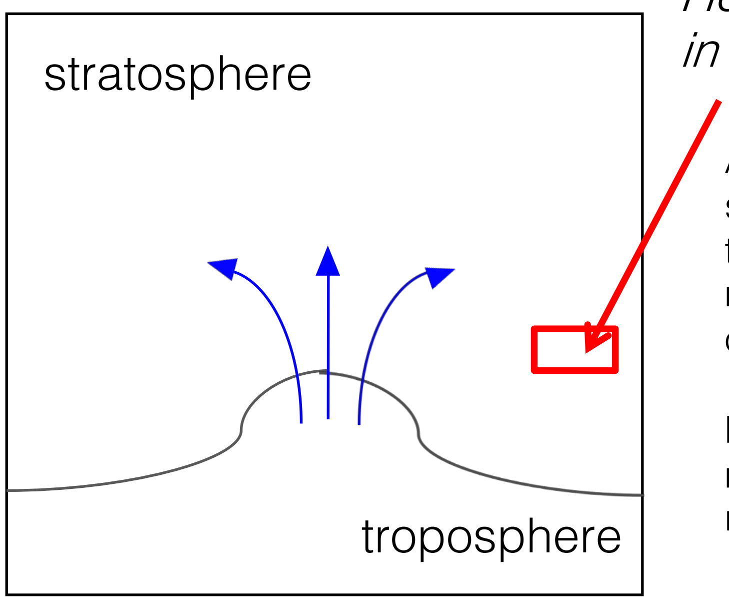
Age of Air in the Stratosphere from Observations

Marianna Linz *mlinz@seas.harvard.edu*
with R. A. Plumb, E. P. Gerber, F. Haenel, G. Stiller, D. Kinnison, B. Birner, A. Gupta, and J. Neu

EGU 2020: Rather than just upload my standard style presentation (which usually has very little text), I've tried to create a version designed to be read. I'm highlighting a few recent studies with links included.

What is Age of Air?

How long has this air been in the stratosphere?



Age is how long air has been in the stratosphere. Really, there is a range of transit times for the individual parcels that make up the box. A nice modeled example of this is shown in the plot to the right.

For the rest of this talk, I will refer to the mean age of air as the age, and will mostly neglect details of the age spectrum.

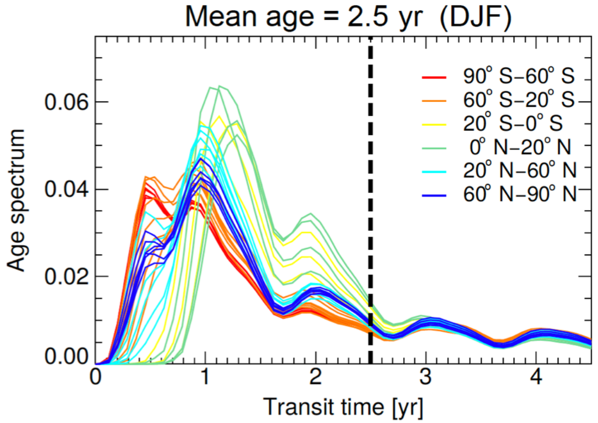
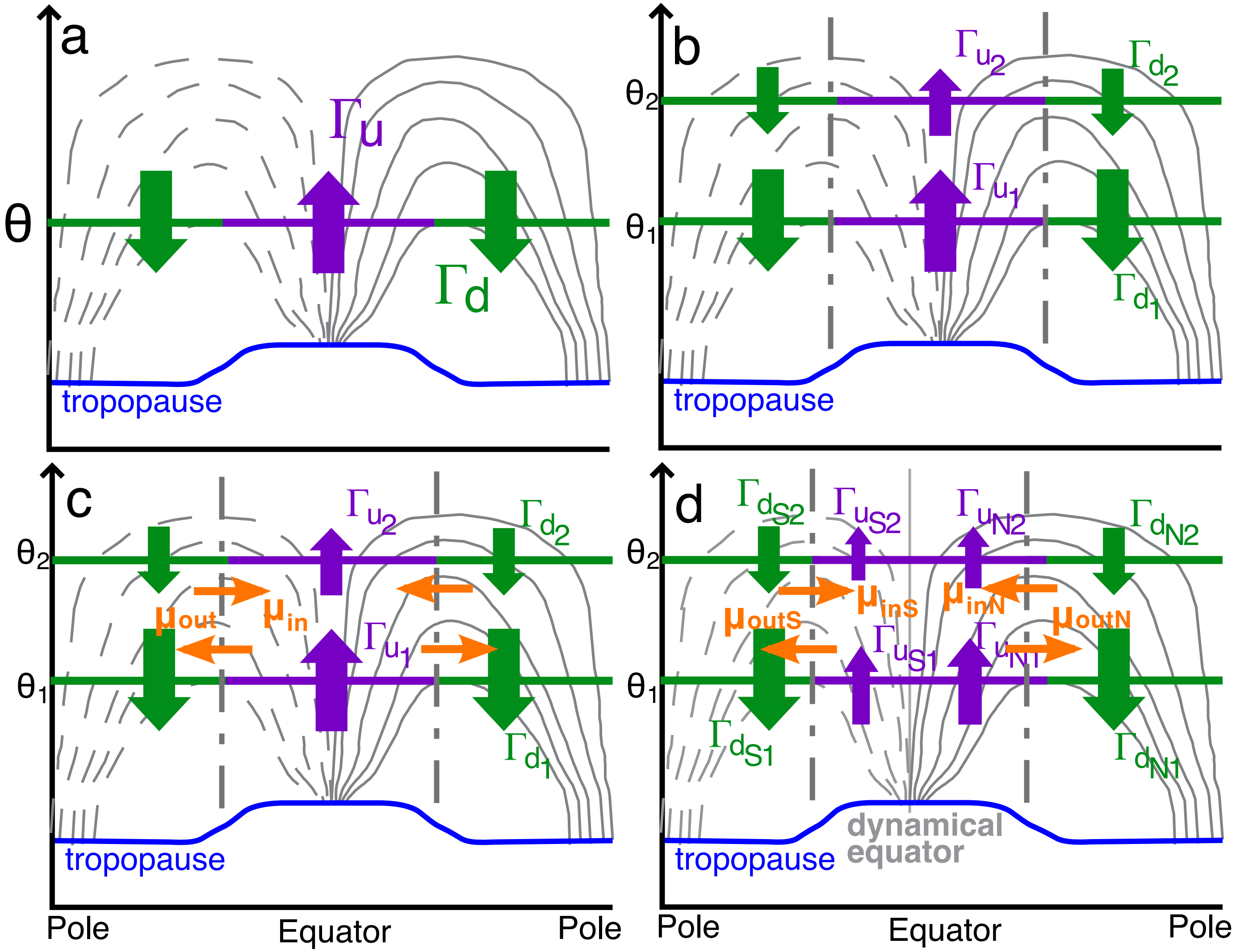


