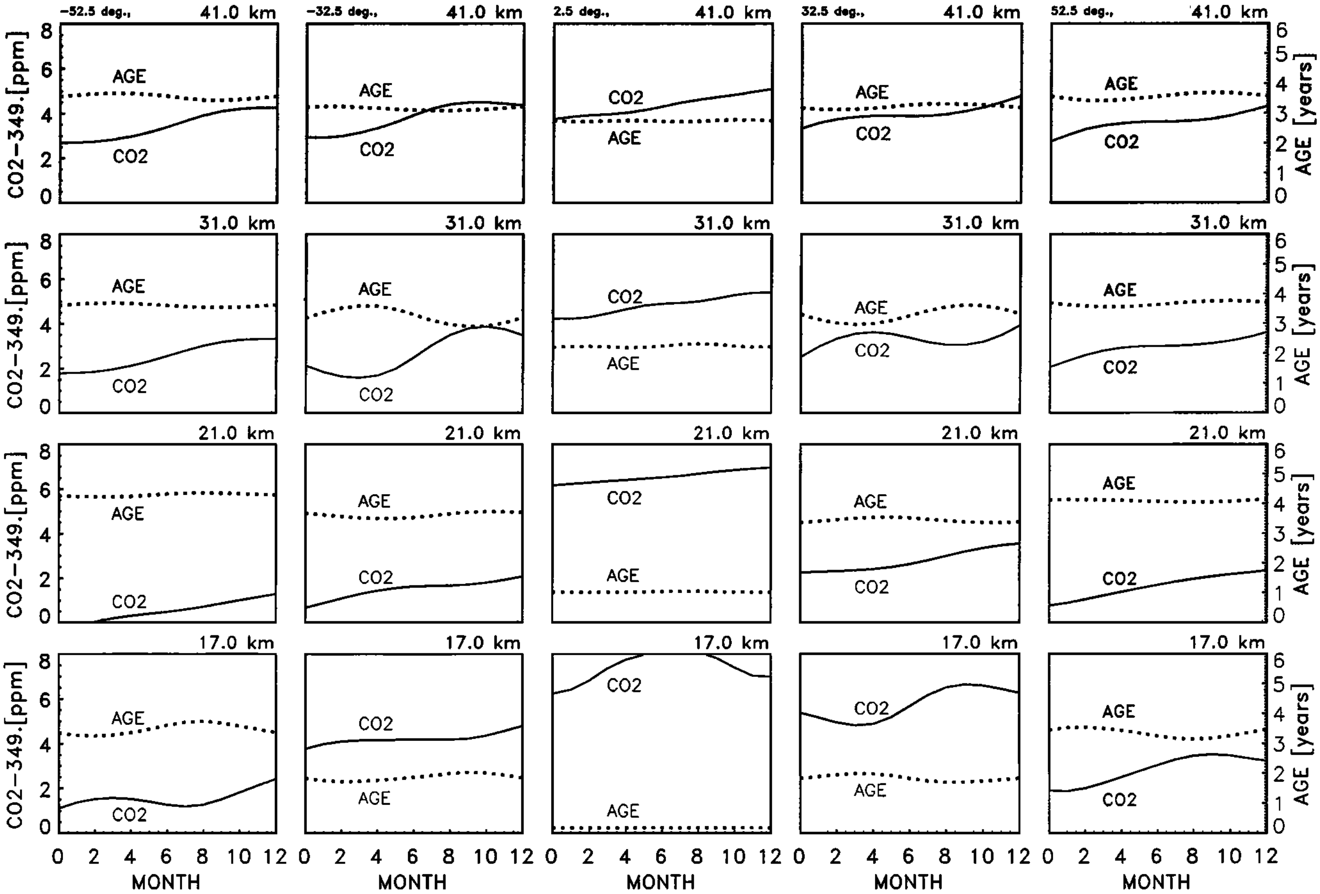

Figure 9. Twelve months time series, starting in late spring, of CO_2 and age for points in the model domain as indicated on the panels.

than the observed values. This applies for all seasons of the SPADE and ASHOE/MAESA campaigns.

In order to examine the sensitivity of calculated CO_2/N_2O correlations to the choice of K_{yy}, runs were made using the large- and constant-K_{yy} distributions, discussed in part 1. Figure 13a compares correlations calculated for the large-K_{yy} case, that is, coefficients multiplied by a factor two compared to the run discussed above, for the Fall of 1992 and the Spring of 1993 in the Northern Hemisphere. The change in slope is minor compared to the small-K_{yy} case shown in Figure 10. It is not possible to call the agreement with observations better or worse for these cases, especially when we recall that important processes such as the quasi-biennial oscillation are not included in this model version. Doubling K_{yy} has an effect on the circulation, both at midlatitudes and in the tropics by continuity Upward motions in the tropics and the overturning rates in the lower stratosphere increase by approximately 20% on average. However, the change in the circulation pattern affects N_2O and CO_2 similarly. Lines of constant mixing ratio for both species remain more or less parallel.

