Evaluation of Stratospheric Temperature Trends from MW+IR Sounders, GPS RO and Reanalysis using Nonparametric Multivariate Regression Techniques

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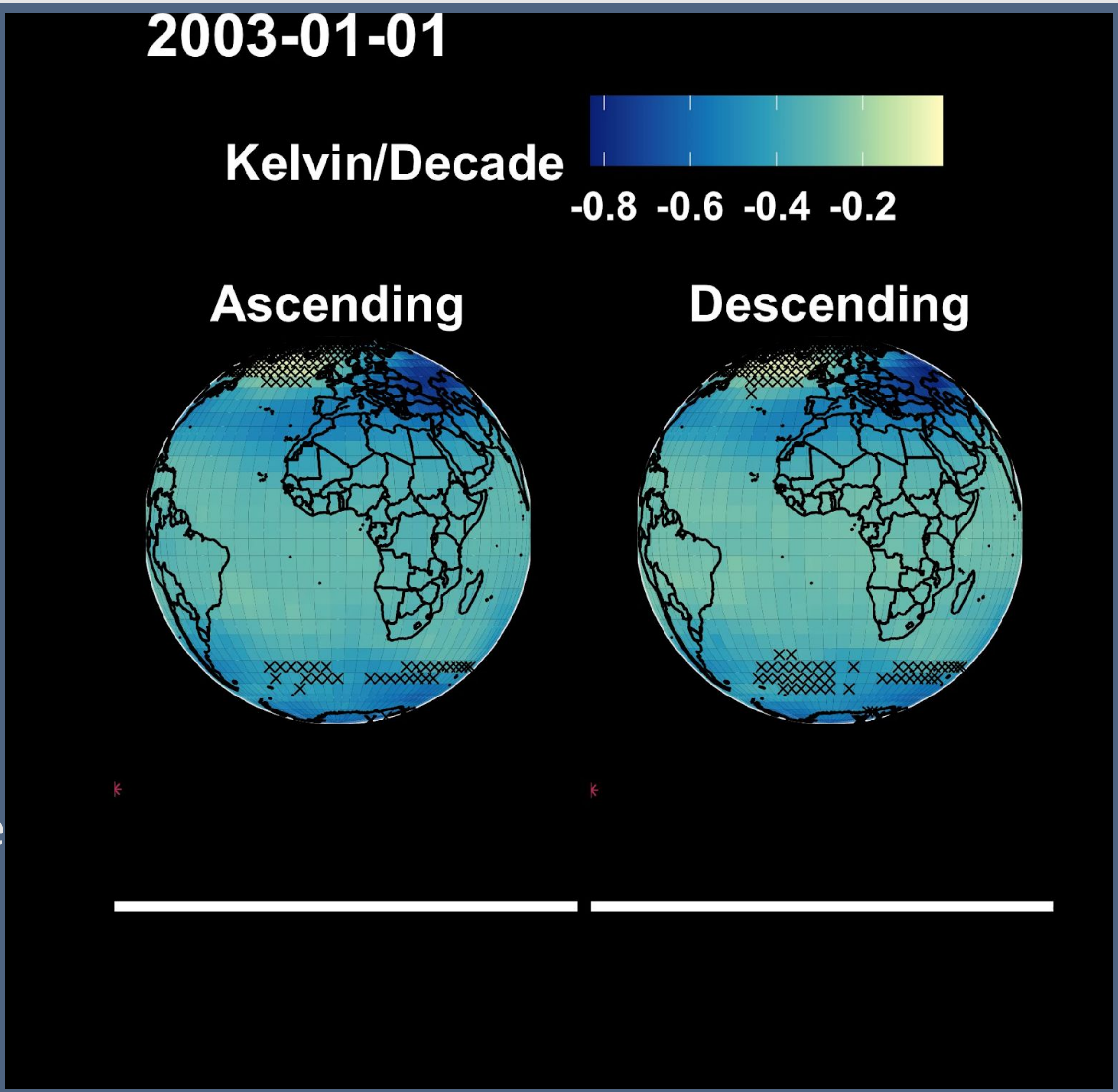
Motivation

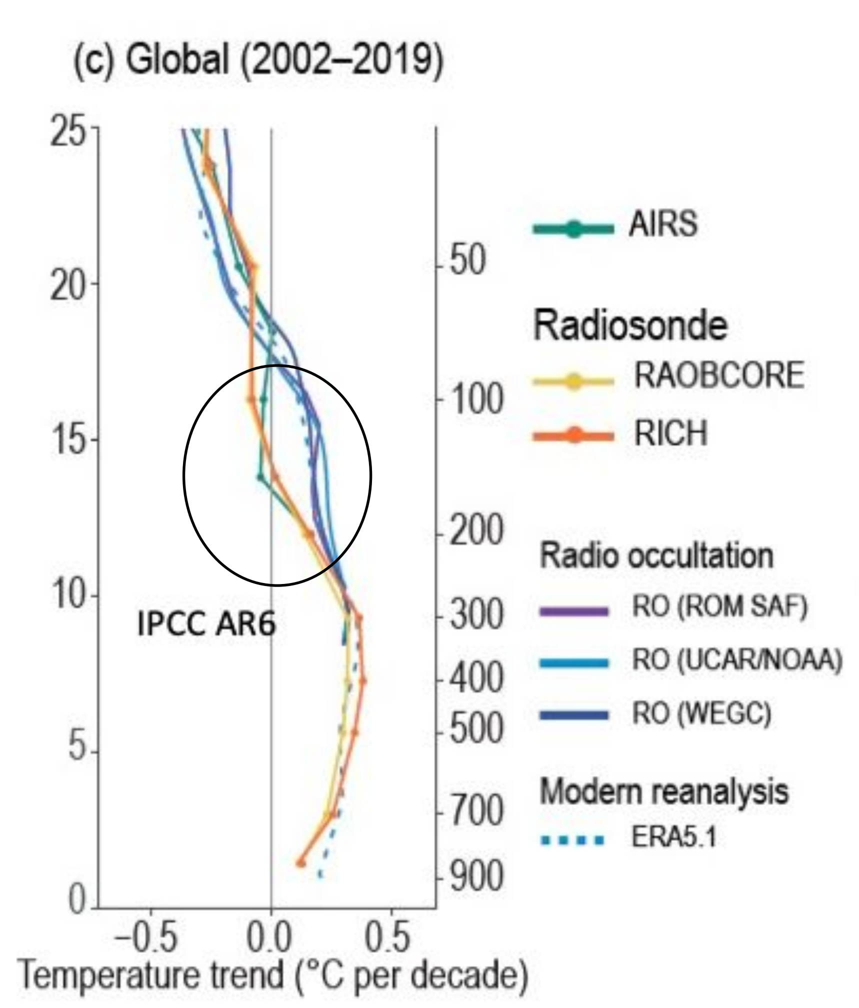
- IPCC AR6: "The troposphere has warmed since at least the 1950s, and it is virtually certain that the stratosphere has cooled…. ***It is extremely likely that anthropogenic forcing,*** both from increases in GHG concentrations and depletion of stratospheric ozone due to ozone-depleting substances, ***was the main driver of upper stratospheric cooling since 1979.*** "
- IPCC AR6: "The effects of human-induced climate change have been clearly identified in observations of atmospheric temperature and some aspects of atmospheric circulation, and these effects are likely to intensify in the future. Tropospheric warming and ***stratospheric cooling are virtually certain to continue with continued net emissions of greenhouse gases***."



AIRS v7 IR Only Stratospheric Trends Daytime (Ascending) and Nighttime (Descending)

Corresponding global mean anomaly with Trend (blue) Daytime (Ascending) and Nighttime (Descending)

Motivation - IPCC Report Figure



IPCC AR6 WGI Chapter 2 Fig 2.12

- IPCC AR6: "Observational capabilities have continued to improve and expand overall since AR5, enabling improved consistency between independent estimates of climate drivers, the combined climate feedbacks, and the observed energy and sea level increase. ***Satellite climate records and improved reanalyses are used as an additional line of evidence for assessing changes at the global and regional scales.*** However, there have also been reductions in some observational data coverage or continuity and limited access to data resulting from data policy issues."
- Consistent cooling in the upper stratosphere.
- Consistent warming in the troposphere.
- Differences between AIRS v6/Sonde and GPS RO between 200 and 100 hPa.
- Evaluating the trends from ***multiple observations and reanalysis is key*** in providing confidence in observed trends.

Overview

***Goal**: Assess the current status of observational and modeled stratospheric temperature trends.*

1. Trend Detection Techniques
2. Climate Quality Assessment of AIRS+AMSU v6 Temperature trends against GPS-RO
3. Evaluation of Stratospheric Temperature Trends from L3 (gridded) Products

Data

Instruments:

- AIRS and AMSU on Aqua
- CrIS and ATMS on SNPP
- Radio Occultations from METOP, COSMIC, CHAMP, and GRACE

1. L2
   - AIRS+AMSU v6
   - COSMIC GPS-RO
2. L3 Monthly
   - NASA AIRS IR Only v6 and v7 (2003-2020) (1x1)
   - NASA AIRS IR+MW v6 and v7 (2003-2015) (1x1)
   - NASA CLIMCAPS Aqua IR Only (2003-2020) (1x1)
   - NASA CLIMCAPS Aqua IR+MW (2003-2015) (1x1)
   - NASA CLIMCAPS SNPP (CrIS and ATMS) Std (2013-2020) (1x1) (uses NASA CrIS L1B product from GESDIS)
   - MERRA2 (2003-2020) (0.625x0.5)
   - ERA5.1 (2003-2020) (0.25x0.25)
   - ROM SAF GPS-RO Multi + METOP (2003-2020) (5 Degree Zonal Grid)

Trend Detection Technique

Goal:

- Select and optimize a trend detection method with high accuracy and high detection rates.

Data:

- 10,000 randomly generated time series

Trend Detection Technique

1. Remove the seasonal cycle (can do this using seasonal averages, harmonics, or more)
2. Further remove natural variability by using stepwise (minimize AIC) multivariate (Quasi Biennial Oscillation, and ENSO) regression to solve for the coefficients (except those in red).

