# Multidecadal changes in the UTLS ozone from the MERRA-2 reanalysis and the GMI chemistry model

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# Introduction

- Historically, reanalyses were not considered suitable for trend studies because of step-changes in their observing systems
- But that's no different than looking at trends using diverse observations: one needs to account for the discontinuities

**Here, we are using the MERRA-2 reanalysis to study lower stratospheric ozone trends between 1998 and 2016**

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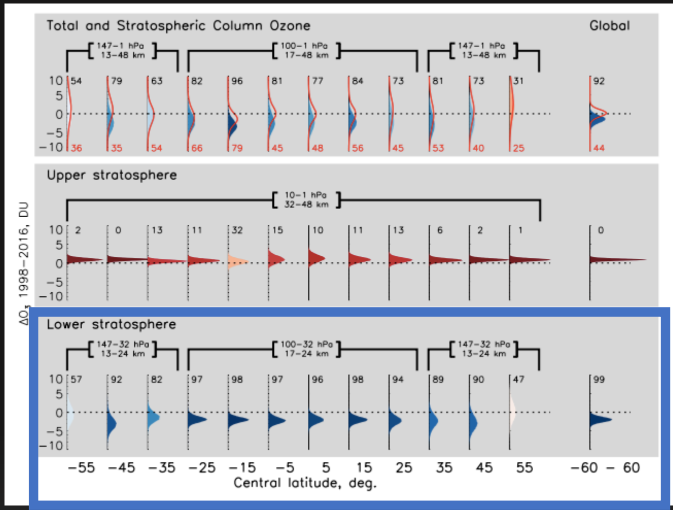
# Motivation




Ball et al., 2018 found a negative ozone trend in the lower stratosphere in observations.

What can we say about this using models and reanalyses?

- Can we confirm it?
- Mechanisms…?

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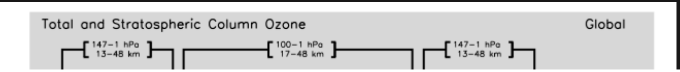


