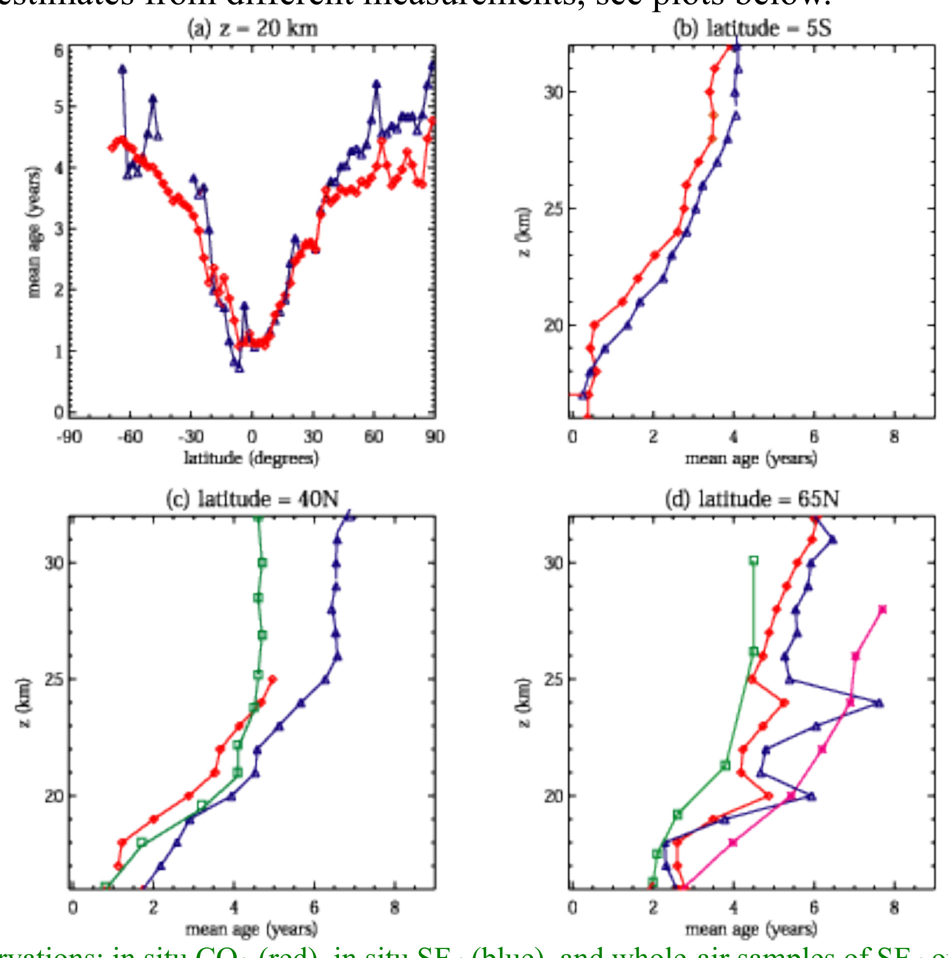
Age of Stratospheric Air

[See Waugh and Hall 2002 for review paper.]

Trace gas observations have been used to infer several different aspects of the transit time distributions ("age spectra") in the stratosphere. Most commonly the ``mean age", but also the modal time as well as the shape of the TTDs. These observational inferences of transport timescales provide stringent tests of numerical models independent of photochemistry, and comparisons of these observations with chemical transport models have highlighted certain problems with transport in the models. The inferences of the transport timescales have also been used to infer the propagation of chlorine into the stratosphere .

