On the estimation of Age of Air Trends from Atmospheric Tracers

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Outline

- What is “Age of Air” (AOA) and why do we study it?
- AOA estimated from **idealized** tracers simulated in a **numerical model** (WACCM)
- AOA estimated from **observations** of **natural** tracers
- AOA **trends** derived from WACCM are inconsistent with observations—Why?
- AOA trends from **natural** tracers simulated in WACCM
- Identify sources of ambiguity in AOA trends derived from **observed and modeled natural** tracers
- Conclusions

What is Age of Air (AOA)?

- The interval, τ, between the time when the mixing ratio of a monotonically increasing tracer reaches a certain value, χ, at some location (θ, z) in the stratosphere and the (earlier) time when the same mixing ratio was reached at a reference point (θ_0, z_0):

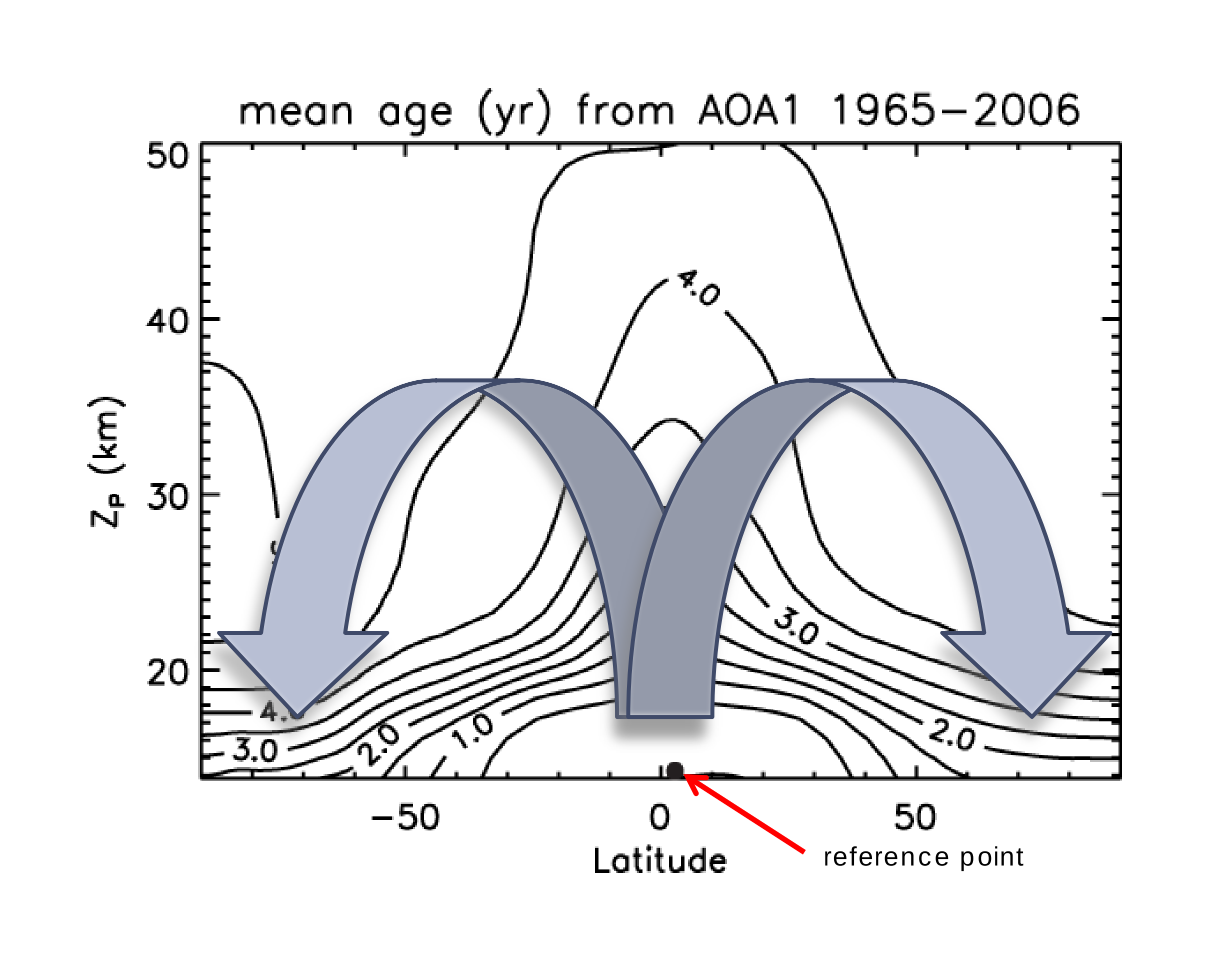
$$\tau(\theta, z) = t(\chi;\ \theta, z) - t(\chi;\ \theta_0, z_0)$$

