Lower-stratospheric tracer trends and variability from reanalyses

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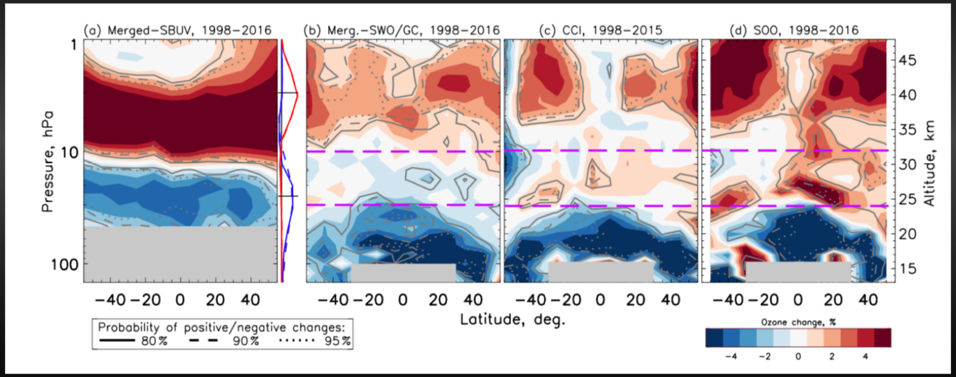
Motivation

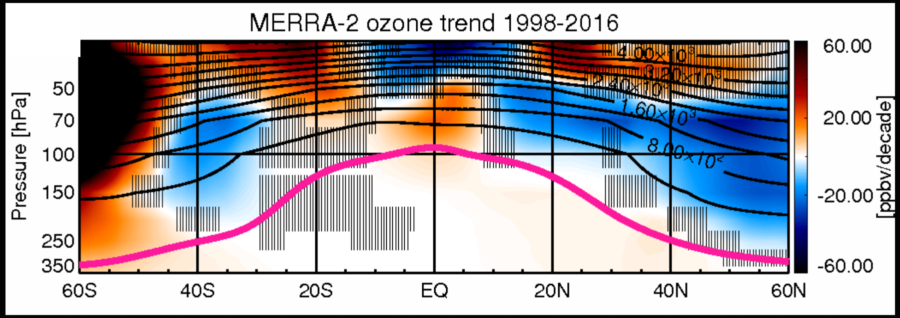
- Stratospheric ozone is recovering following reductions of ozone depleting substances now confirmed (WMO 2018)
- There's a controversy regarding recent changes in ozone in the lower stratosphere (LS): Ball et al. 2018 report continuing decline of LS ozone between 1998 and 2016.



Ball et al. 2018

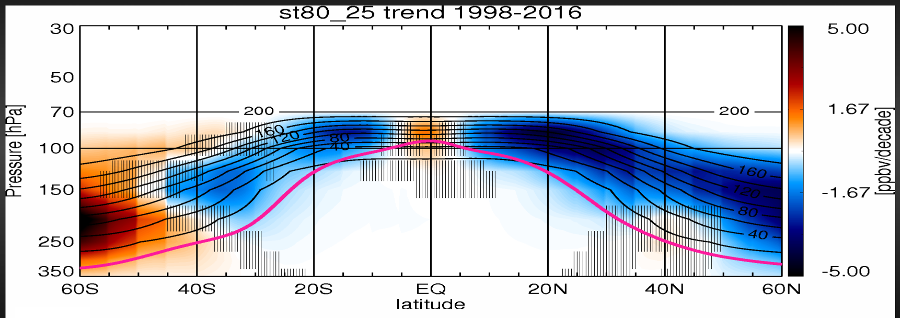
What can we say about LS ozone changes over the last two decades using NASA's reanalysis and models?

Ozone

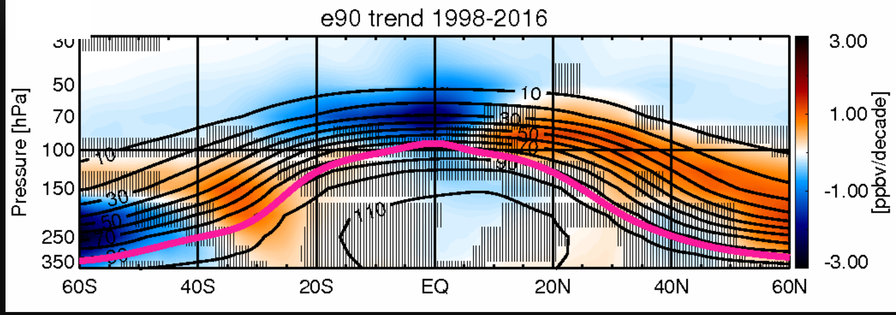


MERRA-2 ozone

Idealized transport tracers



ST80_25: Source at p<80 hPa sink at the tropopause



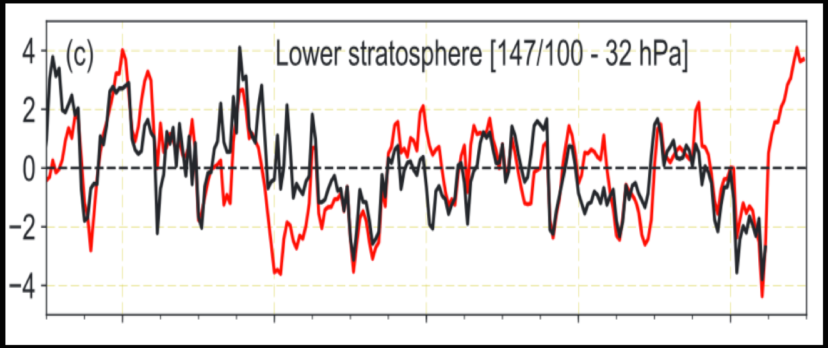
e90: Source at the surface, constant loss rate of 90^{-1} $days^{-1}$

Chemistry or transport? What caused LS ozone changes between 1998 and 2016?

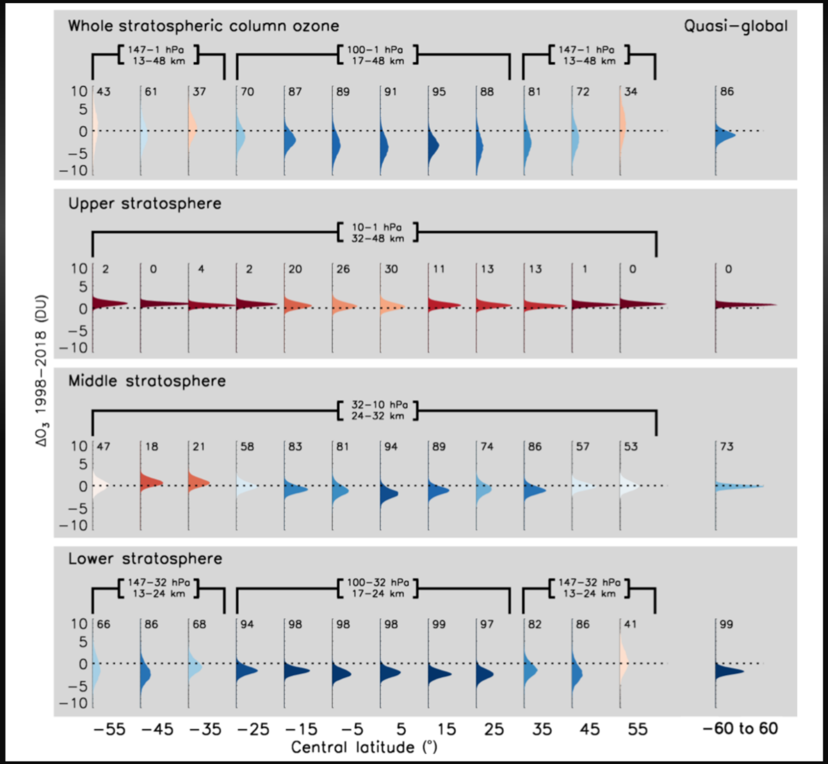
- LS trend patterns consistent between ozone and idealized tracers
- Our hypothesis then: Trends likely result from an intensification of eddy mixing between tropics and extratropics

Wargan et al. 2018

(Transient) response to climate change
OR
Unforced variability?



