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Constraints on meridional transport in the stratosphere imposed by the mean age of air in the lower stratosphere

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Abstract. The sensitivity of mean age of air in the stratosphere to the vertical structure of mass exchange between the tropics and midlatitudes is examined with a two-dimensional model with consistent advective and diffusive transport. We use estimates of mean age of air and age spectra in the midlatitude lower stratosphere, derived from observations of CO_2, to constrain transport from the tropics to midlatitudes. We show that to reproduce the latitudinal gradient in mean age in the lower stratosphere as well as the bimodal age spectra derived for the midlatitude lower stratosphere, the rate of horizontal transport from the tropics to midlatitudes between 20-30 km must be slower than that at higher and lower altitudes. The relative rates of meridional transport above and below this region determine the separation of the two peaks in the age spectra and the overall mean age of air in the lower stratosphere. Slow transport between 20-30 km can generally not be obtained by reducing only the diffusive component of transport. In the model, gravity wave drag must also be reduced in the lower stratosphere to prevent strong horizontal advective transport across the subtropics. We also show that adjusting the diffusive component of transport independently of the meridional circulation can produce mean ages different from those calculated in the fully coupled model by as much as 2 years.

1. Introduction

A major source of uncertainty in reproducing the distribution of trace gases in the stratosphere and in assessing the impact on ozone of anthropogenic perturbations to the chemistry of the stratosphere is associated with deficiencies in the description of transport in the lower stratosphere. The NASA Models and Measurements Intercomparison II (MMII) [*Park et al.*, 1999] revealed that there are large differences between models in the calculated distribution of long-lived trace gases and in the mean age of air, defined as the mean transit time for air to reach a given location in the stratosphere from the tropical tropopause [*Hall and Plumb*, 1994]. It was found that in the lower stratosphere most models significantly underestimated the mean age of air as well as the tropical-extratropical gradient in mean age.

Transport of long-lived tracers in the stratosphere represents a balance between advection by the mean meridional circulation and isentropic mixing by breaking planetary waves [e.g., *Holton*, 1986; *Mahlman et al.*, 1986; *Plumb*, 1996]. There is abundant evidence that the influence of planetary wave mixing does not extend into the tropical stratosphere [e.g., *Trepte and Hitchman*, 1992; *Randel et al.*, 1993; *Hitchman et al.*, 1994; *Grant et al.*, 1996]. The isolation of the tropical stratosphere from the extratropical stratosphere has been described conceptually in terms of a "tropical pipe model" [*Plumb*, 1996]. Tropical isolation, however, is not complete. *Avallone and Prather* [1996], *Minschwaner et al.* [1996], and *Volk et al.* [1996] have suggested that there is significant mixing of extratropical air into the tropics in the lower stratosphere The fact that the mean age of air in the lower stratosphere increases with altitude in both the tropics and extratropics implies that there must be significant poleward transport of tropical air in the lower stratosphere [*Neu and Plumb*, 1999]. In the tropics the increase of mean age with altitude reflects the rising motion of the stratospheric circulation. In the extratropical lower stratosphere, in the descending branch of the circulation, mean age can increase with altitude only if there is a supply of young tropical air to these latitudes.

Recently, *Andrews et al.* [this issue] derived empirical age spectra for the midlatitude lower stratosphere using observations of CO_2 for the period 1992-1997 obtained in the Stratospheric Photochemistry and Dynamics Expedition (SPADE), the Airborne Southern Hemisphere Ozone Experiment/Measurements for Assessing the Effects of Stratospheric Aircraft (ASHOE/MAESA), Stratospheric Tracers of Atmospheric Transport (STRAT), and Photochemistry of Ozone Loss in the Artic Region in Summer (POLARIS) campaigns. The age spectrum, introduced by *Kida* [1983], is a distribution of all transit times to a given location in the stratosphere, and provides a useful tool for analyzing mechanisms for transport. The empirical age spectra for the midlatitude lower stratosphere are bimodal with peaks at ~1 and 5-6 years, suggesting that air is supplied to the extratropical lower stratosphere by two distinct paths, one fast (less than 1 year) and one slow (about 5 years). The bimodal age spectra are consistent with the tropical pipe model of transport out of the tropical stratosphere. Below the subtropical barrier, within a few kilometers of the tropopause, meridional transport of tropical air into the extratropics can account for the first peak in the age spectra. At higher altitudes, air is forced to ascend to the middle stratosphere,

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above the subtropical barrier, and to flow down into the extratropics, producing significantly longer transit times to the extratropical lower stratosphere and thus the second peak in the age spectra.

In models in which the meridional circulation is specified independent of isentropic mixing, balance between advective transport and mixing in the stratosphere is obtained by adjusting separately the strength of the meridional overturning and eddy mixing (parameterized usually as a form of eddy diffusion K_{yy}). However, the meridional circulation is not independent of eddy mixing. Variations in eddy mixing induce compensatory changes in meridional overturning [*Holton*, 1986; *Mahlman et al.*, 1986]. Increased K_{yy}, for example, enhances north-south excursions of air parcels, reducing the horizontal gradients in long-lived tracers. Increased K_{yy}, however, also produces a more vigorous meridional circulation which enhances latitudinal gradients in the distribution of long-lived tracers. Thus the response of long-lived tracers to variations in eddy mixing is significantly different in a model with consistent diffusive and advective transport as compared to an off-line model in which the circulation is prescribed independent of the mixing. For example, *Li and Waugh* [1999] found in their off-line model that larger K_{yy} throughout the stratosphere resulted in older mean ages of air. In contrast, *Schneider et al.* [2000] found that increasing K_{yy} throughout the stratosphere resulted in younger mean ages in their dynamically consistent model. Similarly, *Fleming et al.* [2001] found that increasing K_{yy} in their model, while accounting for the accompanying change in the meridional circulation, produced younger mean ages. Using a dynamically consistent two-dimensional model in which K_{yy} is determined from calculated planetary waves, *Bacmeister et al.* [1998] found that increased wave forcing led to older mean ages of air in the stratosphere. However, in their model, changes in planetary wave forcing were confined to the lower stratosphere, and, as we will show in this study, that could account for the older mean ages calculated by the model in response to greater wave forcing.

Models with consistent diffusive and advective transport are relatively insensitive to variations in K_{yy} as a result of the compensation of the slope-flattening effects of eddy mixing with the slope-steepening effects of the meridional circulation. However, there are other dynamical quantities besides K_{yy} that contribute to zonal forcing in these models. For example, *Schneider et al.* [2000] found that gravity wave drag with timescales for damping less than 90 days in the lower stratosphere (15-25 km) adversely impacted the correlation between abundances of N_2O and CO_2 in the extratropical lower stratosphere. They found that even weak drag in the lower stratosphere generated significant advective transport of air out of the tropics. Horizontal advective transport was the dominant component of transport through the subtropics to midlatitudes. *Bacmeister et al.* [1998] found that mean ages of air in the stratosphere were more sensitive to rates for diabatic heating in the troposphere than to variations of K_{yy} in the stratosphere.

In this study we use the two-dimensional model of *Schneider et al.* [2000], together with estimates of mean age from observations of CO_2 and age spectra derived for the extratropical lower stratosphere [*Andrews et al.*, this issue], to constrain rates of transport in the lower stratosphere. In particular we seek to develop a better understanding of the impact of assumptions about K_{yy} and gravity wave drag on rates of transport in the stratosphere, and thus on mean ages of air, age spectra, and the distributions of long-lived gases, such as N_2O, in the lower stratosphere.

2. Model Description and Sensitivity Experiments

2.1. Model Description

The two-dimensional model is described in detail in *Schneider et al.* [2000]. The model extends from pole to pole and from the surface to 80 km. It has a resolution of 5° in latitude and 2 km in the vertical. The model is interactive in the sense that the mean meridional circulation and temperatures are calculated using heating rates based on model-derived ozone. Calculated heating rates in the troposphere are replaced using the parameterization of *Cunnold et al.* [1975]. The parameterized heating rates are matched in the lower stratosphere with rates calculated for the stratosphere.

The effects of small-scale gravity waves are parameterized in the form of Rayleigh friction. Rayleigh friction coefficients are specified only as a function of height; we do not account for variations in latitude. The profile of the Rayleigh friction coefficients is shown in Figure 1. In the troposphere and middle stratosphere the timescale for damping is about 30 days and decreases to about 5 days at 60 km. Between 10 and 30 km, friction is significantly reduced such that a maximum timescale of 360 days for damping is attained between 18-22 km. We were motivated to reduce friction in the lower stratosphere because *Schneider et al.* [1989] and *Hou et al.* [1991] found that low friction in the lower stratosphere leads to an improvement in latitudinal gradients calculated for ozone. A physical interpretation for this layer of reduced friction is the assumption that as a result of enhanced gravity wave breaking near the tropopause, due to low static stability,

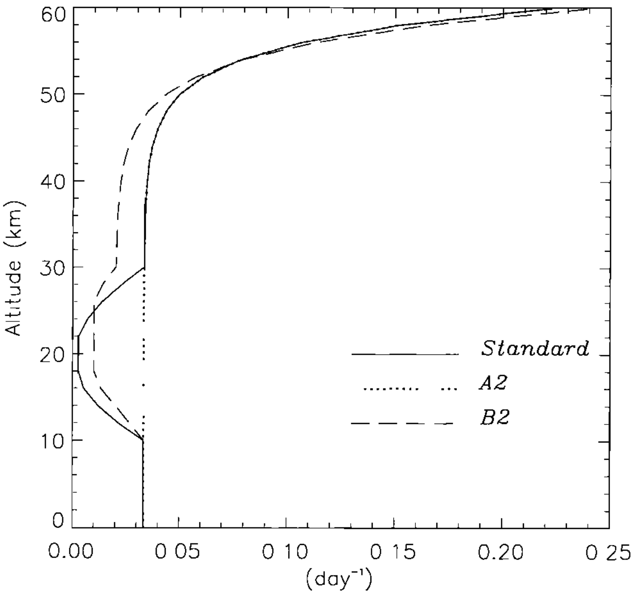


Figure 1. The solid line shows the Rayleigh friction profile used in the standard version of the model. The dotted line shows the profile used in experiment *A2*, and the dashed line indicates the profile used in experiment *B2*.