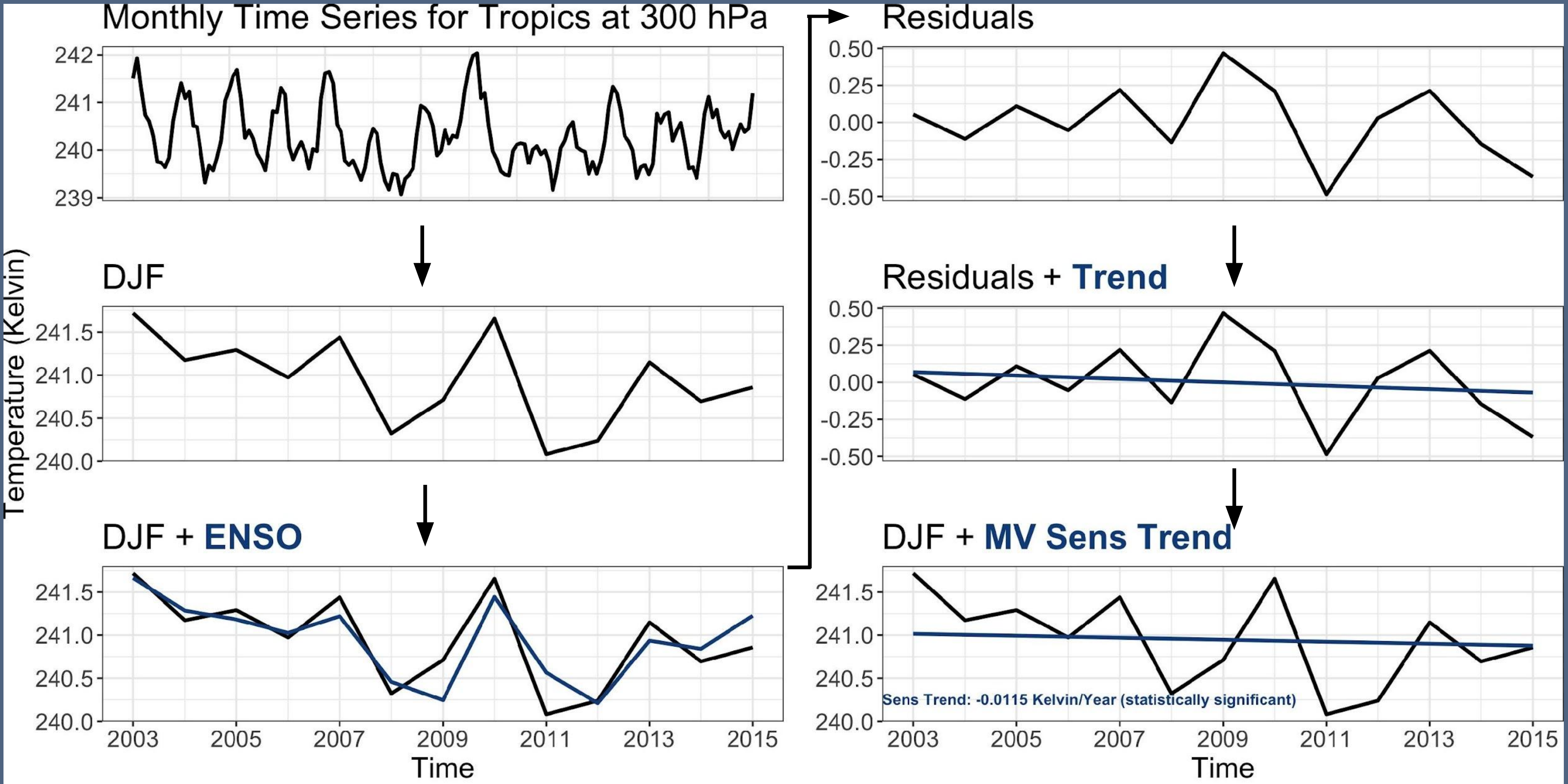
$$s(t) = a + b(t) + \sum_{n} \left(f_1 ENSO(t) + f_2 QBO30(t) + f_3 QBO50(t) \right) + \varepsilon$$

   - Left with the residuals (left hand side – summation). Result:

$$Residuals(t) = b(t) + \varepsilon$$

3. Estimate the trend – b(t) – from the resulting residuals using the Mann Kendall Trend Test (monotonic trend detection hypothesis test) & Thiel-Sens Slope with Serial Correlation Correction (nonparametric trend estimate using the medians).

Example of the Multivariate Trend Detection Technique



Climate Quality Assessment of AIRS+AMSU v6 Temperature trends against GPS-RO (L2)

Goal:

- Determine confidence level of using the long record of AIRS for trend detection.

Data:

- 8 years (2007-2014) of NASA AIRS+AMSU v6 temperature retrievals matched to COSMIC GPS RO

AIRS+AMSU v6 Matchups to COSMIC GPS RO

- Matchups courtesy of Michelle (Feltz) Loveless from SSEC using a ‘raypath’ method (Feltz et al. 2014 JGR).
- “This method aims to account for the inherent horizontal resolution, sometimes more clearly termed as the “along-track” resolution, of the GPS RO signal, referring to the averaging that occurs along the path of the GPS signal as it traverses the atmosphere with a dominant horizontal component in the plane of occultation.”

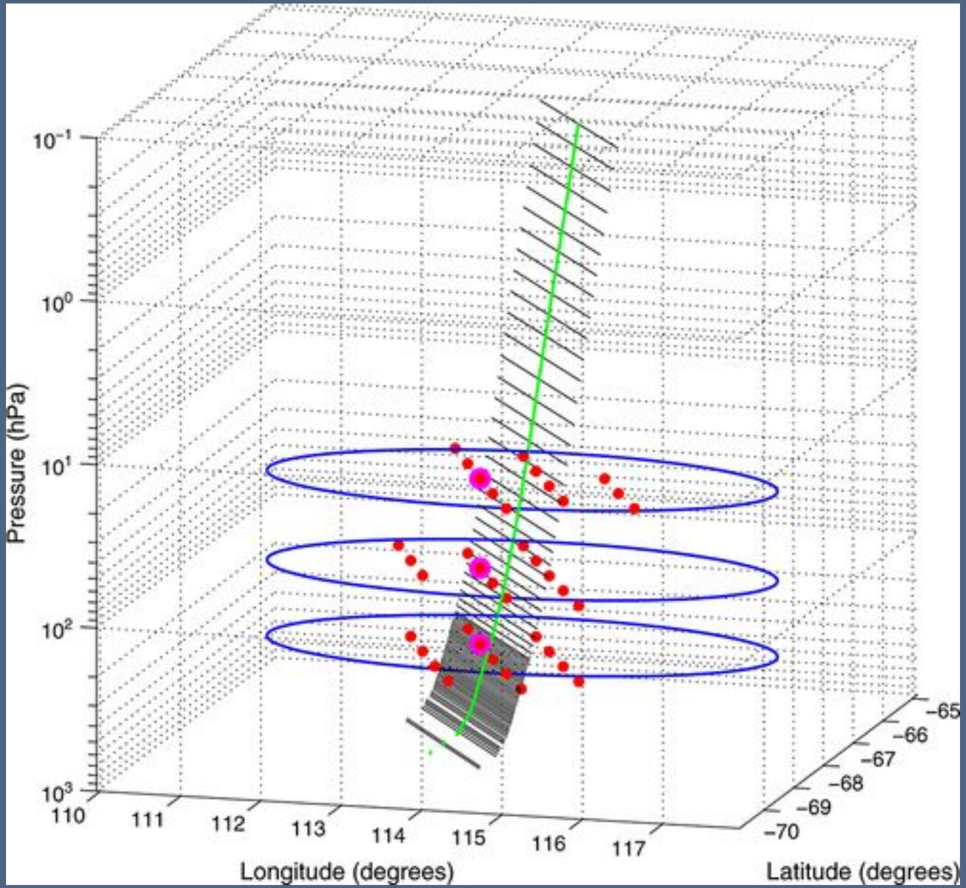
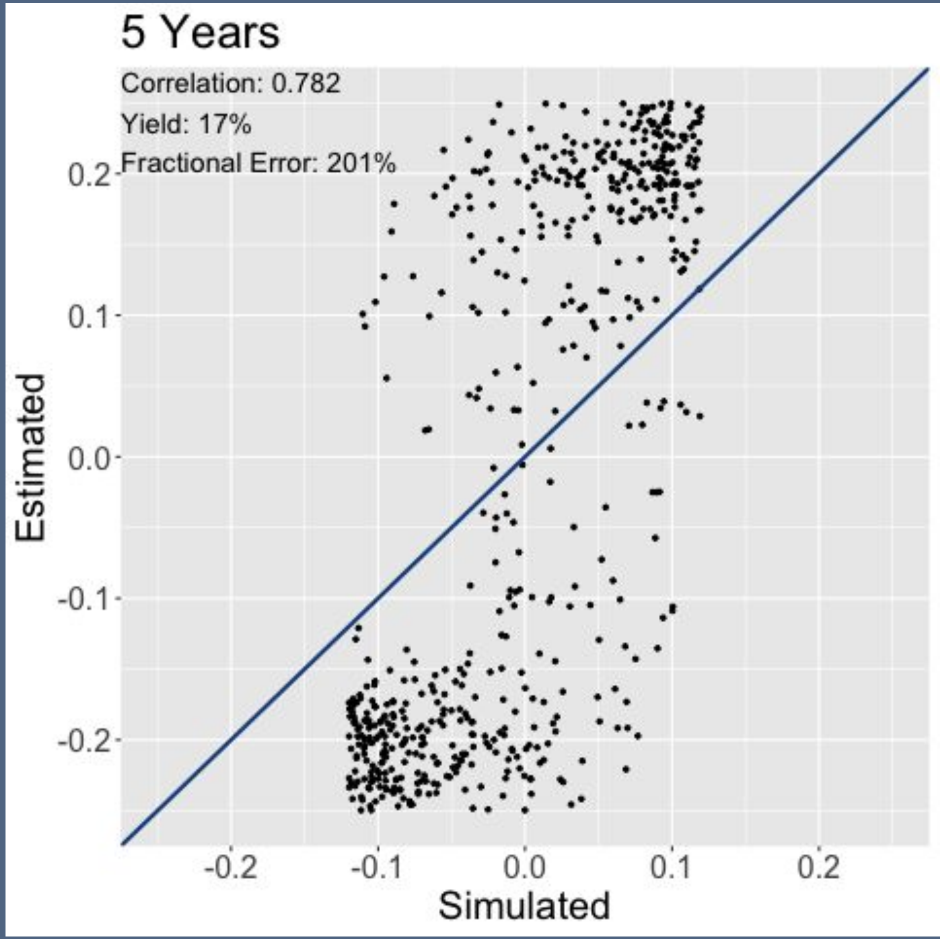


Figure 3 from Feltz et al. 2014 JGR: COSMIC/AIRS matchup example from 19 October 2007 illustrating the closest (large magenta dots), circular (blue circle), and raypath (small red dots) methods for a single GPS RO profile (green dots indicating tangent points with black lines illustrating the RO horizontal extent in the plane of the occultation).