Chipperfield et al. 2018

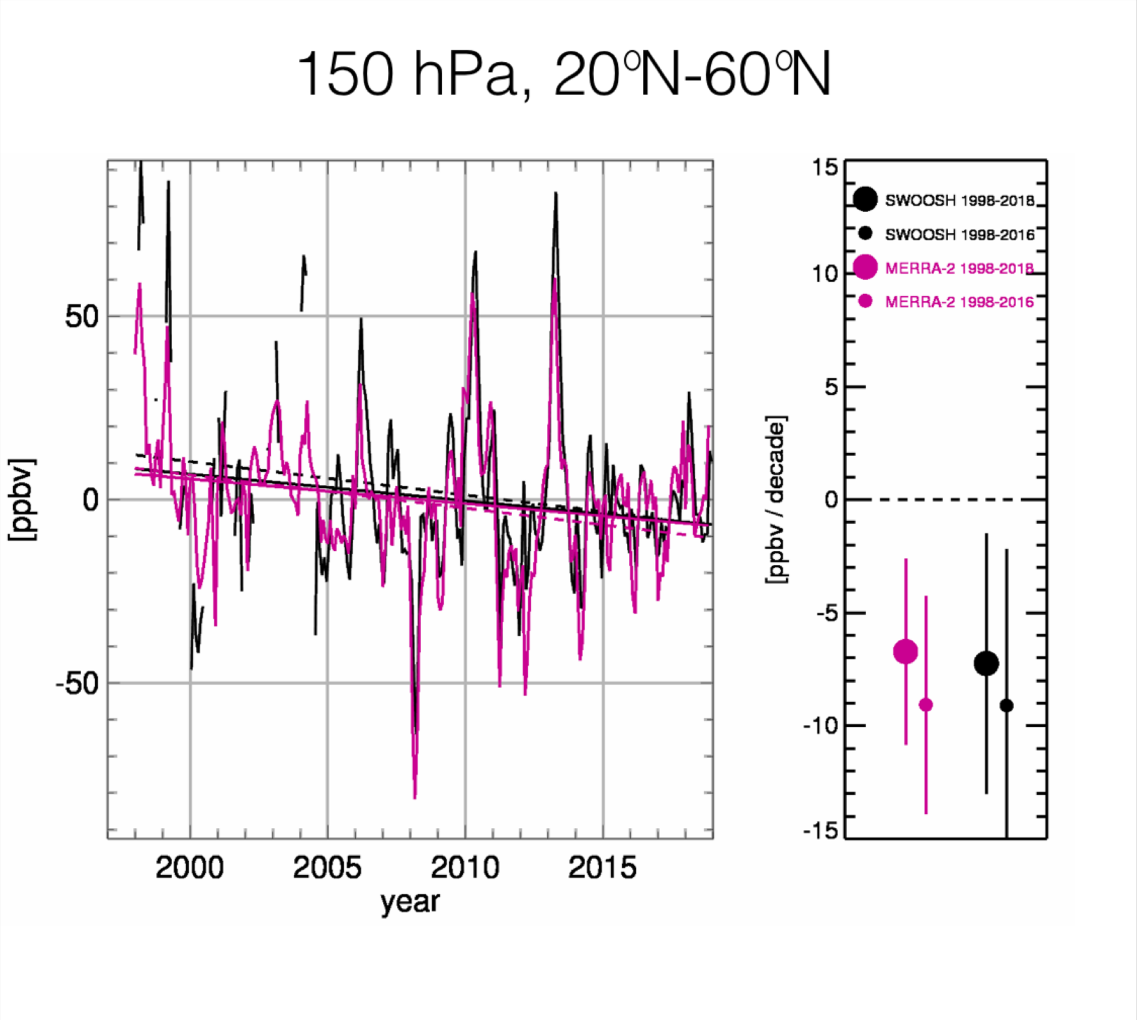


Ball et al. 2019

But the world didn't end in 2016. Has the "trend" continued?

- Chipperfield at al. 2018 argued that the negative trend in the lower stratosphere disappeared when 2017 was included in the analysis, implying strong sensitivity to endpoints
- Ball et al. 2019 showed that a more thorough examination still revealed a negative lower-stratospheric trend between 1998 and 2018

What does MERRA-2 say?



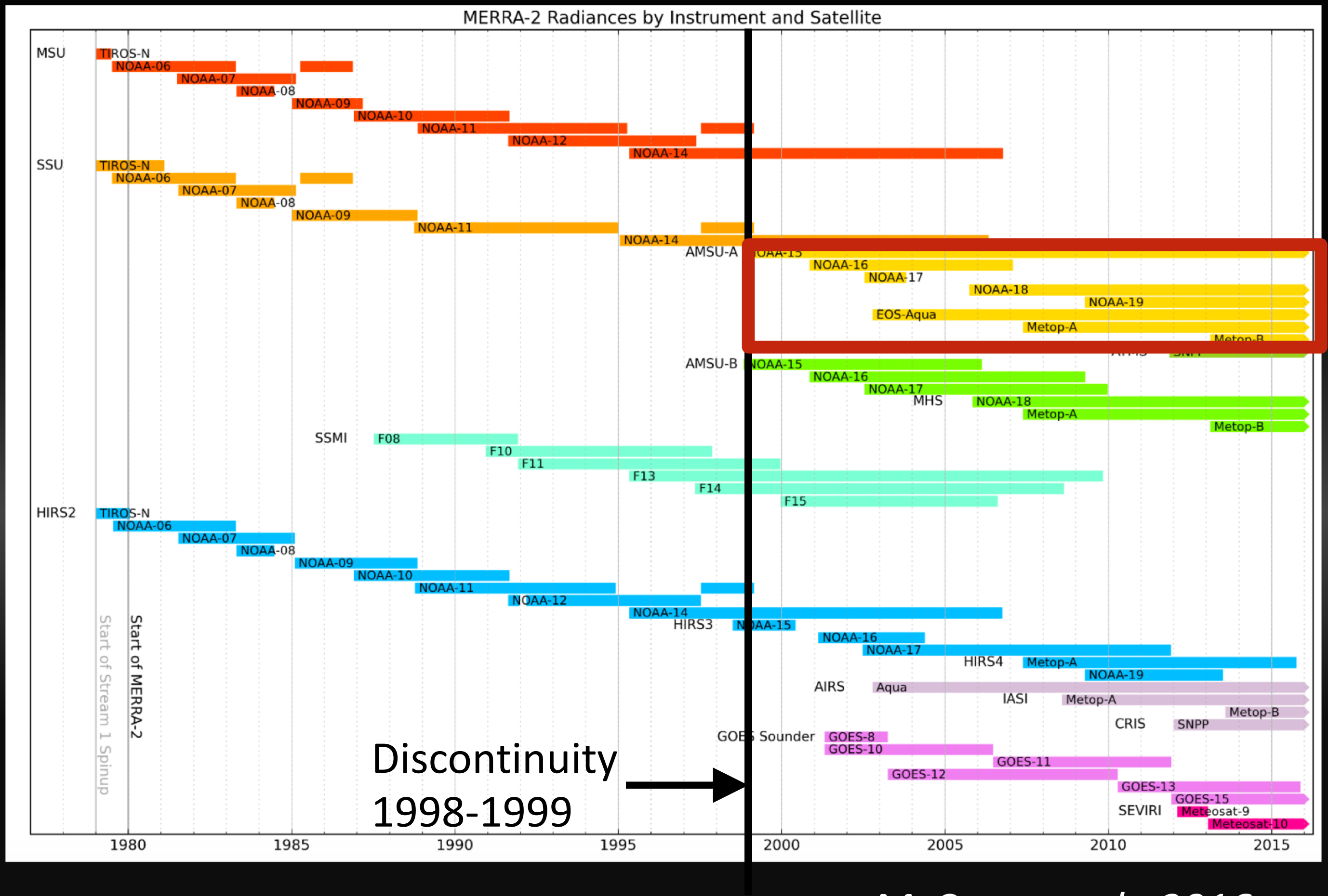
Orbe et al., 2020

- Small but statistically significant negative ozone change in the NH extratropical lower stratosphere between 1998 and 2016 persists when two additional years are included (2017 & 2018)
- The negative change is seen in MERRA-2 and in SWOOSH
- The interannual variability agrees well between MERRA-2 and SWOOSH

What is the mechanism behind the negative ozone change?