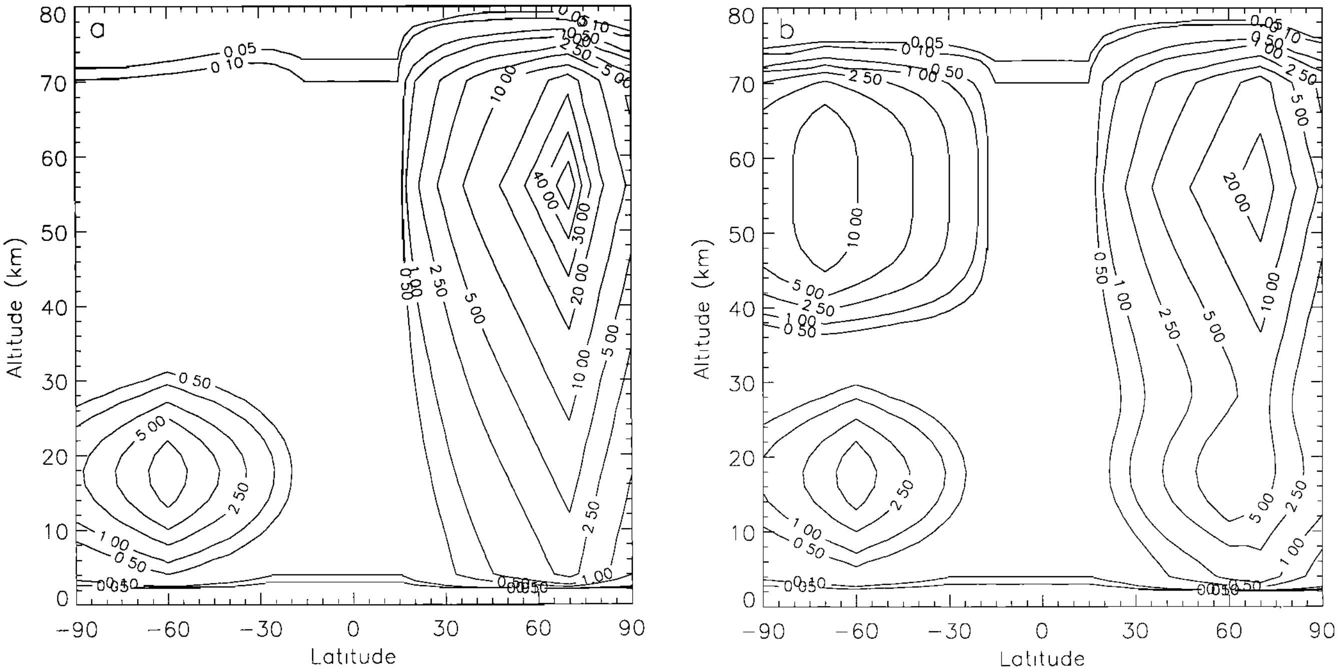


Figure 2. Latitude-altitude cross section of K_{yy} for northern hemisphere (a) winter solstice and (b) spring equinox. Units are 10^5 m^2 s^{-1}.

wave-induced lapse rates remain subadiabatic within a region immediately above the tropopause [*Lindzen*, 1981; *Holton*, 1982].

In the model, mixing due to breaking planetary waves is not calculated explicitly. Instead, it is parameterized as seasonally varying eddy diffusion coefficients K_{yy}, based on *Newman and Schoeberl* [1986] and *Newman et al.* [1988]. Values of K_{yy} are used to parameterize consistently, outside the tropics, both the eddy potential vorticity flux and the transport of long-lived tracers by planetary wave mixing. Thus K_{yy} influences the distribution of long-lived tracers directly through diffusive mixing and indirectly through its influence on the strength of the meridional circulation. The distribution of K_{yy} is shown in Figure 2 for northern hemisphere winter solstice and spring equinox. In the winter hemisphere, K_{yy} exhibits a maximum in the upper stratosphere, near the core of the westerly jets. In the summer hemisphere the maximum is located in the lower stratosphere, reflecting the fact that planetary waves are trapped in the lower stratosphere by the easterly winds of the summer stratosphere. To simulate weaker planetary wave forcing in the southern hemisphere, we assume arbitrarily that maximum values of K_{yy} in the southern stratosphere in winter are half as large as those in the northern stratosphere in winter. Equatorward of about 15° we set K_{yy} at a constant value of 1×10^4 m^2 s^{-1}. Small values of K_{yy} in the tropics, with no measurable impact on transport, are consistent with observations that suggest that planetary wave mixing does not extend into the tropical stratosphere. We realize that there may be additional mixing in the tropics due to other processes; however, no further assumptions about mixing are incorporated in the model.

The small values of K_{yy} in the tropical stratosphere, together with the small friction in the lower stratosphere, contribute effectively to a "pipe" structure in the tropical stratosphere in the model. Transport in the tropics in the model is completely advective. Below 18-20 km there is significant meridional advection of tropical air across the subtropics; at higher altitudes, between 20-25 km, small horizontal velocities inhibit transport to the extratropics. At

Table 1. Sensitivity Experiments

Experiment	K_{yy}	Rayleigh Friction
A1	K_{yy} increased in lower and middle stratosphere	standard
A2	standard	friction increased 10-30 km
A3	K_{yy} increased in lower and middle stratosphere	circulation from standard run (noninteractive run)
B1	K_{yy} increased below 30 km	standard
B2	standard	friction increased 10-25 km while reduced 25-55 km
B3	K_{yy} increased below 30 km	friction increased 10-25 km while reduced 25-55 km

these altitudes it takes longer than a season to advect air from the equator to the subtropics in the model. Above 30 km, larger horizontal velocities result in rapid advective transport out of the tropics.

2.2. Sensitivity Experiments

We performed a number of experiments to explore the response of mean age to variations in the rate of transport in the stratosphere in the model. The individual experiments are described in Table 1. To clearly illustrate the influence of meridional transport on the mean age of air, the simulations are divided into two categories, *A* and *B*. In category *A* we significantly increase advective transport out of the tropics throughout the lower stratosphere (up to about 30 km). In category *B* we repartition transport in the stratosphere such that, relative to the standard version of the model, advective transport out of the tropics is increased moderately below 25 km, while it is reduced at higher altitudes. This change in meridional overturning weakens tropical isolation in the lower stratosphere and enhances it between 25-30 km, relative to the standard version of the model. In each set of experiments we vary Rayleigh friction and/or K_{yy} to obtain changes in meridional overturning. Our goal is to demonstrate that model sensitivity to other dynamical parameters, besides K_{yy}, can significantly influence calculated distributions for mean age of air in the stratosphere.