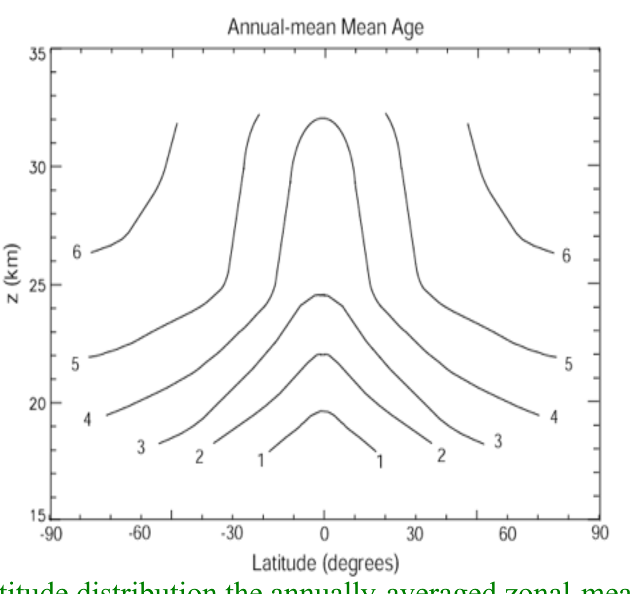
Observations

The mean age Γ can be calculated from measurements of a tracer that is conserved and whose concentration varies linearly with time over the width of the age spectrum. Carbon dioxide (CO_2) and sulfur hexafluoride (SF_6) approximately satisfy these criteria in the stratosphere, and have been measured in the stratosphere. There is generally good agreement between Γ estimates from different measurements, see plots below.



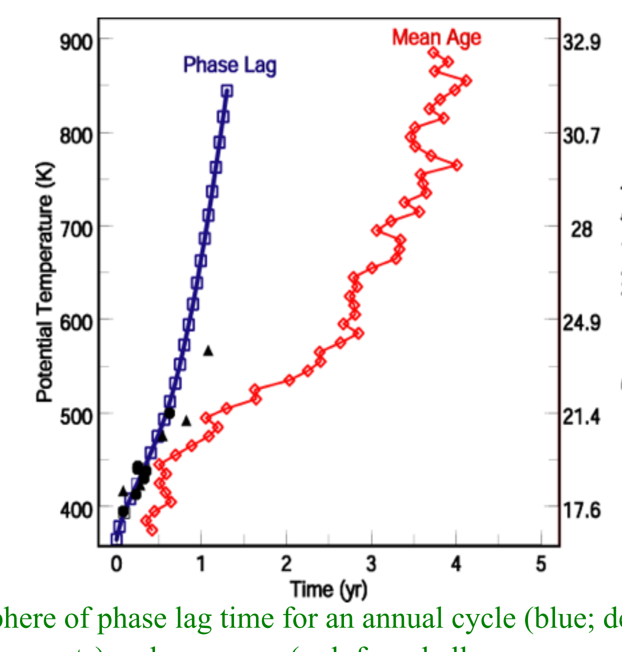
Mean age calculated from observations: in situ CO_2 (red), in situ SF_6 (blue), and whole-air samples of SF_6 outside vortex (green) and inside vortex (magenta). Data available here.

At 20 km Γ increases from around 1 year near the equator to around 4 to 5 years at high latitudes, with large gradients in the subtropics. In general, Γ increases with altitude and there are only weak vertical gradients above 25 km (the spikes in the high latitude profiles in the above plot are due to sampling of fragments of vortex air). Combining all estimates of Γ it is possible to from a schematic diagram of the altitude-latitude distribution the annually-averaged zonal-mean mean age, see below. As it is based almost exclusively on northern hemisphere data the schematic is hemispherically symmetric.



Schematic diagram of the altitude-latitude distribution the annually-averaged zonal-mean mean age based on observations.

As discussed in the Transient Tracers Section, a second class of timescales, phase lag times, can be defined from conserved tracers whose mixing ratios at the tropical tropopause vary periodically. Measurements of carbon dioxide and total hydrogen have been used to estimate the phase lag time of an annual cycle. These observations show that the phase lag time is smaller than the mean age, see plot below. This is consistent with theory and models: The mean age weights the long tails of the age spectra heavily, whereas for an annually periodic signal the tail region is averaged out, and the phase lag time is biased toward the peak in the spectra and is younger than the mean age. (See Hall and Waugh (1997) for details.)