Figure 1. Climatological age spectra for the same mean age of 2.5 years but at different latitude ranges, for December–February. Each line is the average over DJF, with different age spectra of the same colour representing different latitudes within the respective latitude band. The black dashed line highlights the mean age of 2.5 years.

Ploeger and Birner ACP (2016)
https://www.atmos-chem-phys.net/16/10195/2016/

Why is age so important?



Age is important because it can be quantitatively related to the circulation in a rigorous way.

The schematics of the circulation to the left demonstrate.

a) If you look at the difference in age of downwelling and upwelling air through an isentrope, that is how long the air has spent above that isentrope; it is the residence time. The residence time is the ratio of the mass in a reservoir to the mass flux through it. So age can directly get us the mass flux through an isentropic surface.

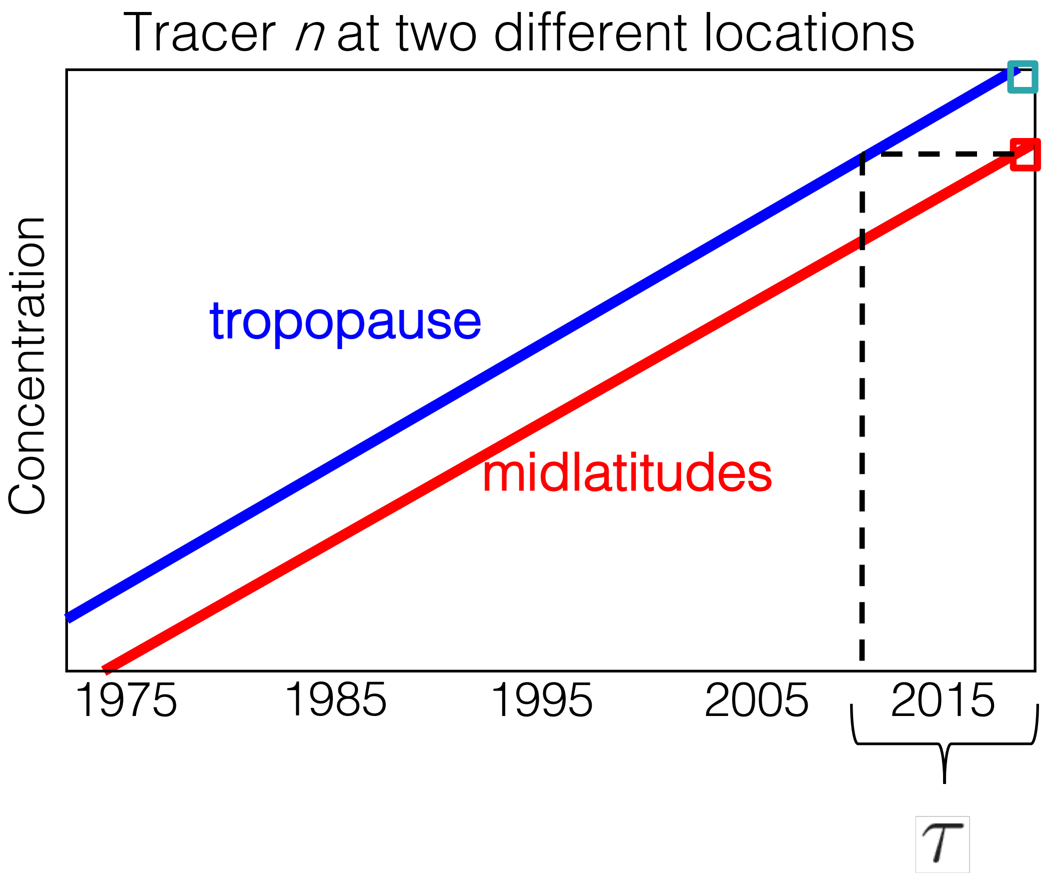
b) Now consider another isentropic surface above the first. If we know the age at the lower level, we know the vertical velocity of air in the tropics. We also know the distance between the two levels. So we can predict the age of air in the tropics at the second level. If it is any older than that prediction, we know this is caused by mixing.