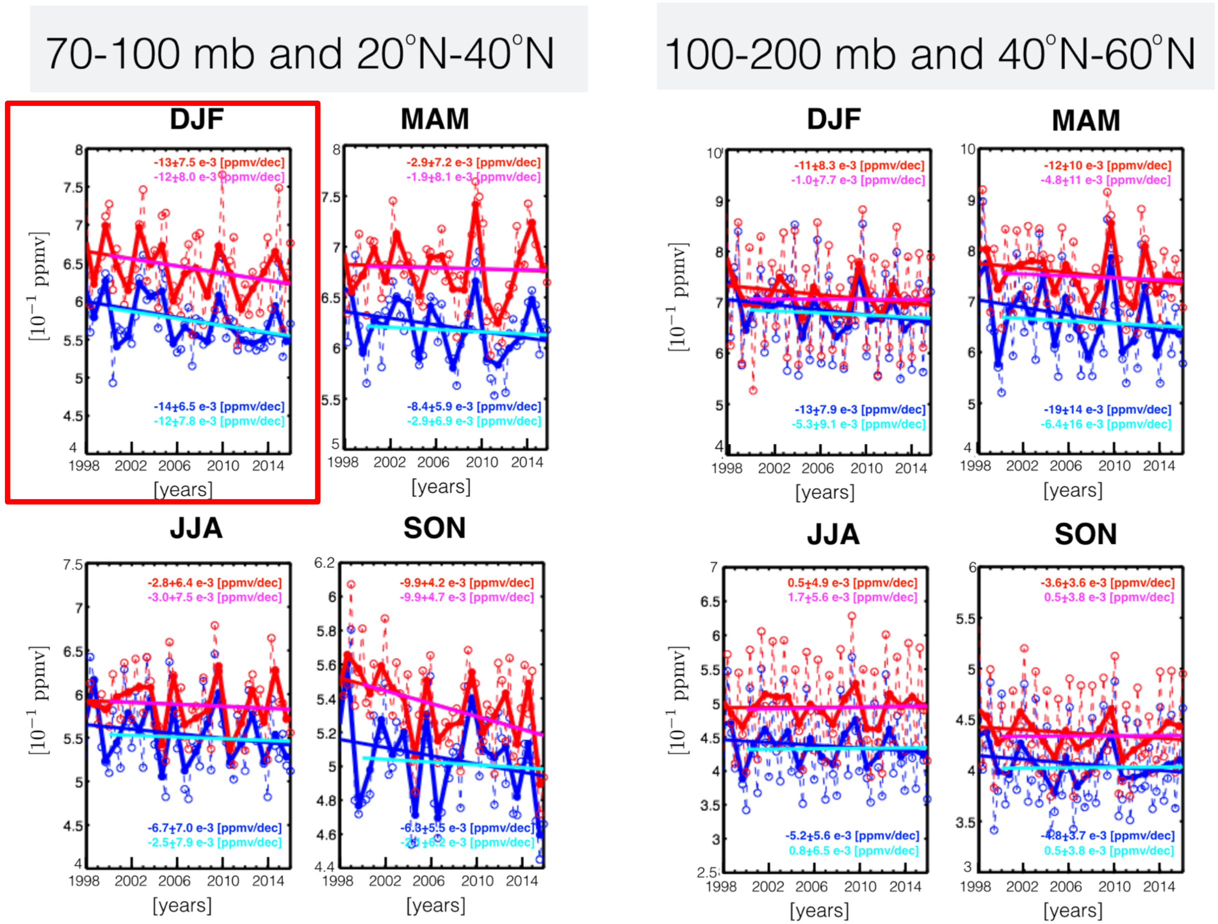
Experiments and methods

- The **MERRA-2** reanalysis (1998–2016)
- **M2GMI**: Specified dynamics (SD) Global modeling Initiative (GMI) constrained by the MERRA-2 Meteorology (1º resolution)
- **FRSCM**: An ensemble of free-running model simulations constrained by observed SSTs, GHGs, and ODSs, using a stratospheric chemistry model, StratChem
- **FRGMI**: as above but using the GMI chemistry model
- **Long-term changes calculated as simple linear fits**



McCarty et al., 2016

Seasonal Mean Ozone in M2GMI (−,−) and MERRA-2 (−,−) over NH Lower Stratosphere

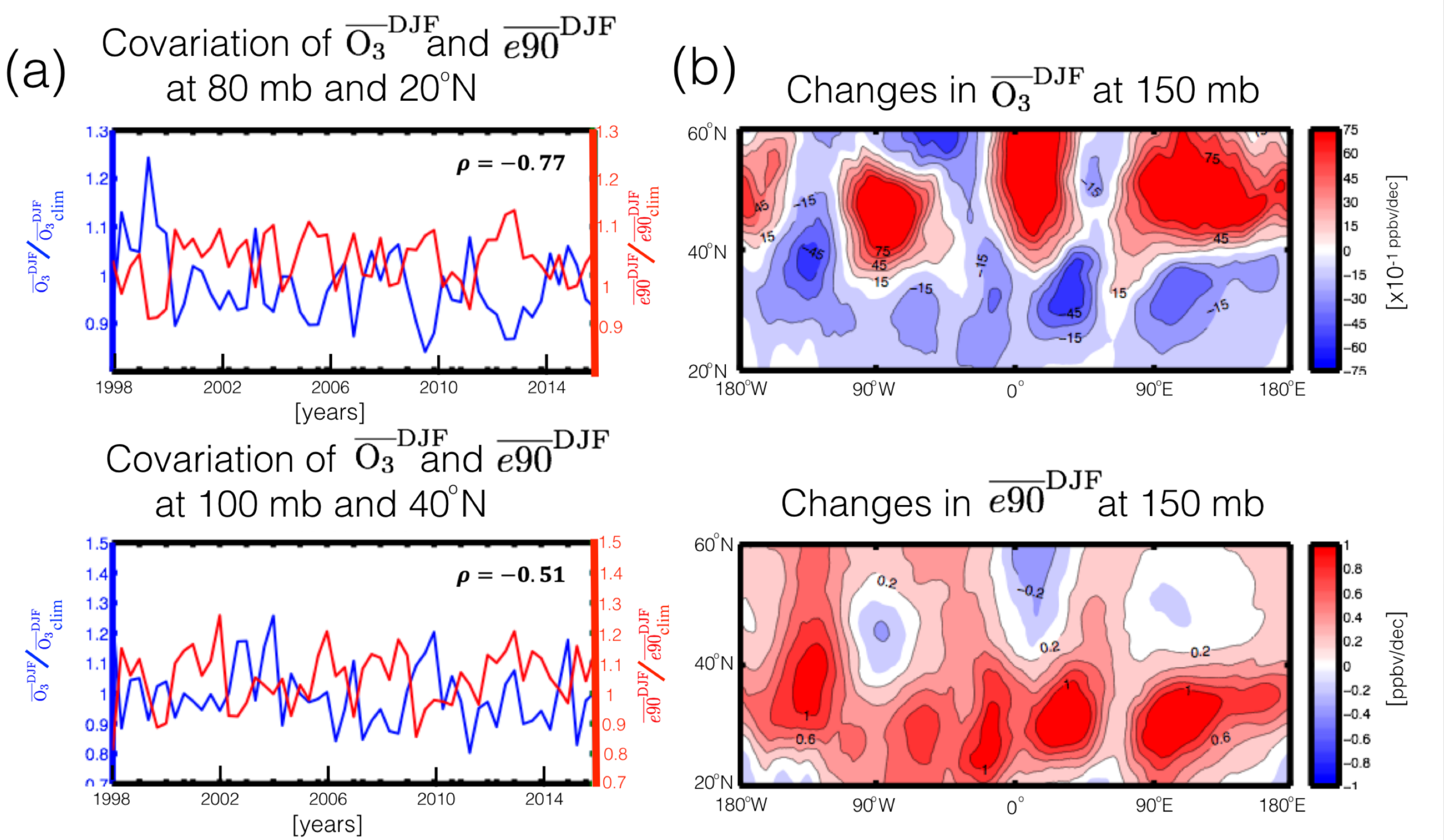


Good agreement between MERRA-2 ozone and M2GMI in terms of interannual variability. This is not obvious: many studies report systematic transport errors in simulations constrained by assimilated meteorology (overview in *Orbe et al. 2017*)

The steepest ozone decline in the NH extratropical lower stratosphere is seen in boreal winter (DJF) in the subtropics. Focusing on that time and region

Orbe et al., 2020

Covariability of Ozone and e90 in M2GMI



Orbe et al., 2020

The idealized tracer, e90:

- Uniform source at the surface
- Uniform sink everywhere in the atmosphere with a 90-day e-folding time

e90 as a (anti)proxy for ozone:

Anticorrelations seen in

- Interannual variability
- Spatial distribution of trends

We look at e90 transport

Transformed Eulerian Mean (TEM) tracer budget

$$\bar{\chi}_t = -\bar{v}^*\bar{\chi}_y - \bar{w}^*\bar{\chi}_z + e^{z/H}\nabla\cdot M - \bar{L} + \bar{X}$$