- The reference point is usually taken to be in the upper tropical troposphere. In the WACCM calculations discussed here we use(θ_0, z_0) = (1° ,130 mb)

- Mean AOA has been used as an indicator of the strength of the stratospheric Brewer-Dobson circulation (BDC). Its *trend* has been used to diagnose *changes* in the strength of the BDC.

Example of AOA from WACCM

WACCM: Whole Atmosphere Community Climate Model
A fully coupled chemistry-climate model covering the altitude range 0–145 km



- Distribution of AOA estimated from a linearly increasing tracer with uniform growth rate
- The WACCM simulation covers the period 1965-2006
- AOA is computed with respect to the reference point denoted by the bold black dot
- AOA increases upward and poleward, following the sense of the BDC

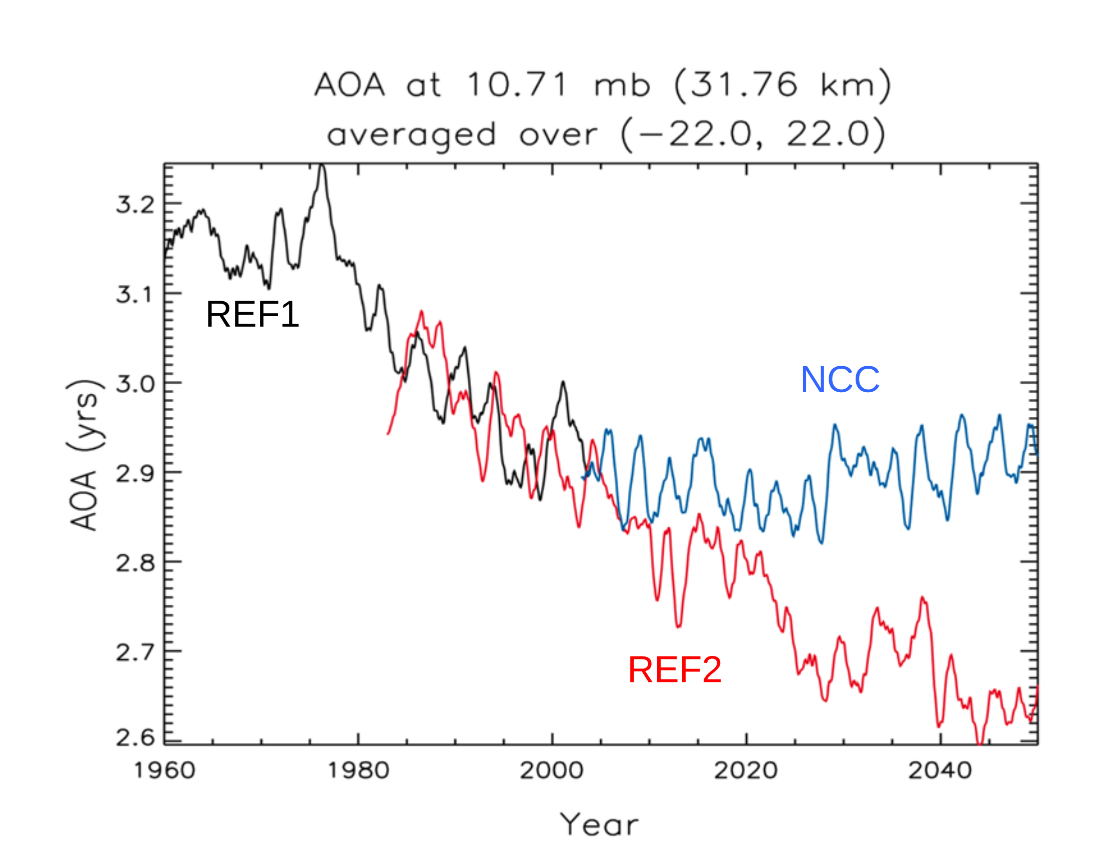
Why do we care about AOA?