c) **The vertical gradient of age is therefore a measure of the strength of mixing into and out of the tropical pipe.**

d) Finally, if we consider a dynamical equator such that the two hemispheres are effectively separate, all of these calculations can be applied to each hemisphere separately, and thus we can examine the transport of each hemisphere.

a) https://journals.ametsoc.org/doi/full/10.1175/JAS-D-16-0125.1
(b-d in Linz et al. in prep. ***Theory section complete and available by request****)*

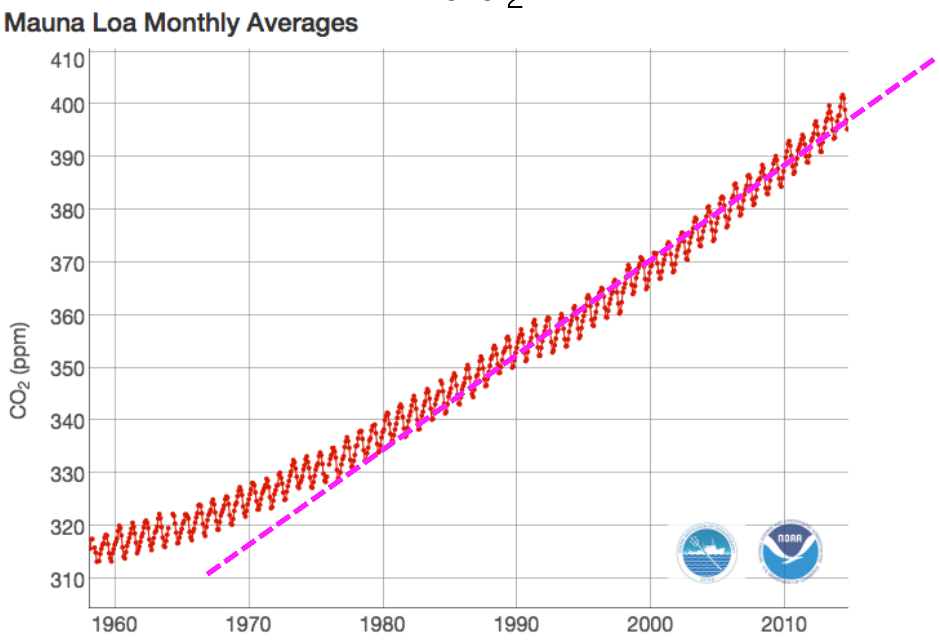
How do we get age from observations?



A tracer with a linearly increasing concentration in the troposphere that is conserved in the stratosphere provides a time lag (the length of time since the air entered the stratosphere—the age.)

How? Right now we can measure the concentration somewhere in the midlatitudes (red box) and at the tropopause (teal box). If we know the slope, we can take the value at the tropopause and find how long ago the concentration there was the concentration in our midlatitude box.

CO_2



http://www.esrl.noaa.gov/gmd/ccgg/trends/graph.html

SF_6 and CO_2 are (approximately) such tracers.

The are observed at the surface, from balloons and aircraft campaigns, and from satellite (SF_6 only, so far).

So does the "approximately" matter?