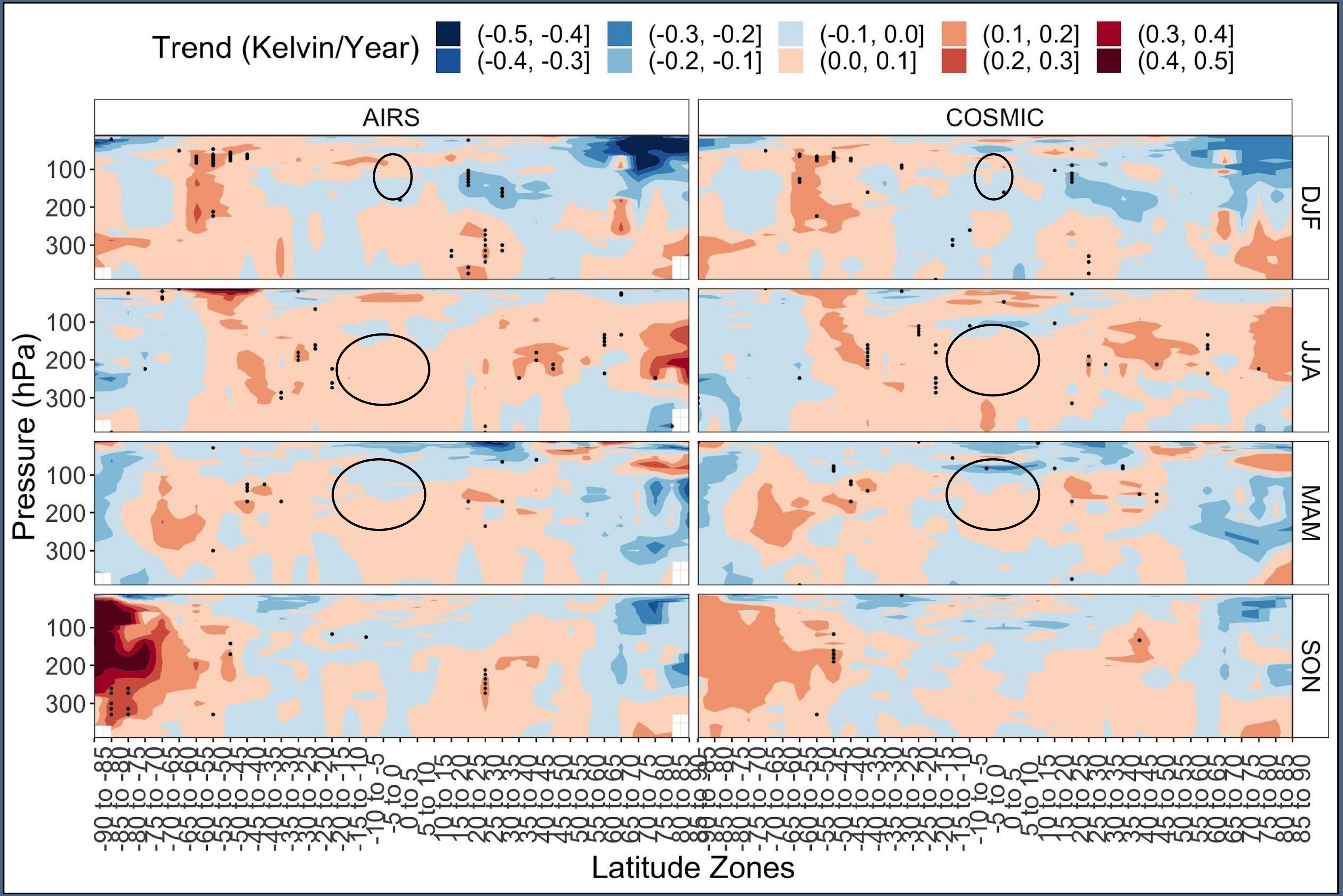
Trend Detection & Time

- The animation on the right shows the impact of the length of a time series on detection rate and accuracy.
- The goal of this assessment is to validate the trend estimates from AIRS - not to find statistically significant trends (8 years is not long enough).
- Think of this technique as a *validation tool*. Later on we will use the longer time period of AIRS to look for statistically significant trends.



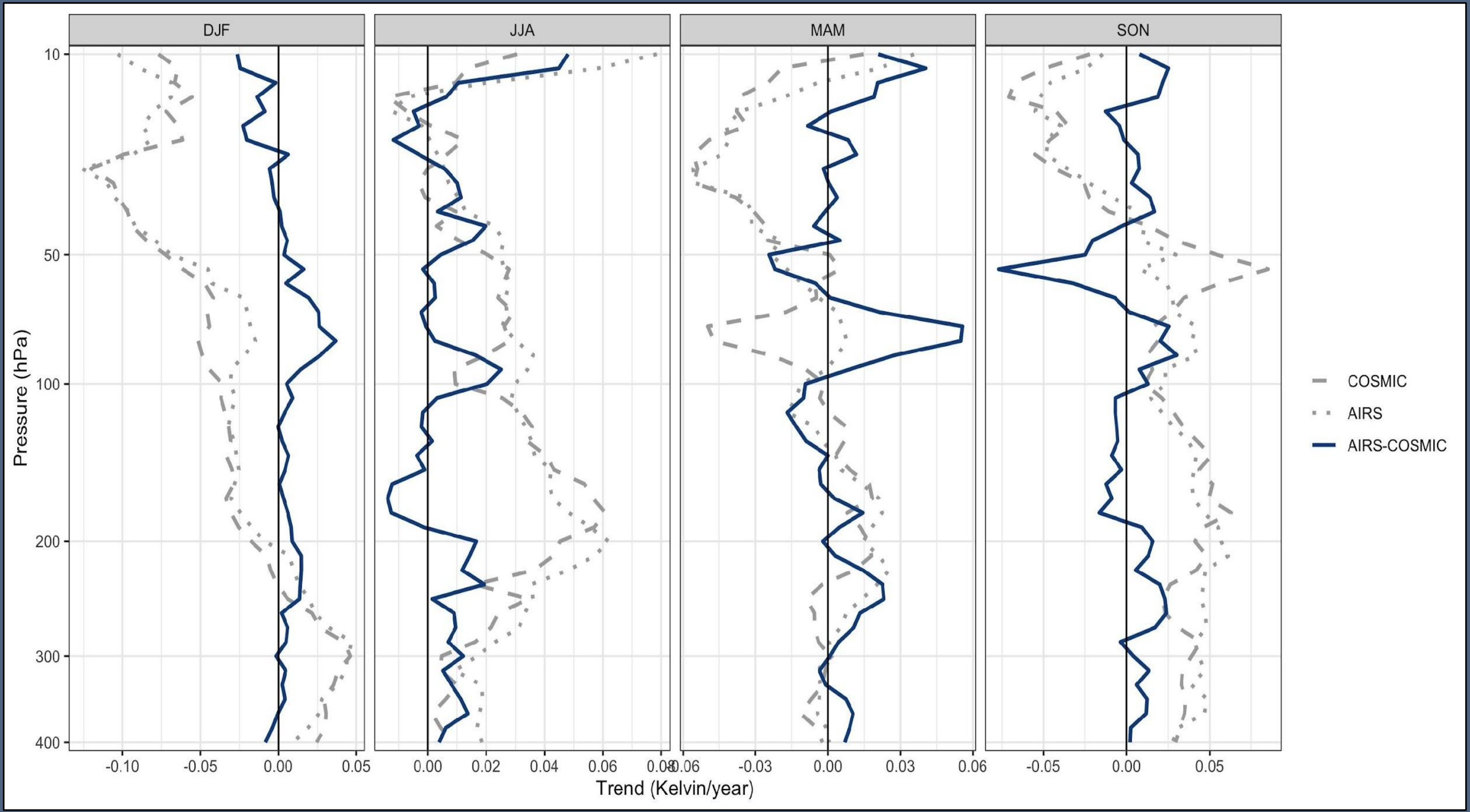
*Yield represents the number of statistically significant results divided by the number of statistically significant results for the full time period (30 years).

Climate Assessment of AIRS+AMSU v6 Temperature Trends Against GPS RO



- Black dots represent statistically significant results (expect more with a longer time series).
- Remarkably similar results.
- Most differences are with respect to magnitude and not direction.