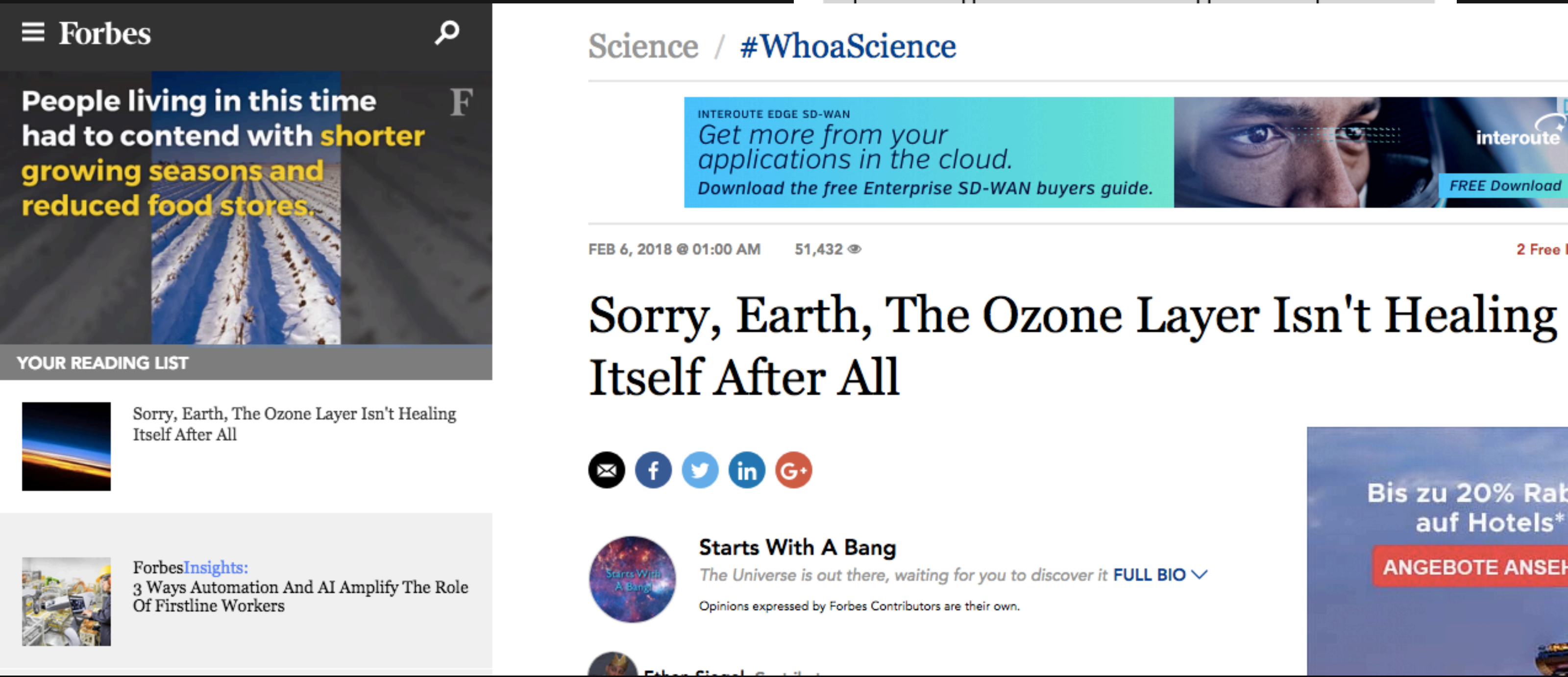


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# "Data sets"

- **MERRA-2 (The Modern-Era Retrospective Analysis for Research and Applications)**
  - GEOS atmospheric general circulation model
  - Meteorology is constrained by radiance and conventional observations
  - Ozone assimilated from SBUV sensors (1980-2004) followed by OMI total ozone and MLS stratospheric profiles (2004–present)

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- **M2-GMI (MERRA-2 Global Modeling Initiative) simulation**
  - GEOS Replay simulation for the 1980-2016 constrained by MERRA-2 U, V, T, P
  - full Stratospheric and Tropospheric chemistry from the Global Modeling Initiative (GMI) chemical mechanism; **ozone is NOT assimilated**
  - Also includes a suite of idealized tracers for transport studies

**All three are run at 0.625° x 0.5° resolution, have well-resolved ozone consistent with assimilated meteorology. A full set of meteorological fields can help interpret the behavior of tracers**

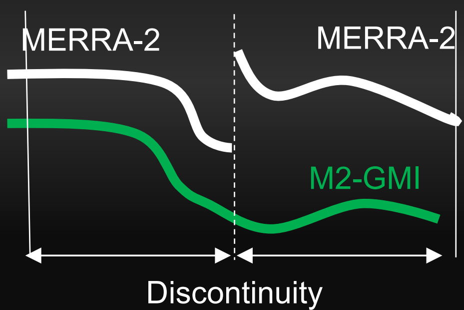
# Dealing with discontinuities

## Main relevant discontinuities in the MERRA-2 observing system

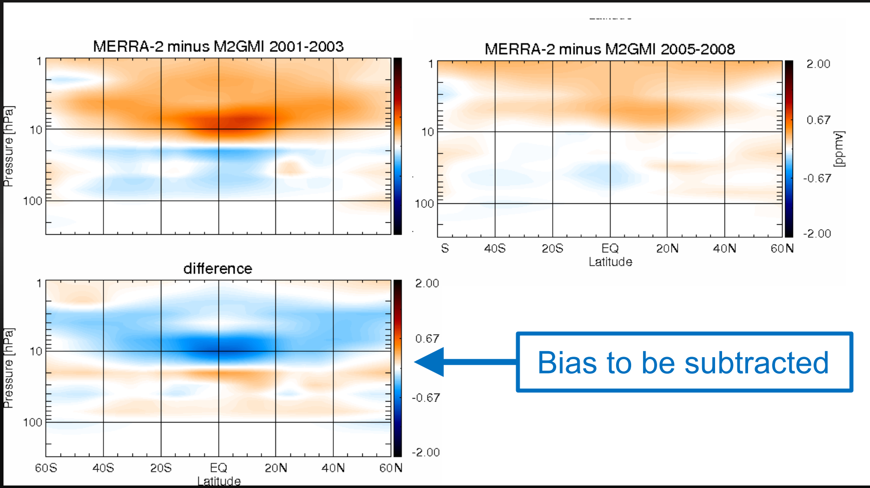
1998 — 2001 — 2004 — 2007 — 2011 — 2014 — 2017

