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**The impact of tropical
recirculation on polar
composition**

S. E. Strahan et al.

The impact of tropical recirculation on polar composition

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

We derive the tropical modal age of air from an analysis of the water vapor tape recorder. We combine the observationally derived modal age with mean age of air from CO_2 and SF_6 to create diagnostics for the independent evaluation of the vertical transport rate and horizontal recirculation into the tropics between 16–32 km. These diagnostics are applied to two Global Modeling Initiative (GMI) chemistry and transport model (CTM) age tracer simulations to give new insights into the tropical transport characteristics of the meteorological fields from the GEOS4-GCM and the GEOS4-DAS. Both simulations are found to have modal ages that are in reasonable agreement with the empirically derived age (i.e., transit times) over the entire altitude range. Both simulations show too little horizontal recirculation into the tropics above 22 km, with the GEOS4-DAS fields having greater recirculation. Using CH_4 as a proxy for mean age, comparisons between HALOE and model CH_4 in the Antarctic demonstrate how the strength of tropical recirculation affects polar composition in both CTM experiments. The better the tropical recirculation is simulated, the better the CH_4 simulation is in the Antarctic. Mean age in the Antarctic lower stratosphere can be compromised by poor representation of tropical ascent, tropical recirculation, or vortex barrier strength. The connection between polar and tropical composition shown in this study demonstrates the importance of diagnosing each of these processes separately in order to verify the adequate representation of the processes contributing to polar composition in models.

1 Introduction

An age spectrum is the distribution of transit times since a stratospheric air parcel last made contact with the troposphere. To conduct an age spectrum experiment, a pulse of inert tracer is released at a model's tropical surface or tropical tropopause, and the model is integrated with loss occurring only at the surface (Hall and Plumb, 1994). The age spectrum is then calculated by normalizing the time series of the age tracer mixing

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The impact of tropical recirculation on polar compositionS. E. Strahan et al.

ratio at all model gridpoints. At each point in the stratosphere, a mean age of air can be calculated which can be used to qualitatively assess a model's transport circulation. Hall et al. (1999) compared mean age in more than a dozen 2-D and 3-D models and found widely different mean age distributions, suggesting a wide range of transport and mixing characteristics in the models evaluated. Mean age derived from aircraft and balloon CO₂ and SF₆ measurements provides the basis for evaluation of model mean age at 20 km (Andrews et al., 2001; Waugh and Hall, 2002). While Hall et al. (1999) found that most models did poorly in the mean age comparison at 20 km, today many models have lower stratospheric mean age that matches observations (Eyring et al., 2006). Good mean age at 20 km is a necessary but not sufficient condition for a credible transport circulation because compensating transport errors can conspire to give reasonable mean age in spite of poor representation of physical processes (Schoeberl et al., 2003; Strahan and Polansky, 2006).

Complete stratospheric transport information is found in the age spectrum. The age spectrum represents the full range of transit times of the parcels arriving at a given point: a short transit time suggests that a parcel took a direct route to that point while longer times usually indicate transit through higher levels of the stratosphere (Waugh et al., 2007). The largest peak in age spectrum, the modal age, is the most probable transit time to that point, while the average over all time elements in the age experiment, the mean age, gives information about the average transit time. Two models may have the same mean age at a particular location but comparison of their age spectra will show whether the models have the same transport pathways. Waugh et al. (2007) demonstrated the importance of transport pathways to chemical composition by comparing two models with identical mean ages in the Antarctic lower stratosphere but very different modal ages (2 years and 4 years). The model with the younger modal age had too little reactive chlorine (Cl_y) in the Antarctic vortex in spring while the model with the 4-yr modal age produced realistic Cl_y (~3 ppb in the 1990's). Realistic transport pathways are essential for credible simulation of chemical composition.

Age spectrum experiments provide insight into model transport processes but unfor-

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The impact of tropical recirculation on polar compositionS. E. Strahan et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Unfortunately age spectra cannot be directly observed. Schoeberl et al. (2005) developed a technique to compute age spectra from long-lived trace gases having different lifetimes. The method requires global observations of at least 4 different species and performs a least squares fit of an assumed spectral shape using parameters that depend on each specie's loss rate. Two key pieces of information that describe the shape of an age spectrum, especially in the tropics, are the mode and the mean, and in some regions of the stratosphere they can be derived from observations. Transport in the tropical stratosphere is dominated by slow vertical advection and weak horizontal mixing (Plumb, 1996). Mote et al. (1996) found evidence for tropical isolation when they observed the upward propagation of the water vapor anomaly that results from the seasonal variation in tropical tropopause temperatures, referring to it as the water vapor tape recorder. This isolation has given rise to the label "tropical pipe" (Plumb, 1996). The upward propagation of the water vapor anomaly is a measure of the vertical transport rate, which is directly related to the modal age in the limit of low vertical mixing (Hall and Waugh, 1997; Waugh and Hall, 2002). Recently, Schoeberl et al. (2008) used 15 years of satellite measurements of tropical H₂O vapor to calculate vertical velocities from 16–32 km. Their empirically determined vertical velocities can be used to calculate transit times, providing a lower limit to tropical modal age.

