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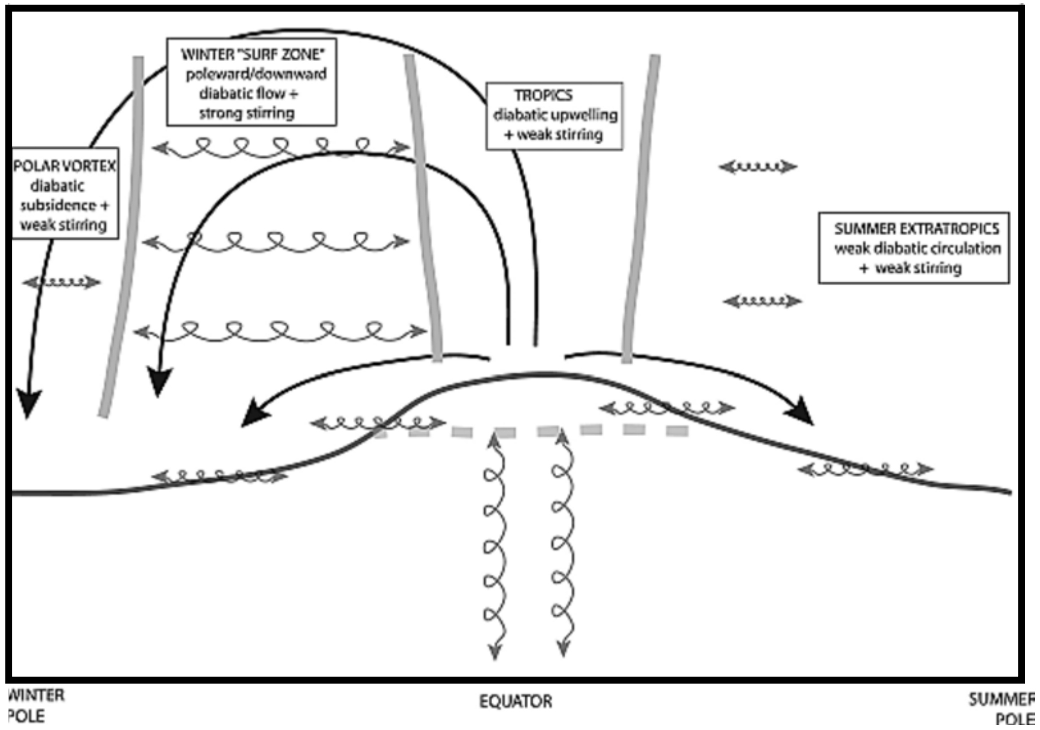
Stratospheric Transport and Stratosphere-Troposphere Interaction

Clara Orbe

NASA Goddard Institute for Space Studies



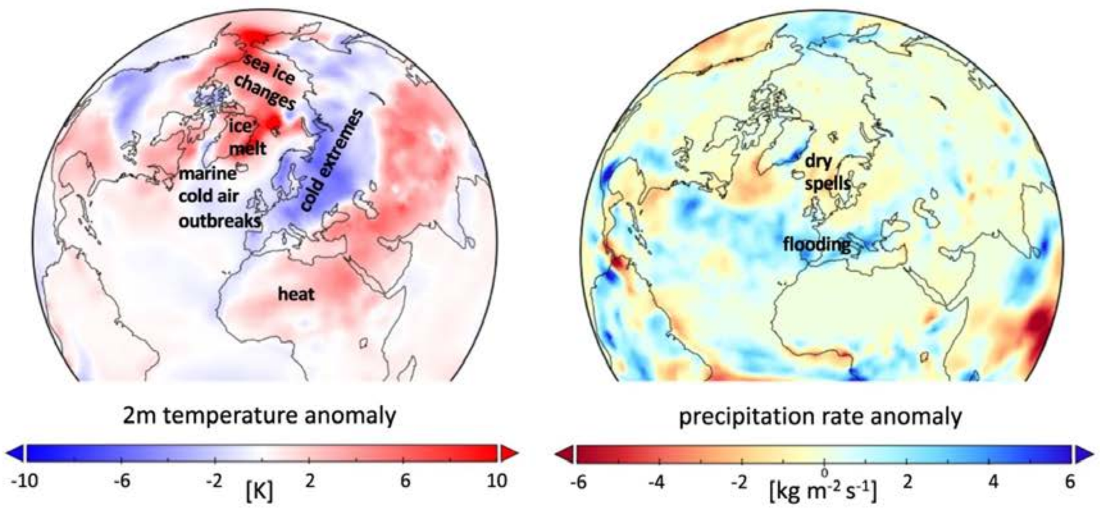
Plumb (2007)

Motivation

- The stratosphere-troposphere exchange of mass and tracers strongly influences the chemical and radiative processes of the troposphere and lower stratosphere (e.g., Morgenstern and Carver, 2001; Park et al., 2005).

- Stratosphere-troposphere dynamical coupling influences the onset of tropospheric weather regimes (Baldwin and Dunkerton, 2001), while the exchange of ozone and water vapor affects the oxidizing capacity of the troposphere and air quality (e.g. Stohl et al., 2000; Hsu et al., 2005).

- More recent studies highlight stratospheric drivers of extreme events at the Earth's surface (e.g., Domeisen and Butler, 2020; right).



Overall Impressions

- More recent reanalyses show key improvements over previous versions (JRA-55 vs. JRA-25, MERRA-2 vs. MERRA), partly reflecting model changes and new observations. However, discontinuities and transitions continue to pose challenges for performing trend analysis, especially in the middle and upper stratosphere (< 10 hPa).

- Increased emphasis on incorporating stratospheric composition (ozone, aerosols) is important for capturing stratospheric compositional influence on troposphere and surface climate. Additionally, this provides new ways to constrain the (Lagrangian) Brewer-Dobson Circulation.

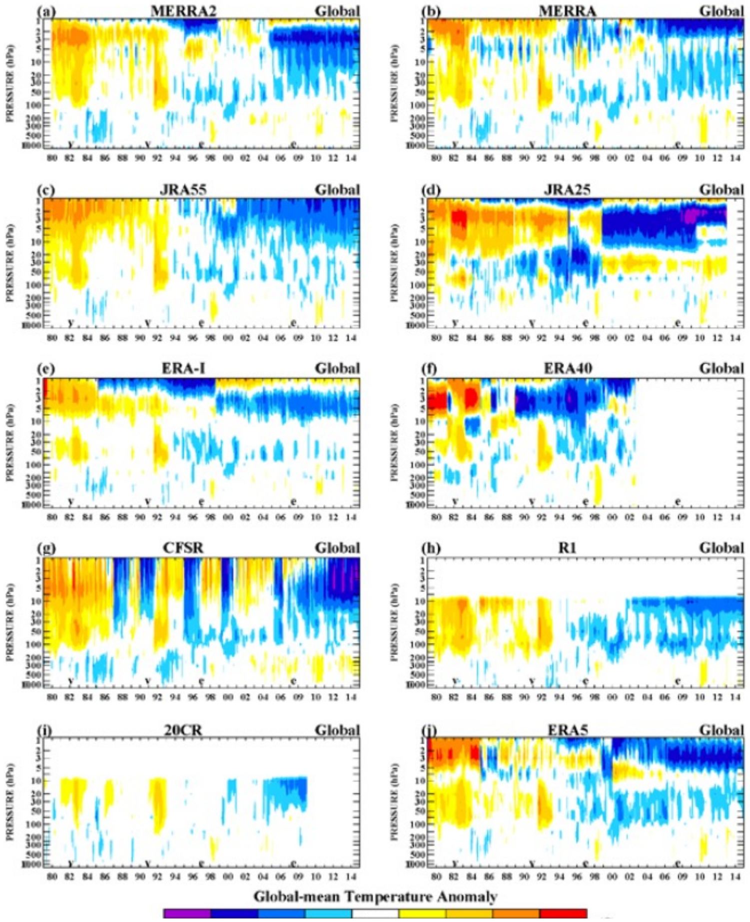
- Successful efforts like the SPARC Reanalysis Intercomparison Project (S-RIP) provide a community resource for better understanding the differences among current reanalysis products and underlying causes. More coordination of simulations of the transport circulation are needed, along the lines of the SPARC CCMVal (2010) and Phase 1 Chemistry Climate Modeling Initiative (2013) efforts.

Assimilated Observations

- Radiosondes provide high vertical resolution temperature and zonal wind (~30 hPa) and humidity (~200-300 hPa) measurements, with limited horizontal coverage (Northern Hemisphere middle/high latitudes).

- Satellite radiances, which provide more homogenous (horizontal) spatial coverage, include microwave and infrared sounders from the TOVs suite (1976-2006) and ATOVs suite (1998-present) including the SSU, MSU and AMSU sounders.