Mean tracer tendency

Advection by mean residual circulation

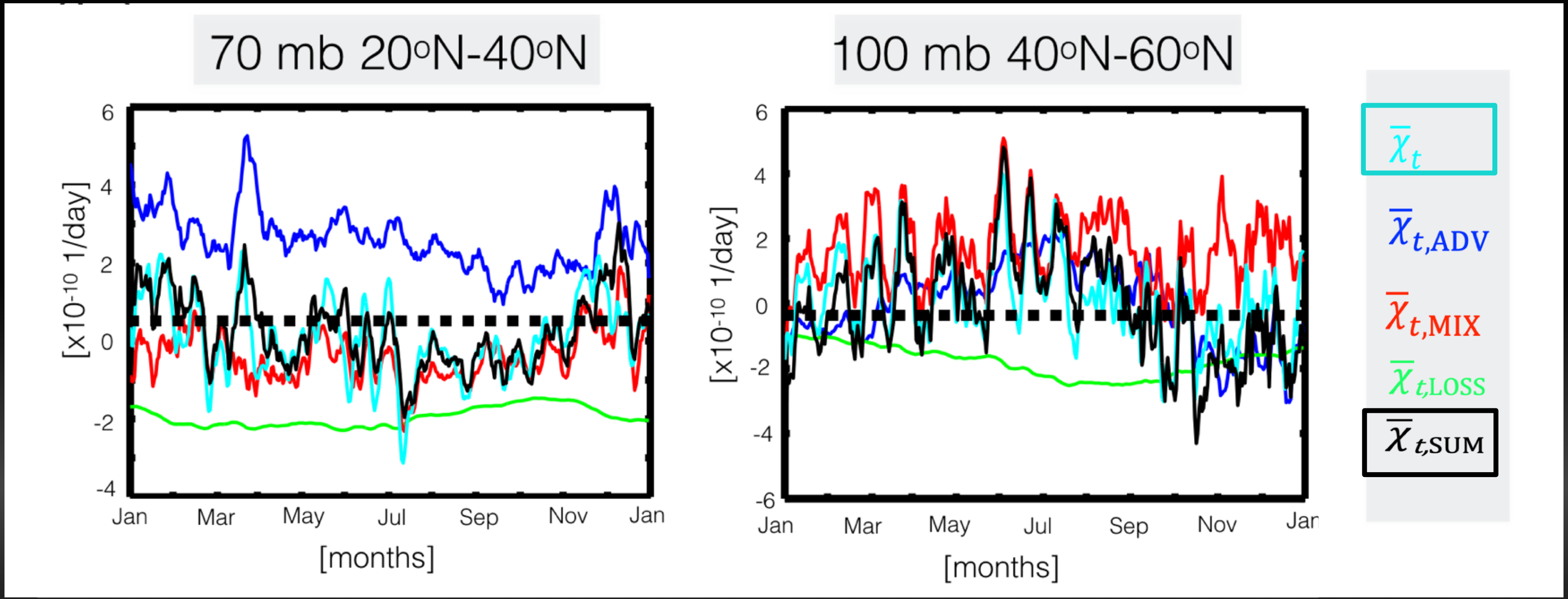
mixing

Loss and subgrid-scale processes

$$M = -e^{-\frac{z}{H}}\left(\overline{v'\chi'} + \frac{\overline{v'T'}}{S}\bar{\chi}_z,\ \overline{w'\chi'} - \frac{\overline{v'T'}}{S}\bar{\chi}_y\right)$$

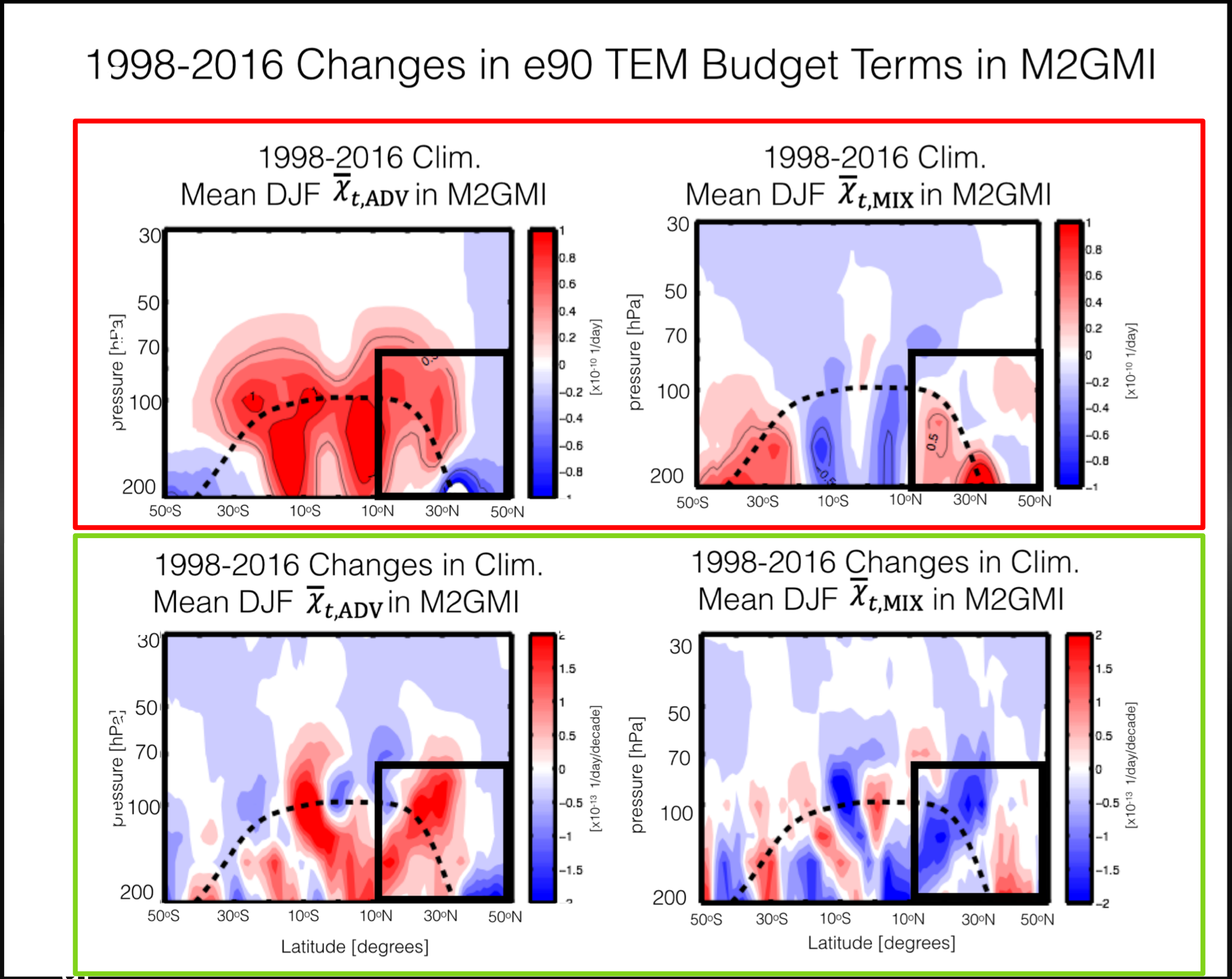
horizontal

vertical



Orbe et al., 2020

- The budget closes very well in the lower stratosphere
- Near-cancelation between the advective and loss terms dominates between 20°N and 40°N

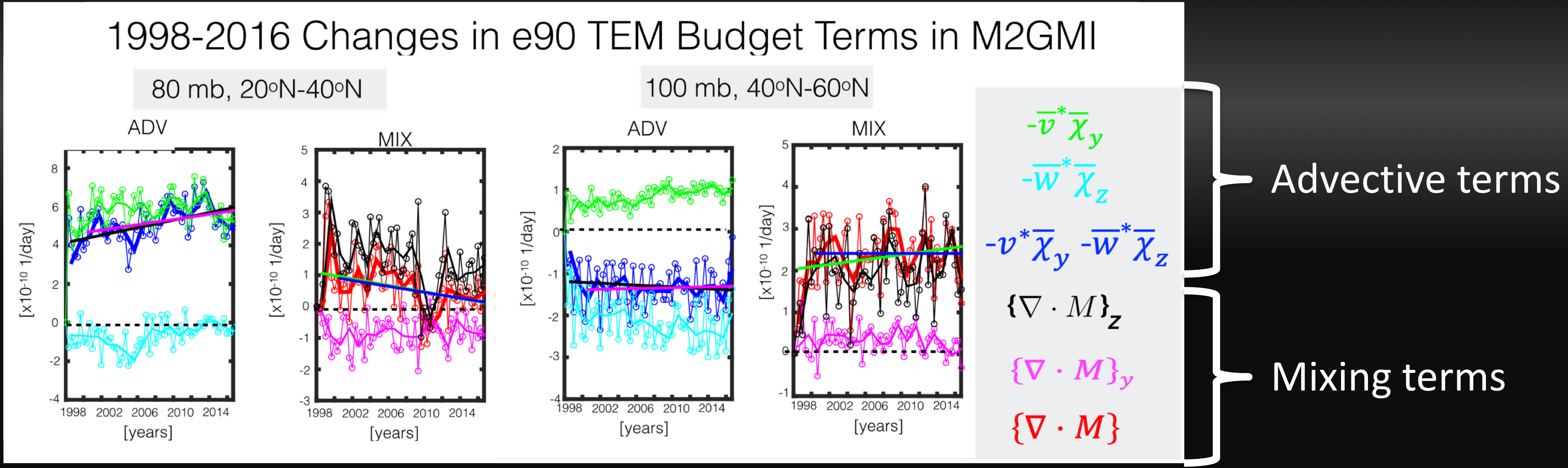


- The advective term dominates over mixing

- Long-term changes exist in both terms
- Changes in mixing and advection nearly cancel each other – but not completely