Mean age can be derived from long-lived species such as CO₂ and SF₆ that have well-known annual growth rates in their source function. Their tropical profiles are a function of both the mean vertical ascent rate and horizontal mixing across the subtropics. Andrews et al. (2001) used aircraft measurements of CO₂ to estimate mean age from 70° S–80° N at 20 km, and using balloonborne measurements of CO₂ and SF₆ they derived mean age profiles from the tropopause to ~33 km at 7° S, 35° N, and 65° N. If empirically determined tropical modal age profiles were also available, we would then have the two pieces of information needed to characterize a tropical age spectrum, that is, a spectrum consisting of a single peak with a long tail. The tropical modal age (the peak) is a diagnostic for the approximate net vertical transport rate (advection plus vertical mixing) while the mean age represents the combined effects of vertical transport

and horizontal mixing with the extratropics. The separation of the mean and modal ages reflects the degree of horizontal mixing (recirculation) that occurs during ascent. When used for model evaluation, these diagnostics could show, for example, whether the cause of a model's low tropical mean age was too rapid ascent or too much tropical isolation.

In this paper we calculate modal ages in the tropical stratosphere (16–32 km) using the vertical velocities calculated from the 15-year water vapor data set in Schoeberl et al. (2008). These empirically derived modal ages are combined with tropical mean age profiles to evaluate vertical transport and tropical recirculation in Global Modeling Initiative (GMI) chemistry and transport model (CTM) simulations using meteorological fields from the Goddard Earth Observing System Version 4 (GEOS4) general circulation model (GCM) and the GEOS4 data assimilation system (DAS). We show that tropical vertical transport in the GEOS4-GCM is well simulated and that its mean age deficiency stems from too much tropical isolation. We link the behavior of age tracer and CH₄ distributions to demonstrate how age in the tropical pipe affects age in the Antarctic. We compare the behavior of the GMI-GCM simulation with a GMI simulation using GEOS4-DAS meteorological fields, which have greater tropical recirculation, to see how greater recirculation affects polar composition. The importance of tropical recirculation to polar composition is demonstrated by comparisons of GMI CH₄ simulations with a multi-year average of Upper Atmosphere Research Satellite (UARS) Halogen Occultation Experiment (HALOE) CH₄ measurements. The results of this study stress the importance of independent diagnosis of tropical ascent, tropical recirculation, and vortex barrier strength in models so that the model processes contributing to polar composition can be individually evaluated.

2 Observational analyses and models

Two observational analyses are used to create diagnostics for tropical vertical transport rates (modal age) and horizontal recirculation (mean age). Tropical modal age from 16–

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



32 km is approximated from the vertical velocities calculated by Schoeberl et al. (2008) from a 15-yr time series of satellite tropical water vapor measurements from the AURA Microwave Limb Sounder (MLS) (Waters et al., 2006; Read et al., 2007) and the UARS HALOE (Russell et al., 1993). Tropical mean age profiles from 400–900 K (~ 18 –32 km) were derived from CO₂ and SF₆ balloon-borne measurements at 7° S by Andrews et al. (2001). To demonstrate the relationship between a long-lived tropospheric source gas and age tracer, we use global CH₄ measurements from UARS HALOE (Russell et al., 1993) from 1993–2001. We calculate annual means and Antarctic seasonal mean profiles from the HALOE data set.

Tropical ascent and recirculation are investigated in two versions of the GMI CTM. One version used a 5-year time series of meteorological fields from the GEOS4-GCM (Bloom et al., 2005) with source gas boundary conditions for 1994–1998. The other version used a 3-year time series of meteorological fields from the GEOS4-DAS and source gas boundary conditions representing 2004–2006 (Bloom, et al., 2005). Simulations using these models are referred to as GMI-GCM and GMI-DAS. Both versions have been run with an age spectrum tracer (Hall and Plumb, 1994) and with a full troposphere-stratosphere chemical mechanism (the “Combo” model). The GMI CTM does not transport water vapor and thus a direct comparison with the observed water vapor tape recorder is not possible. In the age of air experiments, an inert tracer is released at the surface from 10° S–10° N for 1 month; tracer loss occurs only at the surface. The GMI-DAS simulation is integrated for 20 years by recycling 1 July 2004–30 June 2005 meteorological fields; the GMI-GCM recycles the 5-year sequence of wind fields four times to complete a 20-yr integration. Both versions of the CTM are integrated at 2° latitude by 2.5° longitude resolution with 42 vertical levels and a model lid at 0.01 hPa. Spatial resolution in the upper troposphere/lower stratosphere is 1 km or less. Details of the GMI Combo CTM and the credibility of its lower stratospheric transport can be found in Strahan et al. (2007) and Duncan et al. (2007).

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

3 Stratospheric circulation and the tropical pipe

3.1 Mean and modal age in the tropics

Figure 1 shows empirically derived tape recorder velocities and their 2σ uncertainties from Schoeberl et al. (2008) and transit times calculated from them. The velocities, which were calculated at 2-km intervals from 17–31 km, are assumed to represent the mean velocity over a 2-km range centered at the level at which the velocity was derived. Uncertainty in transit time is propagated upward using the 2σ velocity uncertainty at each level. As discussed in Schoeberl et al. (2008), their calculated velocities are in good agreement with a number of other data and model studies between 20–26 km.