Monthly Global Temperature Anomalies

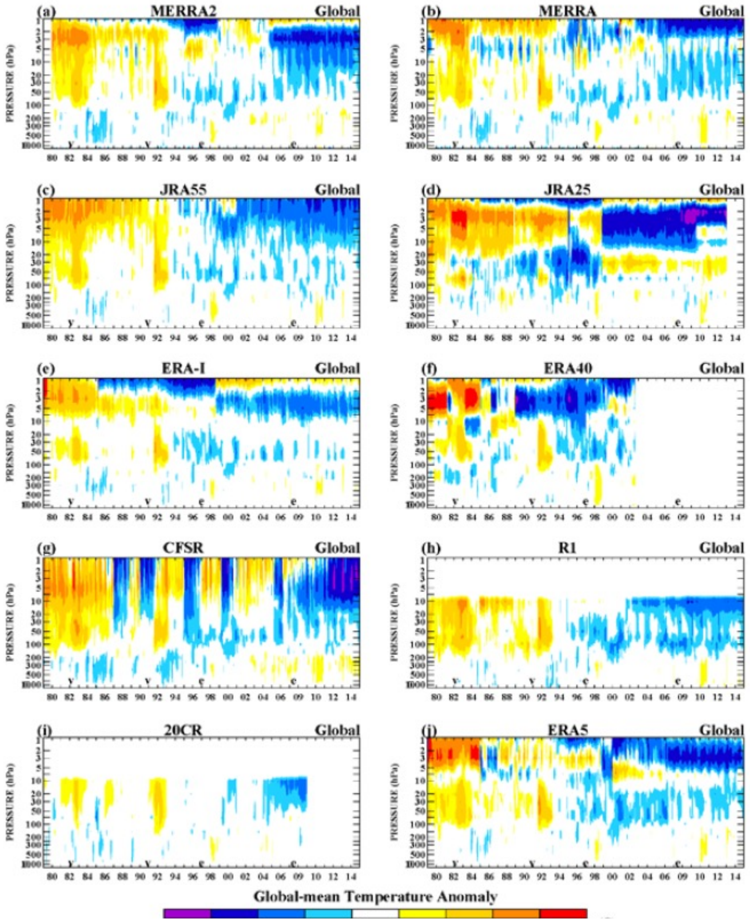


Adapted from Long et al. (2017)

Assimilated Observations

- The transition to ATOVs in 1998 had a profoundly disruptive influence on temperature in several reanalyses, as AMSU-A included five additional channels in the stratosphere (Gelaro et al., 2017).
- Discontinuities evident not only in temperature, but also ozone and other constituents (Stauffer et al., 2019).

Monthly Global Temperature Anomalies

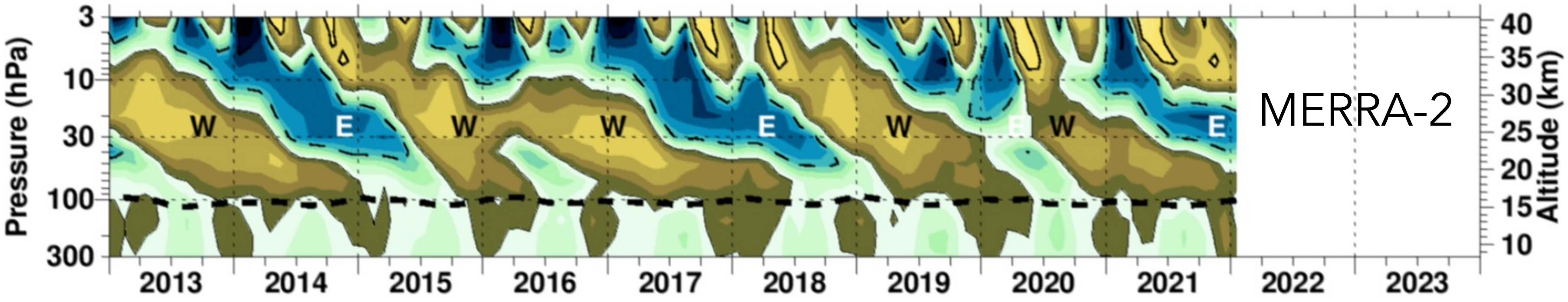


Adapted from Long et al. (2017)

Underlying Models

A few ingredients needed for credible representation of the stratosphere:

a) High vertical resolution within the upper troposphere/lower troposphere (UTLS) and a high model top (ERA-5 (137 σ-p, 0.01 hPa), JRA-55 (60 σ-p, 0.1 hPa), MERRA-2 (72 σ-p, 0.01 hPa), CFSv2 (64 σ-p, 0.266 hPa)
b) Mesospheric sponge layer (<1 hPa) and Rayleigh frictional damping
c) Parameterized Gravity Waves, including both orographic sources (all reanalyses) and non-orographic sources (ERA-20C/ERA-5, MERRA/MERRA-2, CFSv2). Convective sources not included but may be needed to overcome persistent biases in tropical winds (forecasting QBO disruptions, QBO-NAO teleconnections).



Source: Paul A. Newman, Larry Coy, Leslie R. Lait, Eric R. Nash (NASA/GSFC)

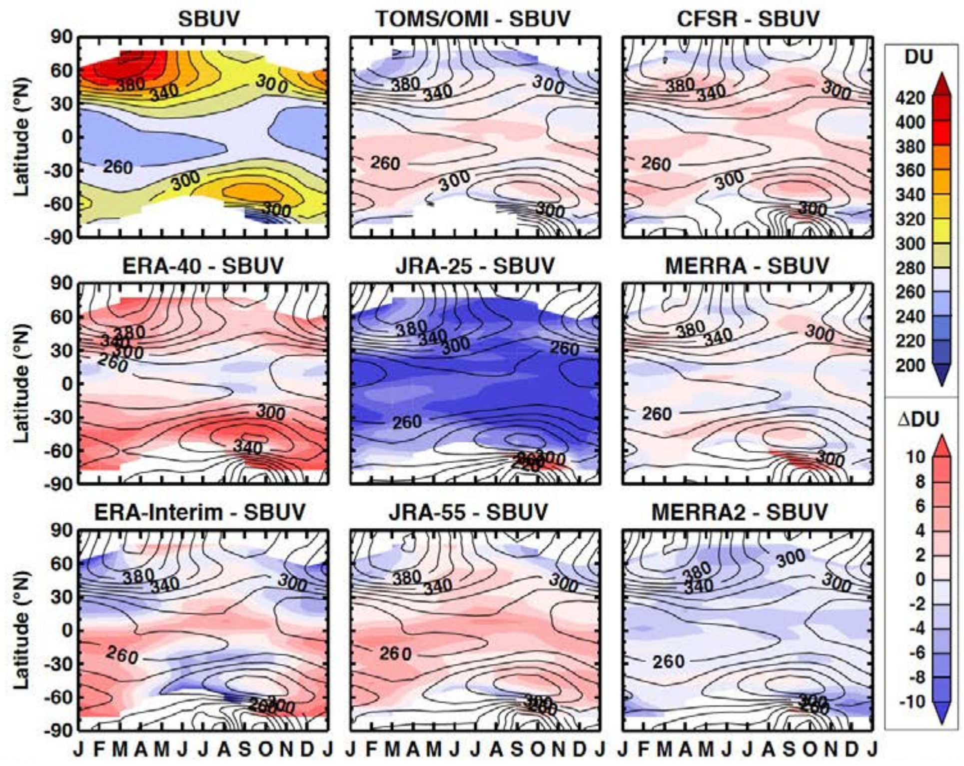
Underlying Models

Treatment of constituents varies widely among reanalyses:

d) Ozone: Latest generation models assimilate total column ozone (TCO), although there are large differences in assimilation technique and use of ozone within radiative calculations. Improved chemical parameterizations that include heterogenous chemistry may improve errors in TCO in the Antarctic, although more polar night observations also needed.

e) Aerosols: Wide range in treatment of aerosols, with some reanalysis products only including climatological aerosols (CSFR, JRA-55), in contrast to active assimilation of aerosols (MERRA-2).

