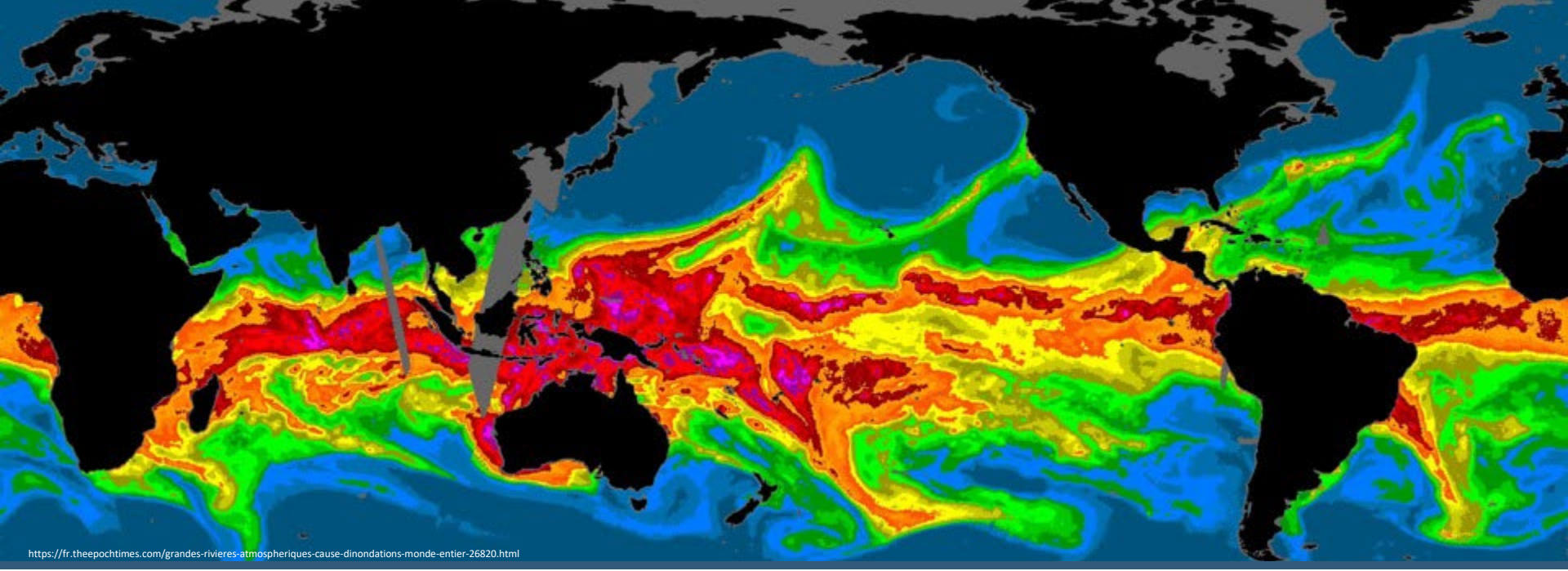


Atmospheric Temperature Change: Recent Advances and Open Issues

Ben Santer, Stephen Po-Chedley, Qiang Fu, John Fyfe, Carl Mears, Susan Solomon, Andrea Steiner, Frank Wentz, and Cheng-Zhi Zou

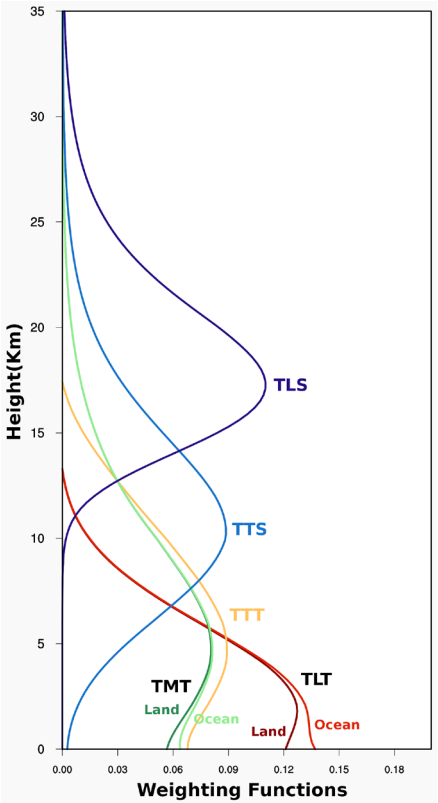
OPAC-IROWG, Sept. 8, 2022

My background

What my talk will cover

- Recent advances
  - IPCC AR6 and Steiner et al. (2020)
  - Seasonal cycle of tropospheric temperature
  - “Vertical fingerprinting”
- Outstanding challenges

Comparing tropospheric and lower stratospheric temperature trends in models and observations



- Use local weighting functions to calculate synthetic satellite temperatures from model simulations
- Requires atmospheric temperature at standard pressure levels and surface type (land, ocean, sea-ice)

Data source:ftp://ftp.ssmi.com/msu/weighting_functions

What my talk will cover

- Recent advances
  - IPCC AR6 and Steiner et al. (2020)
  - Seasonal cycle of tropospheric temperature
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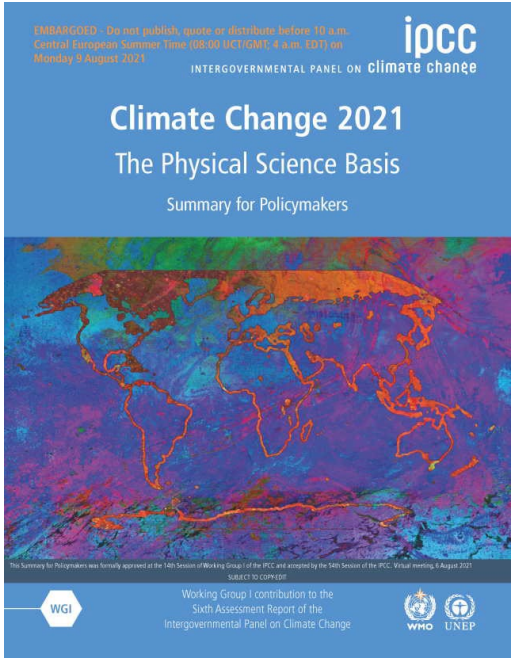