The water vapor tape recorder vertical velocity is not equivalent to the Eulerian vertical velocity nor is it exactly the residual vertical velocity (see Andrews et al., 1987, for conditions under which the residual vertical velocity is the transport velocity). Waugh and Hall (2002), however, show that for an oscillatory signal in a low diffusion environment, the bulk velocity diagnosed from the tracer oscillations approximates the modal age, although vertical mixing will cause the tape recorder to increase in tilt and thus overestimate the velocity. Thus, the velocities diagnosed from the tape recorder can be considered to be an upper limit, providing a lower limit on the transit time (modal age) due to vertical advection.

Figure 2 shows a tropical age spectrum from the GMI-GCM middle stratosphere; this shape, a single, narrow peak followed by a long tail, is typical of both the GMI-GCM and GMI-DAS tropical age spectra. The main pulse of tracer arrives ~ 1.5 years after release at the surface, the result of slow ascent in the tropical pipe. The long tail of the spectrum results from the recirculation of midlatitude (older) air into the tropics. The simulation's mean age represents the integrated effects of transport by advection and mixing. We assume that mixing due to numerical diffusion and vertical diffusion are small, and thus the difference between the tropical modal and mean ages is a measure of the strength of recirculation (horizontal mixing) into the tropical pipe. If there were no tropical mixing, the mean age would equal the modal age.

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Figure 2b shows the modal age derived from analysis of the water vapor data in Schoeberl et al. (2008) (asterisks) and the mean age of air derived from CO₂ (diamonds) and SF₆ (triangles) (Andrews et al., 2001). Above 30 km, the SF₆ age is too high because no mesospheric loss was included in the age calculation (Waugh and Hall, 2002). The mean and modal ages have significant differences by 20 km, indicating the importance of recirculation in the lower stratosphere. Figure 2c shows contoured GMI-GCM tropical age spectra. The maximum of the spectrum at each level (the most probable value) is the modal age and it depends on the mean ascent rate; the maxima are shown by a dashed red line. The means of the spectra, which include the effects of recirculation, are shown with the solid red line. The overlay of the empirically derived mean and modal ages shows that the GMI-GCM ascent is slightly slower than the ascent implied by the empirically derived modal age above 20 km. This is consistent with the model vertical velocity shown in Fig. 1a. Between 20–26 km, the model tropical vertical velocity is in close agreement with that derived from the tape recorder but too slow above and below this range. This results in longer transit times (higher modal ages) for the model. Because the modal ages are derived from the vertically propagating water vapor anomaly they include the effects of ascent and vertical diffusion, and therefore represent an upper limit to the vertical advective velocity. In a model age spectrum experiment, the tropical modal age is controlled primarily by the mean ascent rate; diffusion acts to broaden the width of the mode although it may also shift its altitude. The model mean age above 20 km is too young by up to 1.2 years; from this we conclude that the GEOS4-GCM wind fields used in the GMI-GCM create a tropical pipe that is too isolated above 20 km. The uncertainty in the observationally derived mean age (Andrews et al., 2001) was not reported, however, the variability in the published CO₂ and SF₆ profiles suggests that ±0.5 year for mean ages above 20 km spans the range of observed variability.

The impact of tropical recirculation on polar compositionS. E. Strahan et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

3.2 Methane and age

The differences between model and observed tropical mean age are reflected in the differences between the model and HALOE CH_4 . Methane is long-lived in the lower and middle stratosphere but is destroyed by O^1D , OH and Cl radicals in the upper stratosphere; its annual average photochemical lifetime from 0.5–3 hPa is 6–12 months. Because of this, CH_4 is sensitive to the amount of time spent in the upper stratosphere, which it reaches through tropical ascent, thus it is anti-correlated with age. (The correlation weakens as CH_4 goes to very low values in the upper mesosphere.) Figure 3a shows the annual zonal mean HALOE CH_4 distribution and Fig. 3b shows the annual zonal mean CH_4 from the GMI-GCM simulation; Fig. 3c shows their differences. The model CH_4 below 10 hPa is too high by no more than 100 ppb (<10%) compared to HALOE at most latitudes, but larger differences are observed above. The agreement is worst in the tropics above 4 hPa where the model is high by more than 350 ppb (~100%). At 4 hPa the lifetime is fairly long, almost two years, suggesting that the disagreement is likely due to transport, either by too rapid upward advection in the tropics or too little recirculation through the tropical lower or middle stratosphere. The good agreement between modal ages (Fig. 2c) indicates the problem is not with the rate of vertical transport below 32 km (~10 hPa). Although we cannot eliminate uncertainties in the chemical loss calculation as a contributor to the excess CH_4 , high CH_4 caused by too little tropical recirculation is consistent with the low mean age found in the model tropical middle stratosphere.