Climate Assessment of AIRS+AMSU v6 Temperature Trends Against GPS RO: Global Mean Difference



Mean Difference:

- DJF: 0.002K/year +- 0.011
- JJA: 0.007 K/year +- 0.012
- MAM: 0.006 K/year +- 0.016
- SON: 0.003 K/year +- 0.018

Evaluation of Temperature Trends

Goal:

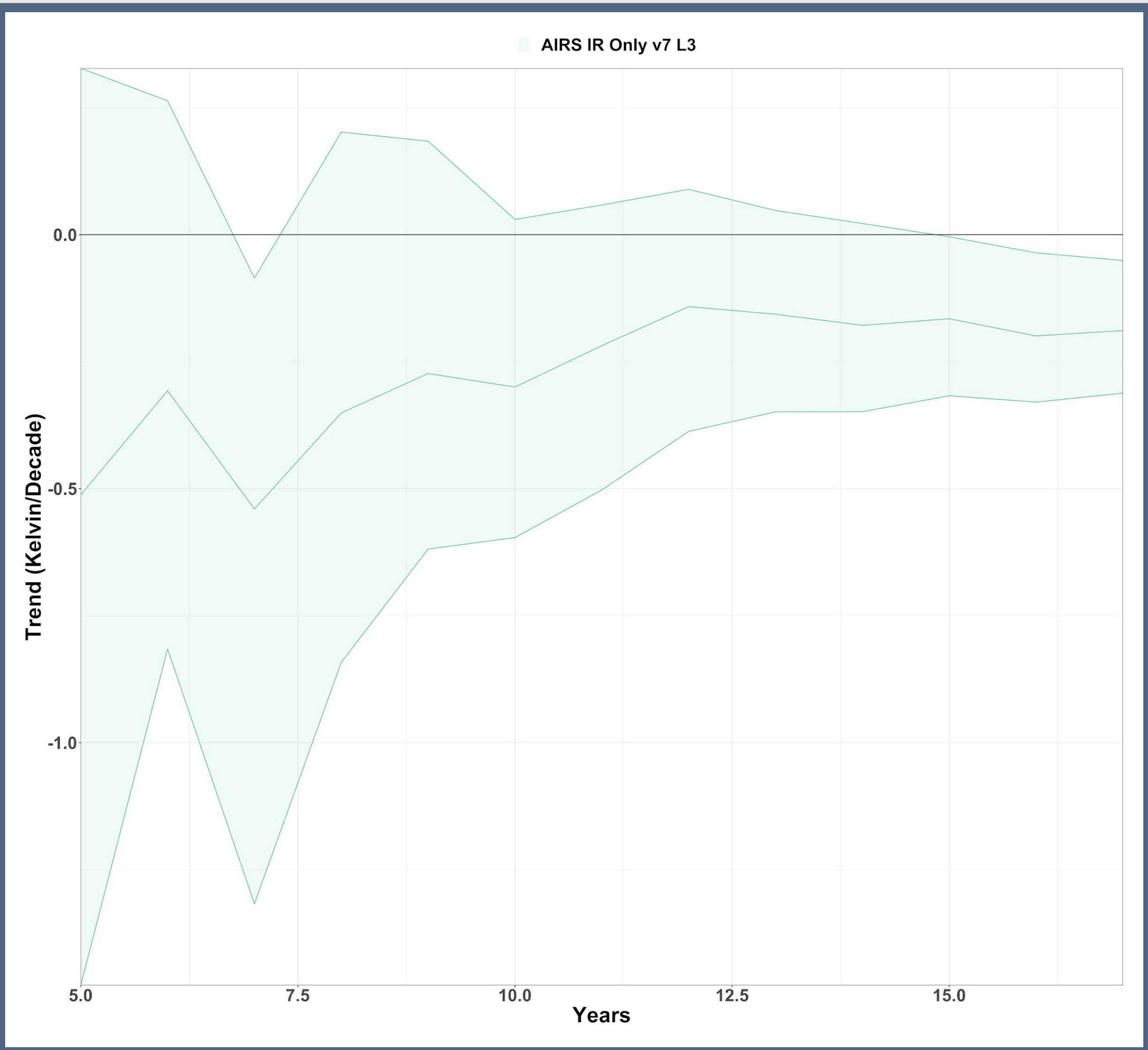
- Compare trends from observations and reanalysis.

Data:

- Not collocated
- Based on gridded L3 products
- 3 Periods: 2003-2015 (AIRS IR+MW, IR Only); 2013-2020 (AIRS IR Only, SNPP), 2003-2020 (AIRS IR Only)

A Note on Uncertainty

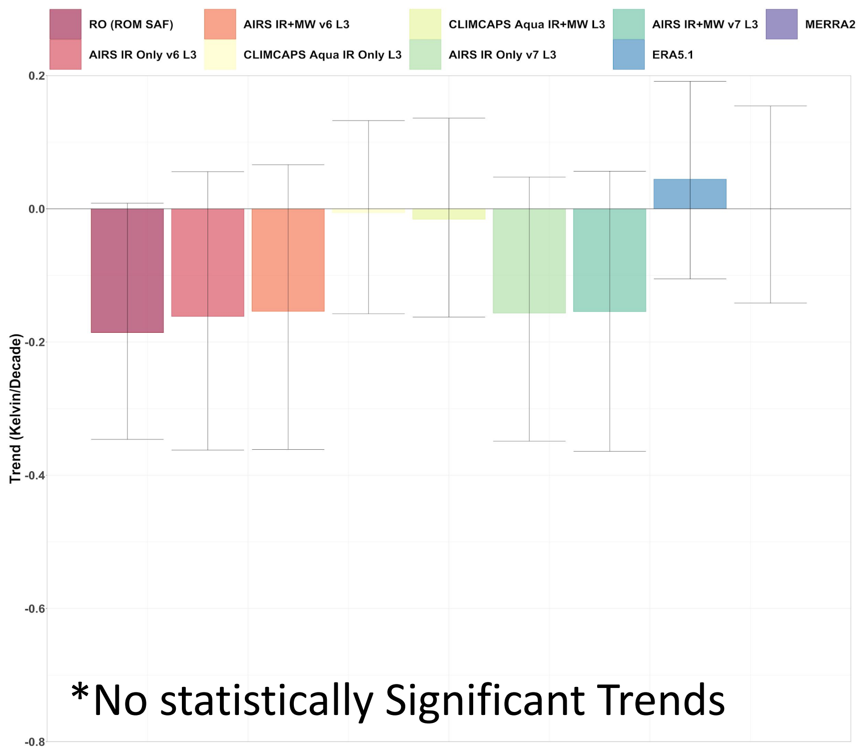
- Since we are not eliminating the potential influences of sampling biases we need to emphasize statistical significance.
- Statistical significance is influenced by the variability in the time series and the strength of the signal.
- Generally, as the length of the time series increases, your confidence in the result will increase (e.g. the confidence interval will get smaller).



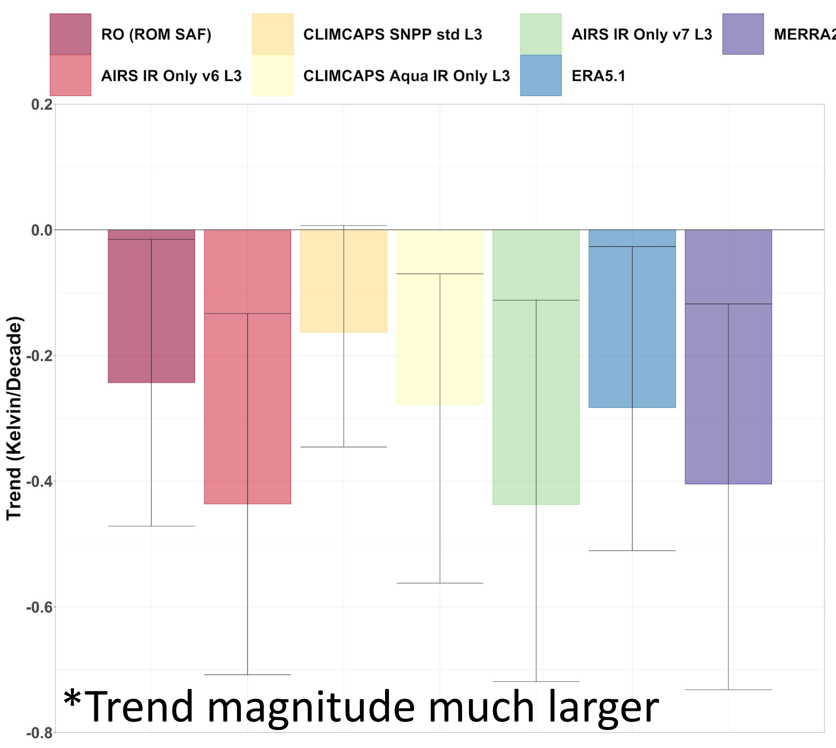
Global Mean (70 N to 70 S) Stratospheric (150 – 10 hPa) Temperature Trends with 95% confidence interval (error bars)

- Statistically significant cooling of about -0.2 Kelvin/decade over the entire time series.
- Similar trend estimates from MERRA2 an CLIMCAPS (MERRA2 is the apriori for CLIMCAPS).