- Chemistry climate models predict a strengthening of the Brewer-Dobson Circulation as greenhouse gases (GHG) increase (e.g., Garcia and Randel, *JAS,* 2008)

- This implies that AOA should become younger with time. When AOA in WACCM is calculated from a **linearly-growing tracer with uniform growth rate**, this expectation is verified

- But AOA determined from observations of quasi-inert **natural tracers**, SF_6 and CO_2, is inconsistent with this prediction (that is, AOA does not become younger with time)

AOA from WACCM simulations



Garcia and Randel (*JAS*, 2008)

- These AOA estimates are based upon the evolution of a **linearly increasing tracer with uniform growth rate** in WACCM.
- This is an **idealized tracer** that meets exactly the conditions necessary for unambiguous evaluation of AOA trends.
- AOA evolution shows a clear negative trend under increasing GHG abundances, consistent (in sign **and** magnitude) with the acceleration of the BDC seen in the model

Three WACCM runs:

- REF1: 1960-2003, driven by observed increases in GHG
- REF2: 1980-2050, driven by observed + projected increases in GHG
- NCC: ("no climate change") 2000-2050, GHG held to 2000 levels

AOA estimated from observations

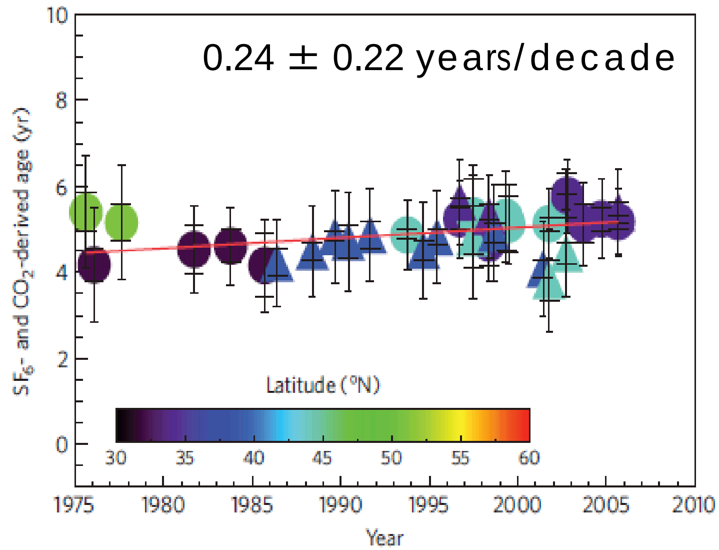


Figure 3 | Long-term evolution of mean age above 24 km altitude. SF_6-derived age values are shown by circles; triangles denote CO_2-derived mean age. The colour code shows the (northern) latitude of the measurements. The inner error bars show the 1 sigma standard deviation of the mean-age values between 24 and 35 km for each individual flight. The outer (larger) error bars denote the overall uncertainty of the mean-age value, including an assessment of the representativeness of a single profile observation (see the Methods section and Supplementary Information for more details). The overall uncertainty has been taken into account for the calculation of the long-term trend.

Engel et al, *Nature Geo.*, 2009

Triangles: AOA from CO_2
Circles: AOA from SF_6

The trend estimated from observations (statistically, **no trend**) **does not** support the conclusion that the circulation accelerates with increasing abundance of GHG

Why?

Analysis of AOA trends

Use Holton's (*JGR*, 1986) 1-D global model:

- Formulation leads to a single advection-diffusion equation for the global mean mixing ratio of a tracer
- Vertical profiles of tracer mixing ratio are the result of balance between mean vertical advection and horizontal eddy transport
- Model can be solved numerically and analytically
- Useful tool for interpreting evolution of AOA

Analytical Solutions for AOA

Solution to 1-D model equation for two idealized cases yields the following results (cf. Hall and Plumb, *JGR*, 1994):

(a) Linear growth: $\tau_L = z / W$ (mean AOA ⇔ transit time)

where W is a measure of the strength of the meridional circulation and z is the altitude of the point where AOA is calculated

$\Rightarrow$ **τ_L decreases as W increases** (faster circulation implies younger AOA)