In order to examine the influence of seasonal variations in K_{yy}, results from the constant-K_{yy} case are

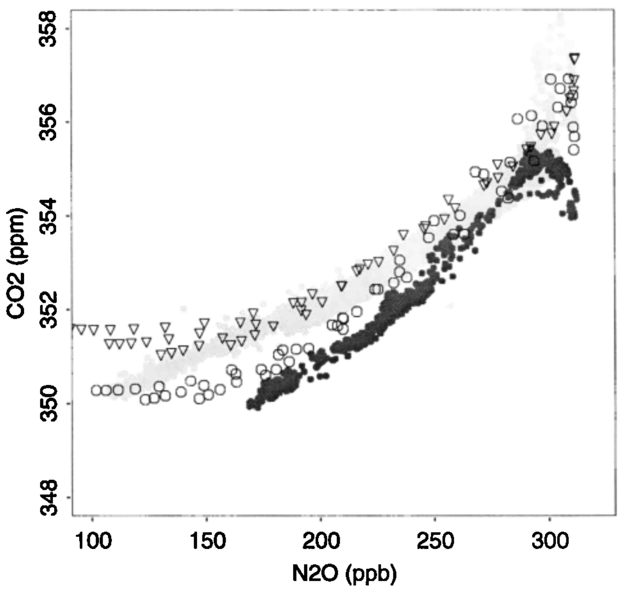

Figure 10. Correlations between CO_2 and N_2O. Shaded areas indicate data gathered during the SPADE campaign. The dark shading are measurements from fall 1992, and the lighter shading are data from spring 1993. Model results for fall 1992 are indicated by open circles. Triangles are model results for spring 1993.

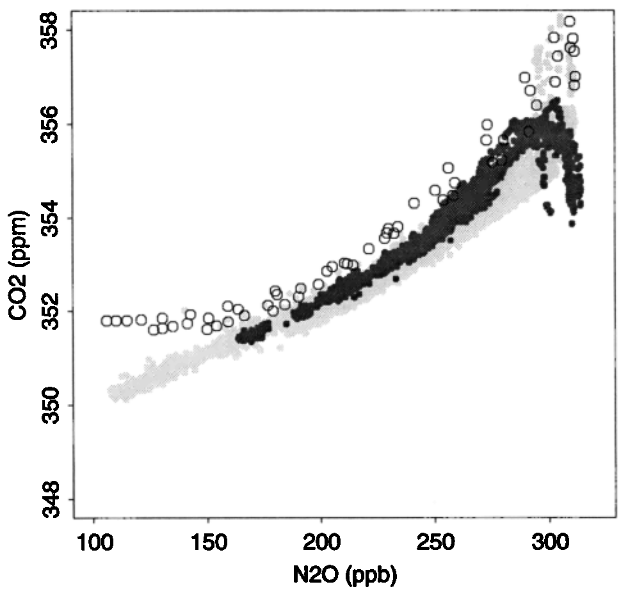

Figure 11. As in Figure 10 but for fall 1993. Dark shaded areas indicate the measurements, model results are shown by open circles. Model correlations have been computed for the latitude region between 20° and 60° and between 12 and 20 km in height. Data for spring of 1993 (light shading) are shown for reference.

compared with observations in Figure 13b. The change in the slope of the correlations during winter is comparable to that in the previous cases. It follows that the seasonality induced by the time-varying flow across the subtropics is the dominant contribution to the change of the slope of the correlation curves.

If K_{yy} is reduced drastically, the annual increase in CO_2 is not transported fast enough to midlatitudes and and high latitudes in the lower stratosphere. The result for very small diffusion in the Southern hemisphere, $K_{yy} = 10^4$ m^2 s^{-1}, is shown in Figure 14 together with the ASHOE/MAESA data for spring. These model results are clearly unacceptable. The value of K_{yy} needed to obtain agreement with the measurements is approximately 10^5 m^2 s^{-1}. Once diffusive transport in the winter hemisphere exceeds this threshold, correlations between CO_2 and N_2O are relatively insensitive to K_{yy}.