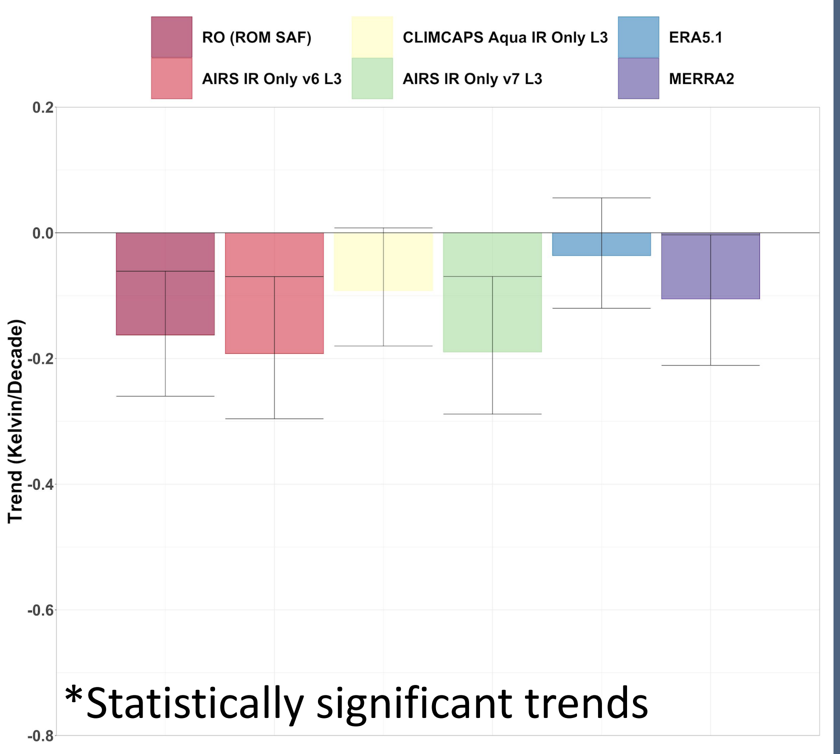
2003-2015



2013-2020



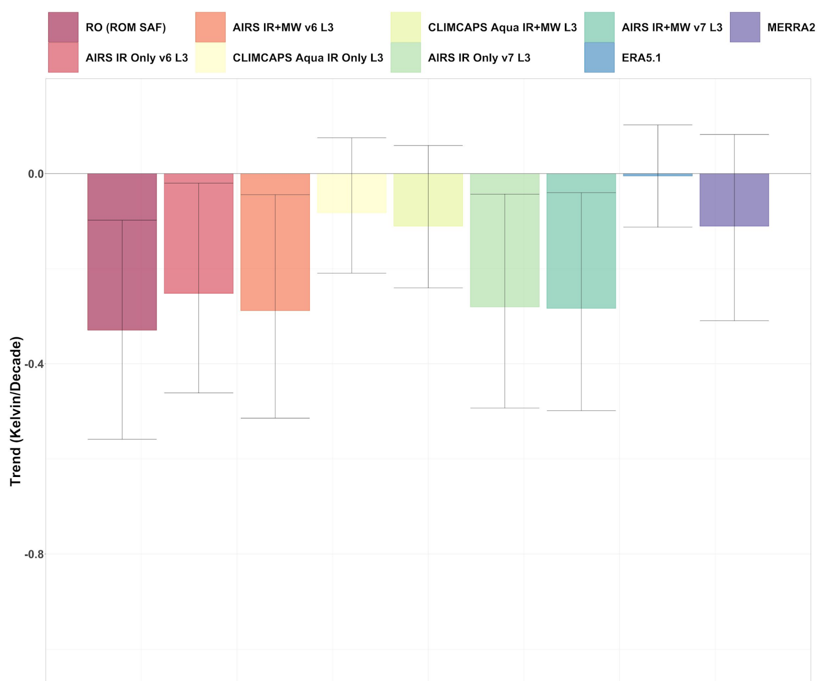
2003-2020



Global Mean (70 N to 70 S) Upper Stratospheric (50 – 10 hPa) Temperature Trends with 95% confidence interval (error bars)

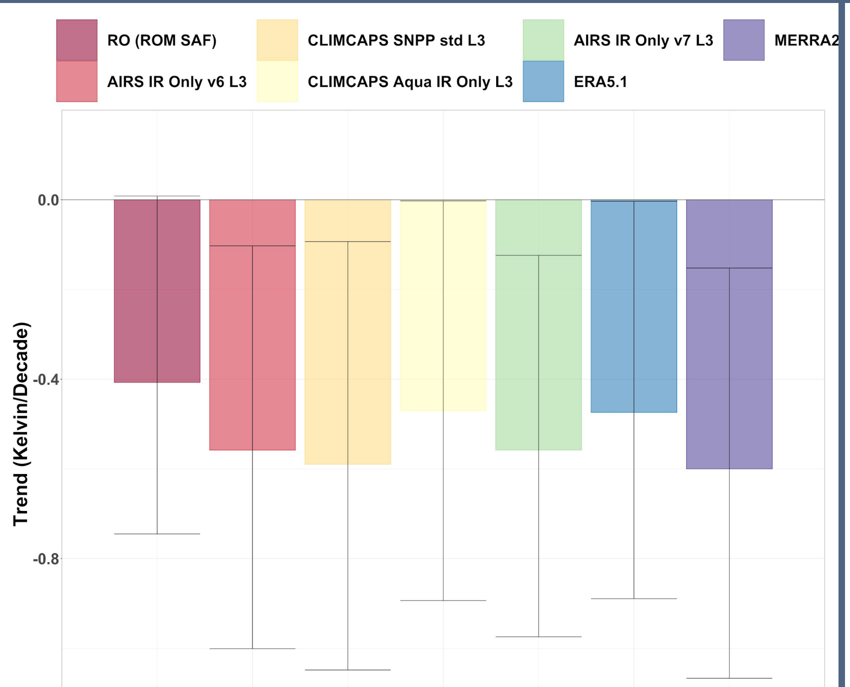
- Strong evidence of cooling in the upper stratosphere of about -0.3 Kelvin/decade.
- Consistent cooling observed from RO & AIRS regardless of the time period.

2003-2015



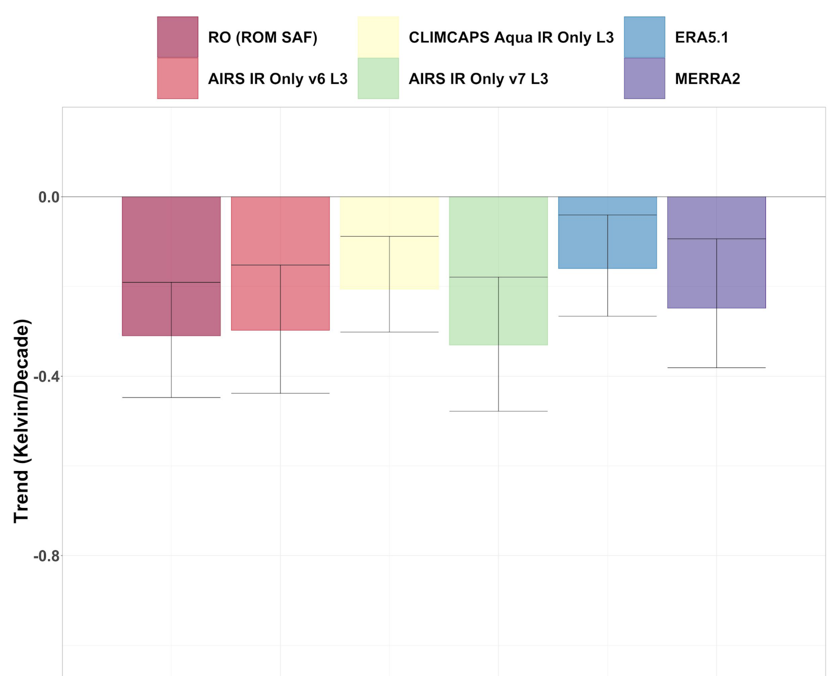
*AIRS v6, v7,and RO are Stat. Sig.

2013-2020



*Trend magnitude much larger

2003-2020

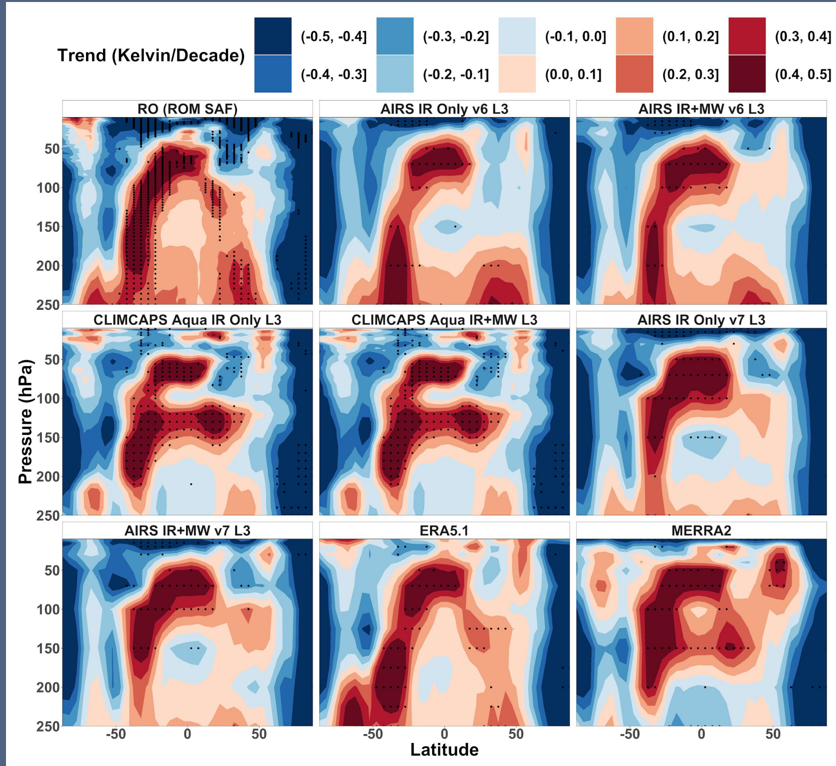


*Statistically significant trends

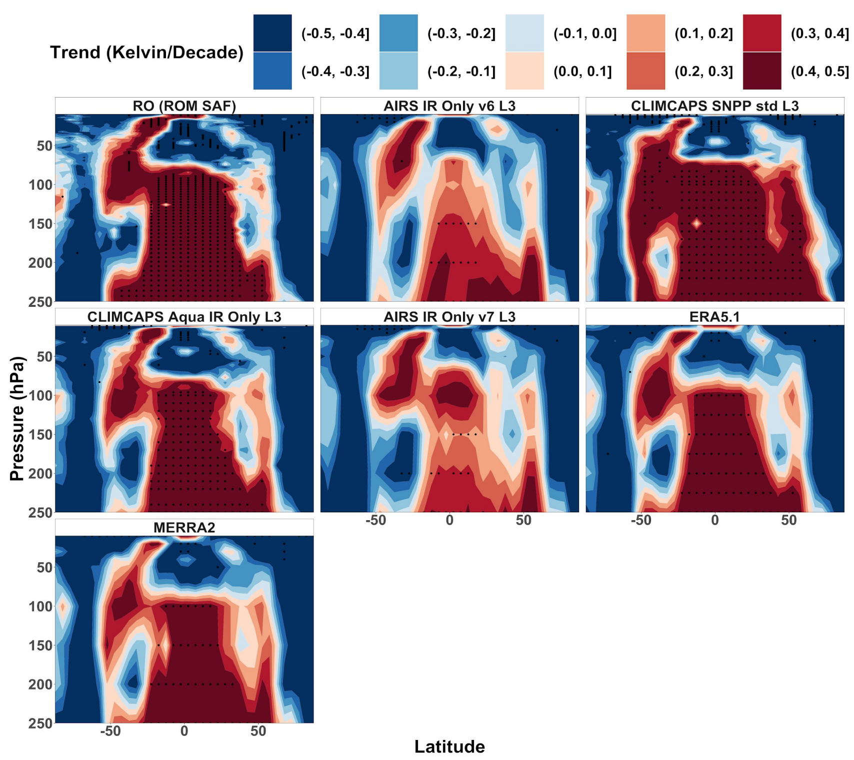
Zonal Mean Temperature Trends Statistically Significant trends marked by dots

- Similar vertical and spatial structure among the reanalysis and observations.
- Trend magnitude is much larger in CLIMCAPS SNPP compared to CLIMCAPS Aqua IR Only (perhaps due to MW).
- MERRA2 and CLIMCAPS follow similar patterns but the trend magnitude is generally smaller in the troposphere for CLIMCAPS and larger in the stratosphere.
- Consistent upper stratospheric cooling of ~ -0.2 Kelvin/decade.
- There are notable differences between AIRS v6 and airs V7.