- 1998: **Introduction of AMSU radiances: Not evaluating trends before 1998**
- 2004: **Introduction of MLS and OMI data**
- 2014: **MLS V2.2 replaced with v4.2**

## Using M2-GMI to bias correct MERRA-2



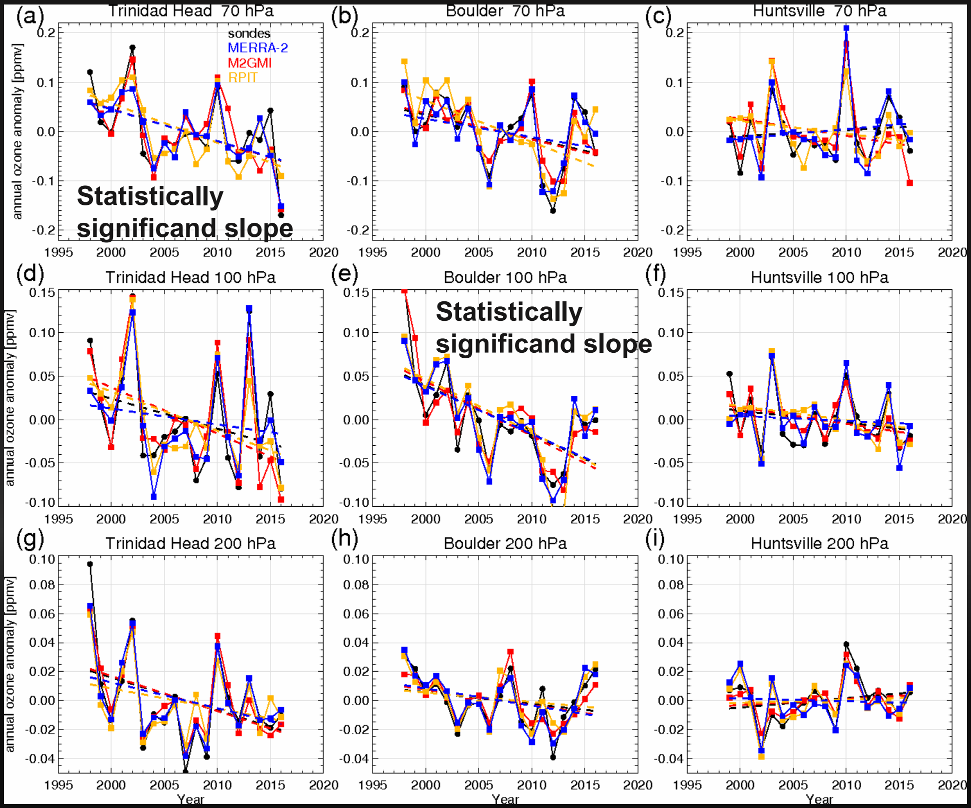

## Results for the SBUV→ Aura switch in 2004




**Bias correction is applied to all major step changes in MERRA-2 and GEOS-RPIT**

# Comparison with selected ozonesondes

## Annual mean anomalies: ozonesondes, MERRA-2, M2-GMI and GEOS-RPIT




The sonde data are reprocessed with the Skysonde algorithm [*Sterling et al., 2017*] to account for changes affecting long-term records
[ftp://aftp.cmdl.noaa.gov/data/ozwv/Ozonesonde/](ftp://aftp.cmdl.noaa.gov/data/ozwv/Ozonesonde/)

Good overall agreement between MERRA-2, M2-GMI, GEOS-RPIT and the sondes.

Large interannual variability dominates but simple linear fit has negative slopes at Trinidad Head and Boulder.