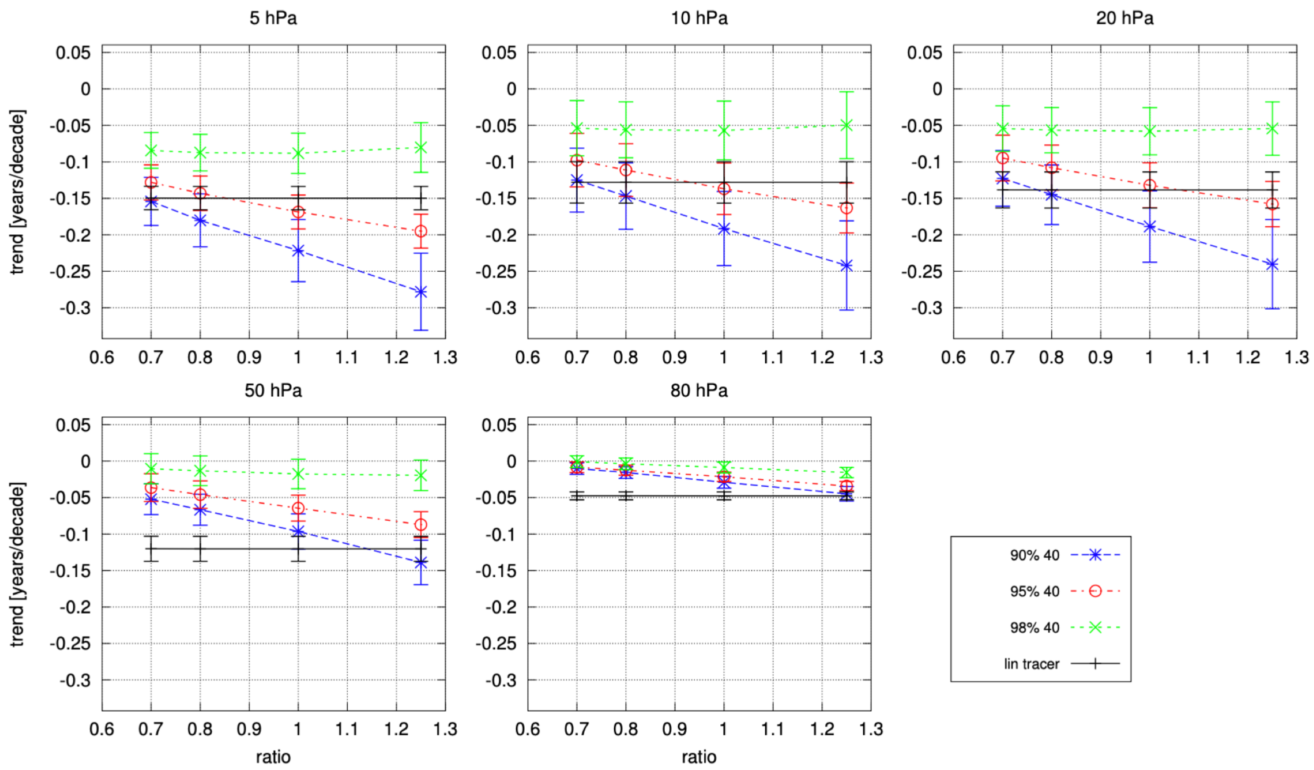


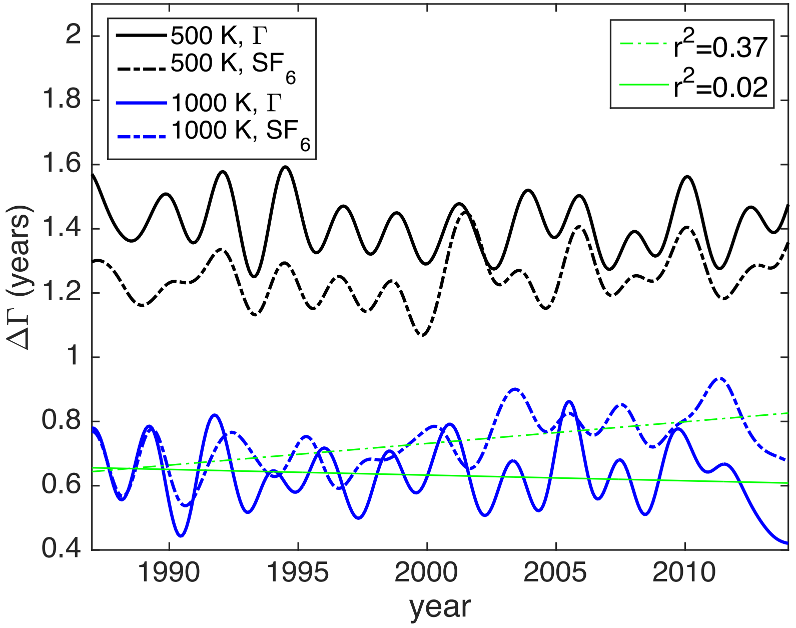
Figure 5. Overview of the trend in mean AoA derived from SF_6 (dotted lines) and a linear tracer (solid line) for different ratio of moments (x-Axis) and fractions of input (colors) at 40° N. The panels show different pressure levels. The trend calculation considered the time series from 1975 to 2011. The error bars show 1σ which is the 68 % confidence levels.

Fritsch et al. ACP 2020 (accepted) https://www.atmos-chem-phys-discuss.net/acp-2019-974/

Yes. Assumptions about the shape of the age spectrum change the magnitudes a little, but the trends can be quite different.

Recent work has been done on improving the age spectrum by using multiple tracers and a model in conjunction: Hauck et al. 2019, 2020.
https://www.atmos-chem-phys.net/19/5269/2019/
https://www.atmos-chem-phys-discuss.net/acp-2020-167/

Ideal tracer and SF_6 age difference



If biases were uniform in latitude, then they would not impact our estimation of the circulation strength (since what matters is the age difference between extratropics and tropics). But no such luck. The plot to the right shows the age difference on two different isentropic surfaces in the WACCM free running model calculated with an ideal age tracer and with a SF6-like age tracer. Like Fritsch et al., we find an increased bias higher in the stratosphere that leads to different apparent circulation trends.

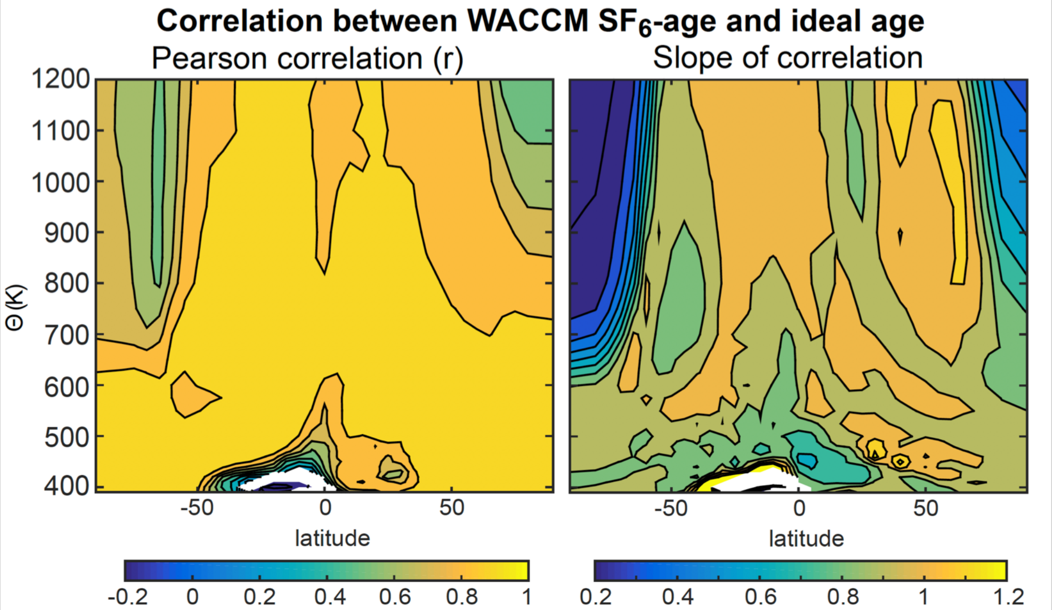
Can we get age from satellite measurements?