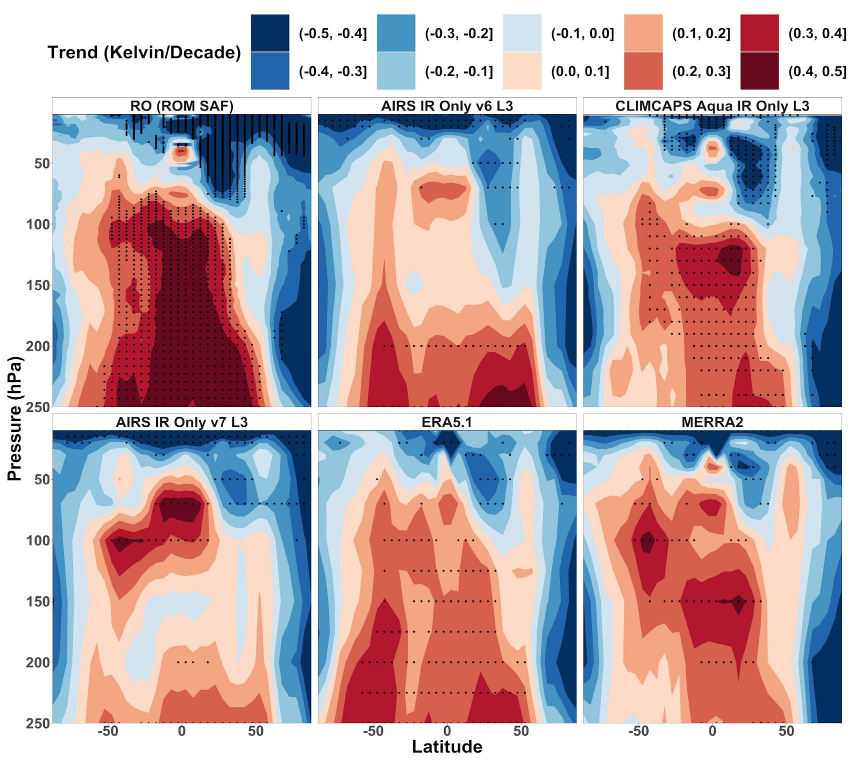
2003-2015



2013-2020

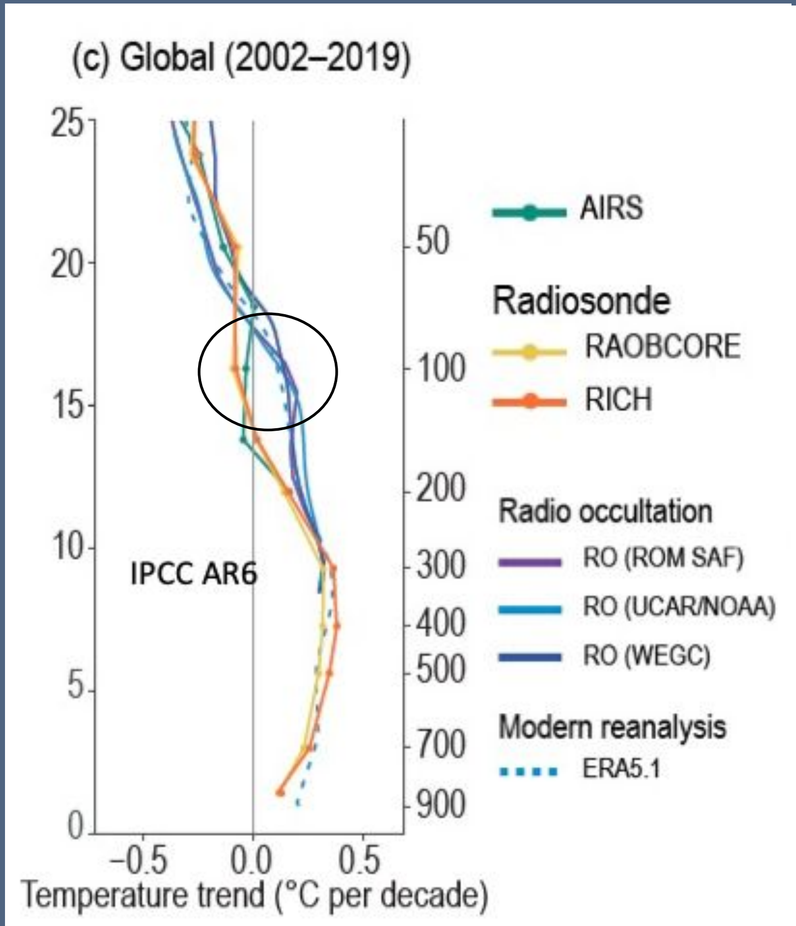


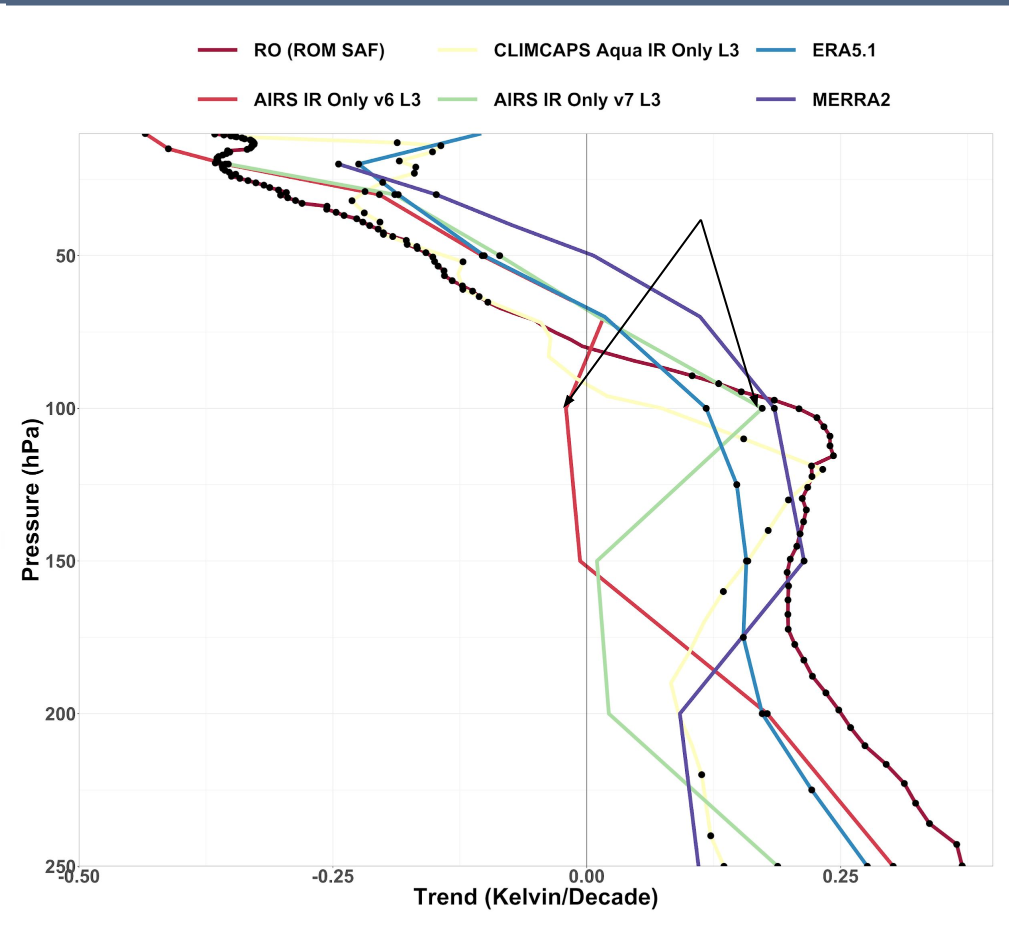
2003-2020



Version Changes

- Although the trends in the IPCC figure are not statistically significant, the right hand version (from 2003-2020) shows that the updated AIRS (v7) results in a statistically significant trend at 100 hPa, consistent with ROM SAF.
- Version changes are important to monitor and allow us to improve the product.



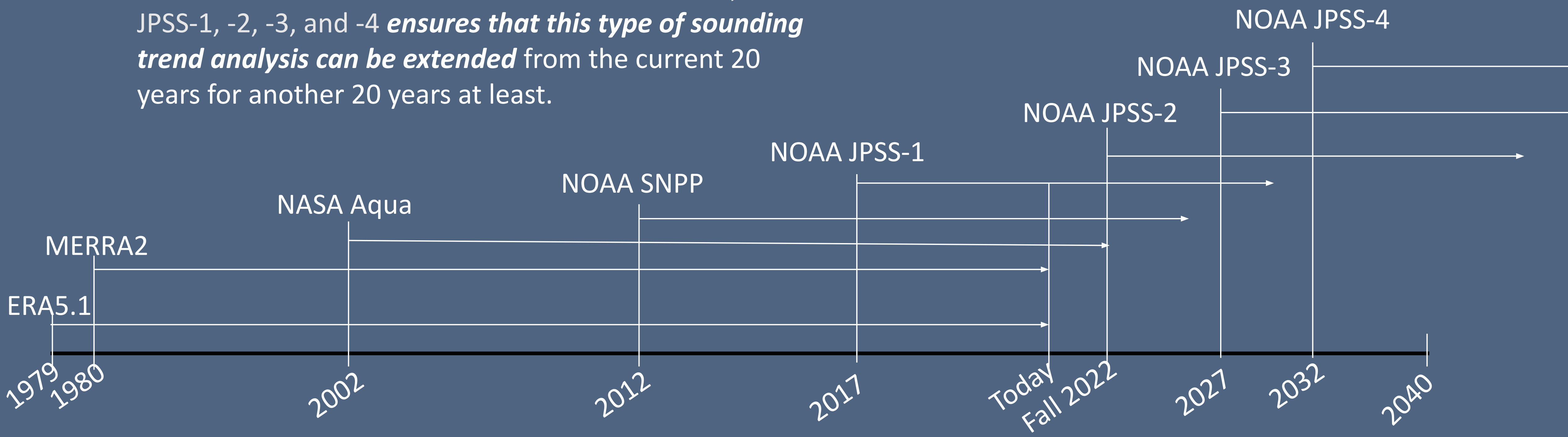


Take home Messages

- There is high confidence that the ***upper stratosphere*** is cooling at roughly ***-0.3 Kelvin/decade***.
- Both reanalysis (except ERA5.1) and observations show a ***cooling in the stratosphere*** of about -0.2 Kelvin/decade.
- Where ***disagreements*** emerge, ***confidence intervals*** tend to be ***large*** making it difficult to interpret results.
- Version changes do impact the trend results (ERA5 to ERA5.1 as well as AIRS v6 to AIRS v7).
- Differences in the spatial and vertical sampling, ***sampling biases***, of the products could ***explain inconsistences***.