1981-2010 TOC (Reanalyses – SBUV)

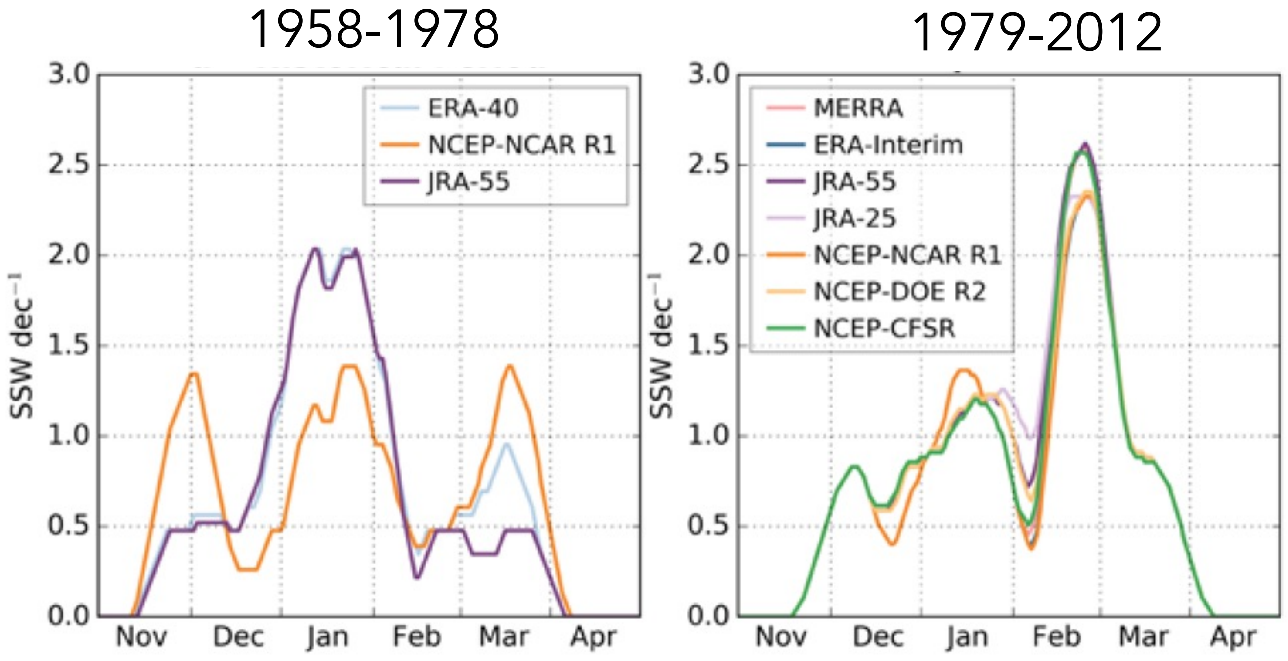


Adapted from Davis et al. (2017)

Stratosphere-Troposphere Dynamical Coupling

- Good agreement among reanalyses in terms of mean frequency of stratospheric sudden warmings (SSWs) (~5-6 events/decade).
- Larger disagreement in the seasonality of SSWs among reanalyses and between historical (1958-1978) and satellite (1979-2012) periods.

Stratospheric Sudden Warming Frequency

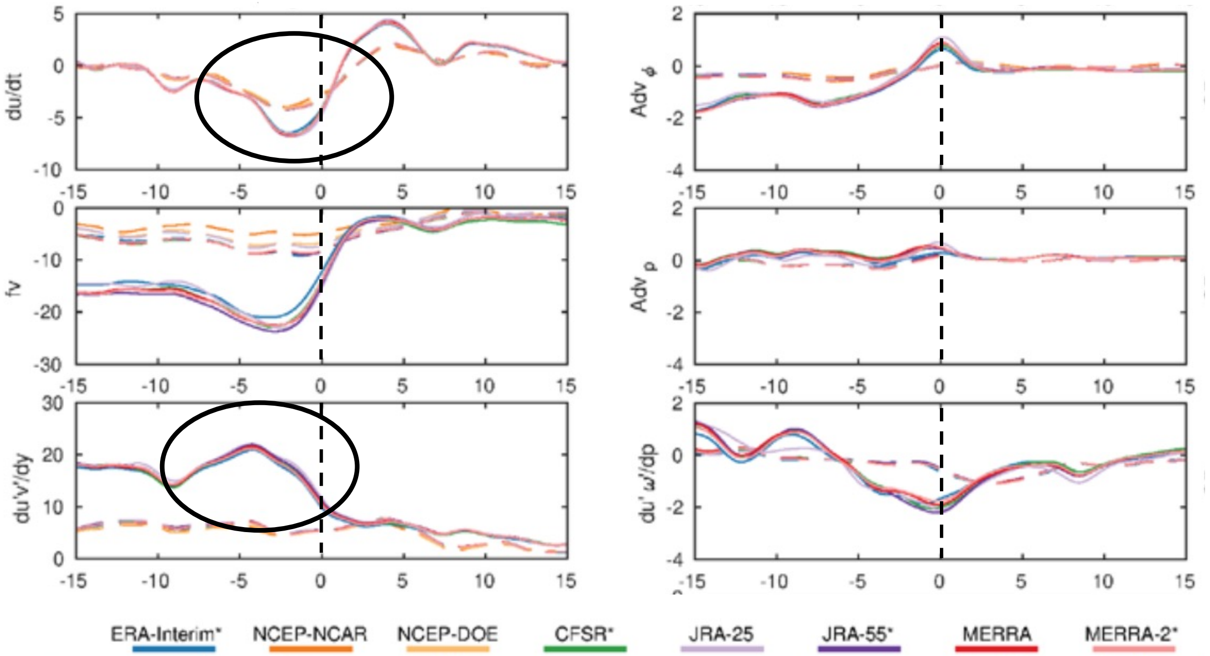


Adapted from Ayarzaguena et al. (2019)

Stratosphere-Troposphere Dynamical Coupling

- Good agreement across reanalyses in terms of the momentum forcing of stratospheric sudden warmings, which suggests that models are capturing similar underlying dynamics.
- More precisely, reanalyses agree in terms of the strong deceleration of zonal mean zonal winds preceded by strong convergence of meridional fluxes of momentum.

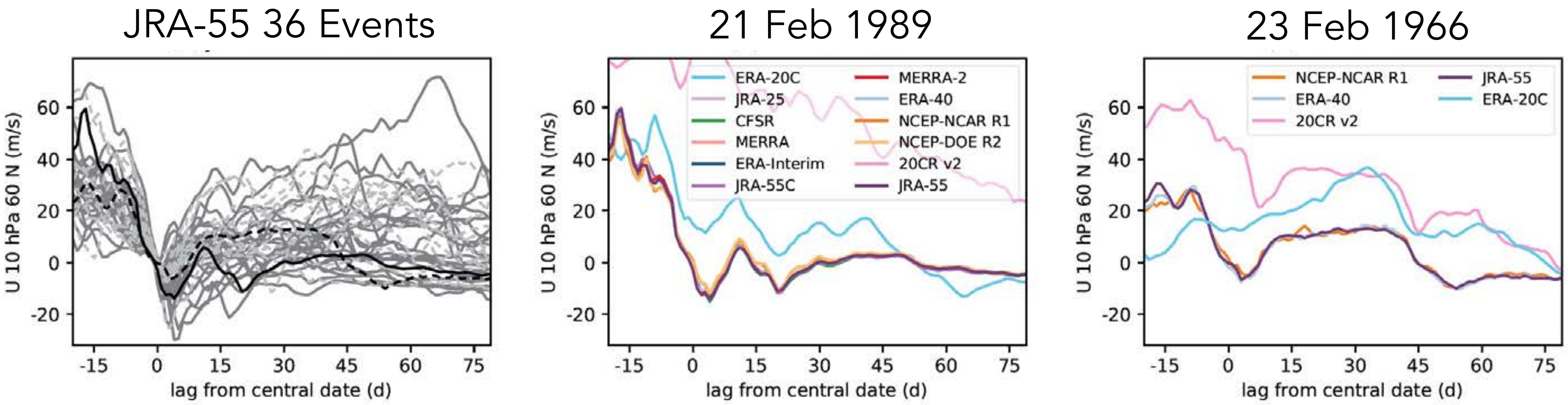
Stratospheric Sudden Warming Momentum Forcing at 10 hPa (—) and 3 hPa (--)



Adapted from Martineau et al. (2018)

Stratosphere-Troposphere Dynamical Coupling

- However, studies of stratosphere-troposphere coupling are seriously limited by considerable dynamical variability.
- Uncertainty contributed from dynamical variability can significantly exceed observational uncertainty (and associated assimilation within reanalyses).

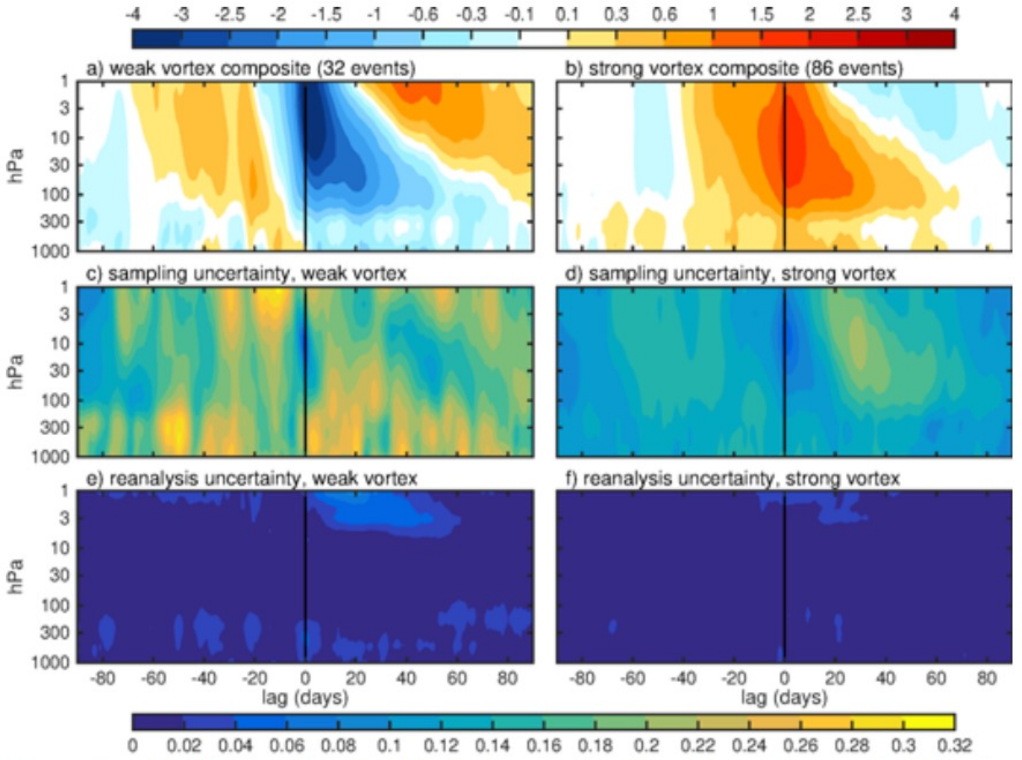


Adapted from Hitchcock (2019)

Stratosphere-Troposphere Dynamical Coupling

- Uncertainty due to dynamical variability not only dominates the stratosphere, but also the "downward" propagation of stratospheric wind anomalies.