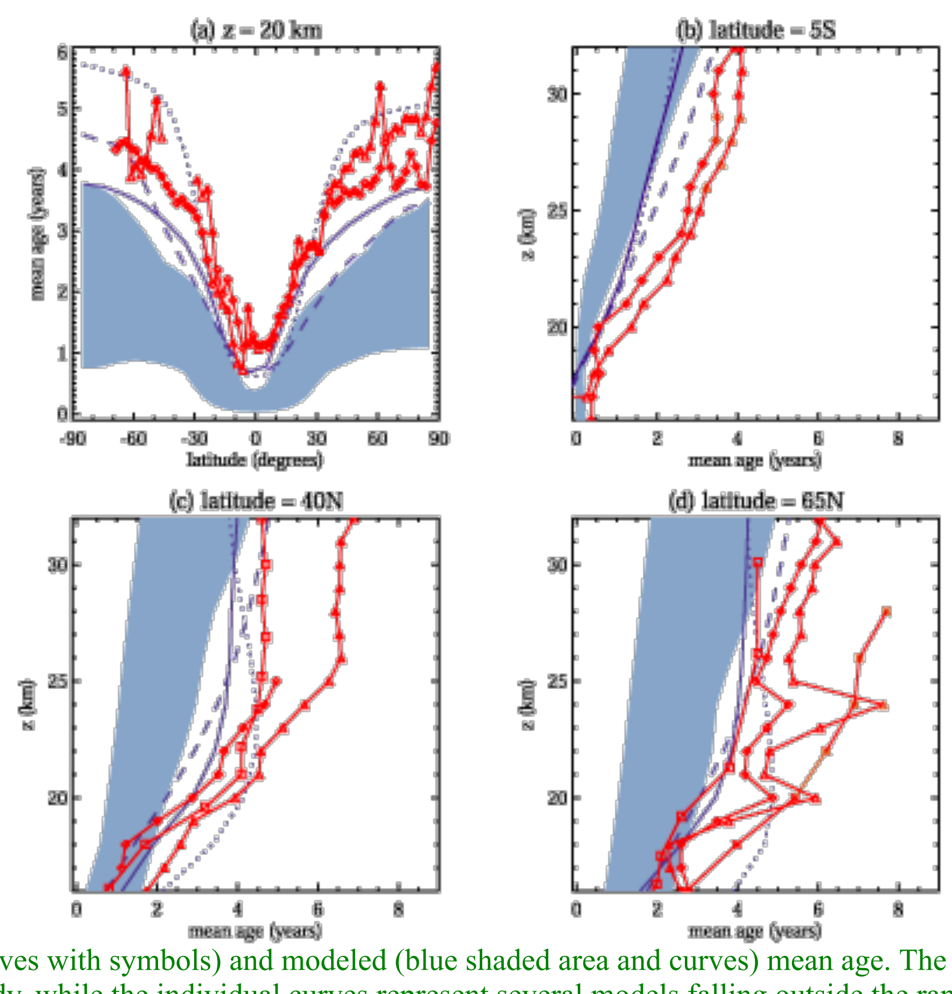


Vertical variation in the tropical stratosphere of phase lag time for an annual cycle (blue; determined from 4 years of HALOE H_2O and CH_4measurements) and mean age (red; from balloon measurements of CO_2).

Models

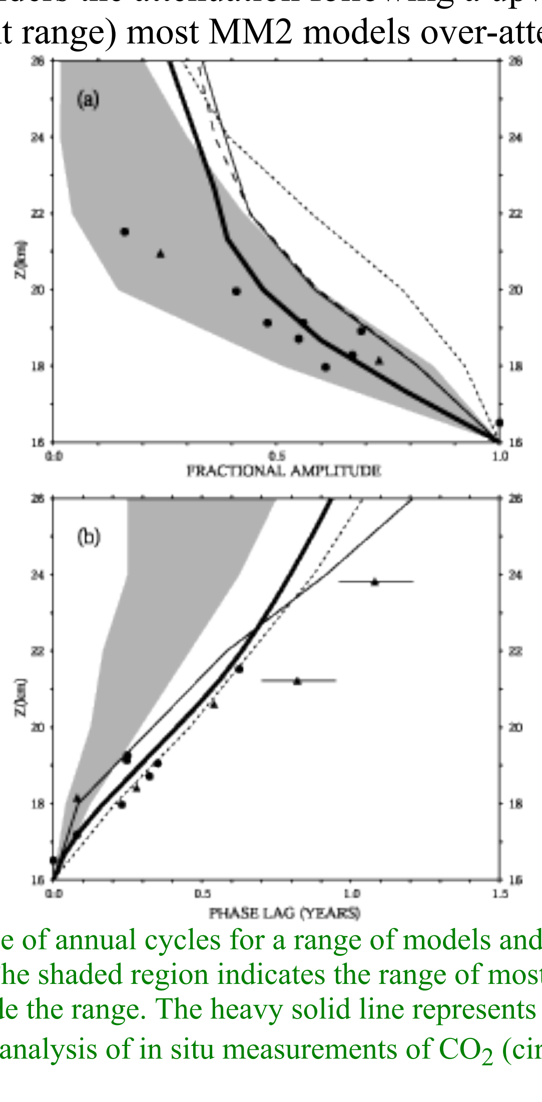
Many modeling studies have exploited the stratospheric age spectrum and mean age as a transport diagnostic. For example, in the NASA Models and Measurements II (``MM2") study simulations of the age spectrum and transient tracers from more than 20 models were compared to each other and to observations. These intercomparisons are discussed in detail in Hall et al. (1999).