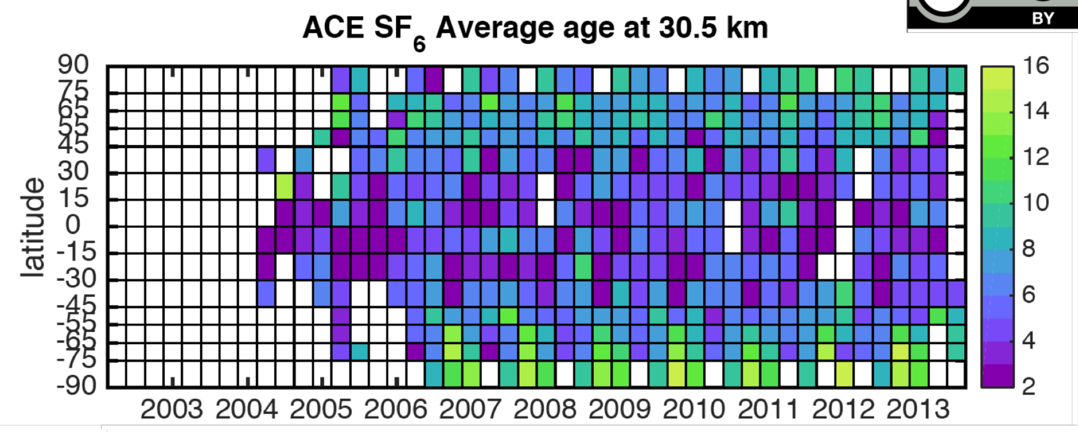
SF_6 can be used to calculate an approximate age.

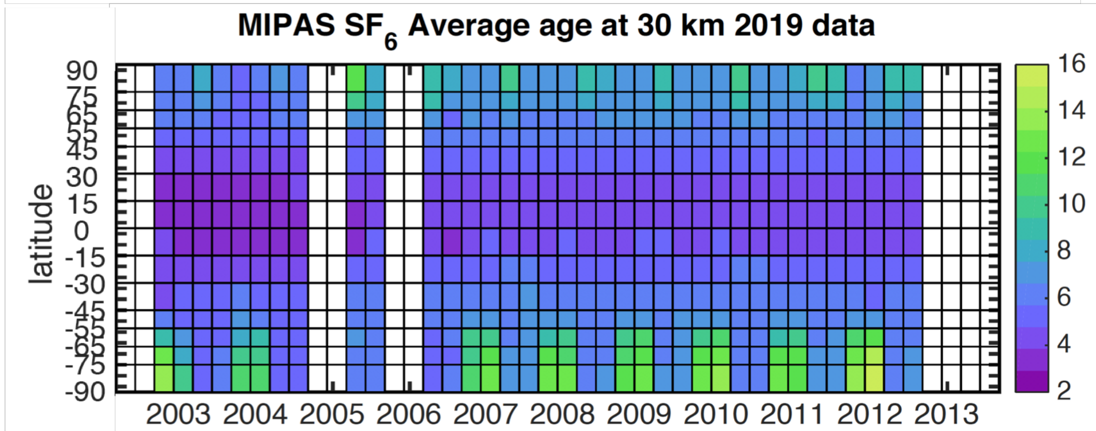
SF_6 is a tricky measurement (just ask Gabi!), and updates to the product are continuing to improve the information from MIPAS. This means that our calculations are still evolving.
ACE-FTS is still flying, but it has **very limited** coverage in the tropics, thus the bias seen to the plots at right.

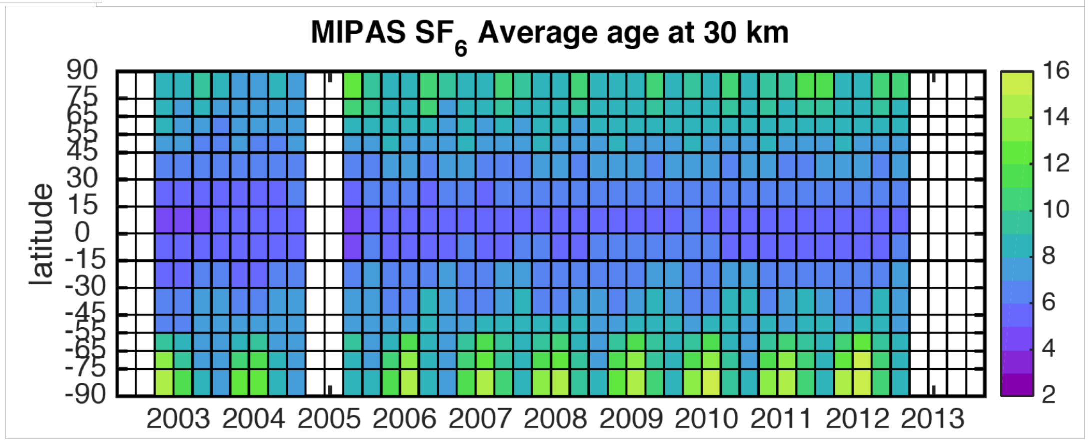
CO_2 is currently not retrieved well enough from limb to calculate age

SF_6 is approximate because there is a strong mesospheric sink, so there is a bias wherever there is mesospheric influence. This is quantified using a weak SF6 sink in WACCM in the plot below.