Orbe et al., 2020

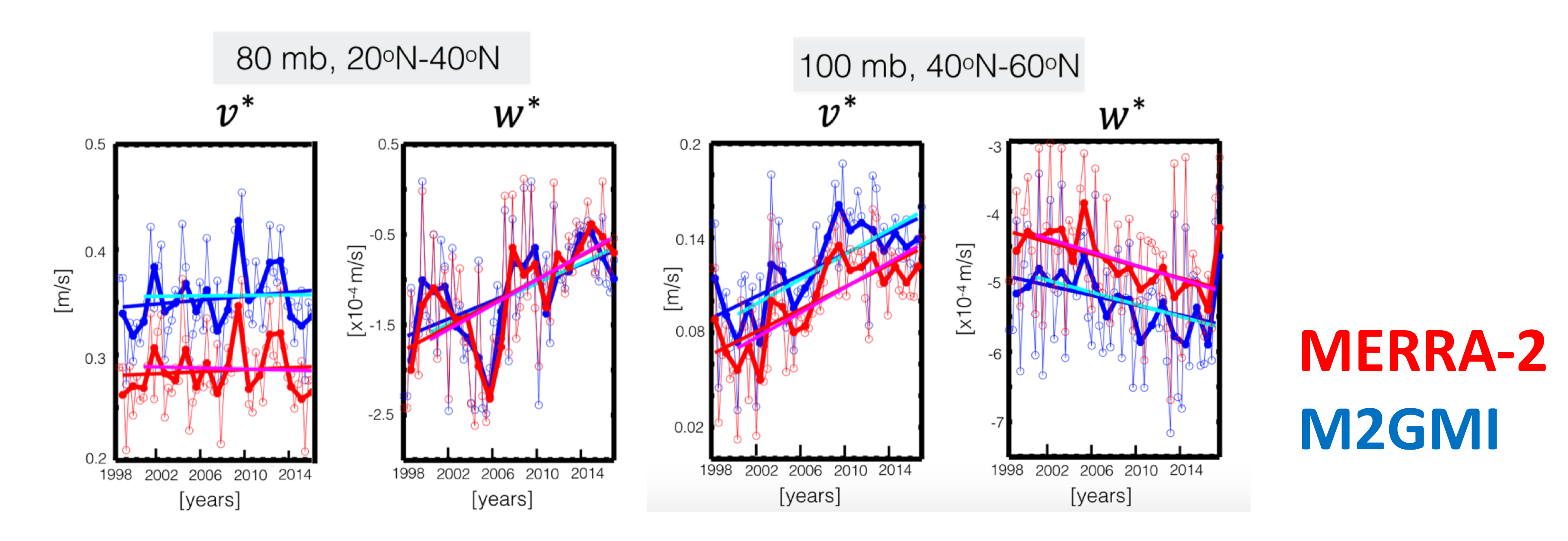
- Long-term changes in the e90 budget are dominated by changes in the (vertical and horizontal) advective component, rather than mixing
- Evidence of an expansion of the residual circulation:
  - Subtropics: enhanced meridional and reduced vertical e90 advection
  - Midlatitudes: enhanced downwelling



Orbe et al., 2020

Taking a step back: the residual circulation

- Increasing v* in the subtropics and midlatitudes
- Increasing w* in the subtropics (weakening downwelling); decreasing w* at midlatitudes (strengthening downwelling)
- Again, a remarkable consistency between the reanalysis and the reanalysis-driven simulation; not obvious!



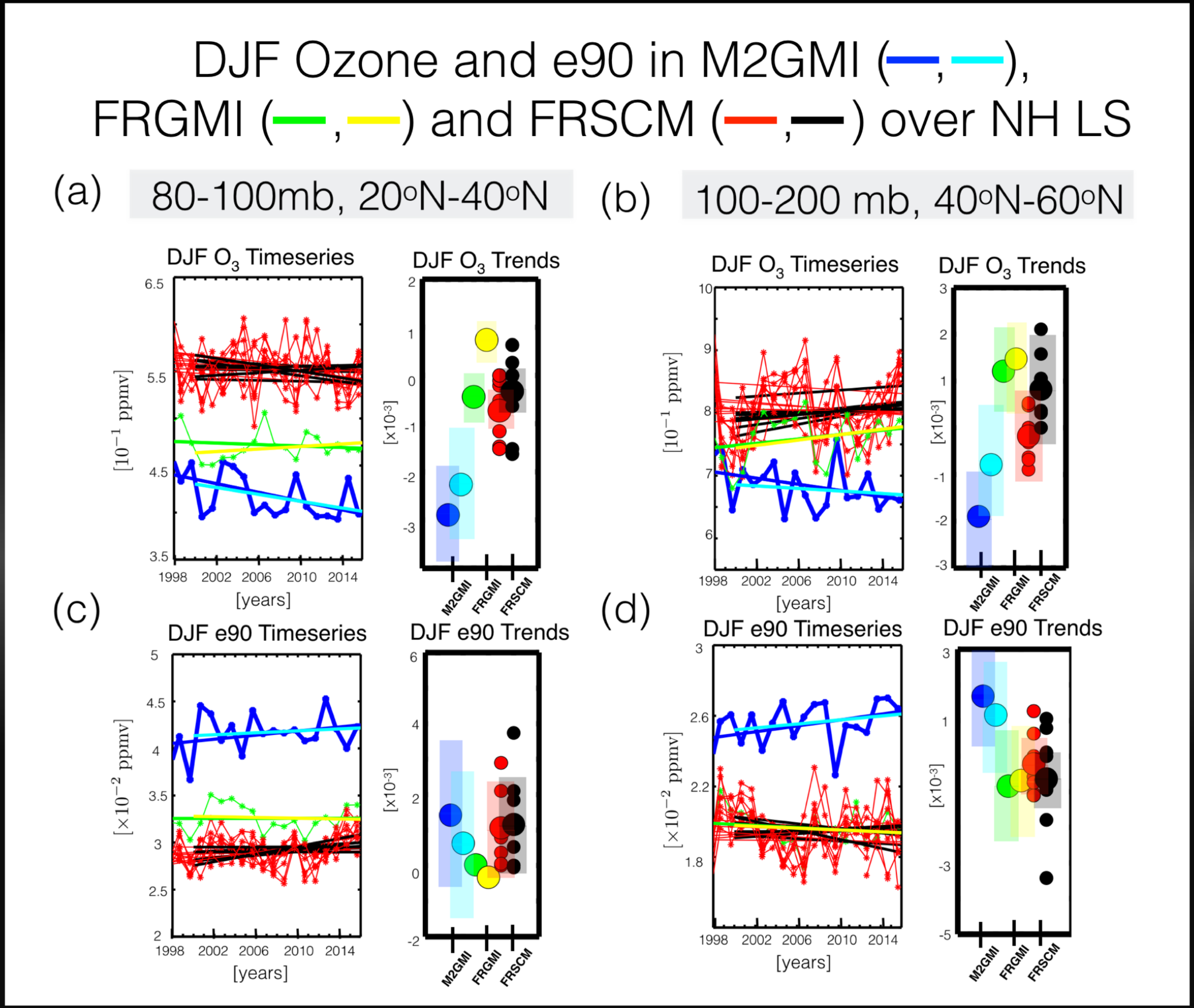
Orbe et al., 2020

Consistent with a widening of the Hadley cell

Summary so far

- MERRA-2 driven simulation produces negative ozone changes over 1998–2016, consistent with MERRA-2 and observations
- The decreases in ozone are largest in boreal winter and are associated mainly with an increased TEM advection in the NH subtropics as part of a broader expansion of the TEM circulation in the lower stratosphere