Frictional damping in the lower stratosphere is a sensitive parameter in the model. For the runs discussed so far, frictional damping timescales exceed a season in the altitude region between 15 and 25 km. We have not allowed for any latitudinal structure in Rayleigh friction anywhere in the model because of the lack of information about gravity wave spectra and gravity wave breaking in the atmosphere.

As long as friction is applied independent of latitude in the lower stratosphere, mass exchange between tropics and midlatitudes is drastically altered when the Rayleigh friction parameter is increased. Meridional coupling provided by friction induces a large horizontal flow component in the subtropics, resulting in an overestimate for CO_2 in the midlatitudes of the lower stratosphere and in lower concentrations at higher altitudes. However, friction alone cannot induce transport of long-lived tracers to high latitudes that would be fast enough to explain the CO_2 concentrations found in southern high latitudes during the ASHOE/MAESA campaign.

5. Summary and Discussion

Measurements of age and CO_2 provide stringent constraints on the flow of air across the subtropical region

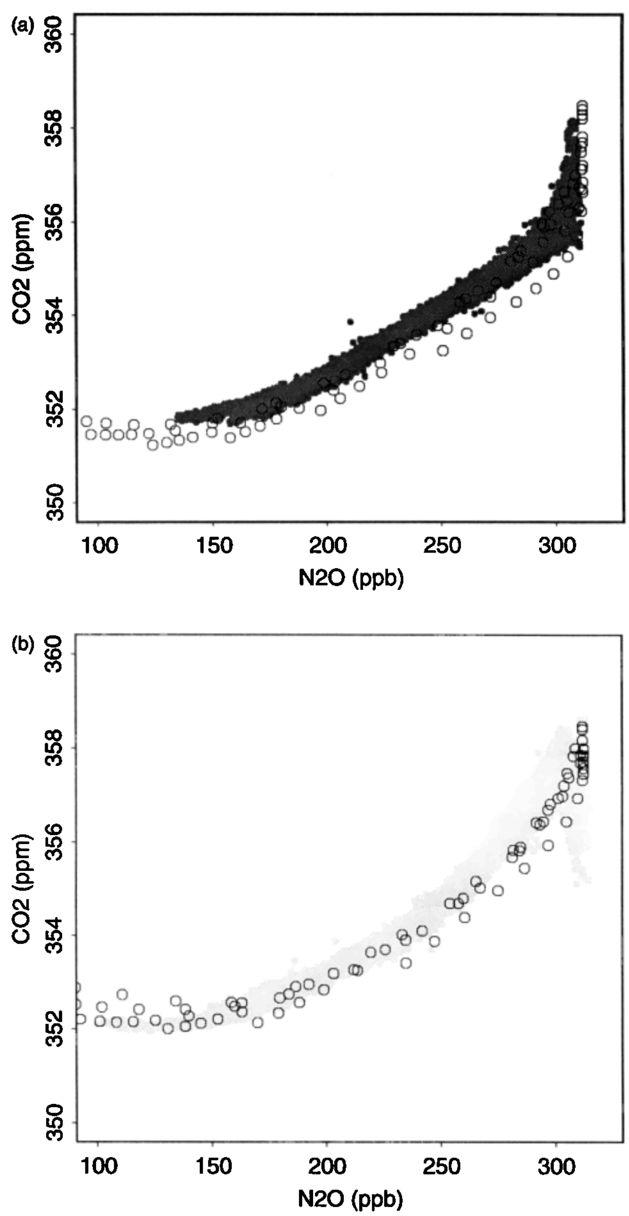

Figure 12. (a) Correlations between CO_2 and N_2O for the Southern Hemisphere in spring 1994. Shaded areas are data from the ASHOE/MAESA campaign, and model results are represented by the open circles. (b) As in Figure 12b, but for fall 1994.