What about in situ data?

In situ data are limited in location and in time, but we do have a record from balloons and aircraft.

Aircore technology holds potential to vastly improve our data record with both SF_6 and CO_2

Engel et al. ACP 2017 https://www.atmos-chem-phys.net/17/6825/2017/

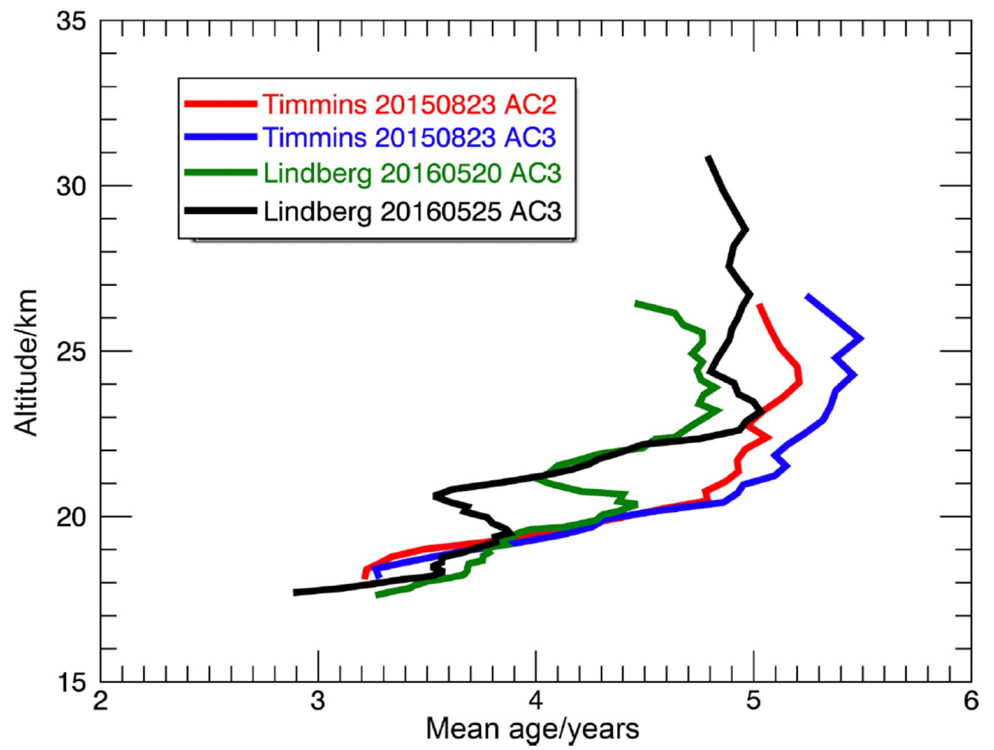


Figure 11. Vertical profiles of CO_2 derived mean age for the AirCore observations by the University of Frankfurt in 2015 in Timmins, Canada and 2016 in Lindenberg, Germany.