3.3 The effect of tropical isolation on polar composition

Could excessive tropical pipe isolation affect the mean age elsewhere? To explore this we look at the seasonal behavior HALOE CH_4 in the Antarctic using CH_4 as a proxy for mean age. Figure 4a shows the 9-year HALOE Antarctic vortex mean profile calculated by contouring PDFs of observations between 80–68° S, the highest latitudes measured by HALOE in October and November (spring). Below 3 hPa the probability

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The impact of tropical recirculation on polar compositionS. E. Strahan et al.

distribution functions (PDFs) split into two branches, one representing deep vortex air (lower CH₄) and the other midlatitude air (higher CH₄). The vortex profile has low CH₄, low variability and almost no vertical gradient between 0.7–20 hPa. The low CH₄ values and low variability indicate high mean age in the vortex and the absence of influence by younger air. Higher CH₄ in the midlatitude profile indicates the influence of younger air, and the PDF minima between the profiles demonstrate how well isolated the older vortex air is from midlatitude air. Compared with HALOE, the GMI-GCM CH₄ shows many of the same transport signatures, such as the degree of isolation indicated by the lack of vertical gradient, the bimodal PDFs, and low variability. In spite of this, model CH₄ in the Antarctic upper stratosphere (Fig. 4b) is too high by >200 ppb and is thus too young.

The explanation may be found by considering upper stratospheric and lower mesospheric transport processes in the Antarctic fall and winter. In the austral fall, wave activity transports low latitude air to the polar region while strong cooling causes descent of mesospheric air (Rosenfield and Schoeberl, 2001; Fisher et al., 1993). Figure 5a shows the 68–80° S HALOE mean CH₄ profiles averaged over all February and March (black) and all October and November (red) measurements. Compared to the fall profile, the HALOE spring profile (red) shows increased CH₄ above 7 hPa. Descent cannot produce this increase because CH₄ in the mesosphere is lower than in the upper stratosphere (Fig. 3a). The seasonal increase of more than 100 ppb CH₄ above 7 hPa must therefore be the result of poleward transport of high CH₄ from lower latitudes in the upper stratosphere or lower mesosphere. This increase due to poleward transport from lower latitudes in fall has also been seen in UARS CLAES CH₄ data (Strahan and Douglass, 2004). The model spring profile (red), Fig. 5b, shows a CH₄ increase of more than 300 ppb in the upper stratosphere compared to fall, much greater than the increase observed by HALOE. As model CH₄ also decreases with height in the upper atmosphere (Fig. 3b), the model's increase in spring must also be the result of horizontal transport of low latitude air in the previous seasons. Regardless of the relative contributions of descent and horizontal transport in the model, the large increase

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

in the model Antarctic spring profile identifies the low latitude upper stratosphere as a contributor to high latitude composition. This demonstrates a pathway for tropical composition problems to be transported to Antarctic.

In contrast to the disagreement between the model and observations in the polar middle and upper stratosphere, between 30–68 hPa the modeled and observed spring vortex profiles agree very closely (Fig. 4b). Increasing CH₄ with decreasing altitude indicates the influence of younger air inside the vortex below 30 hPa. The HALOE vortex profile increases below 20 hPa while the model vortex increases only below 30 hPa. This difference in the height at which younger air begins to influence the model vortex is a compensating error that results in the near perfect agreement with the observations from 30–68 hPa. That is, the lack of young air influencing the model vortex from 20–30 hPa keeps the mixing ratios constant while the observations show an increase, “catching up” with model mixing ratios at 30 hPa. This suggests that the model age spectrum in the Antarctic lower stratosphere may have too few young air elements.

3.4 The effect of increased tropical recirculation

If we had a knob to turn up tropical recirculation we could test its effect on polar composition. As this is not possible, we turn instead to a GMI-CTM age spectrum experiment using GEOS4-DAS meteorological fields which has greater tropical mean age than the GMI-GCM simulation. Figure 6a compares tropical mean and modal ages from the two CTM experiments. The GMI-DAS simulation has a lower modal age than the GMI-GCM in the tropics indicating faster vertical transport. The GMI-DAS has better agreement with the water vapor modal age, but as previously noted, the empirical modal age may contain the effects of vertical diffusion and represents an lower limit on the ascent rate. Like the GMI-GCM, the GMI-DAS mean age is too young above 22 km but it is consistently ~0.3 yr higher than the GMI-GCM. The difference between the mean and modal ages indicates the degree of recirculation, and this is 0.6–0.7 years greater in the GMI-DAS. Consistent with greater recirculation into the tropical pipe, the GMI-DAS tropical CH₄ has a smaller disagreement with HALOE in the tropical upper stratosphere (i.e.,

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



250 ppb too high compared to >350 ppm too high in the GMI-GCM). This can be seen by comparing Fig. 6b with Fig. 3c. Lower CH₄ in the GMI-DAS cannot be attributed to greater photochemical loss rates. GMI-DAS CH₄ loss rates are actually 20–40% smaller than in the GMI-GCM in the tropical upper stratosphere; if the loss rates were equal there would be even greater differences. Thus, the small CH₄ loss rates in the