A direct and quantitative comparison of mean age from MM2 models and observations is shown below: The blue shaded regions represent the ranges of mean age simulated by a majority of the MM2 models, the blue curves represent other selected MM2 models, and the red curves and symbols show the observed mean age. These plots illustrates the large spread in the model mean ages, and shows the unrealistic features of mean age in many models: (1) most models underestimate the magnitude of mean age; (2) most models do not reproduce the steep latitudinal gradients in the subtropical lower stratosphere; (3) several models exhibit a lower stratospheric Γ maximum at middle and high latitudes, which is not observed. These model-data differences indicate that most models have significant inaccuracies in their transport.



Comparison of observed (red curves with symbols) and modeled (blue shaded area and curves) mean age. The shaded region indicates the range of most models in the MM2 study, while the individual curves represent several models falling outside the range. The symbols represent mean age from observations of CO_2 or SF_6. Data and Model Output available here.

The propagation into the stratosphere of the annually periodic tracer signals complements mean age as tests of model transport. The plots below shows the phase lag time and the peak-to-peak amplitude as functions of height in the tropical stratosphere for the MM2 models as well as the observations. Most MM2 models propagate the annual signal too rapidly in the vertical, and if one considers the attenuation following a upwelling seasonal impulse over a year (rather than attenuation over a fixed height range) most MM2 models over-attenuate the signal.

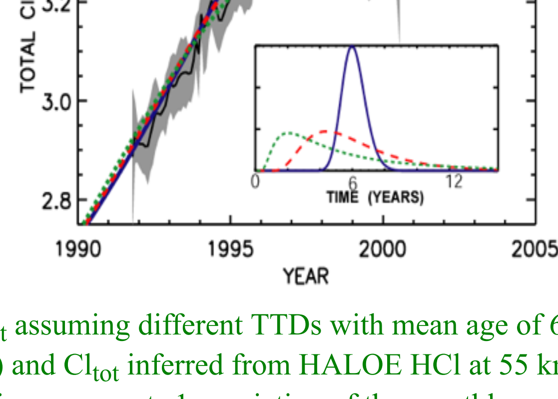


Equatorial profiles of (a) amplitude and (b) phase of annual cycles for a range of models and observations. All amplitudes are normalized to unity and the phase lag taken as zero at 16 km. The shaded region indicates the range of most models in the MM2 study, while the individual (thin) lines represent several models falling outside the range. The heavy solid line represents the analysis of HALOE H_2O [Mote et al., 1998], and the symbols represent analysis of in situ measurements of CO_2 (circles) and H_2O (triangles).

Total Chlorine

Chlorine in the stratosphere, whose sources are primarily CFCs, is the major agent of ozone destruction, and monitoring the evolution of atmospheric chlorine in response to international treaties is critical for understanding ozone depletion and eventual recovery. In the stratosphere chlorine exists in several chemical forms, and it is difficult to measure them all to obtain ``total chlorine" Cl_{tot}. However, the age spectrum has proved an effective way to estimate the evolution of total chlorine in the stratosphere

This is illustrated below where the ``stratospheric" Cl_{tot} is shown for three age spectra with the same mean age (6 years) but differing spectral width (see insert). For the narrow spectrum there is very little difference between the time series and that using the mean age to lag the surface time series. However, for more realistic broader spectra there is significant non-linearity over the width of the age spectrum and the two time series differ. In particular, the convolution over the spectrum results in a reduced peak in stratospheric Cl_{tot} and a more gradual turnover than at the surface or inferred using the mean age as the time lag. Also shown is the Cl_{tot} at 55 km estimated from HALOE HCl, which turns over earlier and decays more rapidly than expected. The reason for this earlier decay is currently unknown. See Waugh et al. (2001) for more discussion.



Time series of ``stratospheric'' total chlorine Cl_{tot} assuming different TTDs with mean age of 6 years but differing width (TTDs are shown in insert). Also shown are surface Cl_{tot} (dotted curve) and Cl_{tot} inferred from HALOE HCl at 55 km (thin curve is monthly and global mean values and shading represents 1σ variation of the monthly averages).

See Waugh and Hall 2002 for review paper.

Reference List .

Back to Transit Times in Geophysical Flows.