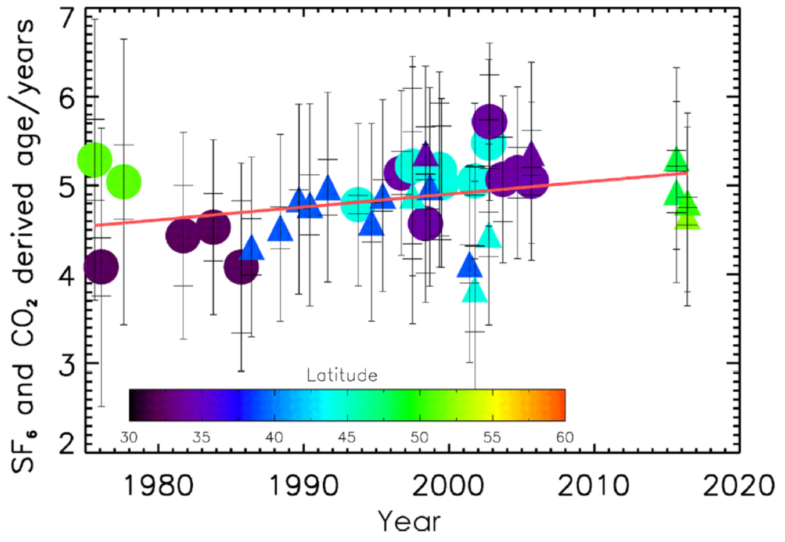


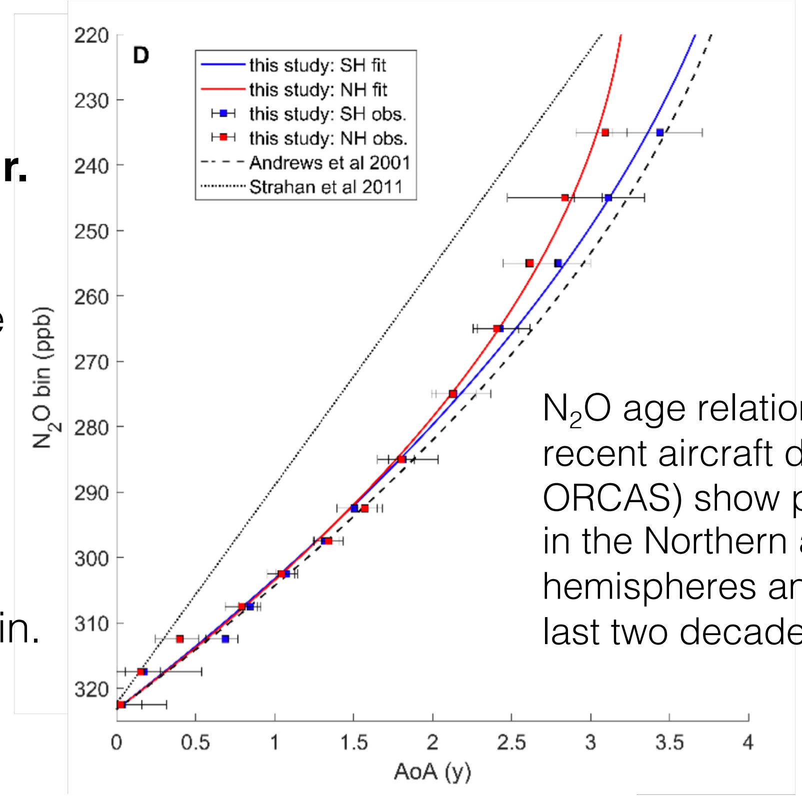
Figure 12. Time series of mean age derived from balloon observations. The data prior to 2010 are those presented in Engel et al. (2009). The data from 2015 and 2016 are derived from the AirCore measurements presented here. Each data point represents the average value of mean age derived above 30 and up to 5 hPa. The inner error bars represent the variability (error of the mean), and the larger outer error bars include the uncertainty as discussed in Engel et al. (2009). A non-significant trend of 0.15 (±0.18) years per decade is derived from these observations.

Other in situ data can also be extremely useful.

Long-lived tracers have a compact relationship with age of air.

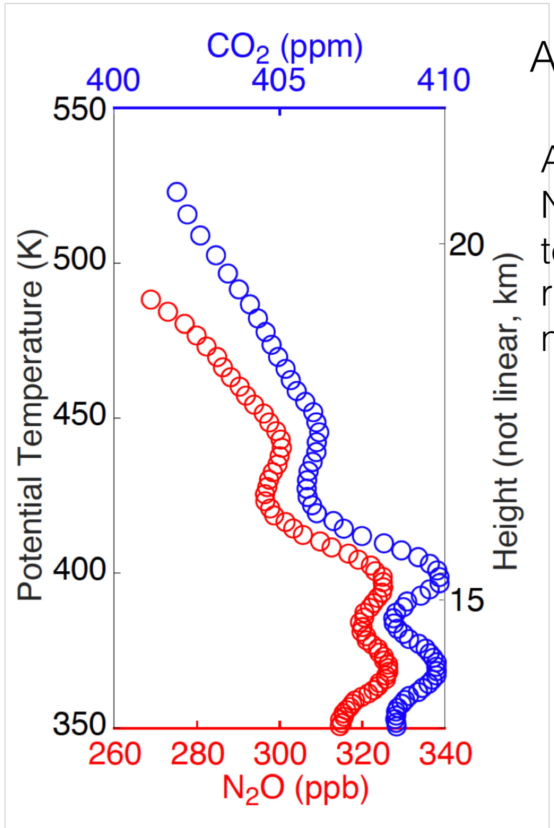
We can take advantage of this compact relationship to better understand transport (characterize the age spectrum) and to use satellite data for different species to calculate age.

These relationships are not necessarily (and should not be) constant in time, however.



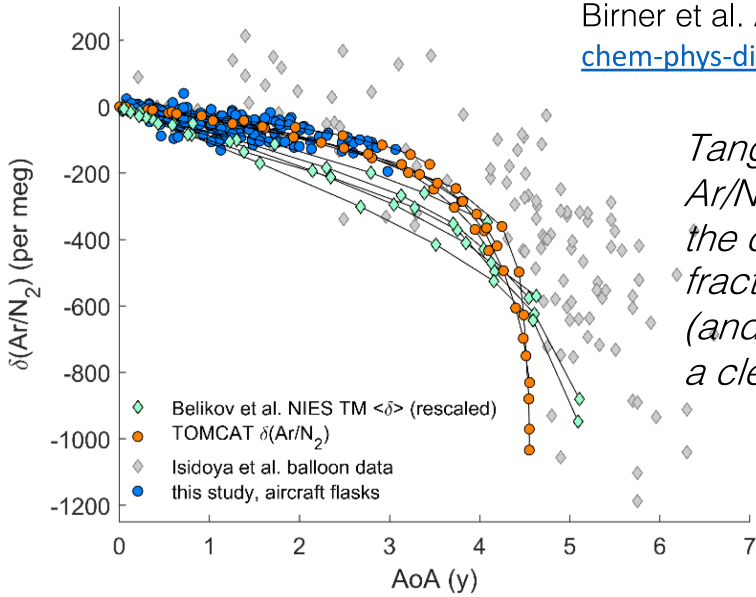
N_2O age relationships based on recent aircraft data (HIPPO, Atom, ORCAS) show possible differences in the Northern and Southern hemispheres and a change in the last two decades.