Figure 7 shows contoured PDFs of GMI-DAS CH₄ from 68–80° S in the Antarctic spring. Similar to the GMI-GCM vortex profile (red dashed line), the GMI-DAS simulation shows good vortex isolation for most of the stratosphere above 50 hPa, although the influence of younger air (higher CH₄) is apparent by the nonzero vertical gradient from ~7–20 hPa; HALOE indicates that this influence should remain small down to 20 hPa. Above 10 hPa, the GMI-DAS vortex profile agrees better with the HALOE data (white line) than the GMI-GCM does by ~100 ppb. This is similar to the differences seen in the tropical upper stratosphere where GMI-DAS CH₄ is 100–130 ppb higher than GMI-GCM CH₄. The seasonal change in upper stratospheric Antarctic profiles shown in Fig. 5 demonstrated the importance of the low latitude transport pathway to the observed spring profile. It is therefore likely that having more realistic recirculation in the tropical stratosphere leads to improved simulation of polar composition.

4 Discussion and summary

We have combined the observationally derived tropical mean age (Andrews et al., 2001) with an estimate of tropical modal age from the water vapor tape recorder to define diagnostics for the independent evaluation of vertical transport rate and horizontal recirculation into the tropics between 16–32 km. Previous studies used a shorter time series of the H₂O vapor tape recorder to determine the vertical transport rate (Mote et al., 1998), or attenuation of the CO₂ seasonal cycle in the lower stratosphere to estimate horizontal mixing (Douglass et al., 1999; Waugh and Hall, 2002). This study increases the altitude range for these diagnostics to 32 km and uses the analysis of a much longer data record for the tropical vertical transport rate (modal age).

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The impact of tropical recirculation on polar compositionS. E. Strahan et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

These diagnostics were applied to two GMI CTM experiments to give new insights into the tropical transport characteristics of two sets of meteorological fields, the GEOS4-GCM and the GEOS4-DAS. Previously, the comparison of model and observed tropical profiles of CH₄ suggested that the model vertical transport was too fast, or the horizontal mixing was too weak, or a combination of both. In the real atmosphere, downward control drives both the vertical transport and horizontal mixing (Haynes et al., 1991) but in a model these processes may also be affected by implementation factors such as resolution. The diagnostics presented here allow us to conclude that vertical transport rates are approximately correct in both sets of meteorological fields and that the disagreement in trace gas profiles results from insufficient recirculation of older air into the tropics. In other words, the model tropics are too isolated. Tropical isolation is greater in the GCM fields than in the DAS fields.

We have used a proxy relationship between CH₄ and mean age to demonstrate how the weak recirculation into the tropical stratosphere in the CTM experiments lowers mean age there and in the polar stratosphere. Examining seasonal changes in the HALOE CH₄ Antarctic profiles, we identified the importance of poleward horizontal transport of low latitude, high CH₄ air in austral fall to the composition of the Antarctic stratosphere in spring. This pathway provides a means to transport mean age or composition features from the tropics to the pole. We found the same pathway to be present in the GMI-GCM simulation by comparing Antarctic summer and spring profiles; the unusually large increase in upper stratospheric CH₄ came from a region where model CH₄ was exceptionally high – the tropical upper stratosphere. The connection between tropical recirculation and polar composition was also demonstrated in the GMI-DAS simulation. Tropical pipe recirculation in the GMI-DAS middle stratosphere is more realistic than in the GMI-GCM, but is still less than observed. Greater recirculation in the GMI-DAS tropical stratosphere (i.e., lower CH₄) resulted in better agreement with HALOE CH₄ in the Antarctic upper stratosphere in the spring.

The connection between polar and tropical composition shown in this study demonstrates the relevance of evaluating tropical transport processes in models when polar

behavior is the issue of interest. Problems in tropical ascent rates or isolation have global consequences for composition. Eyring et al. (2006) showed that mean age from many of the chemistry-climate models (CCMs) participating in the WMO 2006 simulations matched the empirically derived mean age in the Antarctic lower stratosphere to within 0.5 years, but when numerous transport and dynamics diagnostics are applied to these models, significant disagreements are found (Vaugh and Eyring, 2008). Age spectra from these models would undoubtedly show wide variation.

Age spectra from the GMI-GCM and GMI-DAS illustrate how both tropical and polar transport processes play a role in the mean age in the Antarctic upper and lower stratosphere. In Sect. 3.4 we showed how greater tropical recirculation in the GMI-DAS influenced the polar upper stratosphere. This is also seen in Fig. 8a by the older mean age of the GMI-DAS at 3 hPa, which comes from having more age tracer in the tail of the spectrum (greater recirculation). In the lower stratosphere, Fig. 8b, the GMI-GCM has the older mean air in spite of having younger air at 3 hPa. At 52 hPa, the GMI-DAS has a great deal of age tracer arriving in the first 1.5 years of the simulation while the GMI-GCM has almost none. This is the signature of a leaky vortex produced by GEOS4-DAS fields which transport midlatitude air directly into the vortex, resulting in a younger mean age there; this was also demonstrated in Fig. 7 of Vaugh et al. (2007). The lack of age tracer in the Antarctic lower stratosphere in the first year of the GMI-GCM simulation is an indication of the strength of the vortex barrier in the GEOS4-GCM fields; this was previously diagnosed by Strahan and Polansky (2006). However, a model with a strong vortex barrier and young mean age in the tropical upper stratosphere (e.g., the GMI-GCM) will also have a low Antarctic mean age because it has less recirculation in the upper stratosphere (i.e., a shorter tail in the high altitude age spectra). Thus, two different transport deficiencies (weak tropical recirculation and weak polar vortex barrier) can lower polar mean age. To evaluate the credibility of CCMs, it is essential that we separately diagnose tropical ascent rate, tropical recirculation, and vortex barrier strength in order to verify the fidelity of three important transport processes contributing to polar composition.