Northern Annular Mode for
Weak (left) and Strong (right) Vortex Events



Gerber and Martineau (2018)

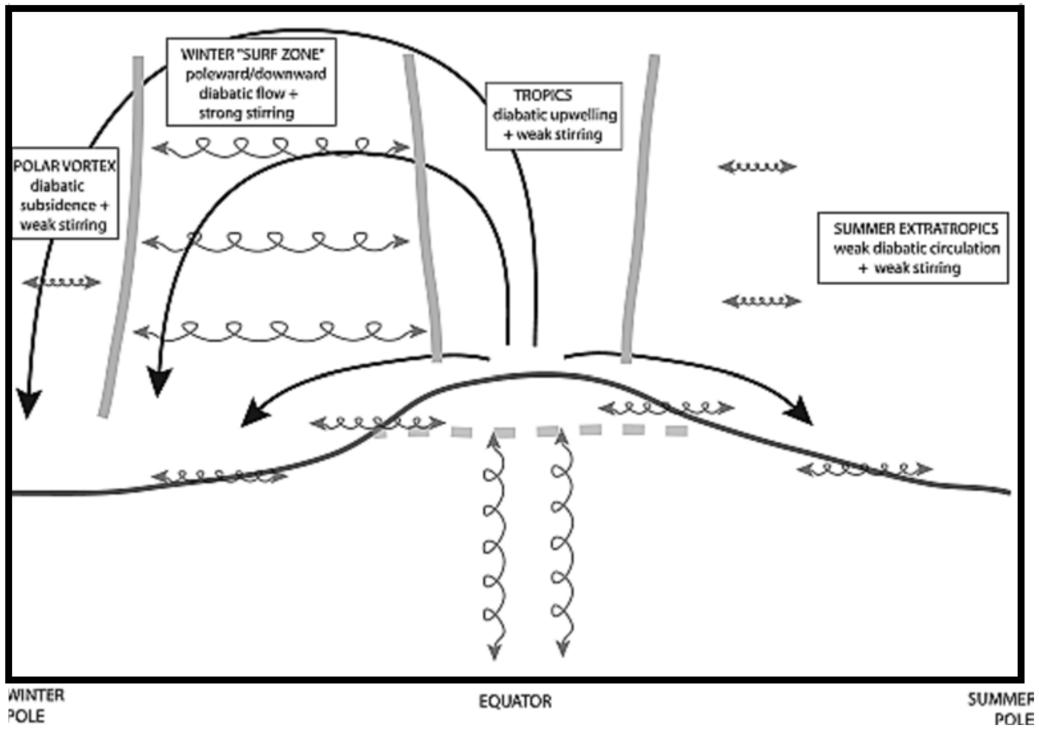
Brewer-Dobson Circulation

- While the stratosphere can be viewed in terms of distinct regions (e.g. polar vortices, QBO), the tropics and high latitudes are linked through the Brewer-Dobson circulation (BDC), which describes the mean meridional transport of mass and tracers throughout the stratosphere.

- Constraining the BDC in reanalyses presents a more challenging -- but also more fundamental – goal, as the BDC reflects both a wave-driven advective circulation ($\bar{v}^*, \bar{w}^*$: Transformed Eulerian Mean) and isentropic mixing.

$$\bar{v}^* = \bar{v} - \partial_p\left(\frac{\overline{v'\theta'}}{\partial_p\bar{\theta}}\right)$$

$$\bar{w}^* = \bar{w} + \frac{1}{a cos\phi}\partial_\phi\left(\frac{\overline{v'\theta'} cos\phi}{\partial_p\bar{\theta}}\right)$$

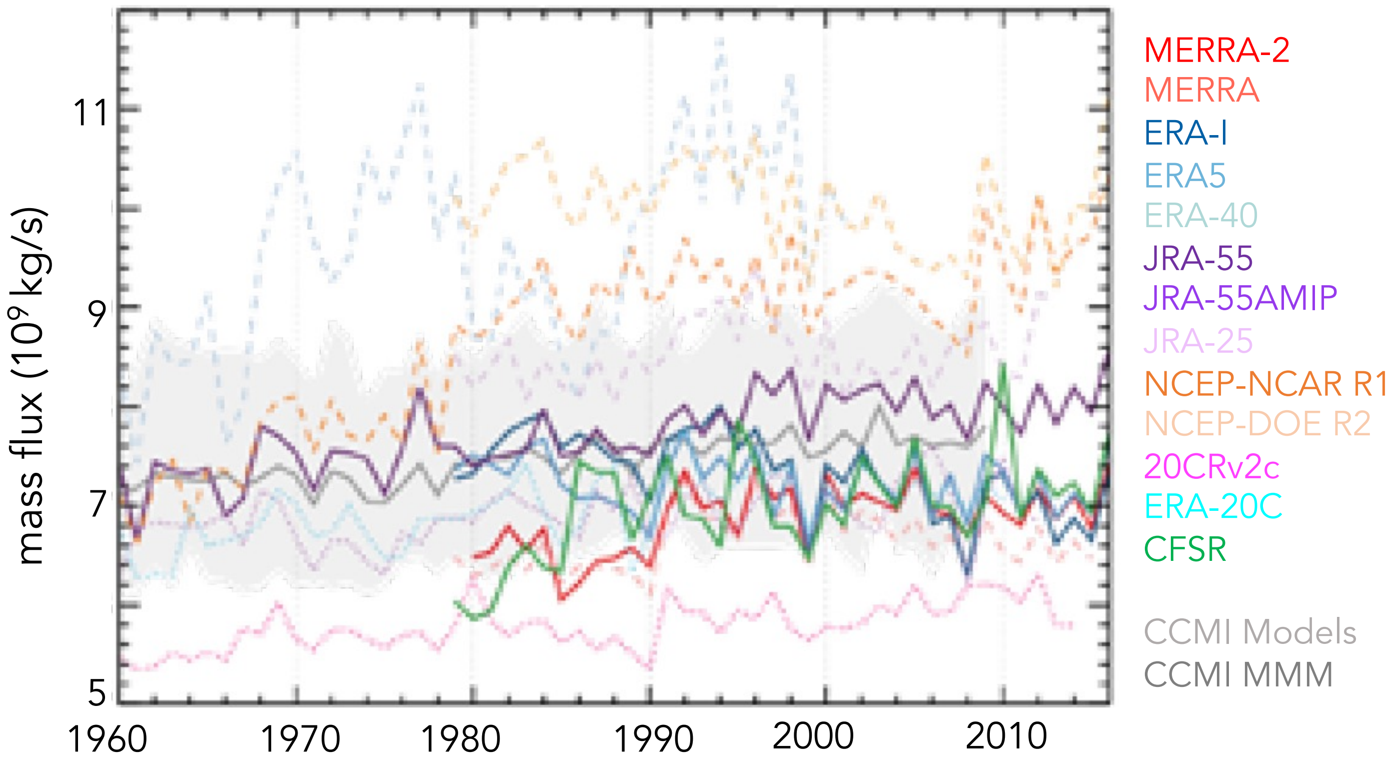


Plumb (2007)

Brewer-Dobson Circulation

- Overall, there is good agreement among reanalyses in terms of the climatological mean strength of the TEM circulation, especially among more recent reanalyses (MERRA-2, ERA-5, JRA-55).