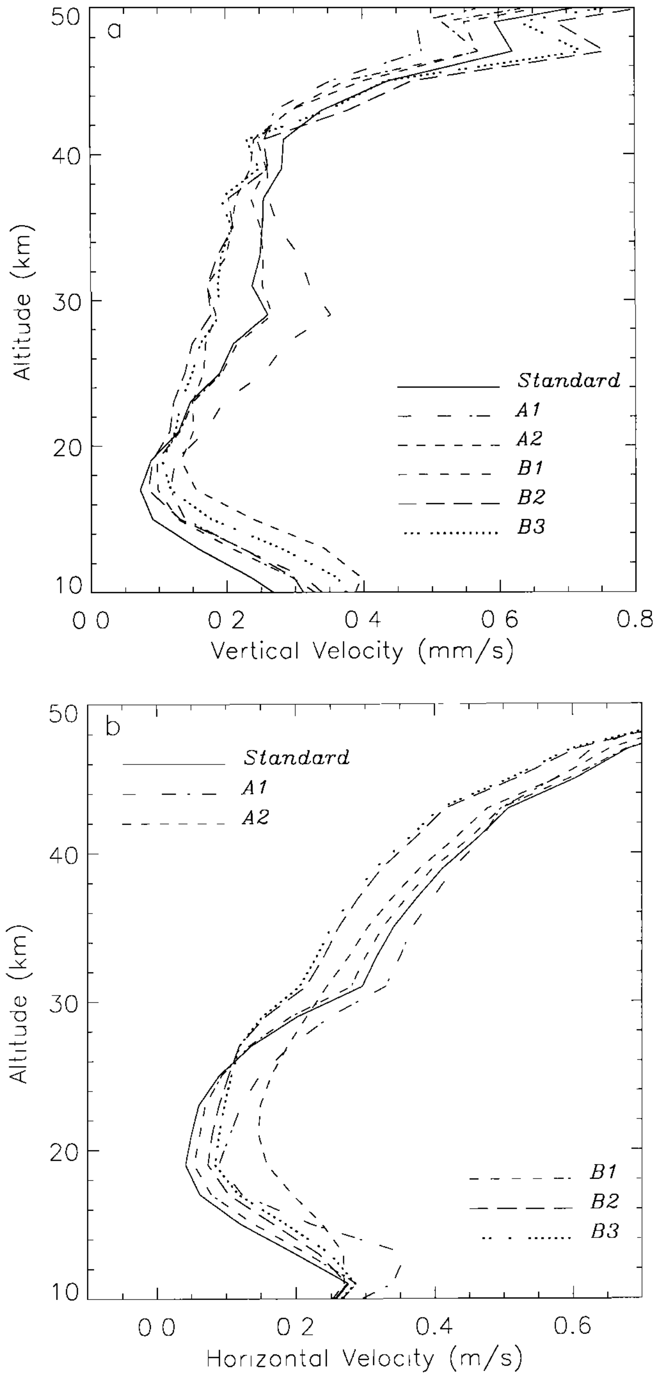


Figure 3. (a) Modeled vertical velocities at 7.5°N and (b) horizontal velocities at 32.5°N for January conditions.

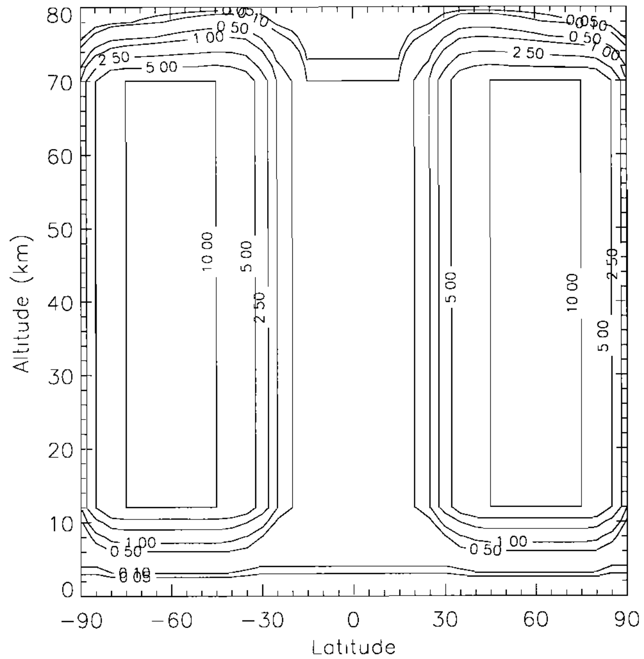


Figure 4. Latitude-altitude cross section of K_{yy} for experiment *A1*. Values are specified independent of season. Units are 10^5 $m^2 s^{-1}$.

In the first experiment, *A1*, we enhanced meridional overturning below 40 km by increasing K_{yy} in the lower and middle stratosphere. The calculated vertical velocities at 7.5°N and horizontal velocities at 32.5°N are shown in Figure 3 for January conditions. The distribution of K_{yy} used in this experiment is shown in Figure 4. In the midlatitudes of both hemispheres, maximum values for K_{yy} were set to $1x10^6$ $m^2 s^{-1}$, independent of season. Equatorward of 15°, we maintained the small values of K_{yy} of $1x10^4$ $m^2 s^{-1}$. We chose an idealized distribution of K_{yy} since for this experiment we are not concerned about the potential influences of spatial variations in K_{yy} on mean ages of air. Furthermore, *Schneider et al.* [2000] showed that K_{yy}-induced seasonal variations in mean ages in the lower stratosphere are comparable to the uncertainties in the measurements of mean age. The latitudinal profile of K_{yy} in the lower stratosphere in this experiment is compared with that of the standard model in Figure 5. At 35°N, for example, values for K_{yy} in this experiment are about a factor of 4 larger than annually averaged values of K_{yy} in the standard version of the model. However, above about 40 km in the extratropical stratosphere, values of K_{yy} are almost a factor of 2 smaller than the annually

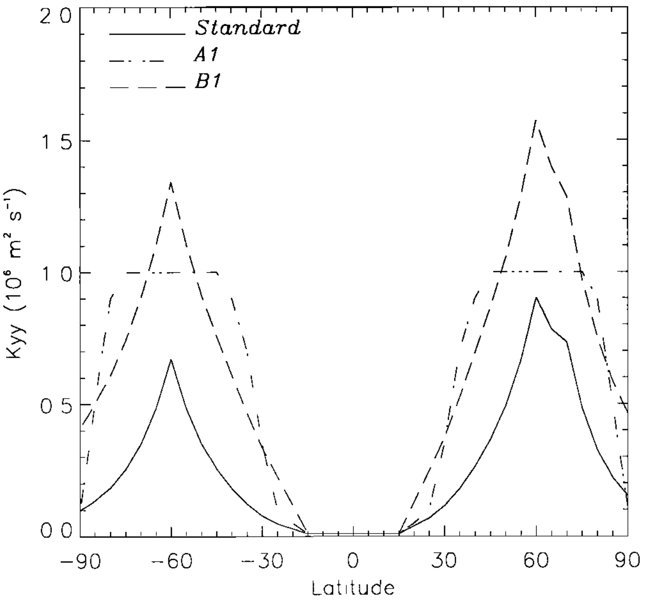


Figure 5. Latitudinal profile of K_{yy} at 20 km. The profiles for the standard model and experiment *B2* are annually averaged values of K_{yy}. Values of K_{yy} in *A1* are seasonally independent.

averaged values of K_{yy} in the standard run (not shown). To isolate the influence of the meridional circulation on the distribution of mean age, we repeated experiment *A1* using the same distribution of K_{yy}, but with the meridional circulation specified from the standard run. This model run is referred to as experiment *A3*.

In experiment *A2* we used the distribution of K_{yy} from the standard model run, but increased Rayleigh friction in the lower stratosphere such that from the troposphere up to 30 km, the rate of damping is 1/30 days^{-1} (see Figure 1). This produced a significantly larger increase in the strength of the meridional circulation in the lower stratosphere (10-30 km) than the result obtained with larger K_{yy} in *A1*. At 32.5°N, for example, horizontal velocities at 20 km were about a factor of 3 larger than in the standard model run (Figure 3b).

In the second set of experiments we adjusted K_{yy} and Rayleigh friction in the lower stratosphere to increase advective transport out of the tropics below 25 km, while decreasing it at higher altitudes. In experiment *B1* we doubled the magnitude of the lower stratospheric maximum in K_{yy} (located at ~17 km). We also decreased the exponential decay in K_{yy}, as a function of latitude, away from the maximum. The latitudinal profile of K_{yy} at 20 km for this experiment is shown in Figure 5. In experiment *B2* we used the distribution of K_{yy} from the standard version of the model, but increased the influence of friction between 18-25 km to 1/100 days^{-1} (see Figure 1). At 30 km, friction was reduced from 1/30 days^{-1} to 1/50 days^{-1}. Finally, in experiment *B3* we incorporated both the increased friction and the larger K_{yy} in the lower stratosphere in the model.