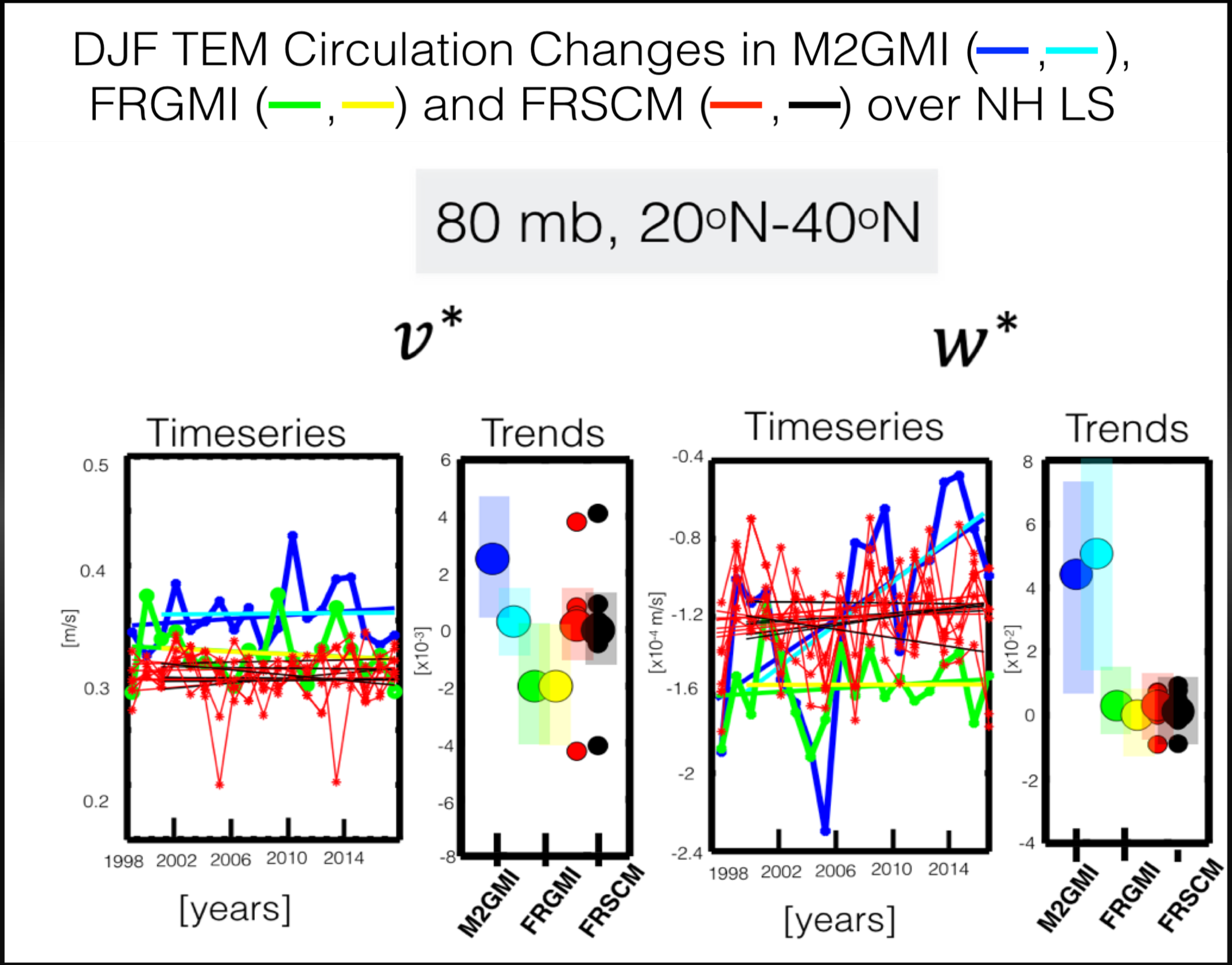
Do CCM free-running simulations reproduce this behavior?



- Some of the free-running simulations do produce negative ozone changes over the same period <u>but the magnitude is much smaller than in the reanalysis and M2GMI</u>
- Analogous conclusion holds for e90.

Changes calculated for 1998–2016 & 2000–2016

Orbe et al., 2020

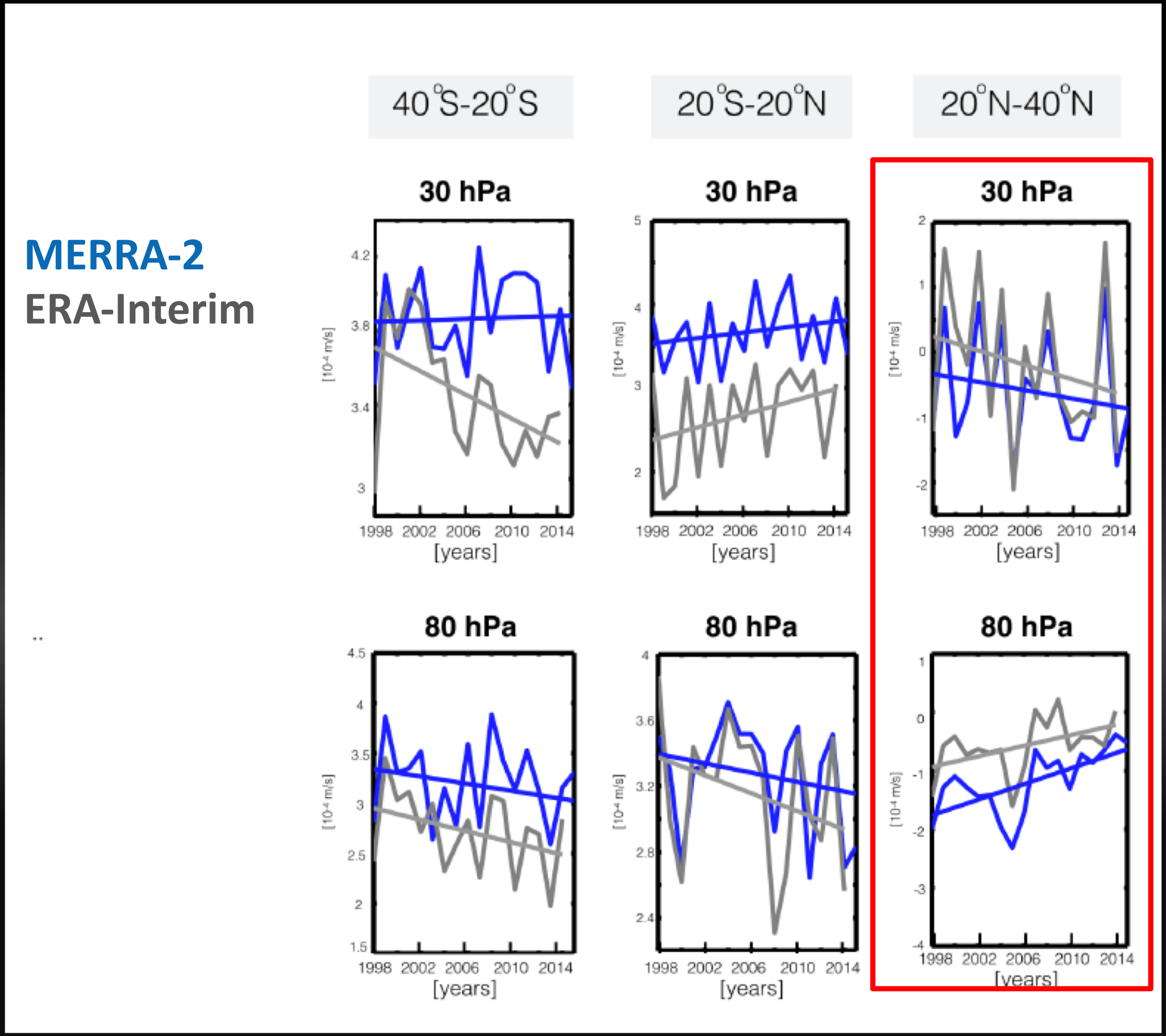


Similarly, the changes in the residual circulation, particularly w*, in MERRA-2 and (MERRA-2-driven) M2GMI are outside the range of those in the free-running simulations

Changes calculated for 1998–2016 & 2000–2016

Orbe et al., 2020

What about other reanalyses?