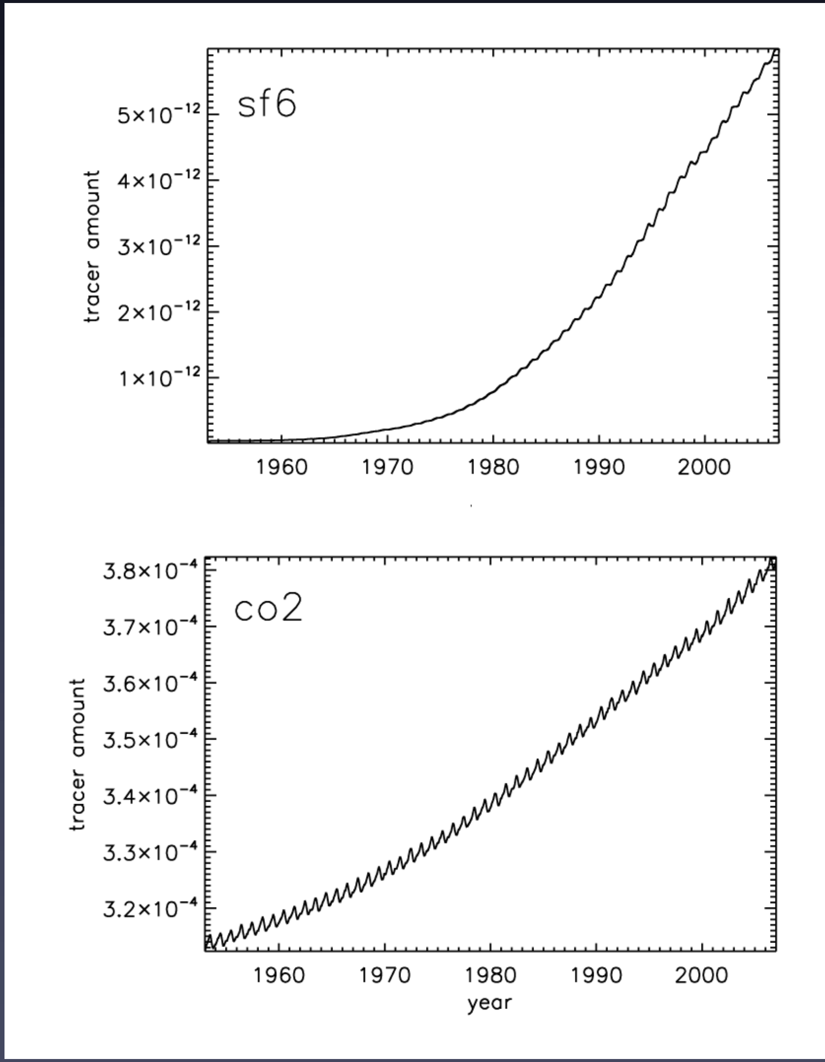
(b) Exponential growth: $\tau_E = (z / W)\,(1 - r\,H / W)$

where r is the growth rate when tracer grows as $\chi \sim \exp(r \cdot t)$

Note that (b) implies that the AOA for exponentially growing tracers is **biased** with respect to τ_L, and should be **corrected** according to:

$$\tau_E' = \tau_E / (1 - r\,H / W)$$

Growth rates of SF_6 and CO_2

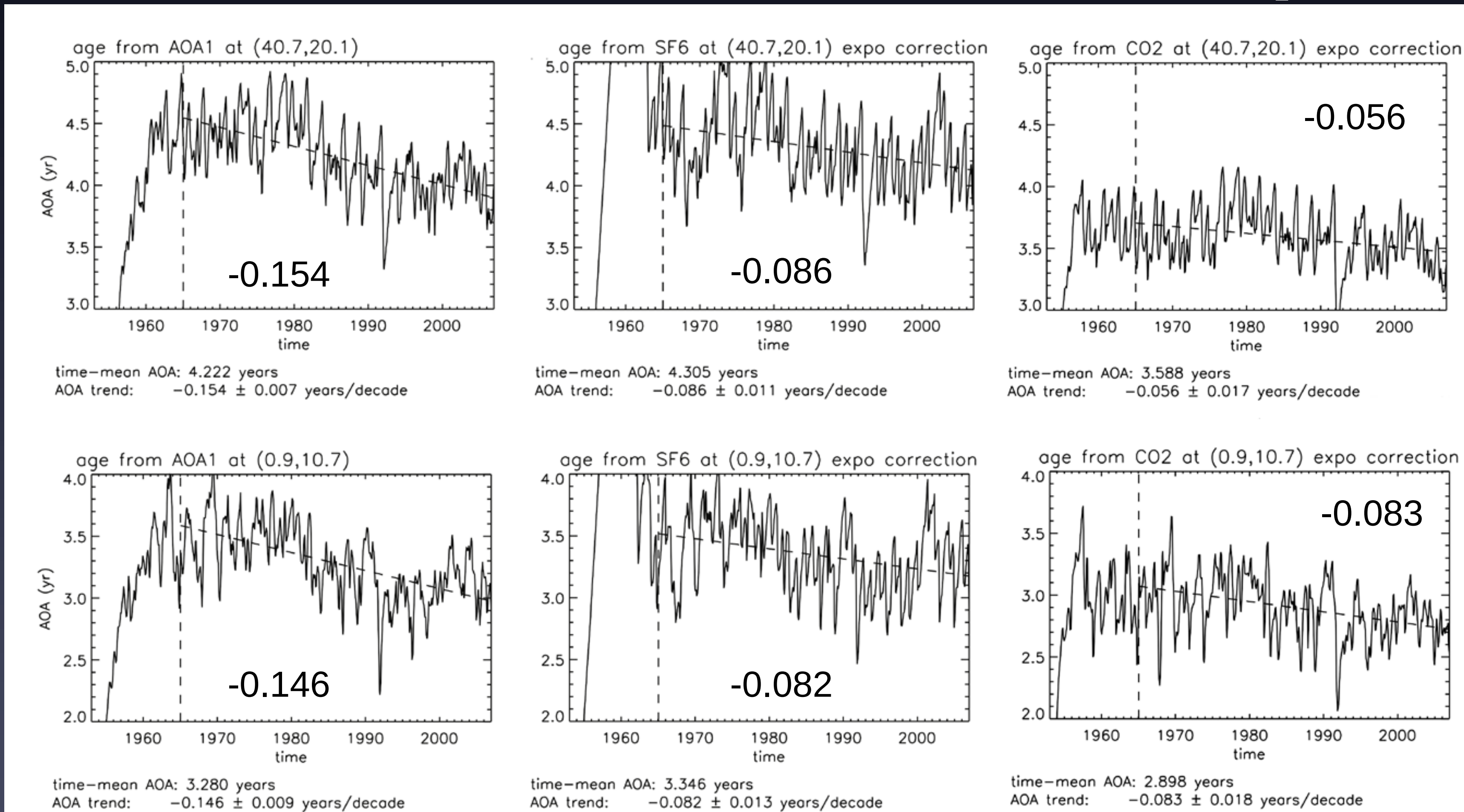


- Naturally occurring tracers **do not in general have linear growth rates**
- Therefore, **corrections must be applied** when estimating AOA and its trend
- What do we find when we look at **properly corrected** AOA derived from natural tracers in WACCM?

WACCM AOA trends (years/decade)