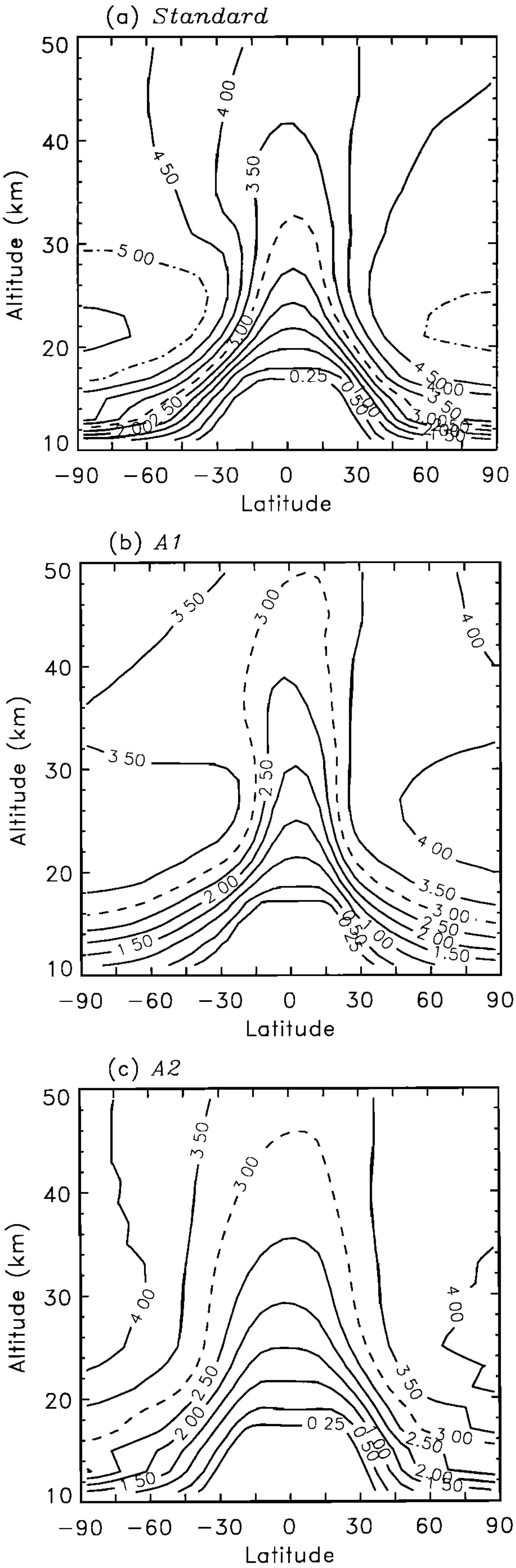
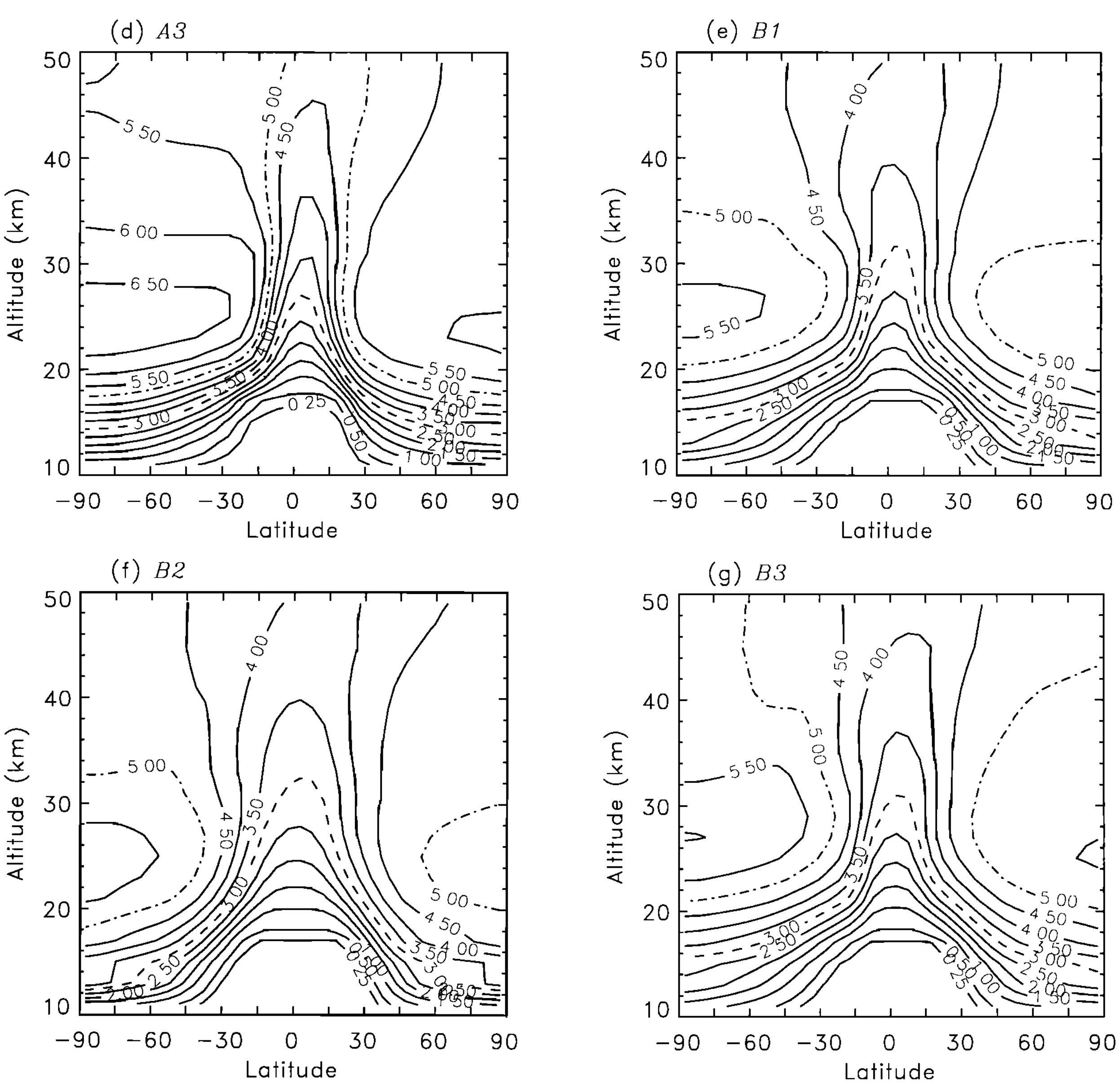


Figure 6. Latitude-altitude cross section of mean ages for January for (a) the standard version of the model, (b) *A1*, (c) *A2*, (d) *A3*, (e) *B1*, (f) *B2*, and (g) *B3*. Units are years.

3. Results

3.1. Mean Age

The calculated distributions of mean age of air in the stratosphere are shown for the various experiments in Figure 6. Mean ages were calculated, as proposed by *Boering*



(d) *A3*

(e) *B1*

(f) *B2*

(g) *B3*

Figure 6. (continued)

et al. [1996], using a passive tracer with a source everywhere in the stratosphere and a sink at the surface. The model was run for 20 years to obtain the steady state distributions of the tracer.

In the standard version of the model, calculated mean ages are oldest in the lower stratosphere, near the poles, where the air is 5-6 years old. Poleward of about 45°, eddy mixing produces weak latitudinal gradients in mean age, whereas equatorward of about 30° the gradients increase significantly. The strong latitudinal gradients in mean age in the standard version of the model agree well with the estimates of mean age derived from observations of CO_2 in the lower stratosphere as illustrated in Figure 7. However, comparison of the vertical profile of mean age with observations shows that throughout the lower stratosphere, below about 22 km, model results are consistently older than observations, whereas at higher altitudes they are too young (see Figure 8).

In experiment *A1*, enhanced upwelling in the tropics associated with increased K_{yy} in the lower and middle stratosphere leads to younger mean ages throughout the stratosphere. Mean ages of air in the upper tropical stratosphere are younger than in the standard model by almost 1 year. As a result of the younger tropical air, in the extratropical lower stratosphere of the northern hemisphere, mean ages are also about 1 year younger than in the standard version of the model. On the other hand, the air is about 2 years younger in the extratropical lower stratosphere of the southern hemisphere. The southern hemisphere shows greater sensitivity to perturbations in K_{yy} because in the standard model we arbitrarily specified the values of K_{yy} in the southern hemisphere to be half as large as those in the northern hemisphere, reflecting weaker wave forcing in the southern hemisphere. In this experiment the latitudinal gradient in mean age in the lower stratosphere is weaker than in the standard run but still agrees with observations (Figure 7).

To separate the influence of K_{yy} on mean age from the effects of the meridional circulation, we performed simulation

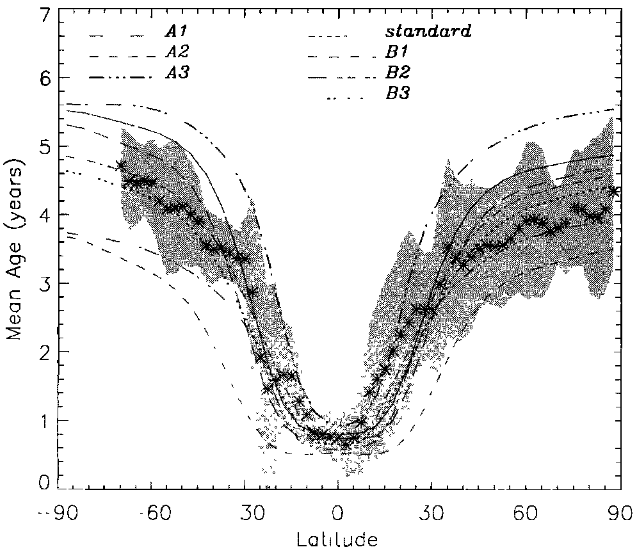


Figure 7. Modeled and inferred latitudinal profiles of mean age of air. Asterisks are mean ages inferred from observations of CO_2 between 19-21 km for the period 1992-1997 [*Andrews et al.*, this issue]. The shaded region indicates two standard deviations of the data. Modeled profiles are annually averaged values of mean age at 19 km.