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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The impact of tropical recirculation on polar composition

S. E. Strahan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The impact of tropical
recirculation on polar
composition**S. E. Strahan et al.

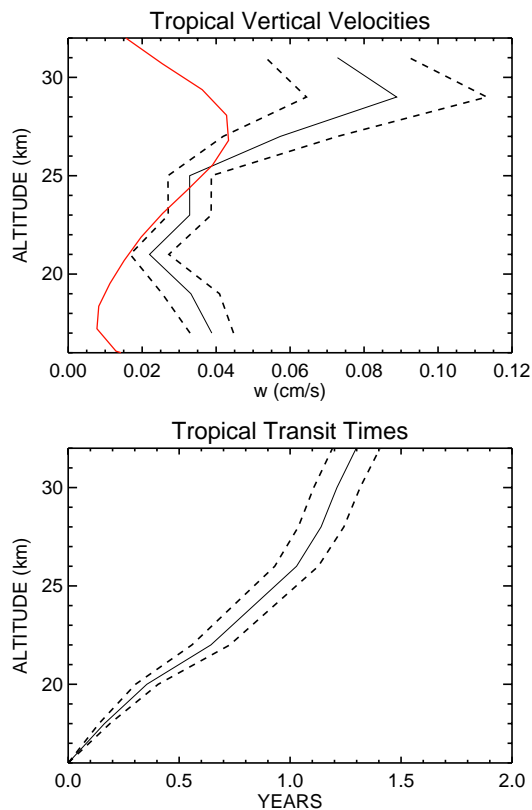


Fig. 1. (a) Tropical vertical velocities and 2σ uncertainties from the water vapor tape recorder analysis of Schoeberl et al. (2008) (black) and the GMI-GCM annually averaged w from vertical advection only (red), 12°S – 12°N , and (b) transit times calculated from the vertical velocities.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

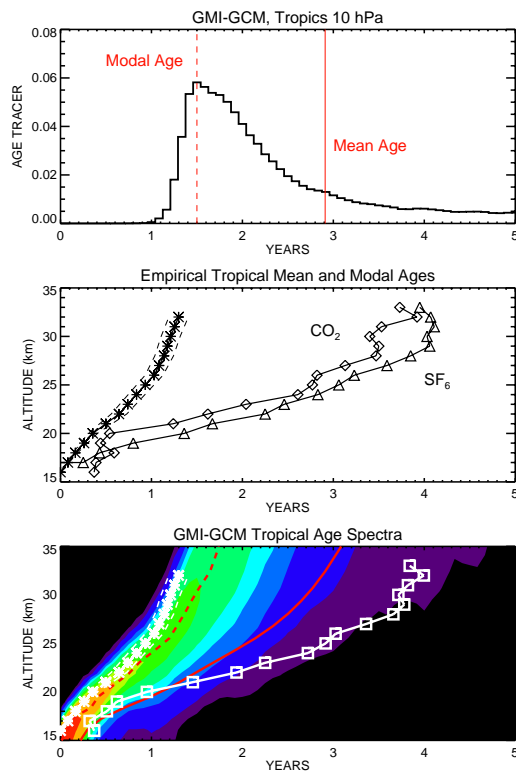


Fig. 2. (a) GMI-GCM age spectrum for 10°S – 10°N , 10 hPa. Modal and mean ages are noted respectively with dotted and solid red lines; (b) Empirically derived tropical mean age from CO_2 and SF_6 balloon profiles (Andrews et al., 2001) and tape recorder modal age and uncertainties as in Fig. 1b, c) Contoured GMI-GCM age spectra with overlays of model modal (red dashed) and mean (red solid) age and of observed modal and mean age (white). Red (purple) indicates highest (lowest) probability values. The observed mean age shown is the average of the two mean age profiles in panel b).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**The impact of tropical
recirculation on polar
composition**S. E. Strahan et al.