Tropical Upwelling ($\overline{w}^*$) at 70 hPa



SRIP Report (2022)

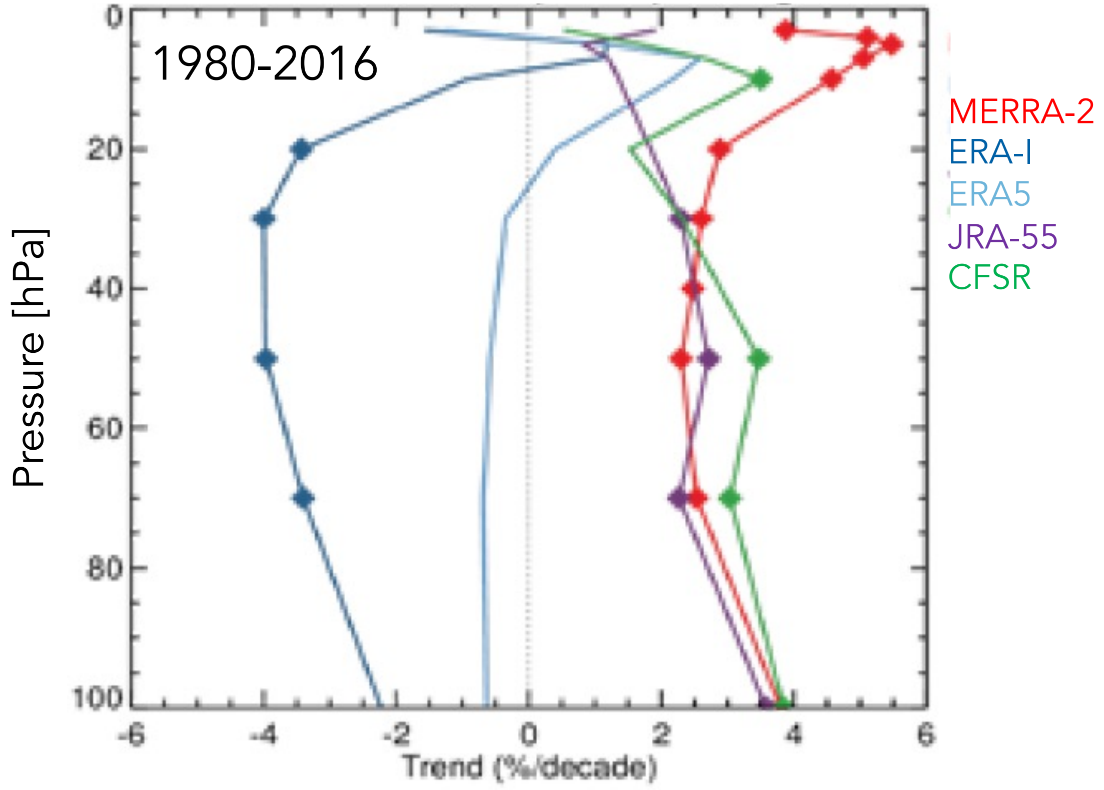
Brewer-Dobson Circulation

- However, reanalyses disagree in terms of tropical upwelling trends, which complicates our understanding of whether or not the BDC has changed over the satellite period:

Tropical $\overline{w}^*$ 1980-2016 Trends (%/decade)

MERRA-2	+**2.5**±1.3
ERA-I	−**3.4**±1.4
ERA5	−0.7±1.3
JRA-55	+**2.3**±0.9
CFSR	+**3.4**±2.0

Trends in Tropical Upwelling ($\overline{w}^*$)

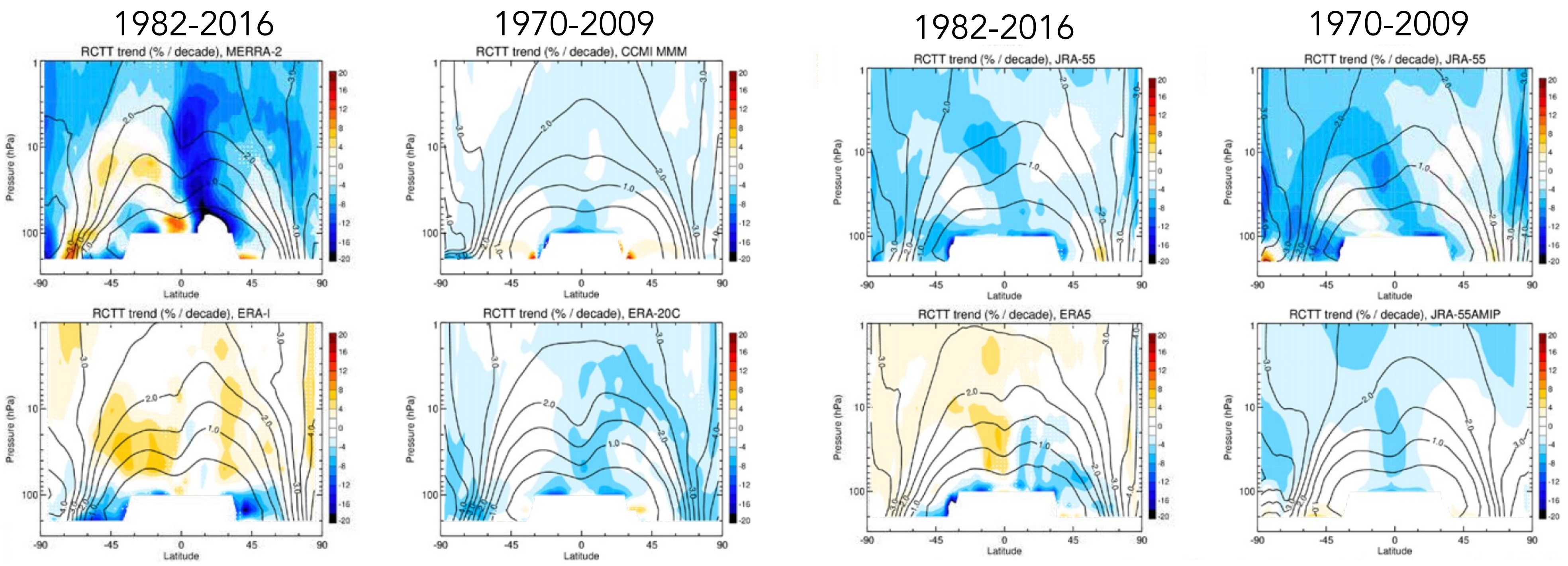


SRIP Report (2022)

Brewer-Dobson Circulation

- The disagreements in upwelling trends among reanalyses are also reflected in more integrated measures of the residual mean circulation (i.e. residual circulation transit times).

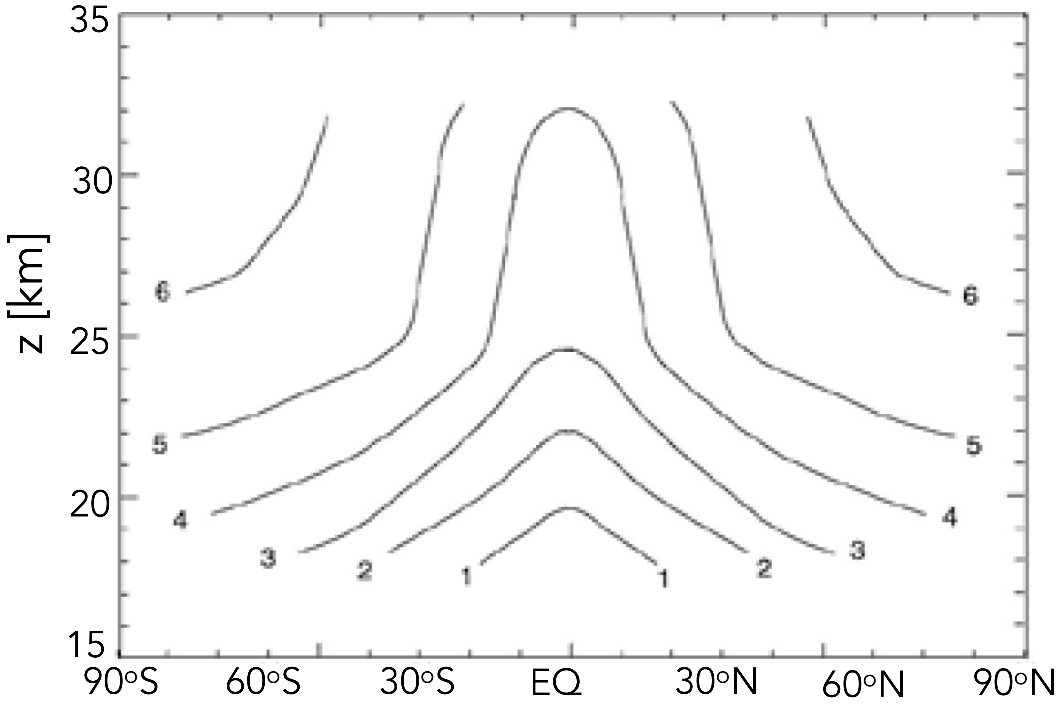
Trends in Residual Circulation Transit Times



Stratospheric Age-of-Air

- A key limitation in constraining the BDC is the lack of direct observational estimates of the diabatic circulation.
- To this end, we often rely on tracers to provide indirect estimates of the BDC, although these also reflect the integrated effects of stratospheric mixing.
- In particular, the mean age-of-air (AOA) provides a measure of the average time since air was last at the tropical tropopause and can be estimated from observations of SF_6 and CO_2 (Hall and Plumb, 1994).