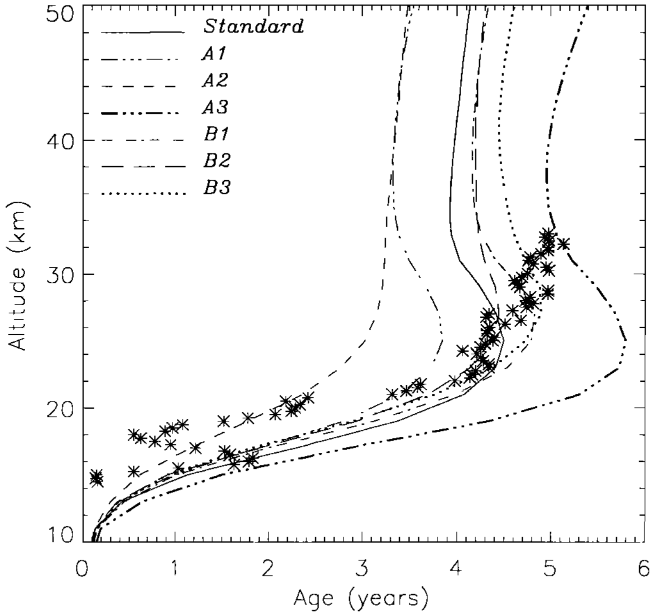


Figure 8. Modeled and inferred vertical profiles of mean age. Asterisks are mean ages inferred from observations of CO_2 at 34.5°N on May 18, 1998. Modeled profiles are mean ages at 32.5°N in May.

A3 using the same distribution of K_{yy} from experiment *A1*, but with the meridional circulation specified from the standard run. This simulation produced the oldest ages in the model (Figure 6d). Mean ages of air in the stratosphere were about 0.5-1 year older than in the standard version of the model. Mean ages are older because, in the absence of a change in the rate of advective transport, larger values of K_{yy} increase the north-south excursions of air parcels near the subtropics, allowing greater recirculation of extratropical air through the tropical stratosphere [*Neu and Plumb*, 1999]. Comparing Figures 6b and 6d, we see that the feedback of the K_{yy}-induced changes in the meridional overturning on mean ages can account for a difference of 1-2 years in mean ages throughout the stratosphere. Furthermore, latitudinal gradients in mean age in *A3* are more similar to those produced in the standard run, supporting the suggestion of *Neu and Plumb* [1999] that it is the meridional circulation that is primarily responsible for determining the tropical-extratropical gradient in mean age.

This dependence of the tropical-extratropical gradient in mean age on the vertical structure of the meridional circulation [*Neu and Plumb*, 1999] is demonstrated more clearly in experiment *A2*. Increased friction in this run produced the largest horizontal velocities across the subtropical stratosphere between 20-30 km and, consequently, the weakest tropical-extratropical gradient in mean age in the lower stratosphere (Figure 7). The profiles of mean age presented in Figure 8 show that the mean ages in experiments *A1* and *A2* are comparable in the extratropical upper stratosphere but are different by almost 1 year below 30 km. In contrast, throughout the tropical stratosphere the differences in mean age between the two experiments are less than 0.2 years (compare Figures 6b and 6c). The mean ages of air below 30 km in the extratropical lower stratosphere are younger in experiment *A2* than in *A1* because of the larger horizontal velocities between 20-30 km in experiment *A2*; meridional transport between 20-30 km provides a faster route for air from the tropics to the extratropical lower stratosphere than transport to the upper tropical stratosphere and then down into the extratropical lower stratosphere.

As discussed above, the standard version of the model overestimates the mean age of air below about 22 km in the

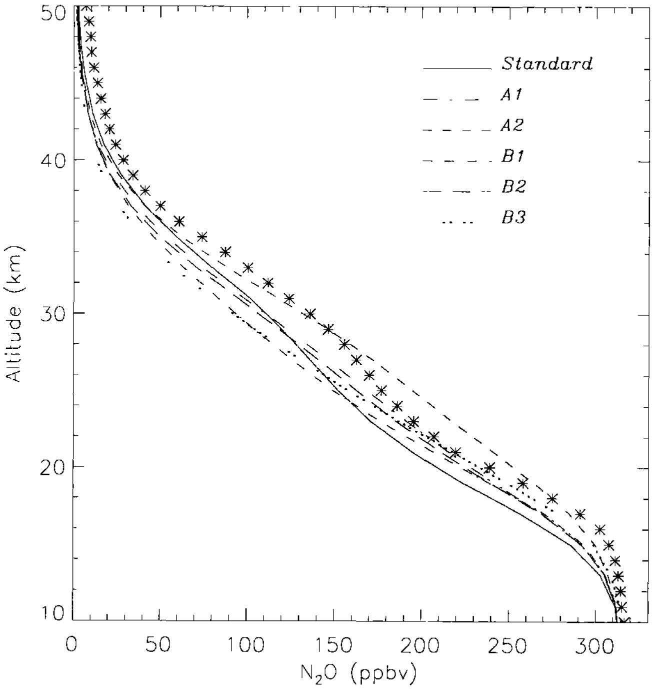


Figure 9. Observed and modeled vertical profiles of N_2O. Asterisks are N_2O as measured by ATMOS in early November 1994. The data were averaged between 33°-44°N. Modeled values are for November, averaged between 30°-45°N

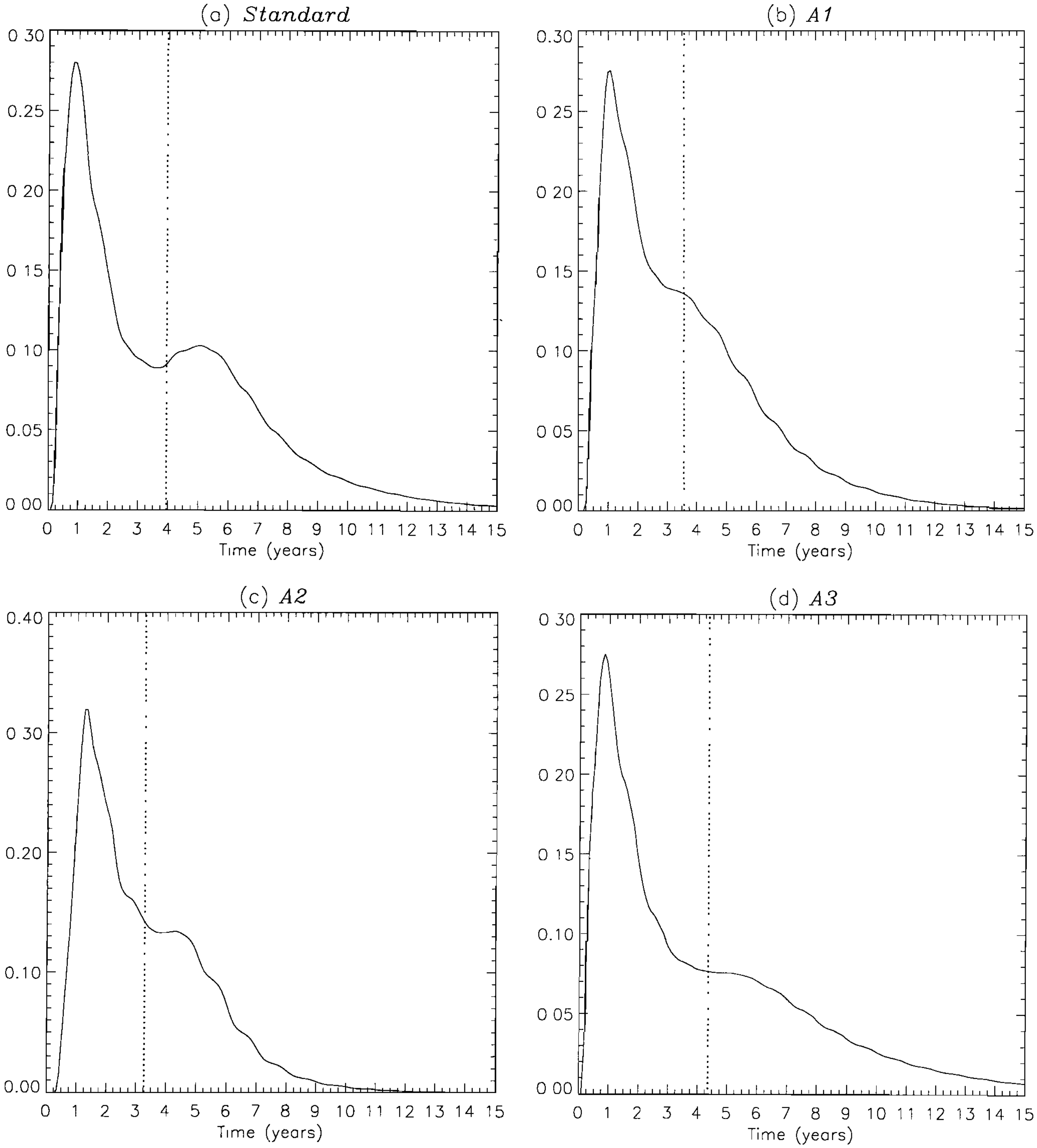


Figure 10. Calculated age spectra at 42°N, interpolated onto the 205 ppbv surface of N_2O, for (a) the standard version of the model, (b) *A1*, (c) *A2*, (d) *A3*, (e) *B1*, (f) *B2*, and (g) *B3*. Dotted vertical lines indicate the mean ages of the spectra.

extratropical stratosphere and underestimates it at higher altitudes. This discrepancy is reduced in the group *B* simulations by varying K_{yy} and Rayleigh friction such that meridional overturning is increased below 25 km and decreased at higher altitudes. In these simulations, faster advective transport of tropical air across the subtropics below 25 km leads to younger mean ages in the lower stratosphere, whereas slower transport at higher altitudes produces older mean ages of air. The increase in mean age above 25 km in these simulations is similar to the response of the interactive two-dimensional model of *Bacmeister et al.* [1998] to increased planetary wave forcing. *Bacmeister et al.* [1998] found that larger planetary wave amplitudes produced older mean ages in the stratosphere. In their model, larger planetary wave amplitudes resulted in greater wave forcing below 18 km. As a consequence, tropical vertical velocities were