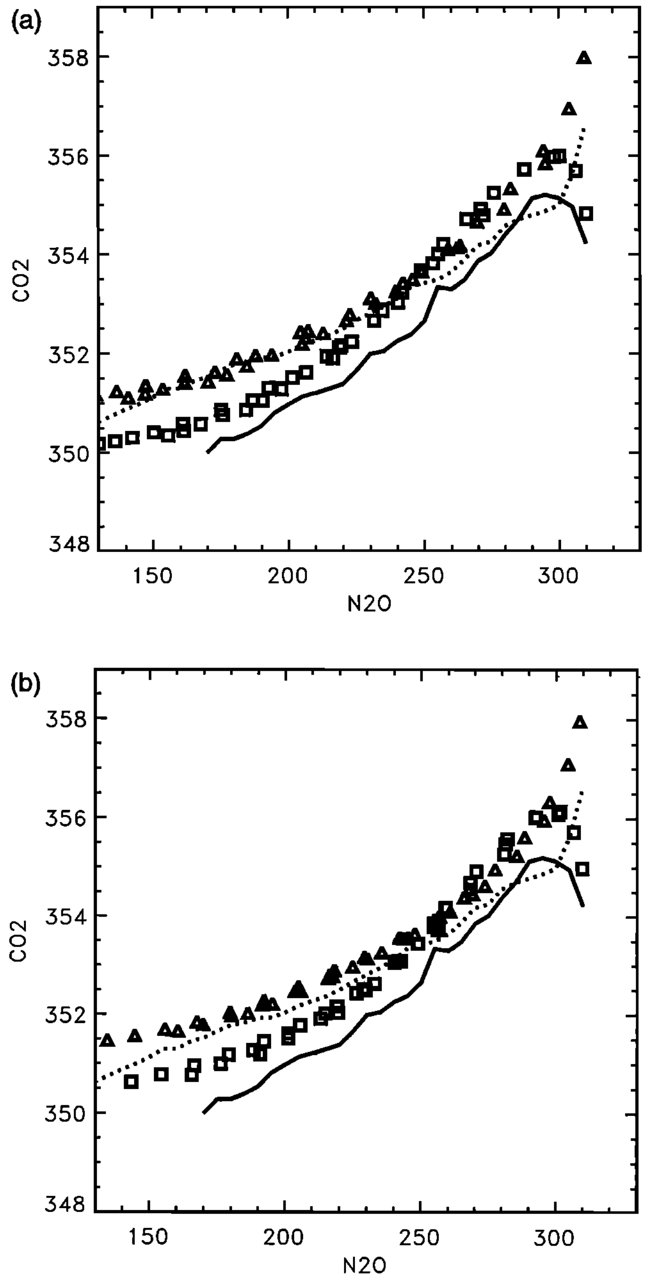

Figure 13. (a) Correlations between CO_2 and N_2O for the Northern Hemisphere midlatitudes for fall 1992 and spring 1993, calculated for the large-K_{yy} case. Averages of the SPADE data, shown in Figure 10, are indicated by the solid line for fall 1992 and by the dotted line for spring 1993. Model results for fall 1992 are indicated by open squares. Triangles are model results for spring 1993. (b) As in Figure 13a, but model results from the constant-K_{yy} case.

at stratospheric altitudes. We have shown that a 2-D residual circulation model gives a good representation of the mean age of air in the lower stratosphere and can reproduce the slope and seasonal variations observed in correlations between CO_2 and N_2O in the midlatitudes of the lower stratosphere.

In order to obtain agreement with observations, mechanical damping due to gravity waves has to be small in the altitude region between 15 and 25 km. The timescale for frictional damping has to exceed a season for most of this altitude range. Gravity wave induced drag had to be present in the layers immediately above the tropopause to affect low level flow from the tropics into the midlatitudes. Our results indicate that the vertical structure of gravity wave induced drag in the lower stratosphere is an important parameter to determine the mass balance between tropics and midlatitudes. However, given the rather coarse vertical resolution of the model, the vertical structure of the lower stratosphere cannot be adequatelty resolved. A more detailed study of the sensitivity to gravity wave induced drag in the lower stratosphere, using a high resolution version of the model, will be described in a forthcoming paper.

The model results are robust as far as assumptions for K_{yy} are concerned. A threshold value for K_{yy} in the lower stratosphere of approximately $(0.5 - 1.0) \times 10^5$ m^2 s^{-1} has to be applied to ensure that sufficient quantities of young air are transported to midlatitudes and high latitudes after having been advected across the subtropical barrier. Once this threshold value is exceeded, the sensitivity of the results to the assumptions for K_{yy} is small. Within the constraints of currently available data, the eddy mixing coefficients can be varied by at least a factor of 2. In addition, the temporal and spatial structure of K_{yy} does not appear to play a determining role for the performance of the model. The