MERRA-2 ozone compares well with independent data in the LS [*Wargan et al., 2017*]

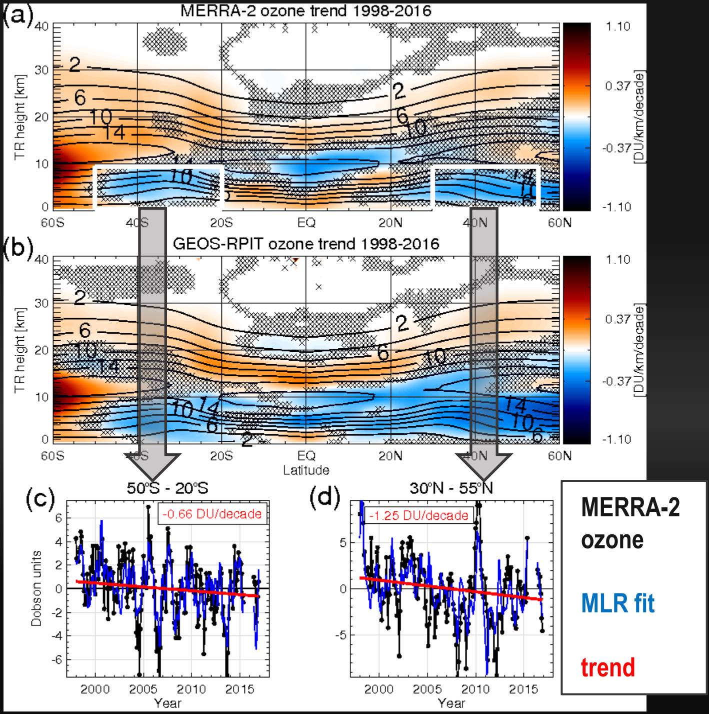
# Ozone trends

$$y(t) = \alpha_0(t) + \alpha_1(t)t + \alpha_2(t)QBO_1(t) + \alpha_3(t)QBO_2(t) + \alpha_4(t)TSI(t) + \alpha_5(t)MEI(t) + \alpha_6(t)AERO(t) + \epsilon(t)$$

$$\alpha(t) = c + \sum_{k=1}^{2} a_k \cos\frac{2k\pi t}{12} + b_k \sin\frac{2k\pi t}{12}$$ Seasonal cycle included in all coefficients

- MERRA-2 and GEOS-RPIT have similar trend patterns:
  - Positive in the middle and upper stratosphere
  - Negative in the 0-10 km layer (above the tropopause) at midlatitudes
  - Alternating (positive/negative) in the tropics
- -0.66 DU/decade in the SH and -1.25 DU/decade in the NH midlatitudes
- The trends are small compared to interannual variability
- The MLR (blue) is doing a good job reproducing the ozone evolution (black)

**Ozone trends in Dobson units/km/decade in tropopause-relative coordinates**

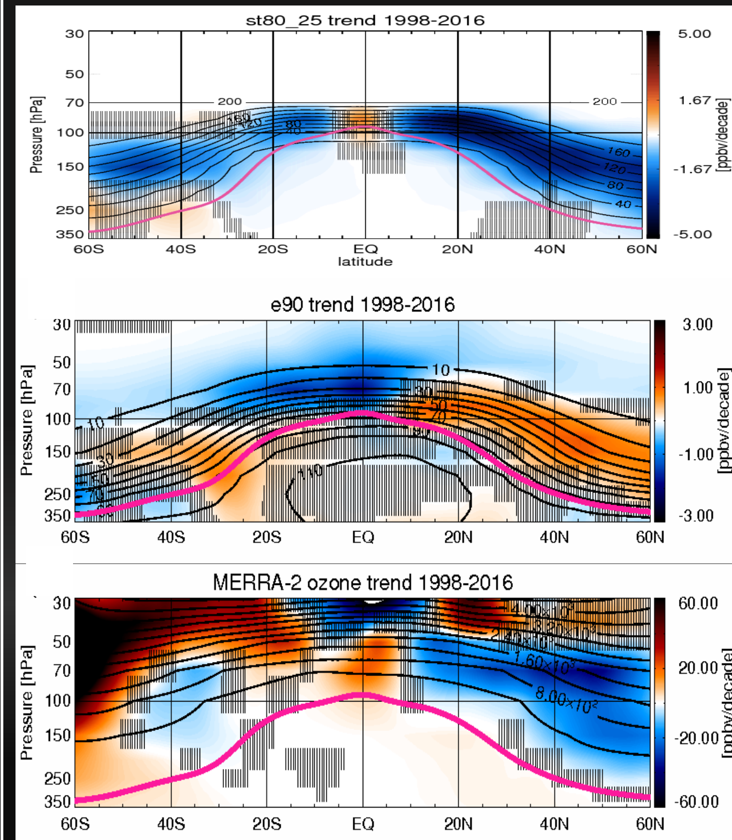


# This is what we have so far

After correcting for step-changes in the observing system, MERRA-2 and GEOS-RPIT show negative ozone trends in the lower stratosphere (LS) at midlatitudes in agreement with Ball et al., 2018