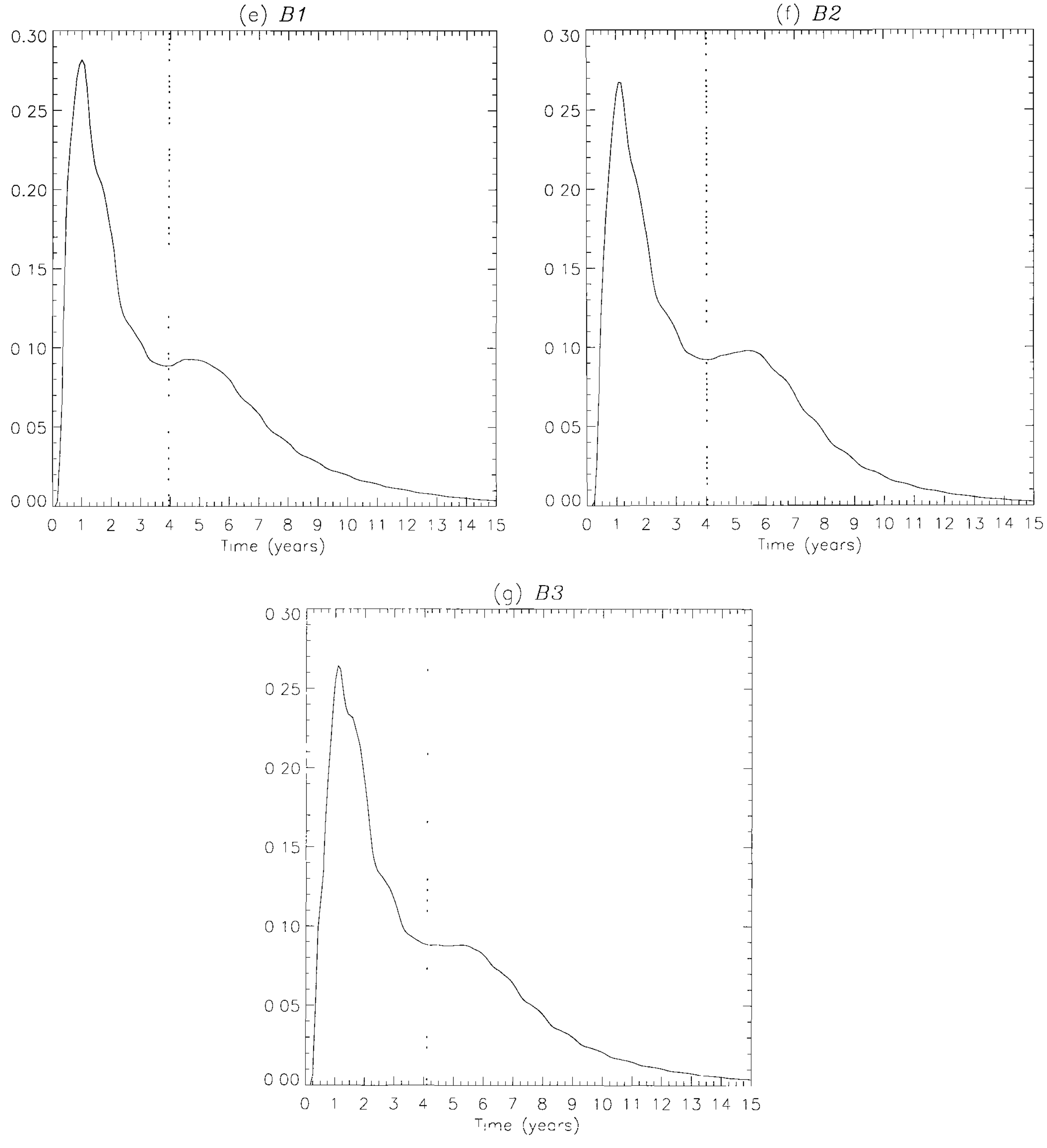


Figure 10. (continued)

enhanced below 18 km and reduced slightly at higher altitudes (see their Figure 8).

Increased advective transport out of the tropics in the lower stratosphere, as in the *B* simulations, also improves the calculated distribution of N_2O in the lower stratosphere in our model. The calculated vertical profile of N_2O at midlatitudes is compared with observations of N_2O from the Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS) in Figure 9. The observations were obtained in early November 1994 and were zonally averaged between 33°-44°N (H. A. Michelsen, private communications, 2000). The modeled profiles represent averaged values of N_2O between 30°-45°N. Throughout the midlatitude stratosphere, the standard model underestimates the abundance of N_2O. In the lower stratosphere the discrepancy is as large as 10-15%. In contrast, experiment *A2*, with significantly greater transport out of the tropics in the lower stratosphere, overestimates the abundance of N_2O between 20-30 km. The agreement between model and observations improves in the lower stratosphere in the other model runs that have moderately larger advective transport below 25 km than the standard run. On the other hand, in these simulations the discrepancy between the model and observations is exacerbated at higher altitudes. These discrepancies are consistent with the fact that the rate of upwelling across the tropical tropopause is too slow in the standard model; in the tropical lower stratosphere, near 20 km, vertical velocities are smaller than those inferred from observations of long-lived tracers [e.g., *Mote et al.*, 1998; *Michelsen et al.*, 2000]. In addition, the modeled tropical vertical velocities increase too slowly with altitude, as compared to inferred rates of ascent, indicating that in all simulations there is too much outflow from the tropics to the extratropics in the middle and upper stratosphere. The imposed variations in K_{yy} and/or Rayleigh friction in the group *B* experiments enhance the meridional mass flux out of the tropics in the lower stratosphere but do not significantly increase the mass flux across the tropical tropopause in the model as that is affected by other process such as diabatic heating and vertical diffusion [*Kogan*, 1999], which we do not modify in these experiments.

The profiles of mean age and N_2O shown in Figures 8 and 9 were obtained at specific latitudes and times and therefore include the effects of individual planetary wave breaking events. Consequently, it is difficult to determine which model simulation better reproduces the observations. The sensitivity runs suggest that the model best reproduces observations when advective transport across the subtropics is reduced between 20-30 km. They also indicate that in the standard version of the model the tropical stratosphere is too isolated below 25 km and not enough at higher altitudes. Below we examine the modeled age spectra and correlations between N_2O and mean age for the midlatitude lower stratosphere to determine which simulation provides the better representation of the stratosphere.

3.2. Midlatitude Age Spectra

The modeled age spectra for the extratropical lower stratosphere are shown in Figure 10. The spectra were calculated from a delta function release of a passive tracer. The troposphere was filled with the tracer for the first 30 days of a 20-year run, after which time the source of the tracer was turned off. A sink for the tracer was specified at the bottom boundary by fixing the mixing ratio of the tracer at the surface to zero. Since in the lower stratosphere N_2O is long-lived and responds therefore to variations in transport similar to the response for mean age, the age spectra have been interpolated on surfaces of constant mixing ratios of N_2O to remove the effects of seasonal variations in transport in the model. This removes the superimposed seasonal signal in the spectra without altering the low-frequency structure of the spectra.

In the standard version of the model the age spectrum in the midlatitude lower stratosphere is bimodal with peaks at about 1 and 5 years (Figure 10a). At higher altitudes, above about 25 km, the midlatitude spectra consist of a single peak in the distribution of transit times (not shown). The bimodal age spectrum in the lower stratosphere is consistent with empirical age spectra derived by *Andrews et al.* [this issue] for the lower stratosphere at midlatitudes using observations of CO_2. The modal times of the first and second peak agree well with the empirical age spectra of *Andrews et al.* [this issue]. The width of the older peak in the model, however, is broader than in the empirical age spectra, and consequently the two peaks in the modeled age spectra are less distinct.