linear tracer | SF_6 | CO_2

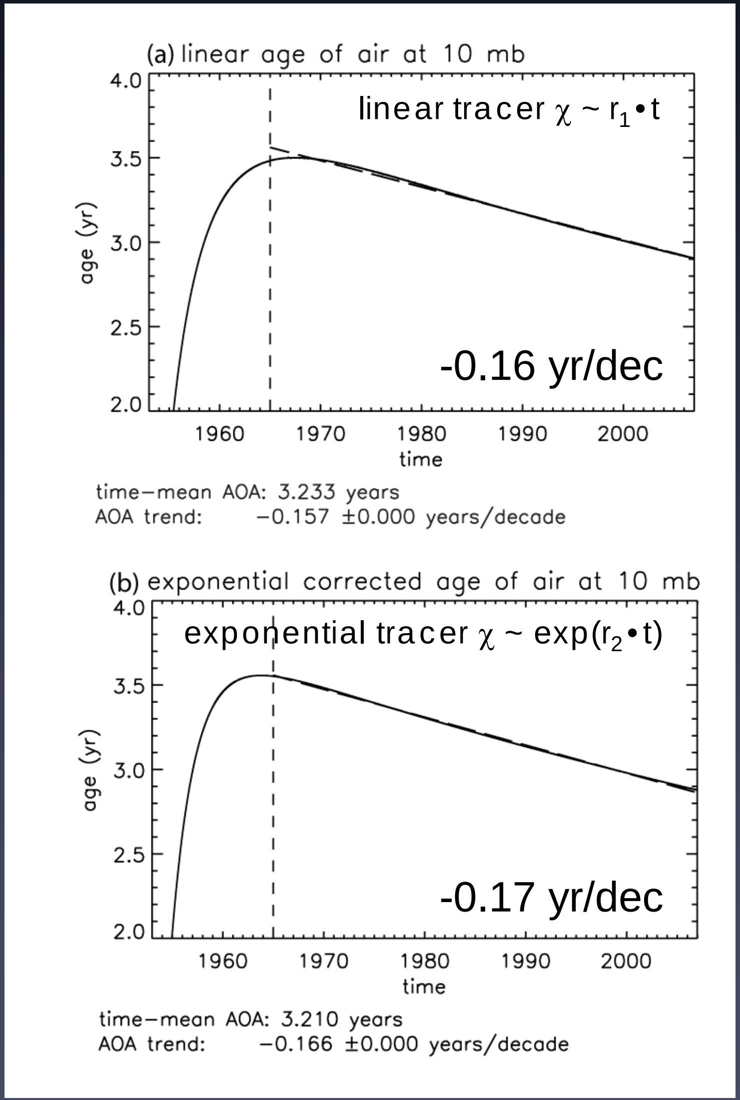
mid-latitude / tropical



SF_6 and CO_2 AOA is corrected for non-linear growth

AOA trends estimated from SF_6 and CO_2 are **corrected for nonlinear growth**, but they are significantly **smaller** than trends estimated from the linear tracer—why?

Is the AOA correction used for exponential growth inaccurate?



1. Use the Holton 1-D global model to compute AOA for tracers with constant growth rates:

- linearly-growing tracer $\chi \sim r_1 \bullet t$
- exponentially-growing tracer $\chi \sim \exp(r_2 \bullet t)$

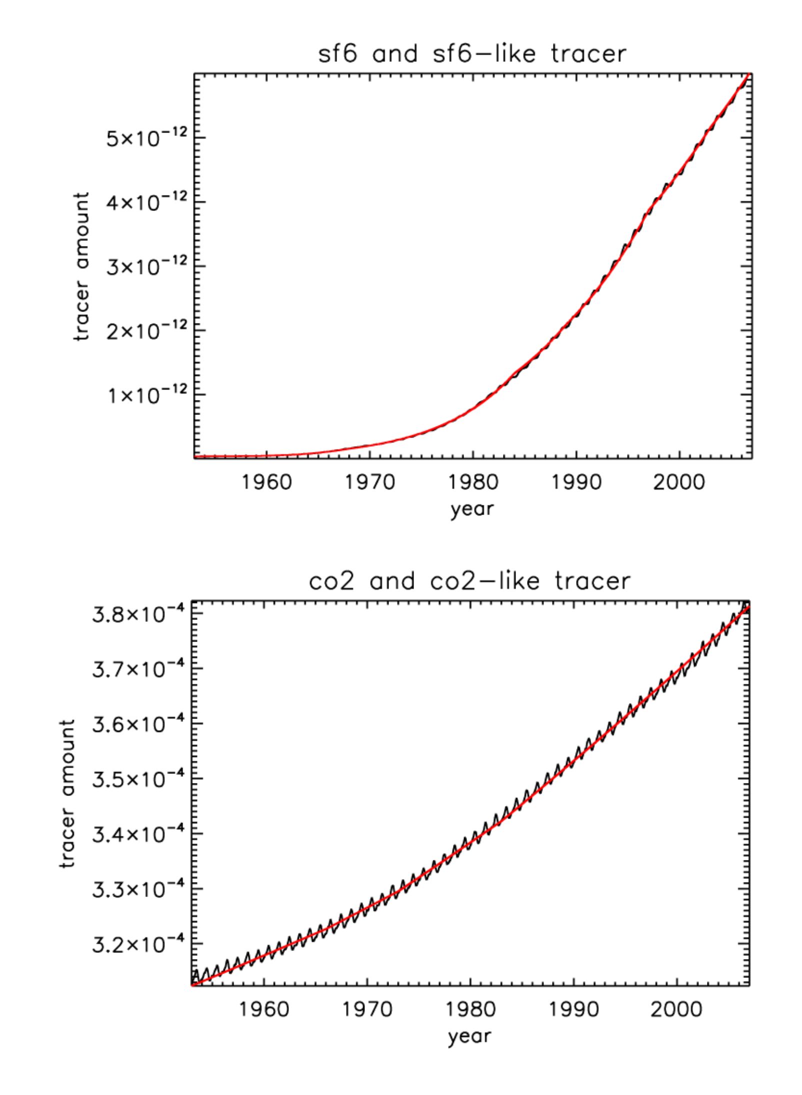
1-D model circulation assumed to strengthen at the same rate as in WACCM

2. **Correct AOA for the exponentially-growing tracer** to account for nonlinear growth