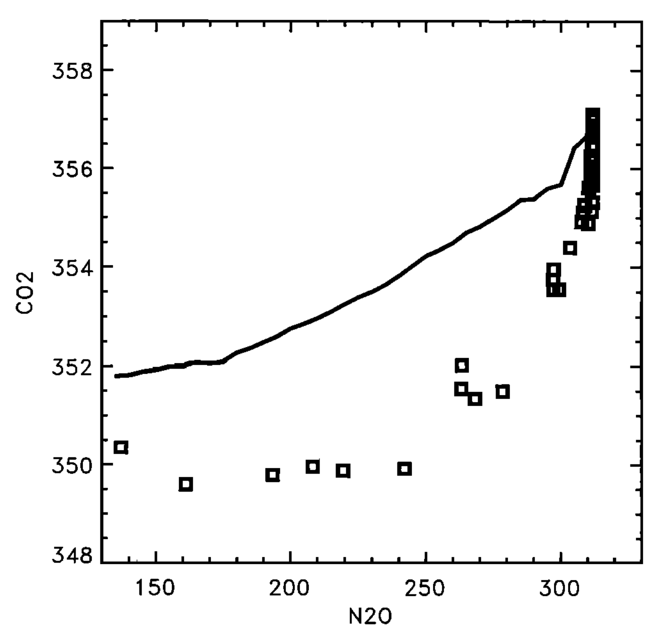

Figure 14. (a) Correlations between CO_2 and N_2O obtained for extremely small K_{yy} in the Southern Hemisphere for spring 1994 (squares). The average of the data, shown in Figure 12a is indicated by the solid line.

relative insensitivity to the magnitude of the assumed Rossby wave diffusion coefficients can be understood by considering the dual role of K_{yy} in regulating the diffusive transport of tracers and in providing a forcing term for the residual mean circulation [*Holton*, 1986].

Changing the wave driving of the circulation by a factor of 2 results in changes of the order of half a year in the calculated mean age of air. Temperature changes are of the order of 1 to 2 K in the lower stratosphere. However, the rate of the stratospheric overturning changes by about 30%. Currently available data on age and long-lived tracers cannot be used to reduce this uncertainty in vertical velocities at the 100 mbar level. The uncertainty is of the same order as was found in attempts to diagnose the residual circulation by calculating heating rates from available data (e.g., *Eluszkiewicz et al.*, 1996; *Rosenlof*, 1996; *Appenzeller et al.*, 1996].

An inherent limitation of a 2-D model is that the troposphere which constitutes the lower boundary for the stratosphere cannot be treated in a self-consistent manner. Convection, latent heat release, baroclinic fluxes, and other important dynamical processes have to be parameterized in one form or other. However, vertical velocities and vertical diffusion at the tropopause level determine the flux of material from the troposphere to the stratosphere. The distribution of a tracer with constant surface concentrations and a sink in the stratosphere will eventually equilibrate, and errors in the treatment of the tropopause will affect the concentration profile to some extent. Tracers whose surface concentrations change on a timescale shorter than the mean age of the stratosphere are much more sensitive to the representation of dynamics in the region near the tropopause.

In our model, parameterized heating rates are used to generate a distribution of temperatures and wind velocities in the troposphere. The parameterization of tropospheric heating rates and the transition to calculated stratospheric heating rates above the tropopause was initially adjusted to yield tropical tropopause temperatures that are close to observations. Since the parameterization consists of a relaxation to specified temperatures and a zonal mean momentum dissipation to ensure finite heating rates [*Cunnold et al.*, 1975], the tropospheric temperatures and the Hadley circulation are not fixed in the model. To some extent, they depend on stratospheric conditions. Increased Rossby wave diffusion, for example, causes more "suctioni" out of the tropics and therefore increased adiabatic cooling and reduced temperatures at the tropical tropopause.

We have made several runs in which the parameterization of tropospheric heating rates was modified, resulting in changes of temperatures at the tropopause level and corresponding changes in vertical velocities and meridional outflow at the bottom of the tropical pipe. Large modifications that induced temperature changes at the tropical tropopause by 4 to 5 K significantly altered the rate at which the annual increase of CO_2 propagated into the stratosphere. Resulting CO_2/N_2O correlations were clearly ruled out by the observations. Circulations obtained with smaller modifications resulting in a change of less than 2 K at the equatorial temperature minimum did not affect computed correlation curves significantly. Tropospheric parameters clearly play an important role in constraining the exchange of mass between troposphere and stratosphere in a 2-D model. For the particular form of the parameterization used in the present model, results for tracer correlations in the lower stratosphere appear to be robust under small parameter variations.

Acknowledgments. This work was supported by DOE grant DE-F02-93ER61708 and NASA grants NAGW-1230 and NAG5-3979. Thanks are due to T. Conway of the NOAA CMDL for providing us with monthly mean CO_2 surface concentrations from 1980 to 1994 and to J. Elkins for the data on the mean age derived from SF_6 measurements.

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(Received July 16, 1999; revised January 14, 2000; accepted March 29, 2000.)