Annual Mean Age-of-Air (AOA) [years]

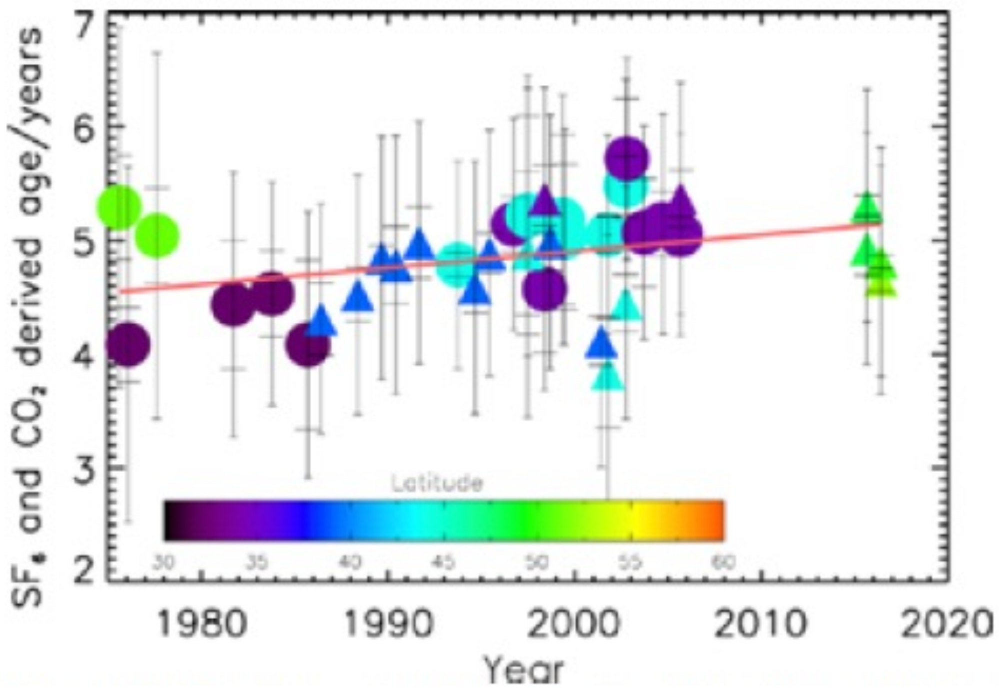


Waugh et al. (2002))

Stratospheric Age-of-Air

- Balloon-based measurements of the age-of-air over Northern Hemisphere midlatitudes suggest that AOA values have been increasing over recent decades (left).

NH Observed Age-of-Air

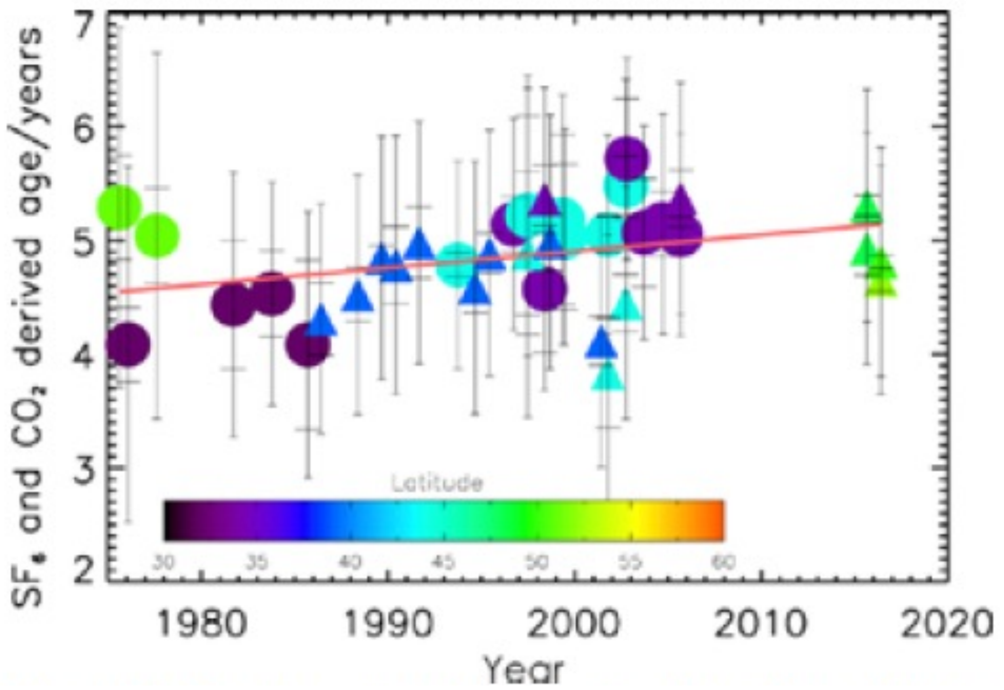


Adapted from Engel et al. (2007)

Stratospheric Age-of-Air

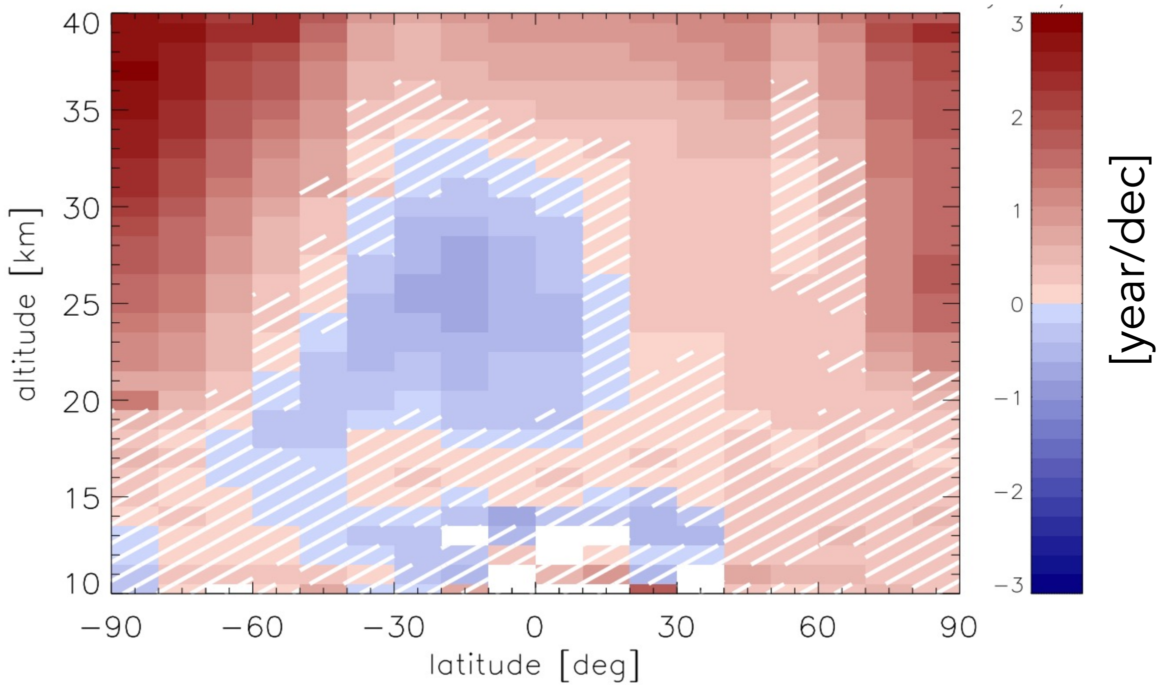
- Independent trends derived from satellite measurements of SF_6 (MIPAS) also show increased AOA values over NH midlatitudes, coupled with decreases over SH midlatitudes (right).

NH Observed Age-of-Air



Adapted from Engel et al. (2007)

AOA Linear Trend 2002-2012 (MIPAS)