To determine the influence of advective and diffusive transport on the timing of the peaks in the age spectra, we examined the budget of the passive tracer from which the modeled age spectra are derived. The contributions of eddy diffusion and horizontal and vertical advection to the total tendency of the tracer are shown in Figure 11. They were deseasonalized by applying a 12-month running mean to the time series. However, to capture the initial pulse of the injection of the tracer into the stratosphere, we did not smooth the first year of the time series. The budget analysis shows that in the subtropics/midlatitudes, at 32.5°N, for example, the timing of the first peak in the age spectrum can be explained by rapid horizontal and vertical advection of air out of the tropics. At higher latitudes eddy mixing becomes important for transmitting the signal poleward from midlatitudes. At high latitudes the second peak in the age spectrum can be produced by advective transport by the mean meridional

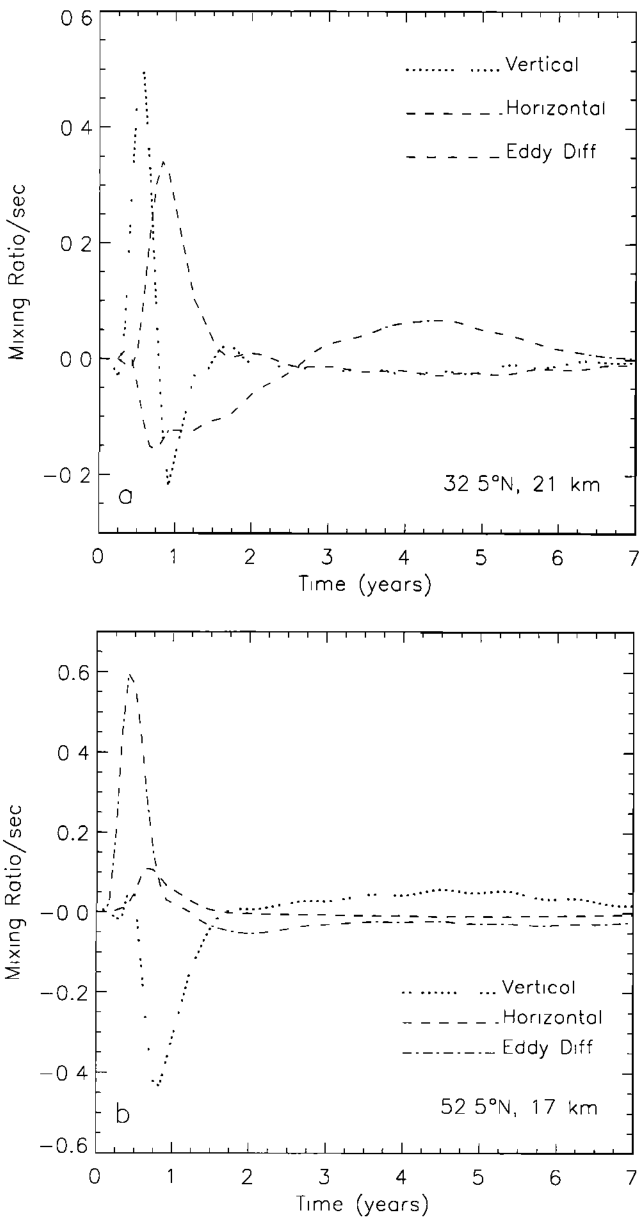


Figure 11. Contribution of eddy diffusion and horizontal and vertical advection to the total tendency of the passive tracer at (a) 32.5°N, 21 km, and (b) 52.5°N, 17 km. The altitudes correspond to the mean location of the 205 ppbv surface of N_2O at these latitudes.

circulation down into the lower stratosphere, with eddy mixing of high-latitude air into midlatitudes rapidly communicating the signal to midlatitudes.

Since the older peak in the age spectra represents the slow downward advection of air by the mean meridional circulation into the extratropical lower stratosphere, a more vigorous circulation should produce a younger second peak. This is indeed the case in model run *A1*. Of all simulations, this run has the most vigorous meridional overturning in the middle stratosphere (Figure 3) and consequently the youngest second peak (Figure 10b). In contrast, experiment *A3* (Figure 10d), which uses the same distribution of K_{yy} as *A1* but specifies the meridional circulation from the standard run, produces an age spectrum that is more similar to the standard run. The modal times of the two peaks in simulation *A3* are comparable to those in the standard run. However, as a result of the larger K_{yy} in *A3* the tail of the age spectrum is longer than in the standard run, and thus the mean ages are older than in the standard version of the model.

Experiment *A2* has the largest rates of advective transport out of the tropics in the lower stratosphere and thus the youngest mean ages. However, in comparison to *A1*, the two peaks in the age spectrum are more distinct (Figure 10c). This is due probably to the fact that the meridional overturning in the middle stratosphere in this simulation is slower than in *A1*. As a result, the second peak in the age spectrum occurs at a later transit time. This confirms that the relative rates of transport through the lower and upper stratosphere determine the extent to which the two peaks in the age spectrum are separated.

In the previous section we showed that the discrepancies in mean age and N_2O between the model and observations were reduced in the lower stratosphere in all *B* simulations, through increased advective transport out of the tropics below 25 km. Comparing the midlatitude age spectra for the standard run and simulations *B1*, *B2*, and *B3* (Figures 10e, 10f, and 10g, respectively) we see that there is little change in the age spectra on the N_2O surface of 205 ppbv. In *B3*, for example, which has the largest change in the rate of advective transport of all the *B* simulations, the modal time for the second peak is only about 0.5 years older than in the standard run, and the difference in modal times for the first peak is much smaller. The mean ages on surfaces of constant mixing ratios of N_2O in these model runs are not much different from those in the standard run. For example, the mean ages of air at 42.5°N on the 205 ppbv surface of N_2O in the standard run and in simulations *B1*, *B2*, and *B3* are 3.96, 3.96, 4.03, and 4.10 years, respectively.

3.3. Tropical-Extratropical Exchange

We can determine the extent of tropical-extratropical exchange in the model by examining the relationship between mean age and the abundance of N_2O. Relationships between abundances of long-lived trace gases have been used extensively to study transport in the stratosphere [e.g., *Murphy et al.*, 1993; *Boering et al.*, 1994; *Avallone and Prather*, 1996; *Minschwaner et al.*, 1996; *Volk et al.*, 1996; *Waugh et al.*, 1997; *Michelsen et al.*, 1998]. In the tropical pipe model of stratospheric transport, relationships between long-lived tracers differ significantly inside and outside the tropics [*Plumb*, 1996]. In the tropics the abundance of long-lived tracers represents a balance between vertical advection and local photochemistry, whereas in the extratropics their abundance is determined by advection by the mean meridional circulation, local photochemistry, and rapid isentropic mixing.

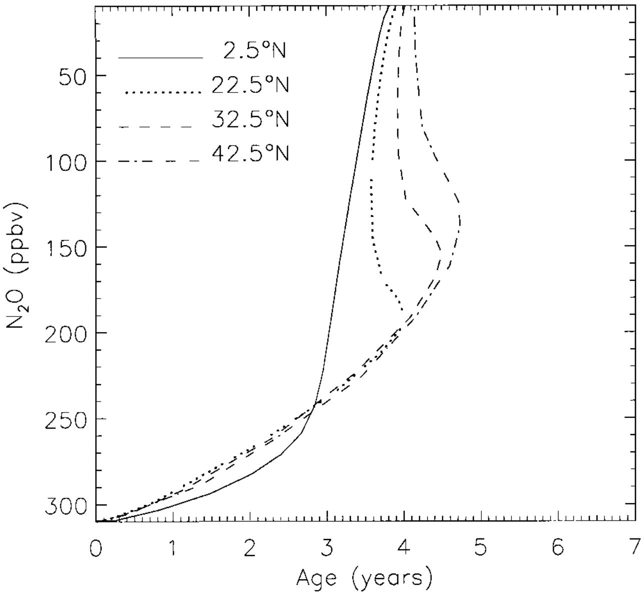


Figure 12. Modeled relationship between N_2O and mean ages of air for May conditions. Results are from the standard version of the model.

The modeled relationship between N_2O and mean age is shown in Figure 12 for May conditions in the standard version of the model. In the lower stratosphere the model shows a distinct separation between the tropical and extratropical stratosphere. Between 22.5° and 42.5°N, below about 200 ppbv N_2O (~24 km), the correlation between N_2O and mean age is compact and distinct from that in the tropics. At 22.5°N and 42.5°N, for example, the curves showing mean age versus N_2O have the same slope, suggesting that, at these altitudes, the timescale for advective transport of tropical air across the subtropics is much longer than the timescale for mixing in the extratropics. At higher altitudes the compactness breaks down as a result of the greater influence of photochemical loss of N_2O and a reduction in the timescale for advective transport out of the tropics, associated with large horizontal velocities in the middle stratosphere.

The modeled relationship between N_2O and mean age is compared with observations in Figure 13. The observations were obtained at 34.5°N on May 18, 1998. Measurements of N_2O are from the Airborne Laser Infrared Absorption Spectrometer II (ALIAS-II) [*Scott et al.*, 1999]. It should be noted that since the observations are from a single balloon flight, we must be careful when assessing the agreement between the model and observations. For example, the cluster of points near values of 100 ppbv N_2O show evidence of transport of air from the arctic vortex to midlatitudes and are therefore not necessarily representative of midlatitude air. In experiments *A1* and *A2*, with strong advective transport out of the tropics in the lower stratosphere, the relationship between N_2O and mean age differs significantly from observations. In contrast, all three experiments in category *B*, with moderately greater advective transport out of the tropics below 25 km and reduced advective transport at higher altitudes, better reproduce the observations. The change in the N_2O/age relationship from the standard version of the model to

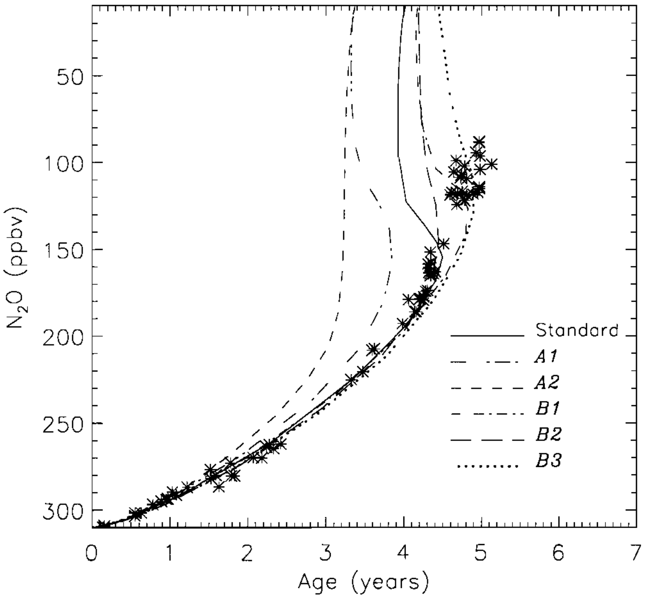


Figure 13. Modeled and observed relationship between N_2O and mean age. Asterisks are observations from May 18, 1998, at 34.5°N. Measurements of N_2O are from ALIAS-II [*Scott et al.*, 1999]. Modeled values are for May at 32.5°N.

simulation *B3* at values of N_2O less than 160 ppbv (altitudes above 28 km) (Figure 13) is similar to the change in the N_2O/age relationship from 32.5° to 42.5°N in the standard model run shown in Figure 12. This is a result of weaker advective transport out of the tropics in the middle stratosphere, where the photochemical loss rate of N_2O is greater.