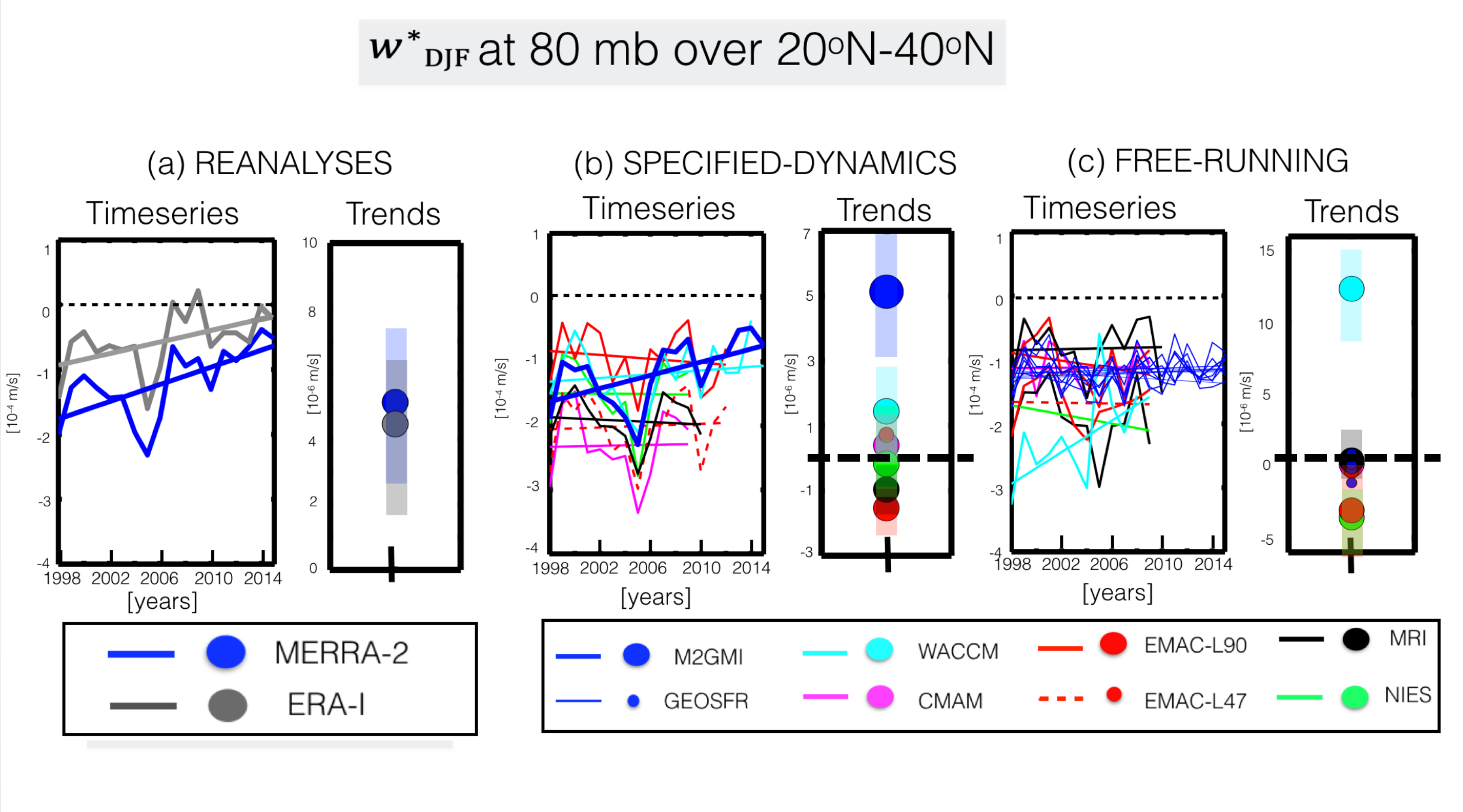


There is not always an agreement between the residual circulation in reanalysis. MERRA-2 and ERA-I disagree in the SH

But

They agree well in the region of interest

Orbe et al., 2020



Orbe et al., 2020

What about other reanalyses and model simulations?

Significant decrease in downwelling (MERRA-2, ERA-I) not present in free-running simulations (with real SSTs & GHG), and not present in most SD CCMI simulations except in the MERRA-2 replay (M2GMI).

- Note that the replay methodology (M2GMI) is differs from nudging used by other SD simulations
- Results above are consistent with WACCM-SD not showing negative ozone change in the LS (Ball et al. 2018)

Latitudinal expansion of the upwelling component of the residual circulation

→ Enhanced mean advection transports ozone-poor air into the subtropics and midlatitudes

→ Negative ozone change 1998-2016(2018)

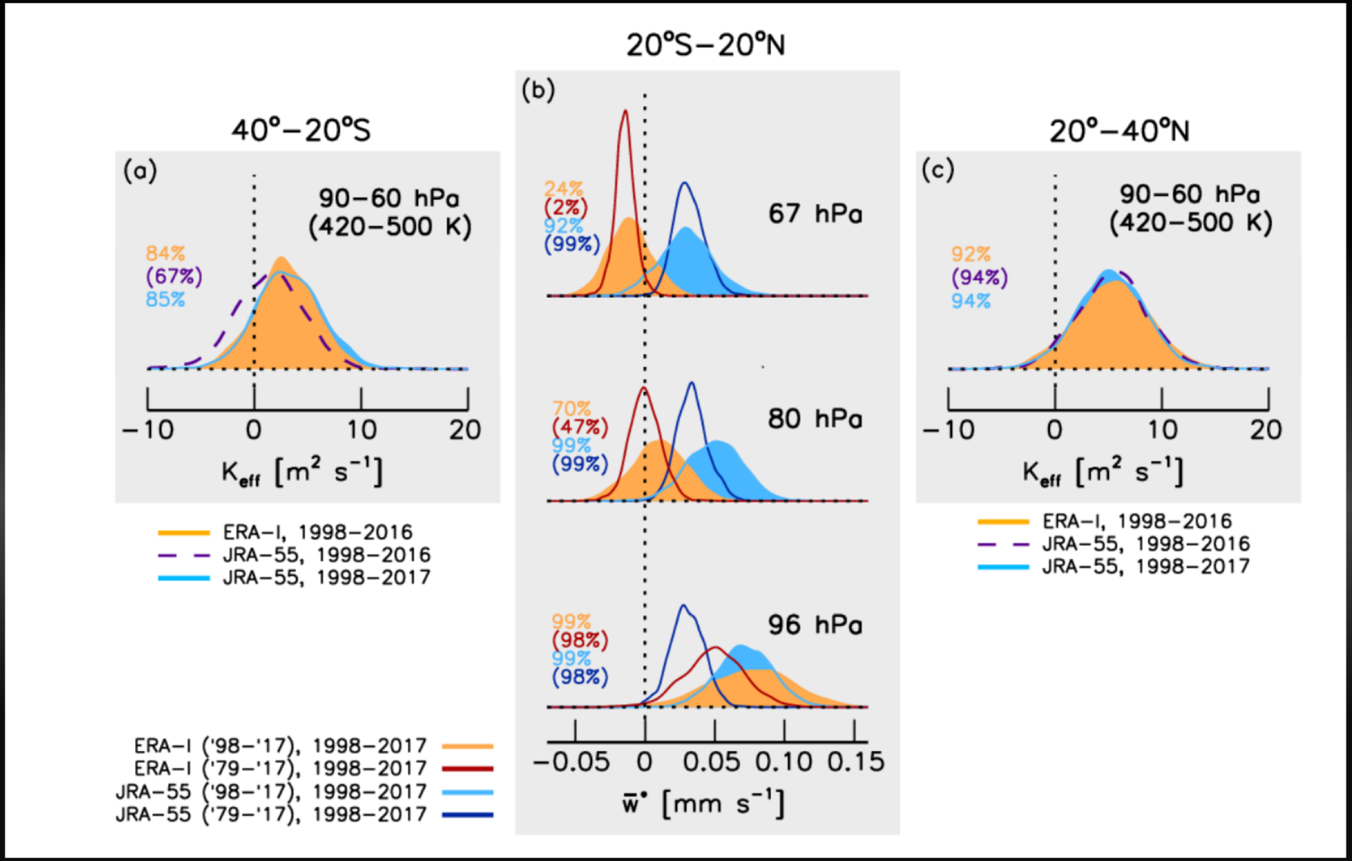
Giving credence to…

Corroborated by satellite data and reanalysis

Key elements

- Ozone variability in agreement between reanalysis (and data) and specified dynamics simulations constrained by MERRA-2 via the replay methodology
- The use of an idealized transport tracer, e90