So what's going on here?

# Idealized tracers in M2-GMI




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

**e90**: Source at the surface 90-day e-folding loss everywhere

**MERRA-2 ozone: transport and chemistry**

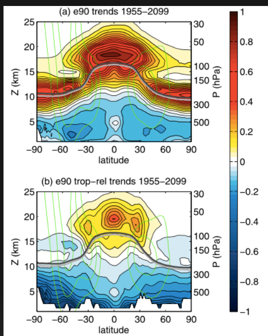
In the lower stratosphere the st80_25, ozone and e90 trend patterns are **remarkably similar** (but with the opposite sign for e90, as expected from reversed gradients)

- Stronger and reaching further in the northern hemisphere
- Tropical-extratropical dipole
- Trends extend into the upper troposphere in the southern hemisphere

This suggest that the ozone trend pattern is also likely driven by changes in the LS circulation

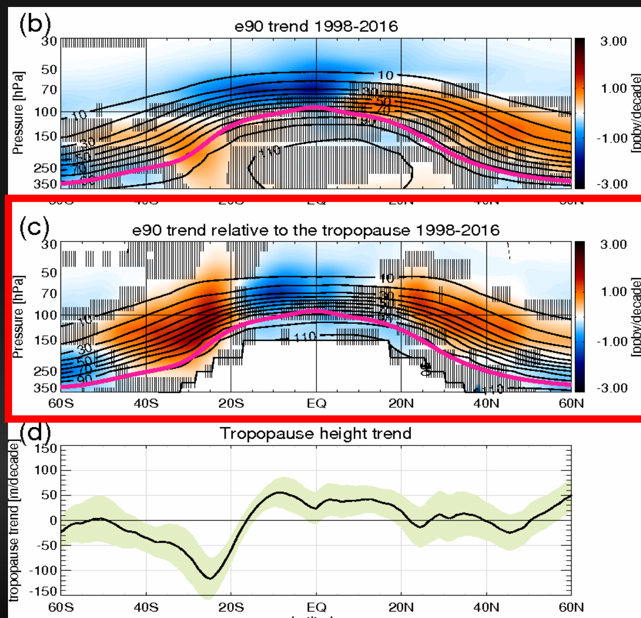
# Idealized tracers in M2-GMI

## Can this trend pattern arise from changes in the tropopause height?




An upward shift of the tropopause results in a positive e90 anomaly in the lower stratosphere