As expected, the model runs that successfully reproduced the observed relationship between N_2O and mean age also correctly estimated the abundance of CO_2 as observed in the lower stratosphere for the period 1992-1997. In Figure 14 the modeled abundance of CO_2, on the 205 ppbv surface of N_2O, is compared with observations. Observed and modeled values of CO_2 are area-weighted averages for midlatitudes (30°-60°N). The model was forced with time-dependent tropospheric mixing ratios of CO_2 obtained from *Andrews et al.* [1999] for the period 1978-1998. The standard version of the model and the *B* simulations reproduce well the observed concentrations of CO_2. The *B* simulations, which have greater advective transport out of the tropics below 25 km than the standard model run, capture a larger component of the seasonal cycle in CO_2. In contrast, experiments *A1* and *A2*, with larger advective transport below 30 km, overestimate abundances of CO_2 on this N_2O surface. Simulation *A3*, which uses the same meridional circulation as the standard model together with values of K_{yy} from *A1*, underestimates CO_2. This is because the larger values of K_{yy} in this noninteractive run allow greater recirculation of extratropical air through the tropics without accounting for the change in meridional overturning that would accompany the larger K_{yy} in an interactive run.

During MMII it was found that some models produced a maximum in mean age in the extratropical lower stratosphere. These models were designated "class *A*" models [*Hall et al.*, 1999]. Models with a monotonic vertical distribution of mean age in the extratropical stratosphere were designated "class *B*" models. As can be seen in Figure 8, the standard version of our model falls into the class *A* category. The maximum in mean age is noticeable also in the relationship between N_2O and mean age, shown for midlatitudes in Figure 13. It has been suggested that the presence of a maximum in mean age in the extratropical lower stratosphere of class *A* models is an indication that values of K_{yy} are too low for the extratropical stratosphere in the models [*Hall et al.*, 1999; *Li and Waugh*, 1999]. However, as mentioned above, in our model this maximum in mean age is not a function of K_{yy}. It is produced because transport out of the tropics in the middle stratosphere (above 30 km) is rapid relative to that in the lower stratosphere. Thus, in experiment *A2*, in which we modified Rayleigh friction to significantly increase the horizontal velocities in the lower stratosphere relative to those in the middle and upper stratosphere, the model produced a weaker maximum in mean age in the lower stratosphere. In fact, experiment *A2* produces a distribution of mean age that is more characteristic of a class *B* model than that of a class *A* model.

4. Summary

We have examined the sensitivity of mean age of air in the stratosphere to rates of transport in the lower and middle stratosphere using an interactive two-dimensional model. The model successfully reproduces the bimodal age spectra derived by *Andrews et al.* [this issue] for the midlatitude lower stratosphere. We showed that, as suggested by *Andrews et al.* [this issue], to reproduce the bimodal age spectra, meridional transport out of the tropics must be small between 20-30 km in the model. Reduced transport at these altitudes is required also to capture the observed latitudinal gradient in mean age in the lower stratosphere. This region of reduced

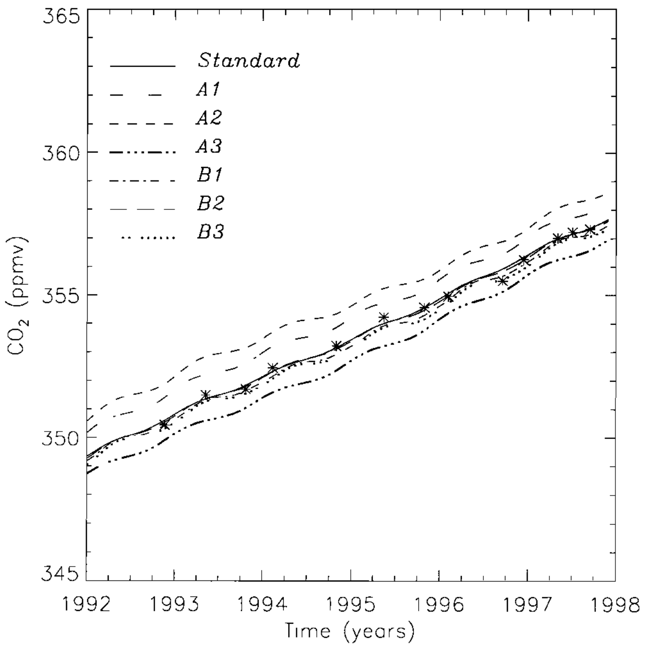


Figure 14. Observed (asterisks) and modeled times series of CO_2 on the 205 ppbv surface of N_2O for the period 1992-1997. Data are from *Andrews et al.* [this issue]. Modeled and observed values of CO_2 are area-weighted averages for 30°-60°N.

meridional transport effectively separates stratospheric transport into an upper and a lower branch, and is consistent with the tropical pipe model of stratospheric transport [*Plumb*, 1996; *Neu and Plumb*, 1999]. Rapid transport out of the tropics below 20 km accounts for the young peak in the age spectra. Transport to the upper tropical stratosphere and down into the extratropical lower stratosphere produces the older peak. Without strong tropical isolation between 20-30 km, meridional transport would provide a faster route to the extratropical lower stratosphere than the upper branch. Consequently, the second peak in the age spectrum would become younger, resulting in younger mean ages of air. Meridional transport at these altitudes also weakens the tropical-extratropical gradient in mean age in the lower stratosphere. In the model, the relative rates of meridional transport in the lower and middle stratosphere determine the separation of the two peaks in the age spectra and thus the overall mean age of air in the lower stratosphere.

Models that do not explicitly calculate planetary wave mixing usually parameterize a tropical pipe by reducing K_{yy} in the tropical stratosphere. To better simulate tropical-extratropical transport, as indicated by observations, *Shia et al.* [1998] parameterized a "leaky pipe" in the Atmospheric and Environmental Research (AER) two-dimensional model by specifying small values of K_{yy} everywhere in the tropics except in the lower stratosphere between the tropopause and 21 km. However, weak mixing in the tropical stratosphere does not guarantee that tropical-extratropical exchange will be inhibited. Strong advective transport out of the tropics can lead to significant tropical-extratropical exchange. In our model it is necessary to assume small rates of friction in the lower stratosphere (damping timescales greater than 90 days) to weaken horizontal velocities and thus inhibit tropical-extratropical exchange in the lower stratosphere.

The strong sensitivity of the mean age of air to the imposed friction in the lower stratosphere is cause for concern because the drag associated with gravity waves and other small-scale processes is difficult to quantify. Clearly, Rayleigh friction is a crude parameterization of the effects of these processes; it does not capture the dependence of gravity wave breaking on the mean flow. There are other more realistic parameterizations of the effects of gravity wave breaking [e.g., *Lindzen*, 1981; *Holton*, 1982; *Hines*, 1997] which attempt to reproduce the interaction between the waves and the mean flow. However, these parameterizations require assumptions about the spectrum of gravity waves propagating into the stratosphere, and the vertical flux of momentum associated with them which are not well constrained. Thus, even in models with more sophisticated parameterizations, gravity wave drag still remains an adjustable parameter.

It has been suggested that the discrepancies between models and observations found during MMII could be resolved either by reducing the strength of the mean meridional circulation or by increasing eddy mixing in the models [*Hall et al.*, 1999; *Li and Waugh*, 1999]. However, as we have shown, models in which the meridional circulation and K_{yy} are adjusted independently can produce mean ages that differ by as much as 2 years from those calculated in fully coupled models. Dynamically consistent models, on the other hand, are generally less sensitive to variations in K_{yy} [*Holton*, 1986; *Mahlman et al.*, 1986; *Bacmeister et al.*, 1998; *Schneider et al.*, 2000]. To improve the current generation of two-dimensional models in a physically consistent manner will require a detailed understanding of their sensitivity to other dynamical parameters besides K_{yy}, such as gravity wave drag and rates of diabatic heating in the lower stratosphere.

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