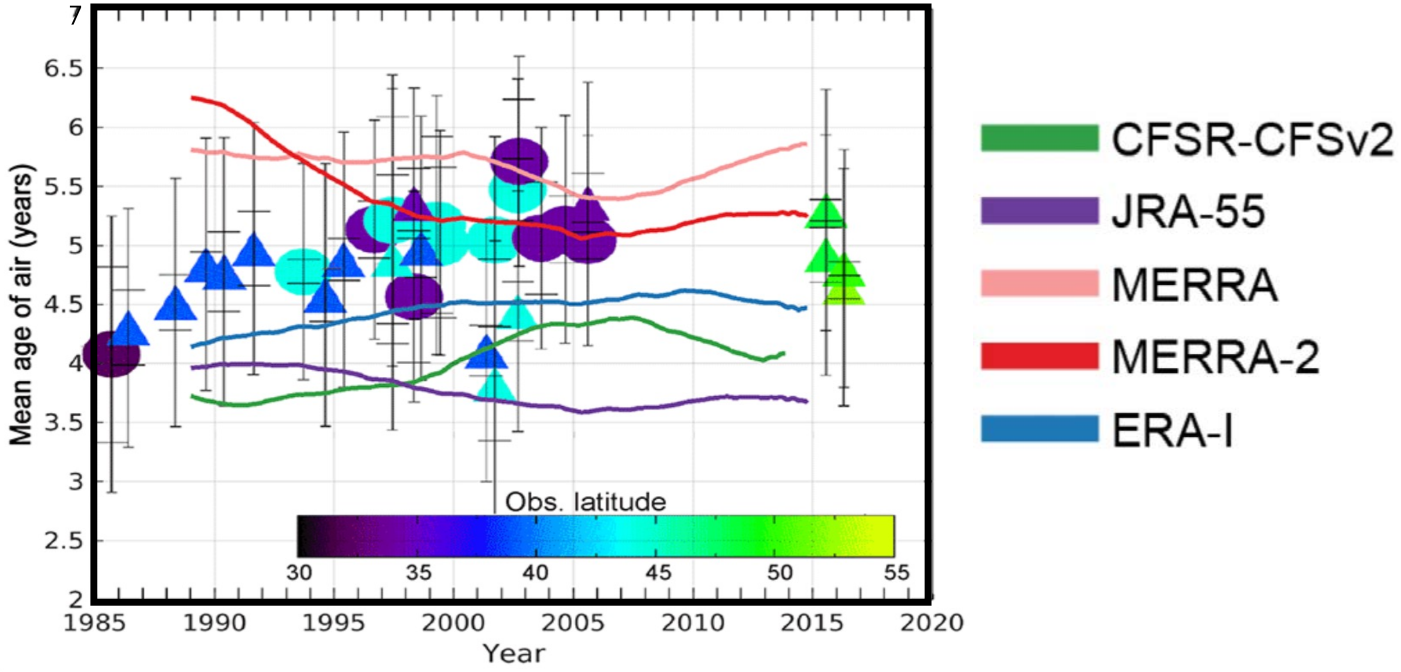


Haenel et al. (2015)

Stratospheric Age-of-Air

- Most reanalyses, with the exception of ERA-Interim/ERA-5, **do not** appear to capture the observed age-of-air trends.

NH Observed and "Reanalysis" AOA



Chabrillat et al. (2018)

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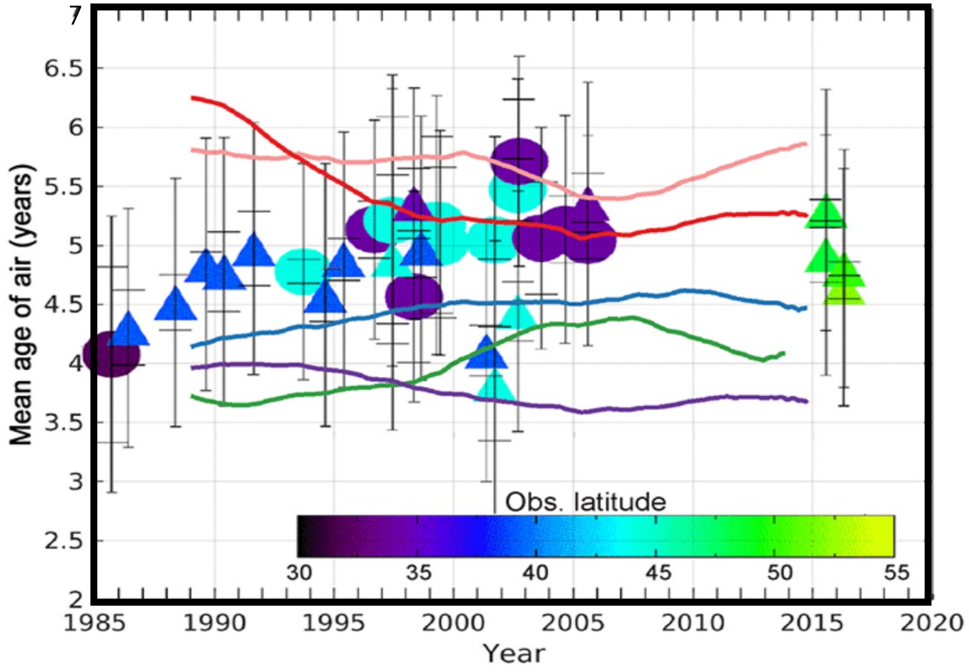
Stratospheric Age-of-Air

- However, there are two key issues that complicate this problem:

NH Observed and "Reanalysis" AOA



Chabrillat et al. (2018)

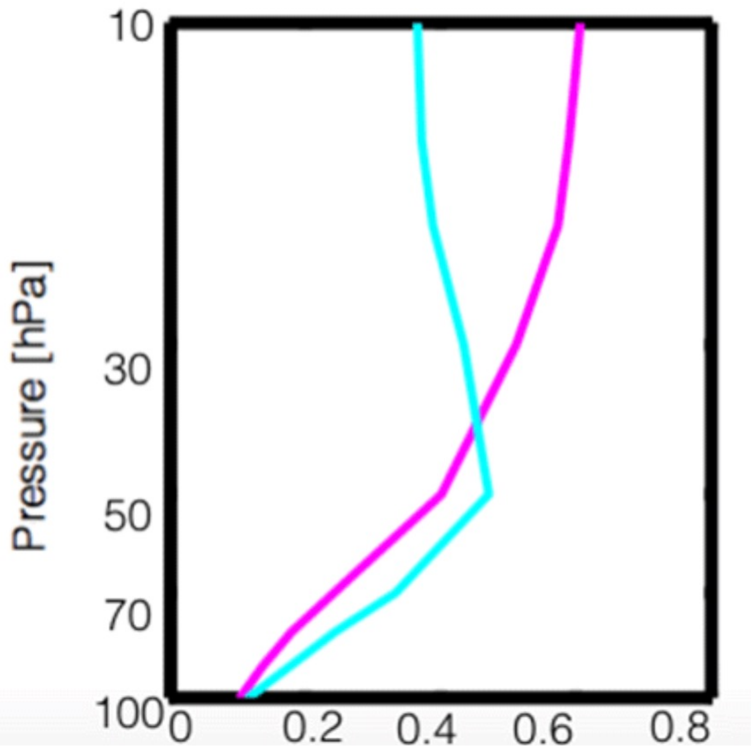
#1. What is the "true" reanalysis mean age?

#2. How sensitive are "trends" to internal dynamical variability?

Stratospheric Age-of-Air

- Since reanalyses do not explicitly integrate age-of-air (or other passive) tracers, one must use offline models (CTMs, nudging) to infer the ages associated with different reanalyses.
- Unfortunately, age-of-air calculations are very sensitive to the methodology used, often exhibiting larger spread than free-running simulations using the same underlying models (left) (Orbe et al., 2020; Chrysanthou et al., 2019).

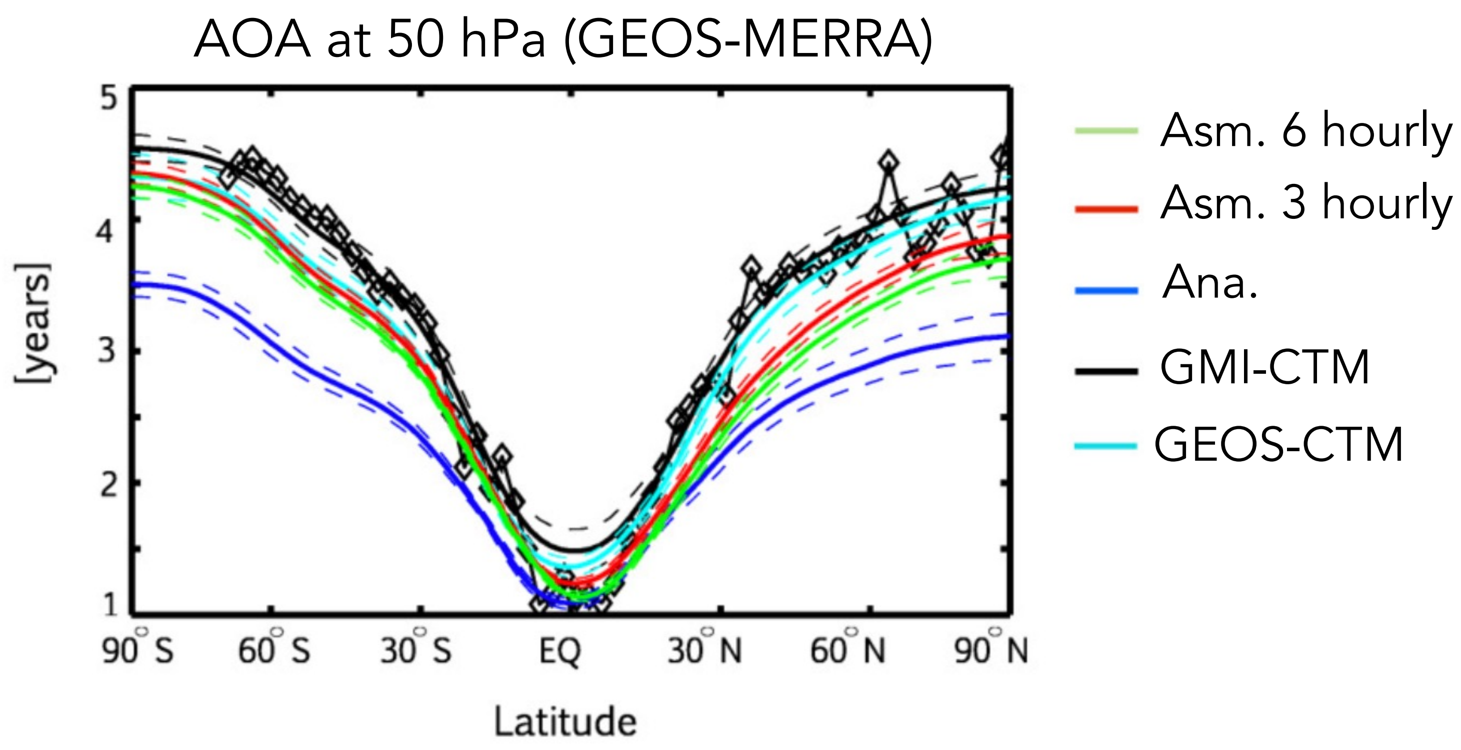
AOA RMS Among Specified-Dynamics and Free-Running CCMI Simulations