The results show that the **AOA trend is consistent for the two tracers**, and is also **consistent with the AOA trend estimated from the linear tracer** in the full WACCM simulations (trend ~ -0.15 to -0.17 yr/decade)

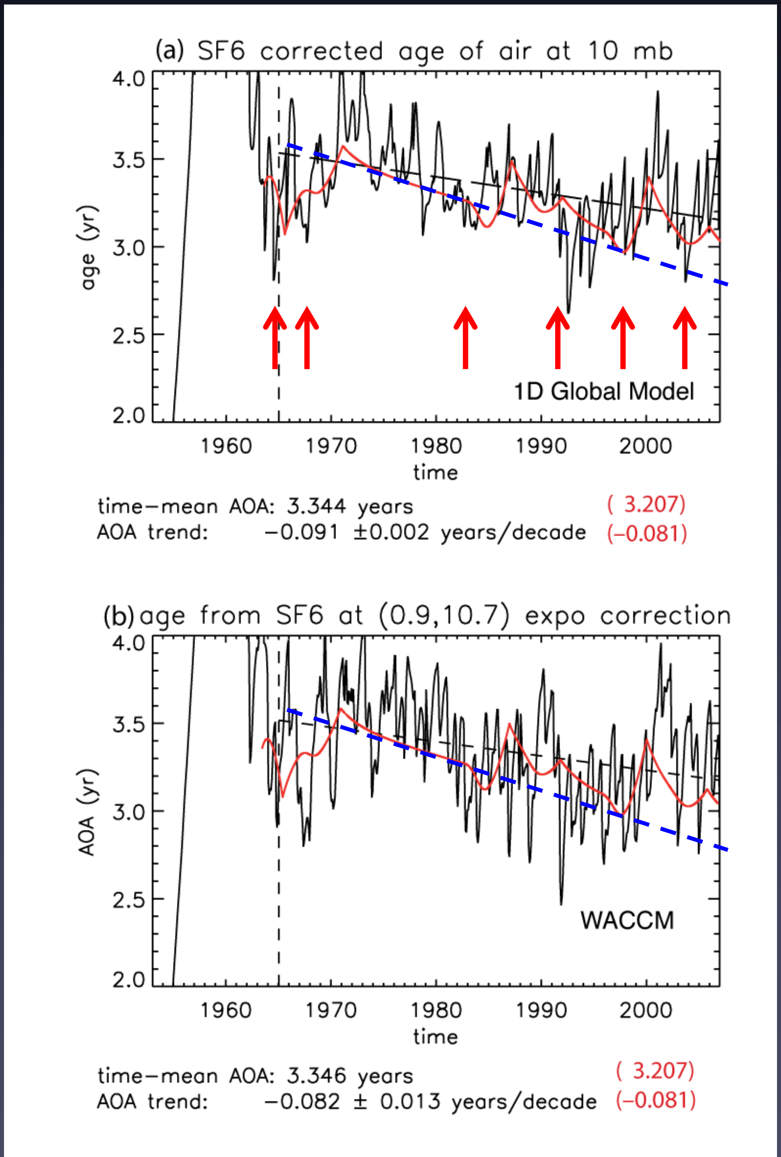
Why is this not the case for SF_6 and CO_2?

Look at low-frequency behavior of AOA from SF_6 and CO_2 in Holton's model



- Use Holton 1-D model, assuming that the circulation strengthens a the same rate as in WACCM
- Fit low-frequency behavior of SF_6 and CO_2 with a series of **piecewise-continuous segments of exponential growth** (red curves)
- The **rate of growth is different for each one of these segments**
- Compare AOA obtained when SF_6 and CO_2 grow as observed with that obtained when they grow according to the piecewise-continuous exponential fits

AOA results for SF_6



Top panel: AOA derived from SF_6 in the Holton 1-D global model:

- Black: SF_6 increases as observed
- Red: SF_6 increases according to the piecewise-continuous exponential fit

Bottom panel: AOA derived from SF_6 in the WACCM simulation (black)

Similar results are obtained for CO_2 (not shown)

Holton model driven by piecewise-continuous fit to SF_6 captures well the low-frequency behavior, including the weak trend in AOA, which suggests that…