***Abalos et al., 2017***

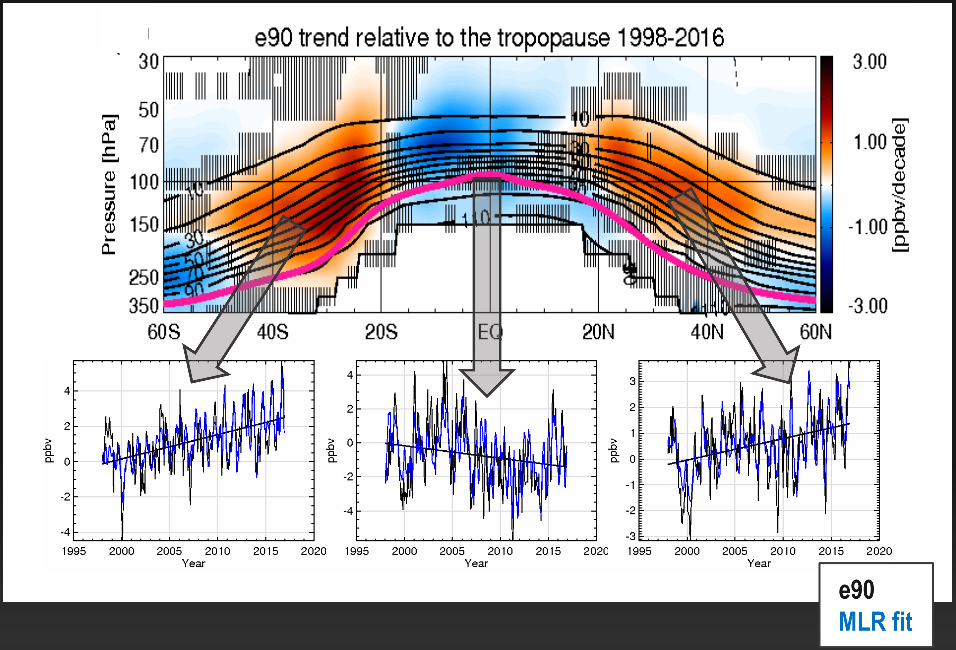



Zonal mean in pressure coordinates

In tropopause-relative coordinates: The effect of tropopause shifts is removed in tropopause-relative coordinates.

**The remaining trends must be due to changes in the LS circulation**

# Putting it all together

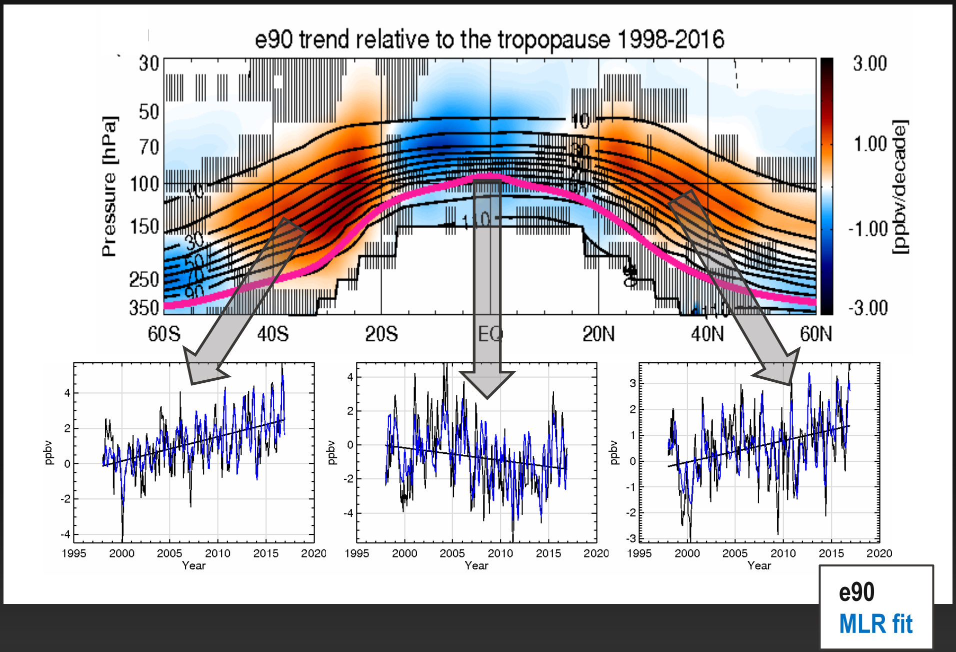


# Putting it all together

LS transport is controlled by the shallow branch of the BDC:

- Advection by the residual circulation
- Two-way quasi-isentropic transport

Both driven by synoptic wave breaking



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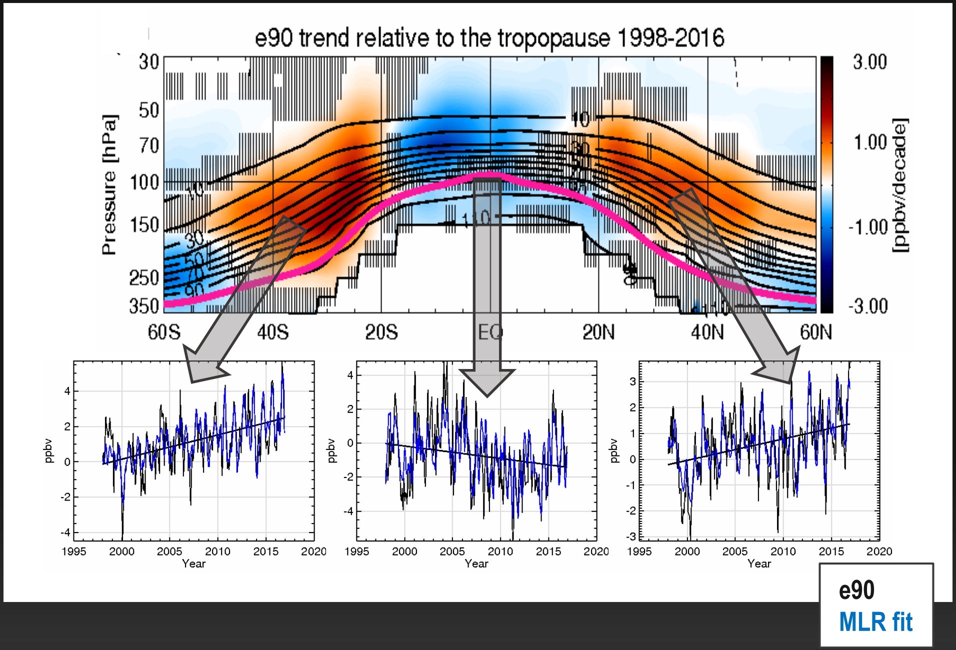

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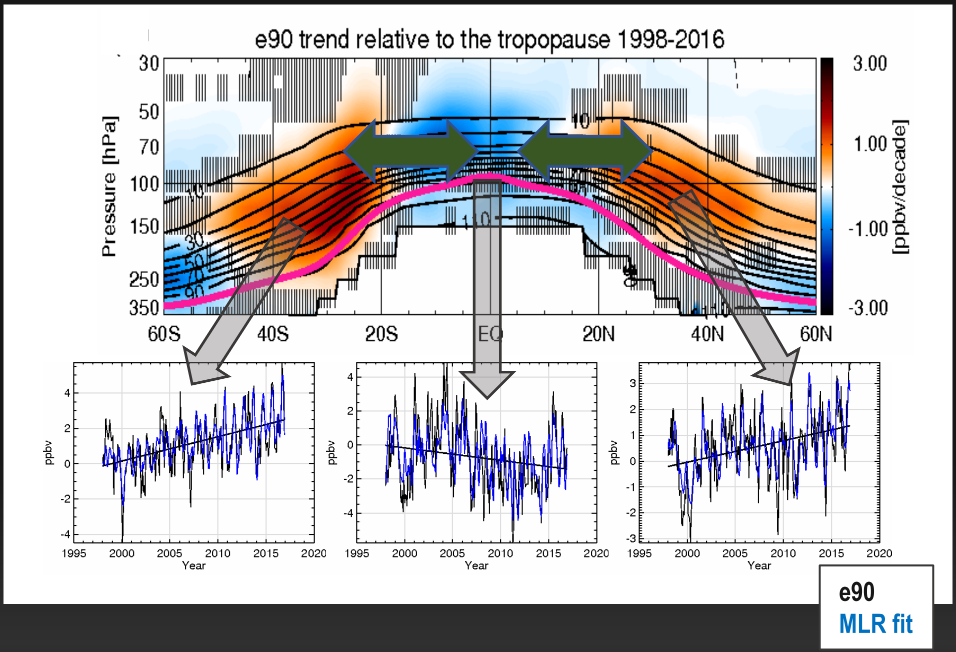
The e90 trend pattern implies an intensification of two-way transport as the dominant mechanism for this tracer




**The same mechanism would lead to the observed lower stratospheric ozone trends between 1998-2016**

# Conclusions

- After correcting for step-changes in the observing system, MERRA-2 shows negative ozone trends in the lower stratosphere (LS) at midlatitudes in agreement with Ball et al., 2018
- The evolution of idealized tracers in the specified dynamics M2-GMI simulation strongly suggests an intensification of two-way transport in the LS as the likely mechanism
- This is the first step towards a comprehensive use of modern reanalyses to ozone trend studies; much more work to be done