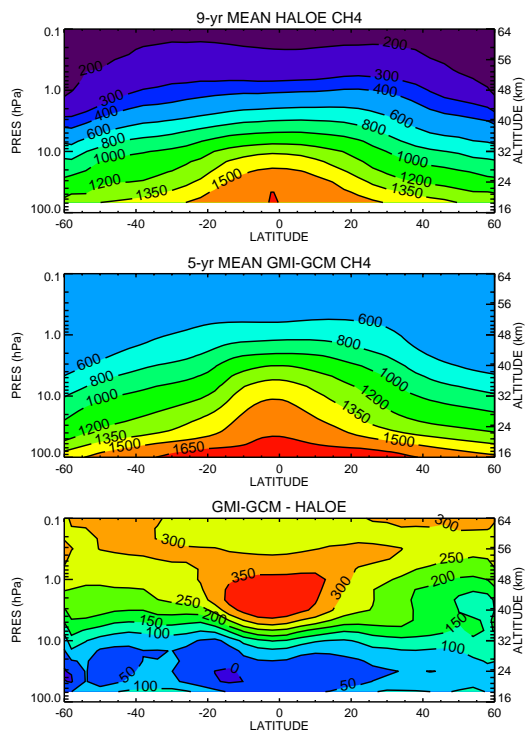


Fig. 3. (a) Zonal annual mean CH₄ from 9 years of UARS HALOE observations; (b) zonal annual mean of GMI-GCM CH₄ from a 5 year simulation, and (c) GMI-GCM – HALOE. Units are ppb.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**The impact of tropical
recirculation on polar
composition**

S. E. Strahan et al.

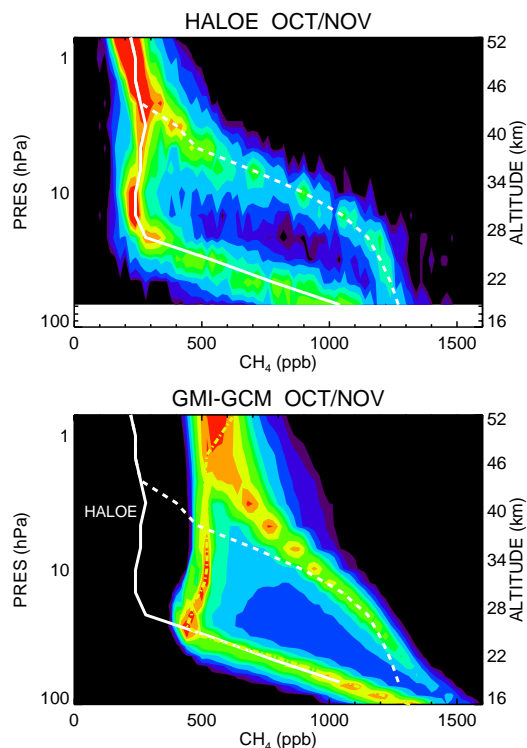


Fig. 4. (a) Contoured PDFs of 9 years of October and November HALOE CH₄ (68°–80° S) showing vortex and midlatitude most probable profiles, and (b) contoured PDFs of 5-years of October and November GMI-GCM CH₄ (68°–80° S) with overlay of HALOE most probable vortex and midlatitude profiles. Red and orange (blue and purple) indicate higher (lower) probabilities.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

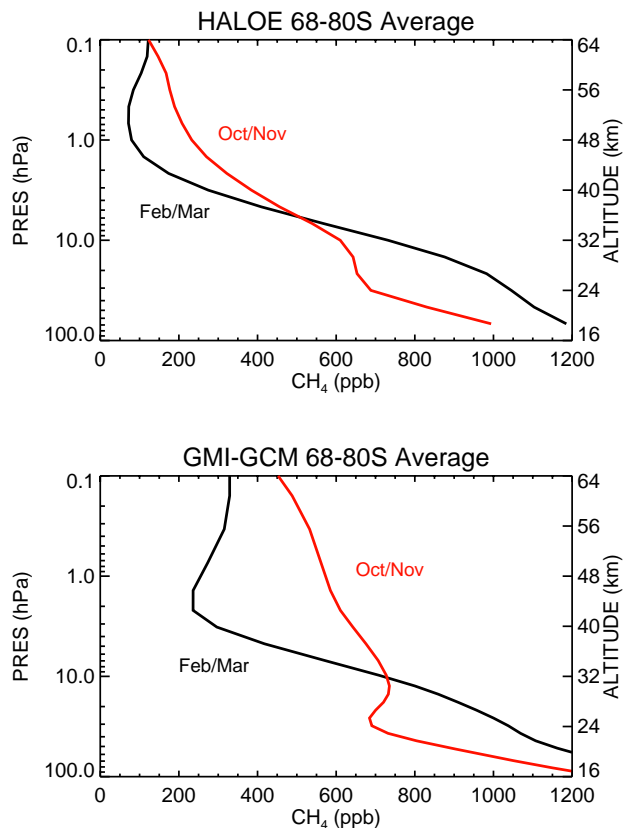


Fig. 5. (a) HALOE CH₄ mean profiles, 68–80° S, for February/March and October/November; and (b) GMI-GCM CH₄ mean profiles, 68–80° S, for the same time periods. GMI-GCM CH₄ in the upper stratosphere increases by nearly 400 ppb in spring, more than twice the increase shown by HALOE CH₄.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