Some discussion

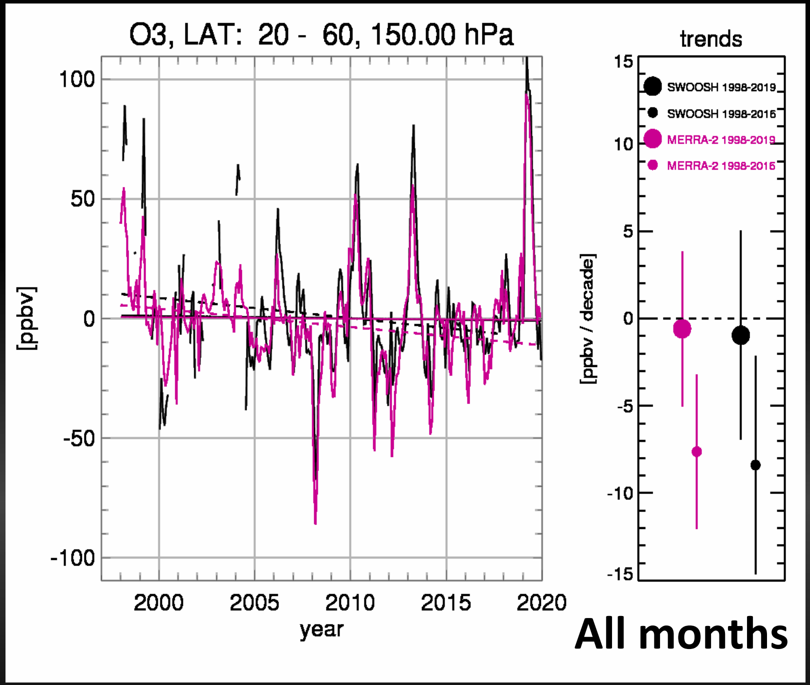


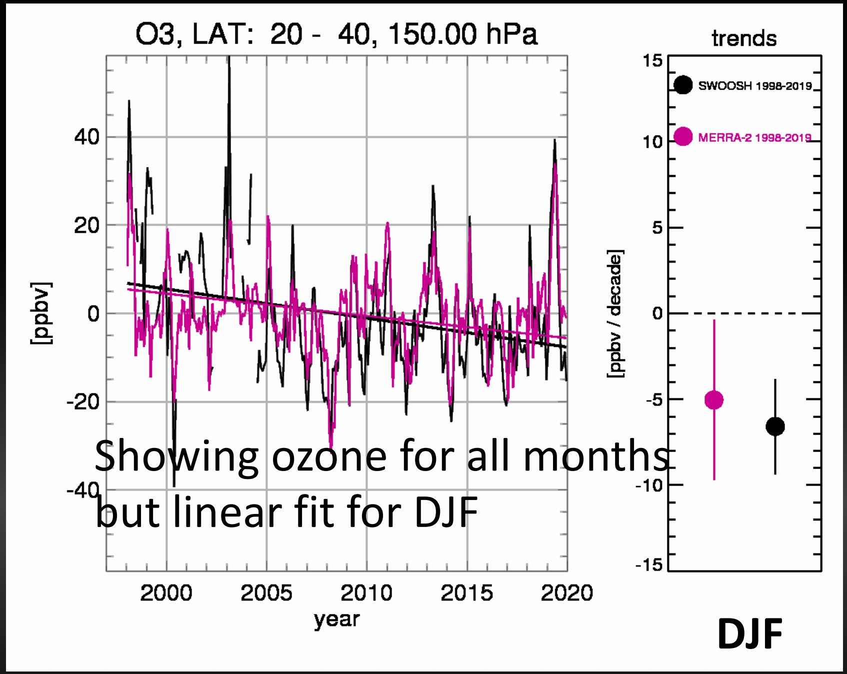
Ball et al., 2019 ACPD

Ball et al. 2019(2020), ACPD demonstrates increased tropical upwelling in the tropics and increased mixing in the subtropics, consistent with Wargan et al. 2018.
Is it at odds with our result (the advective component rather than mixing ha been changing)?

Our definition of mixing (vis TEM budget) is different than theirs (effective diffusivity).

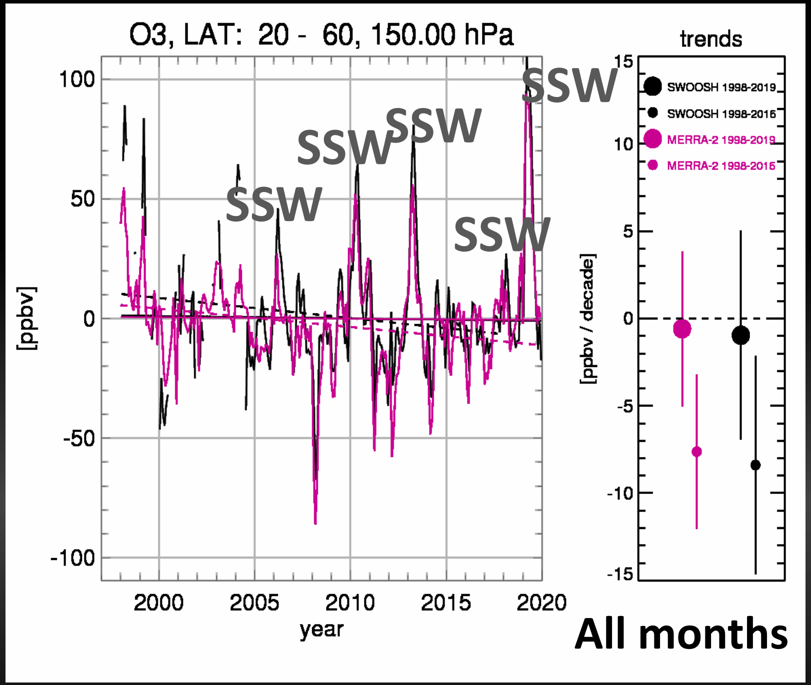
Some discussion

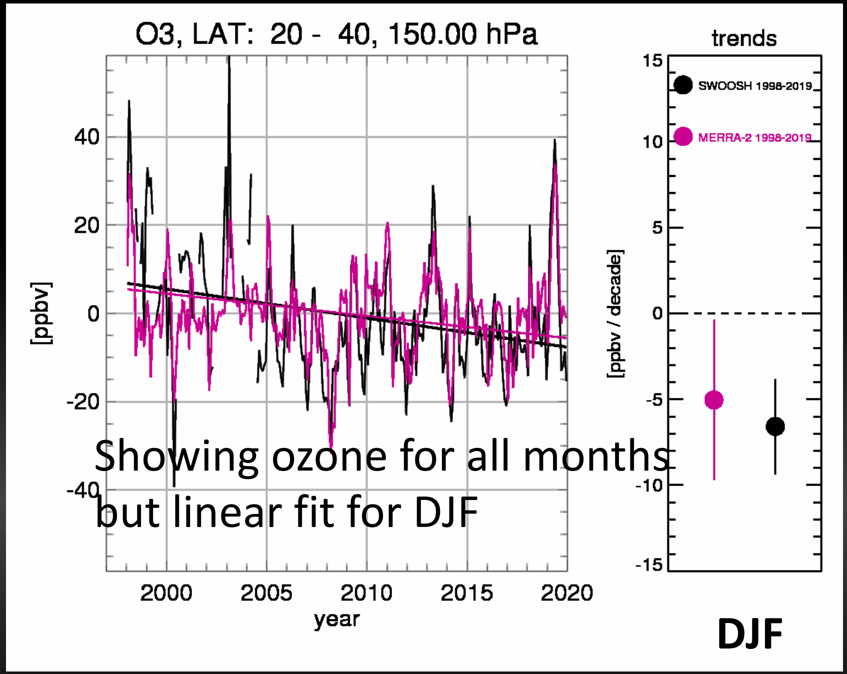




- Very large spike in 2019 (not considered in literature); 1998–2019 ozone change no longer significant in MERRA-2 and SWOOSH.
- <u>But 20ºN–40ºN DJF change discussed here remains significant!</u>

Some discussion





- Very large spike in 2019 (not considered in literature); 1998–2019 ozone change no longer significant in MERRA-2 and SWOOSH.
- <u>But 20ºN–40ºN DJF change discussed here remains significant!</u>
- All large positive excursions since 2006 coincident with major SSWs (converse not true)
- <u>Need to include the effects of SSWs on subtropical/midlatitudinal ozone in these analysis</u>

Summary

- Evidence of negative ozone change in the extratropical LS, 1998–2018; most pronounced in the subtropics in DJF
- This change is consistent with a weaker downwelling in the subtropics – expansion of the upwelling component of the residual circulation
- Forced changes or internal variability? Still an open question
- These features are clear in reanalyses but not seen (or much weaker) in models, including SD simulations, consistent with *Ball et al. 2018 & 2019*

Mechanisms Linked to Recent Ozone Decreases in the Northern Hemisphere Lower Stratosphere

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