*Wargan et al., 2018, Recent decline in lower stratospheric ozone attributed to circulation changes, submitted to GRL*

# backup

# Some items to think about

- To make the argument more quantitative we need to find a good way to calculate tracer budgets from simulations/reanalysis with assimilated meteorology (an elusive goal so far)

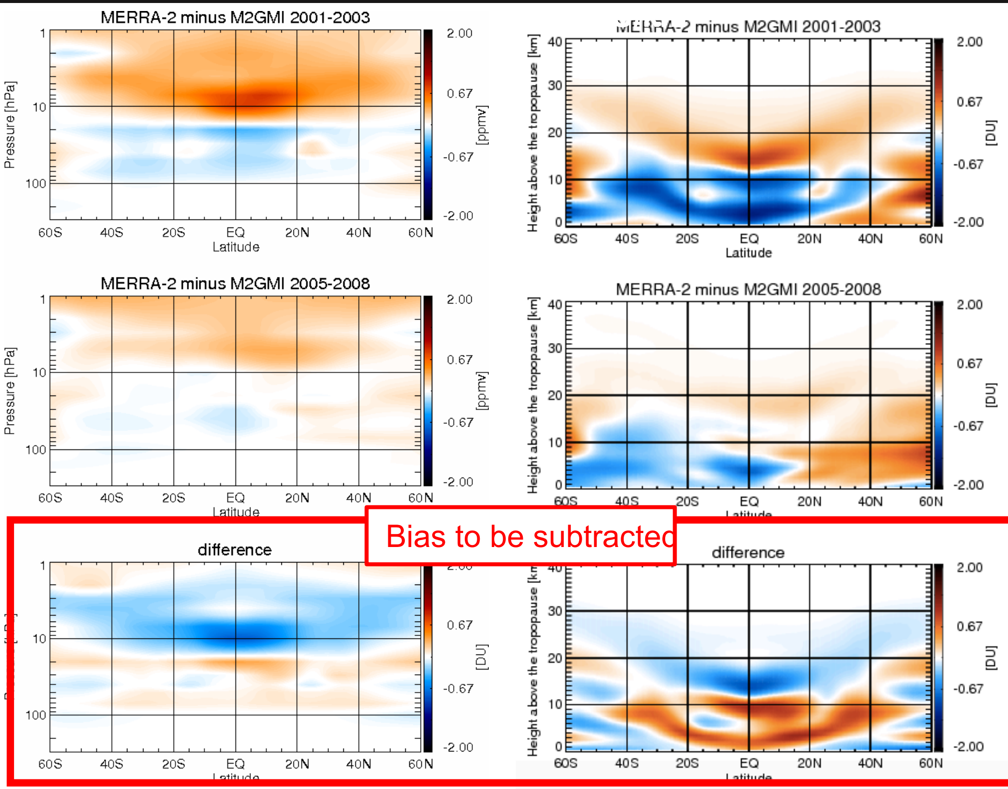
- What are the effects of step-changes in radiance observations in MERRA-2 on tracer transport?
  - Extending the analysis back to 1980: how to deal with the major discontinuity in 1998 (introduction of microwave observations from AMSU)?
  - Can these step-changes have an impact on transport that lasts for several years? What is the magnitude of that effect?

- We may be able to confirm (or disprove) an intensification of two-way mixing in further analyses of tracer observations in the LS seen in the M2-GMI simulation

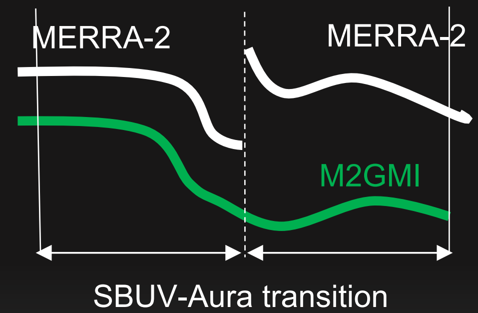
- Beyond the zonal mean: 3-D analysis

# Bias-correcting (homogenizing) the reanalysis

**On pressure levels [ppmv]** **Tropopause-relative**




## Using M2-GMI to bias correct MERRA-2




## Using MLR with a step function prox