Aircores may well be able to help us again.



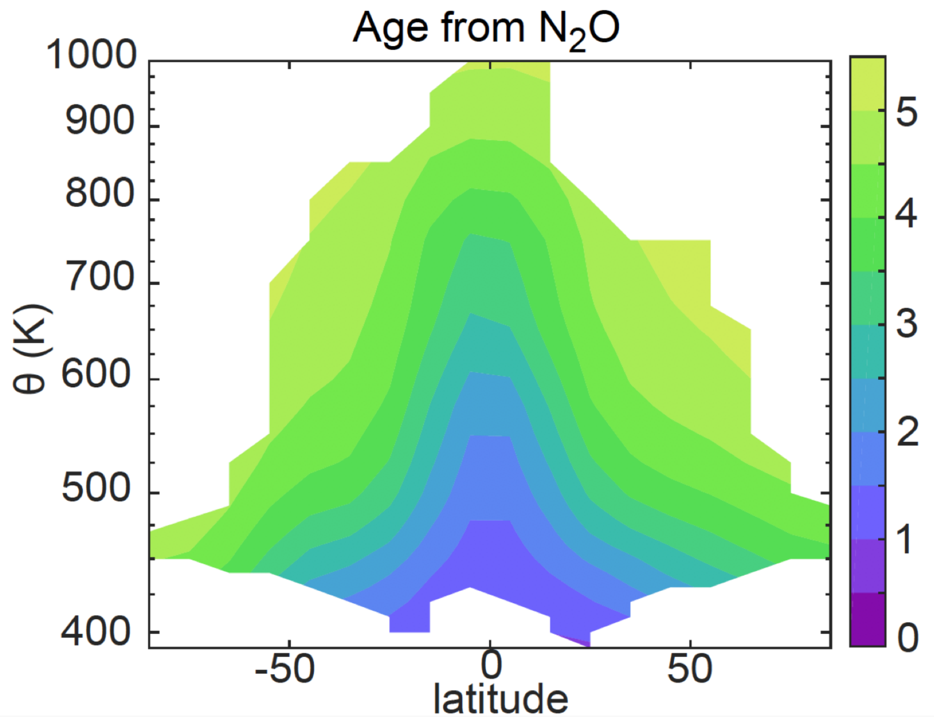
AirCore measurements of CO_2 and N_2O from June 6, 2019 vs. potential temperature. Height is shown on the right y-axis for reference, but it is nonlinear. Data from Colm Sweeney.

Birner et al. ACPD (in revision) https://www.atmos-chem-phys-discuss.net/acp-2020-95/



Tangential, but exciting: ratio of Ar/N_2 is a purely physical tracer of the circulation, since gravitational fractionation is a purely physical (and not chemical process). This has a clear relationship with age of air!

If we take the satellite data so far, what are the results?



First we utilize the tracer-tracer relationship to calculate age from MLS N_2O data (left). Overall this results in lower ages than the SF_6 data.

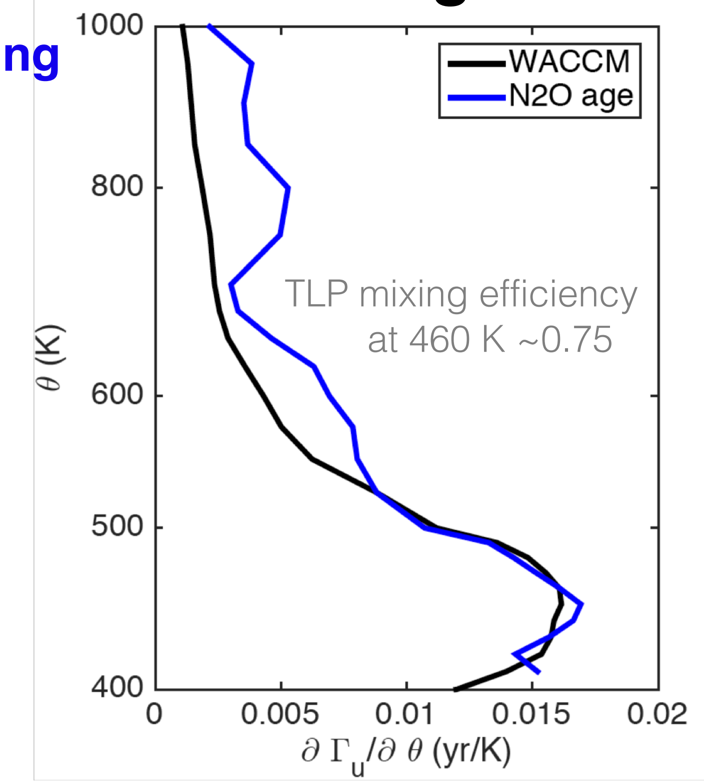
Then we calculate the age difference and vertical age gradient (below).

Diabatic Circulation Strength

Data set	460 K overturning ($x10^9$ kg/s)
MIPAS SF_6-age (old)	**7.4**
MIPAS SF6-age (new*)	***8***
GOZCARDS N_2O	**7.2**
WACCM	7.1
ERA-Interim	6.5
JRA 55	7.9
MERRA	5.5

*preliminary, rough estimate

Mixing



Linz et al. in prep.

Future goal: optimally combine all of these different data products to get a best-guess global mean age of air product (with error).