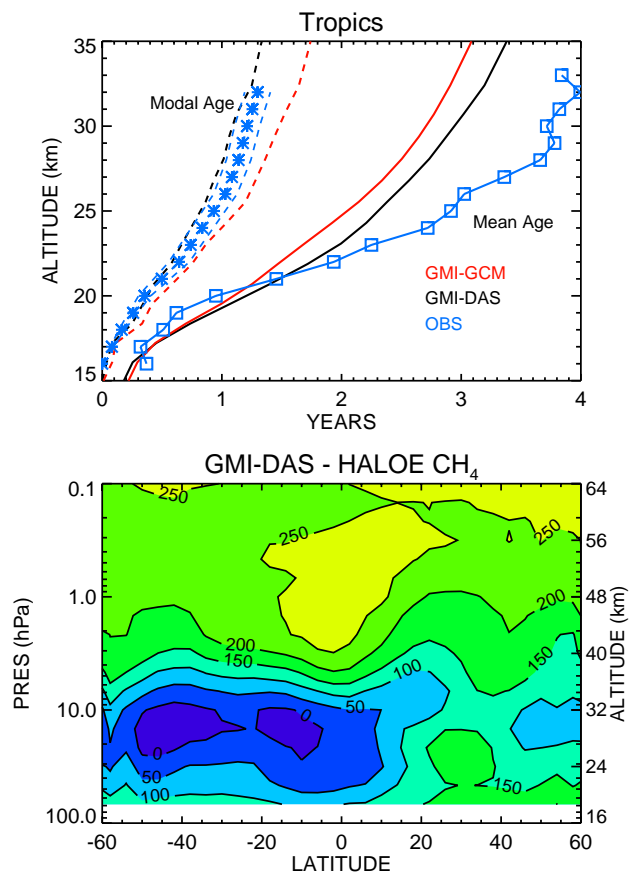


Fig. 6. (a) Tropical mean age (solid) and modal age (dashed) for GMI-GCM (red) and GMI-DAS (black), and empirical mean and modal ages (blue); (b) GMI-DAS-HALOE annual zonal mean CH₄ differences. The GMI-DAS CH₄ is a 3-year average.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The impact of tropical recirculation on polar composition

S. E. Strahan et al.

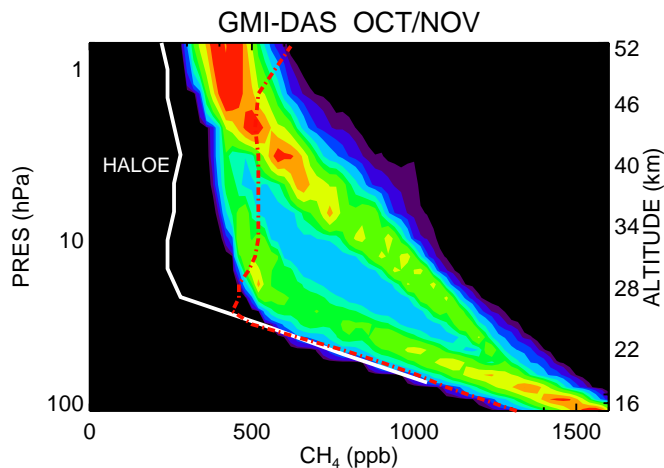


Fig. 7. Contoured PDFs of 3-years of GMI-DAS CH₄ 68°–80° S in October and November. Most probable vortex CH₄ profiles for HALOE (white) and GMI-GCM (red) are overlaid. Red (purple) contours indicates highest (lowest) probability values.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The impact of tropical
recirculation on polar
composition**

S. E. Strahan et al.

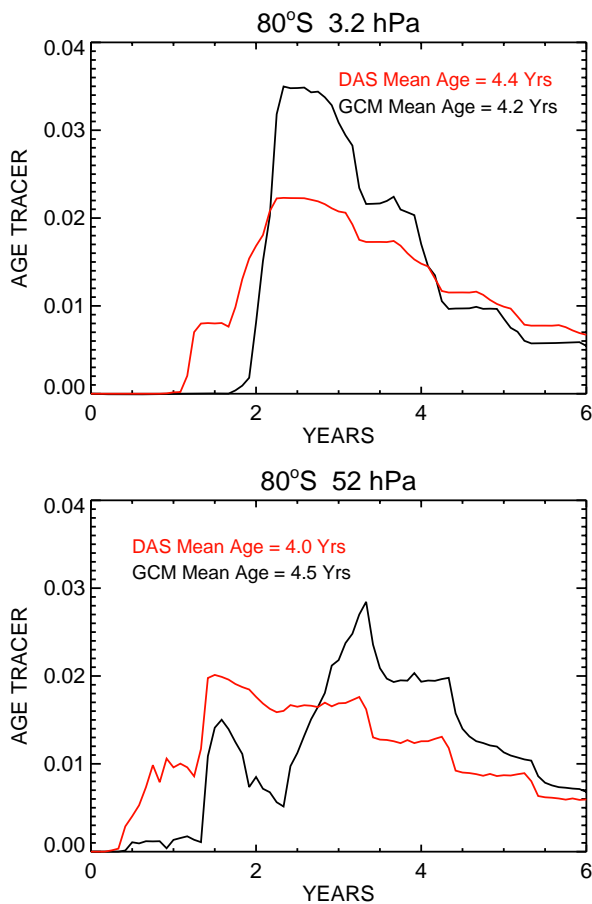


Fig. 8. Age spectra at 80° S in the GMI-GCM (black) and the GMI-DAS (red), **(a)** 3.2 hPa and **(b)** 52 hPa.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)