Importance of Continuity

- Reminder from IPCC AR6: "Satellite climate records and improved reanalyses are used as an additional line of evidence for assessing changes at the global and regional scales. However, there have also been ***reductions*** **in** some observational data coverage or ***continuity***"
  - The ***continuity of radiance data*** records from NASA AIRS on EOS AQUA with NOAA CrIS on Suomi-NPP, JPSS-1, -2, -3, and -4 ***ensures that this type of sounding trend analysis can be extended*** from the current 20 years for another 20 years at least.

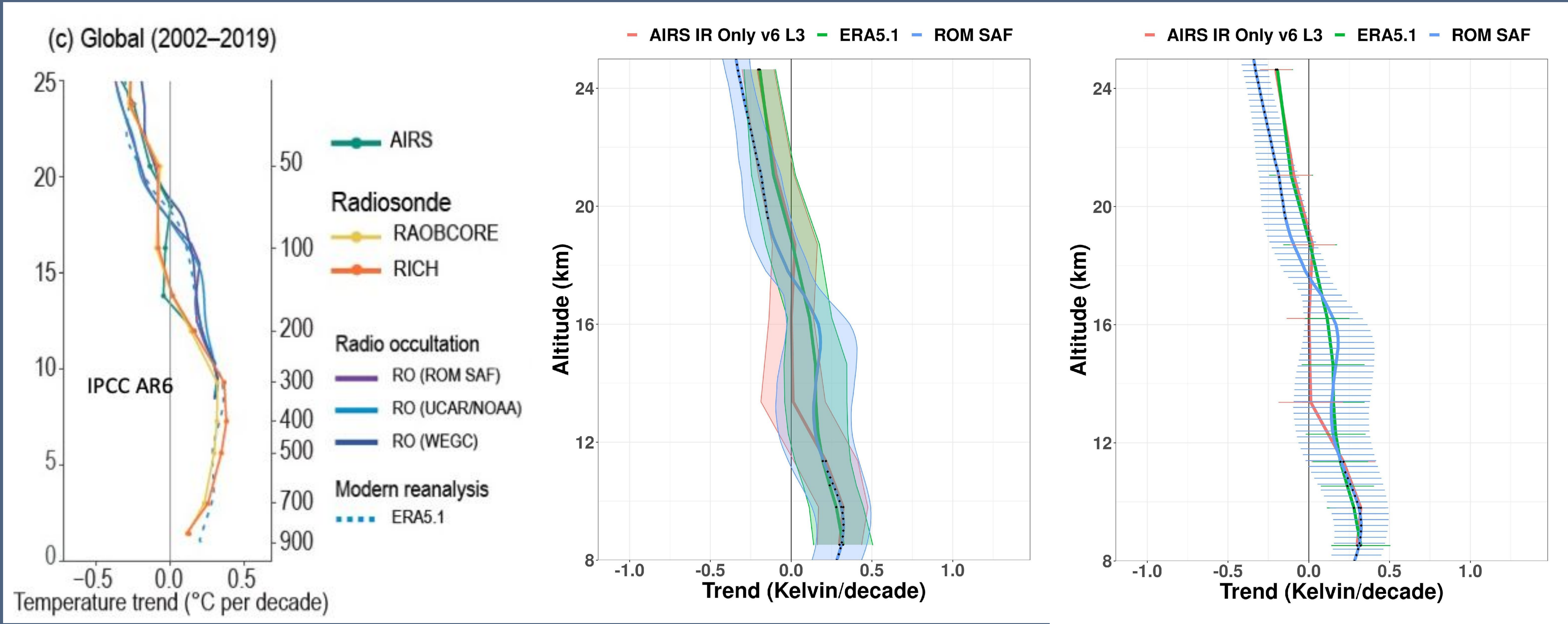


Thanks for listening!

Future Work

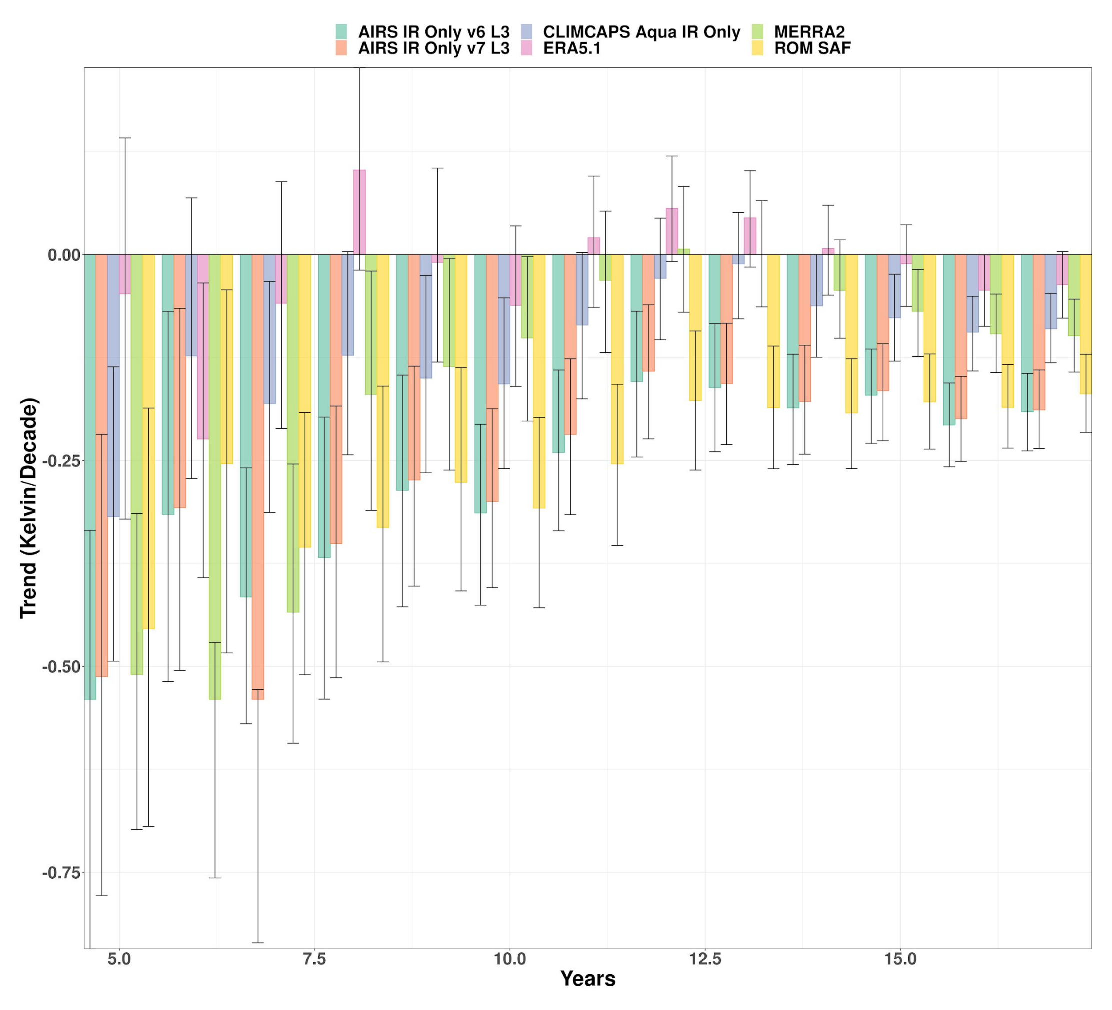
- Look at the impacts of spatial and temporal sampling biases on the trend estimates.
- Look at adding in other variables to the multivariate regression that may explain more of the natural variability.
- Further validate the MERRA2 temperature & specific humidity trends against MW and IR L2 retrievals and assess the possible climate implications of using a reanalysis as a first guess for retrieval algorithms.