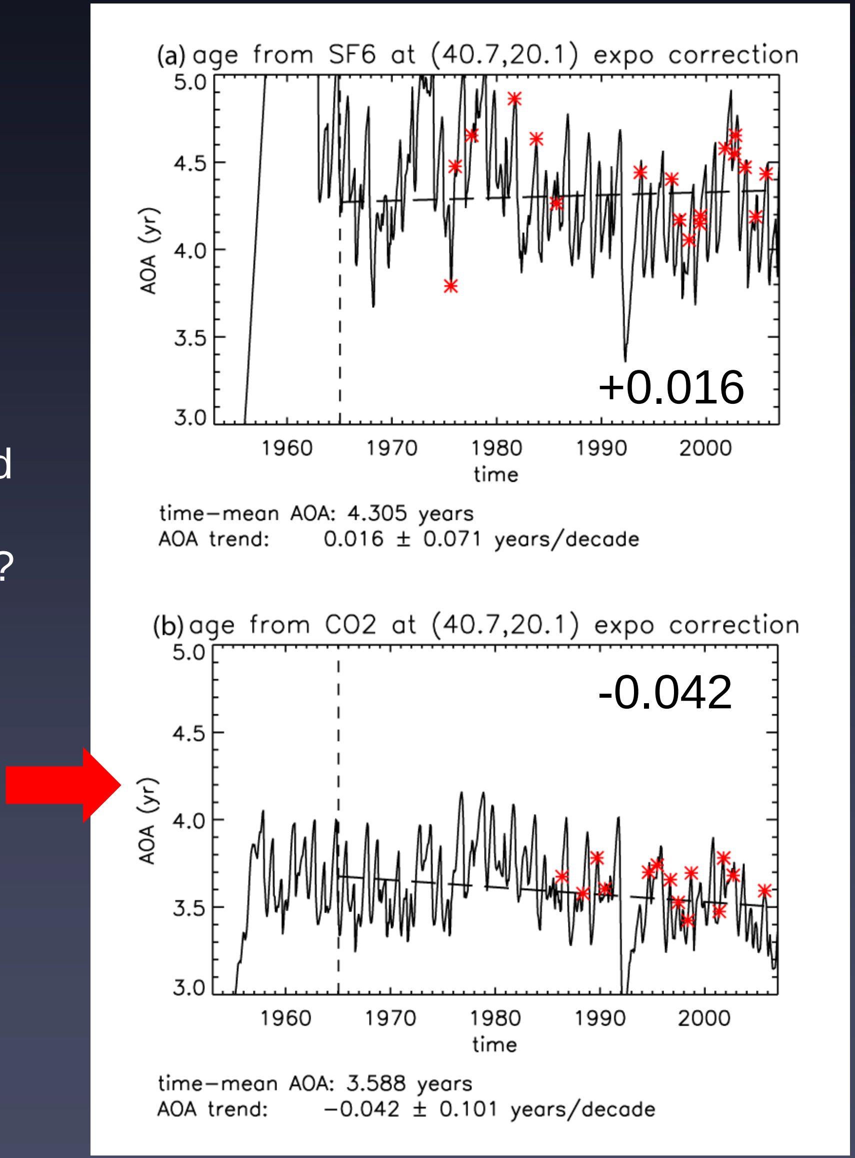
➔ The evolution of AOA is perturbed whenever the growth rate changes (red arrows)

➔ These perturbations prevent SF_6 from following the AOA trend expected for exponential growth with a **constant** rate (blue dashed line)

Sampling effects

- We have seen that the variable growth rate of the natural tracers, SF_6 and CO_2, affects the evolution of AOA and confounds the estimation of AOA trends
- But these AOA trends, albeit small, are still significantly negative
- On the other hand, the AOA trend estimated by Engel et al (2009) from observations is statistically undistinguishable from zero. Why?

This figure suggests an explanation: It shows that sparse sampling (red asterisks) can yield trend estimates that are even smaller than obtained from the full time series of AOA



Conclusions

- AOA trends obtained from WACCM simulations of SF_6 and CO_2 are significantly smaller than trends obtained from a linearly growing tracer with constant growth rate, even when AOA from SF_6 and CO_2 is corrected for nonlinear growth of these tracers

- Analysis using Holton's (1986) global model shows that, when the growth rate of a tracer is not constant with time, the AOA time series does not follow the behavior expected for uniformly growing tracers and confounds the estimation of AOA trends

- The estimation of AOA trends is further complicated by sparse sampling

- These results suggest that it may be difficult to obtain unambiguous estimates of AOA trends (and hence of changes in the stratospheric circulation) from natural tracers

- See Garcia, Randel and Kinnison (*JAS*, 2011) for details