Orbe et al. (2020)

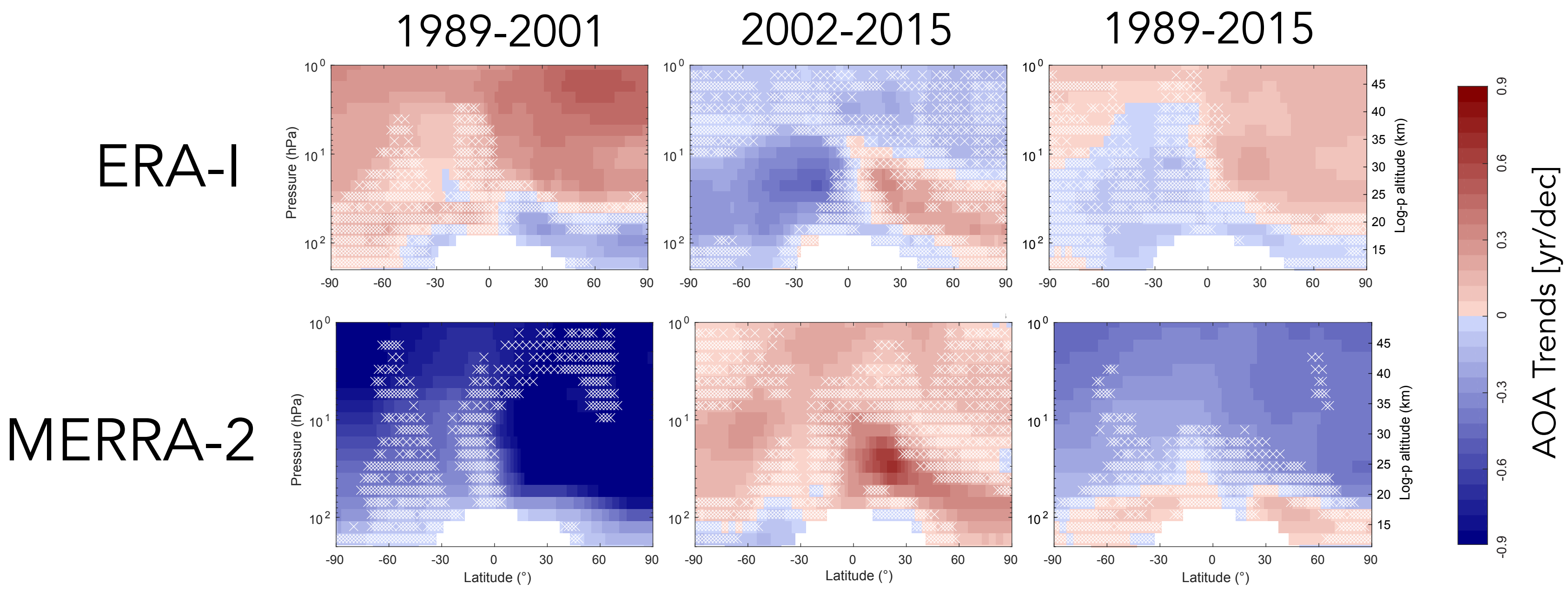
Stratospheric Age-of-Air

- This large spread is exhibited even among simulations constrained using the same model and the same reanalysis product (below) (Orbe et al., 2017).



Stratospheric Age-of-Air

- At the same time, the integrity of reported AOA "trends" may be called into question by large variability over different time periods among the reanalyses.

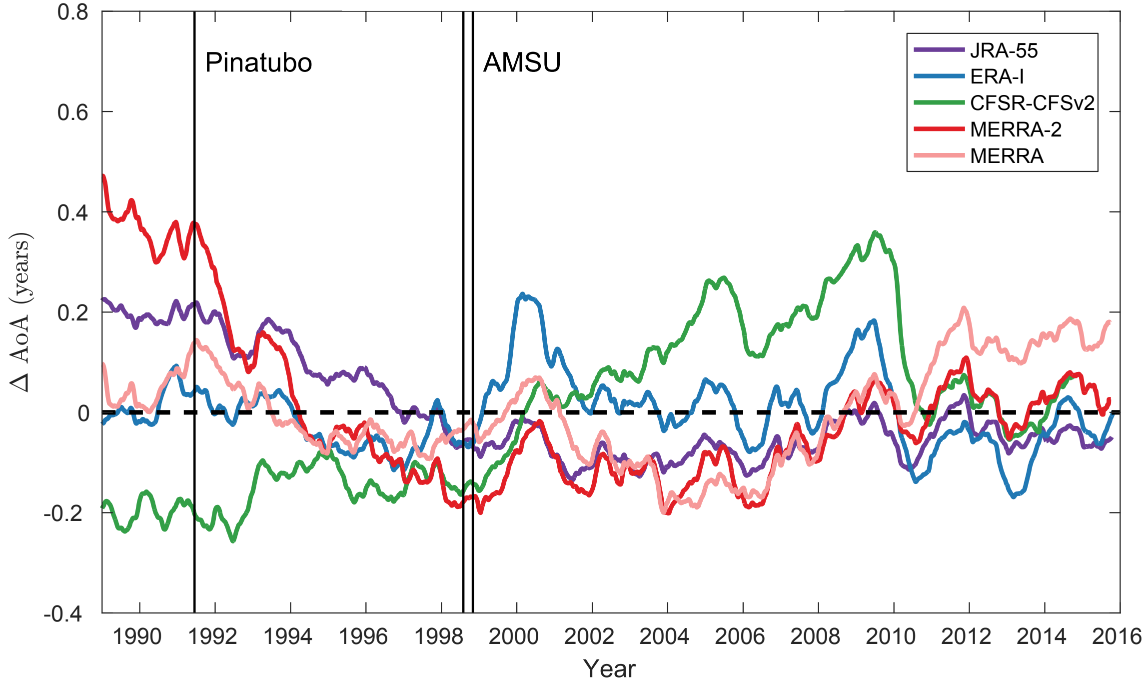


Adapted from Chabrillat et al. (2018)

Stratospheric Age-of-Air

- In addition to contributions from internal variability (QBO), changes in the observing system may also play a role here, which suggest that more attention needs to be paid to improving consistency during the pre-ATOVs period.

AOA Anomalies over 72ºS-72ºN and 16-28 km



Adapted from Chabrillat et al. (2018)

Concluding Remarks

Overall, more recent reanalyses are excellent tools for understanding stratospheric transport and dynamics.

Key Uncertainties:

- Certain biases in stratospheric dynamics persist even in more recent reanalysis products (e.g., tropical winds, Southern Hemisphere polar vortex).
- Trends in the Brewer-Dobson Circulation differ between reanalyses and time periods.
- Tracer-based diagnostics of the Brewer-Dobson Circulation open up possibilities for using new tracer observations to constrain reanalyes (SF_6, CO_2, N_2O). However, mixing introduces a new layer of complexity and attempts to infer the "true" mean age from reanalyses using offline approaches can be very sensitive to the technique used.

Concluding Remarks

Some Proposed Paths Forward:

- Examine how/if the incorporation of more "interactive" non-orographic gravity wave drag sources (i.e. convection) affects longstanding dynamical biases.
- Need to identify the "true" reanalysis transport characteristics by explicitly integrating age-of-air (and other passive) tracers within the DAS.
- Better understand the influence of dynamical variability (QBO) on BDC trends.
- Better understand the influence of the ATOVs transition in trends in constituents.

Guiding Questions

- What do you see are the most significant advances for the field of reanalysis in 5-10 years?
- What do you see are the most significant barriers to progress in the field of reanalysis?
- Which collaborations are currently working and which collaborations need to be fostered?
- What are the critical requirements for consistent Earth system reanalysis?
- What observational datasets are required to support these requirements?
- What modeling components are mature enough to enable reanalysis for your specific science question or application?
- How is uncertainty quantified for your application? Are there significant barriers for quantifying uncertainty in your field?