Example of UQ Importance – especially when not spatially/temporally/vertically matching



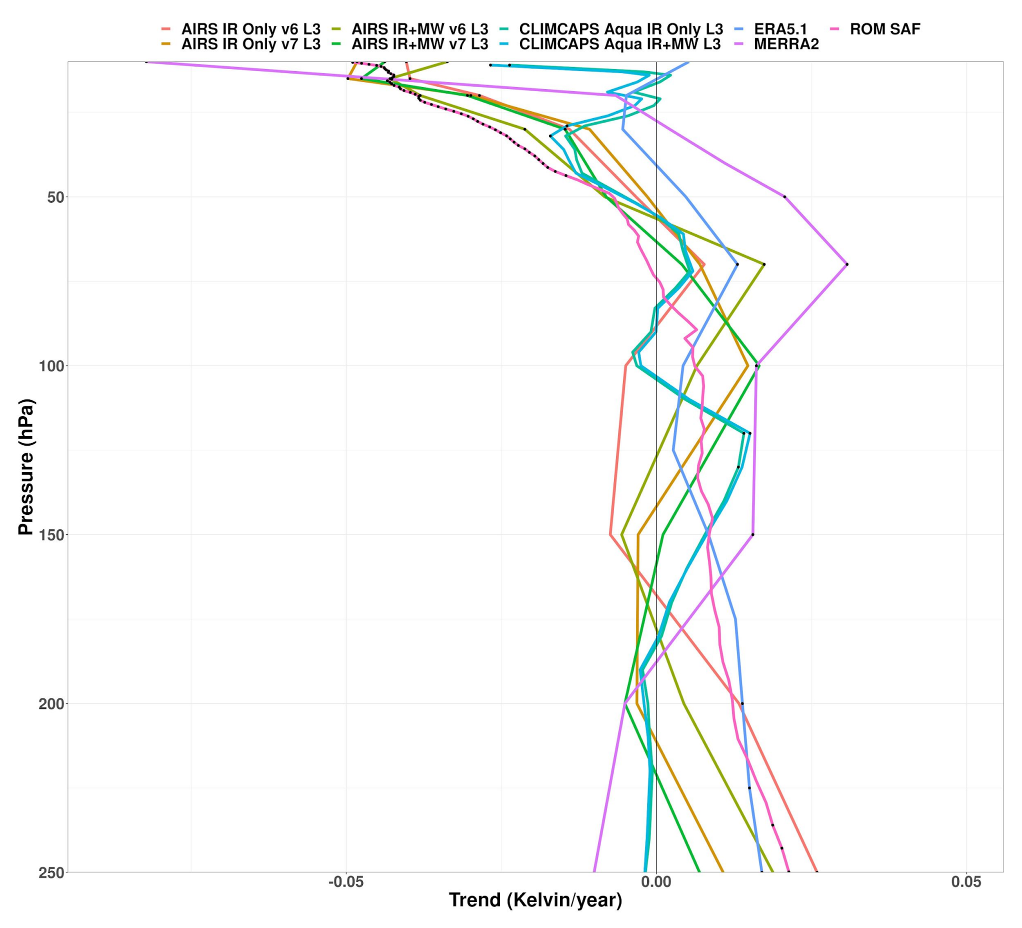
Global Mean (70 N to 70 S) Stratospheric (150 – 10 hPa) temperature Trends as a function of time

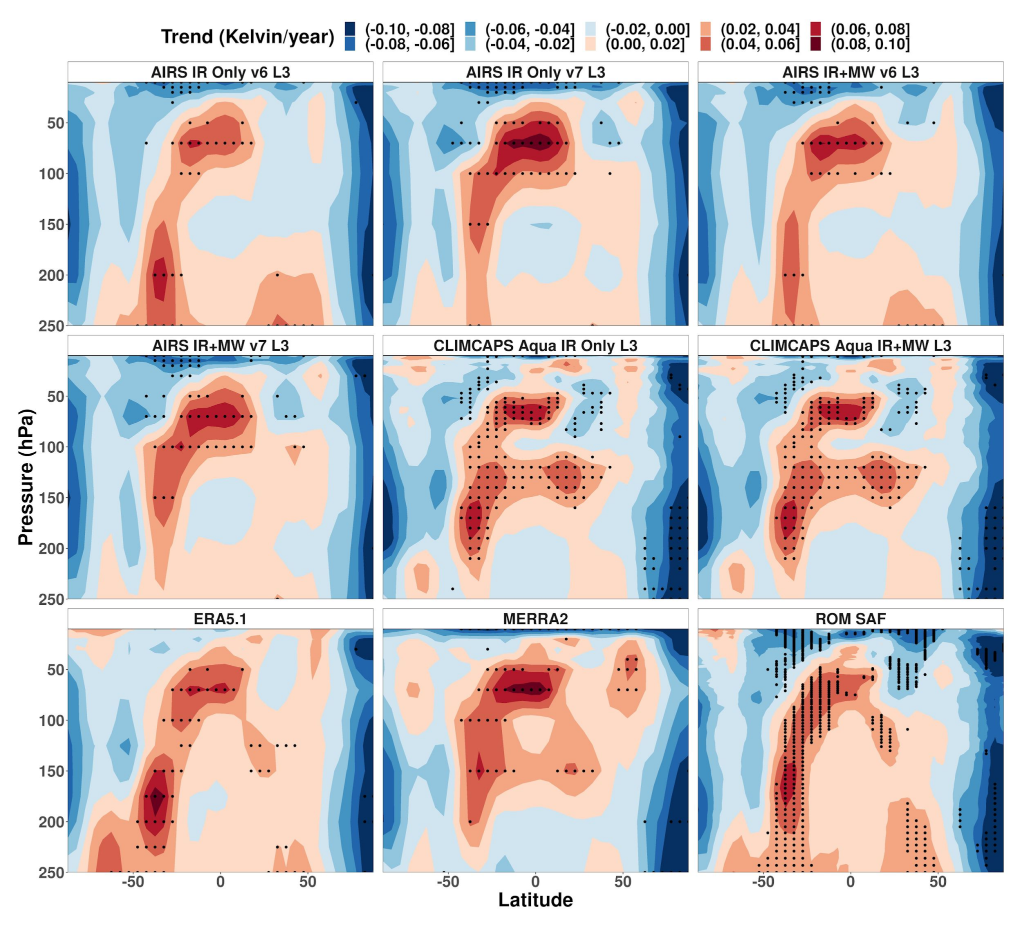
- Error bars get progressively smaller with time
- The positive trend in ERA5 was never stat sig!
- Remarkable agreement between AIRS and ROM SAF
- Agreement between CLIMCAPS And MERRA2 is expected as MERRA2 is the apriori.



2003-2015

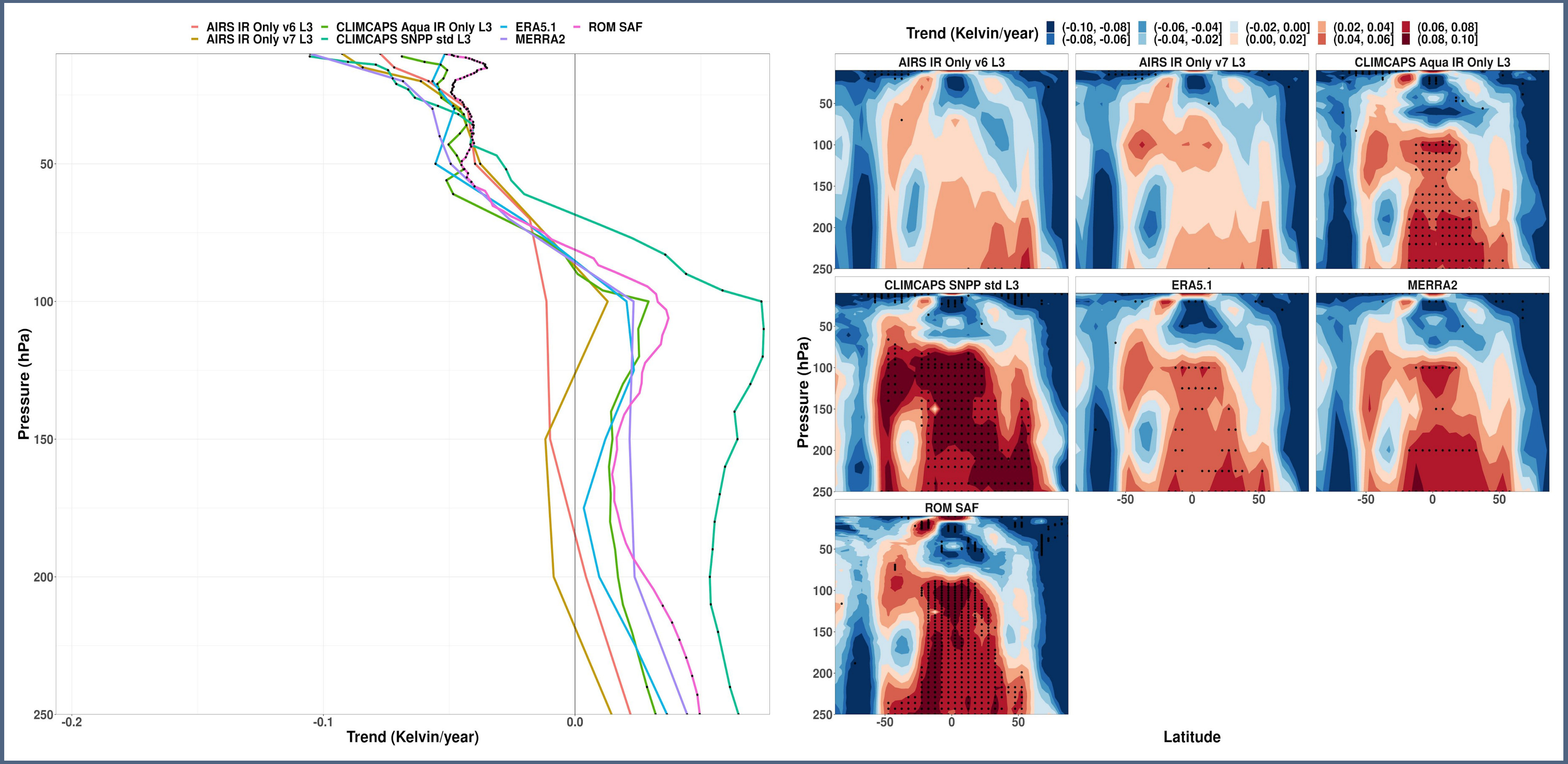
- With the shorter time period – there are few statistically significant trends.
- Similar vertical and spatial structure among the reanalysis and observations.
- In particular, CLIMCAPS and MERRA2 are quite similar.





2013-2020

- Difference between CLIMCAPS Aqua and CLIMCAPS SNPP.
- Trend magnitude is much larger in CLIMCAPS SNPP compared to CLIMCAPS Aqua IR Only (perhaps due to MW)



2003-2020

- More statistically significant trends, especially in the mid-upper stratosphere.
- MERRA2 and CLIMCAPS follow similar patterns but the trend magnitude is generally smaller in the troposphere for CLIMCAPS and larger in the stratosphere.
- Consistent upper stratospheric cooling of ~ -0.2 Kelvin/decade.