Summary of IPCC AR6 atmospheric temperature findings

- It is unequivocal that human influence has warmed the atmosphere, ocean and land
- It is very likely that well-mixed GHGs were the main driver of tropospheric warming since 1979
- Extremely likely that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s

Summary of Steiner et al. findings (J. Climate, 2020)

Observed Temperature Changes in the Troposphere and Stratosphere from 1979 to 2018

A. K. Steiner,[a,b] F. Ladstädter,[a,b] W. J. Randel,[c] A. C. Maycock,[d] Q. Fu,[e] C. Claud,[f]
H. Gleisner,[g] L. Haimberger,[h] S.-P. Ho,[i] P. Keckhut,[j] T. Leblanc,[k] C. Mears,[l] L. M. Polvani,[m]
B. D. Santer,[n] T. Schmidt,[o] V. Sofieva,[p] R. Wing,[j] and C.-Z. Zou[q]

- Results show a robust cooling of the stratosphere of about 1–3 K, and a robust warming of the troposphere of about 0.6–0.8K over the last four decades (1979–2018)
- Overall latitude–altitude trend patterns are consistent between RO and radiosonde records
- Significant warming of the troposphere is evident in the RO measurements available after 2001, with trends of 0.25–0.35K per decade

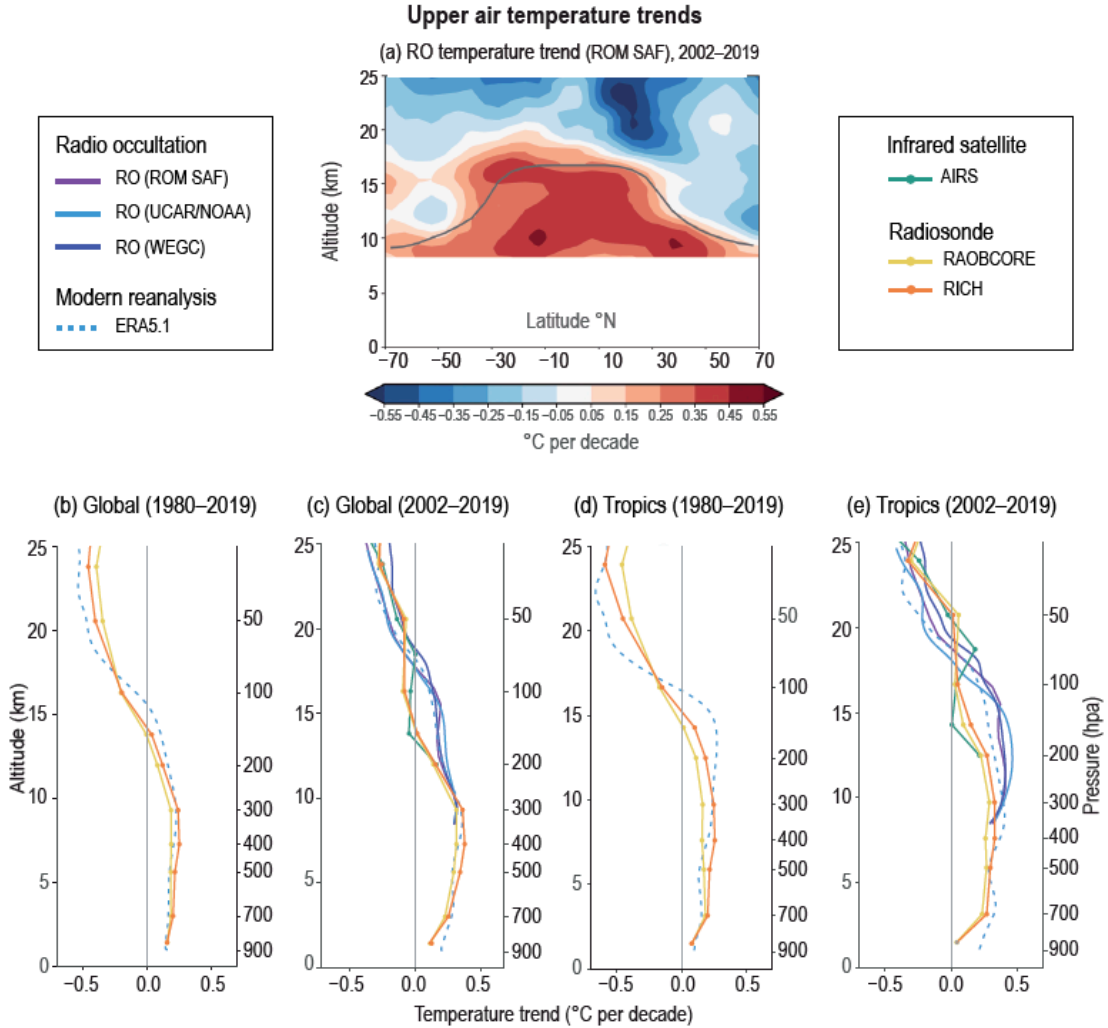
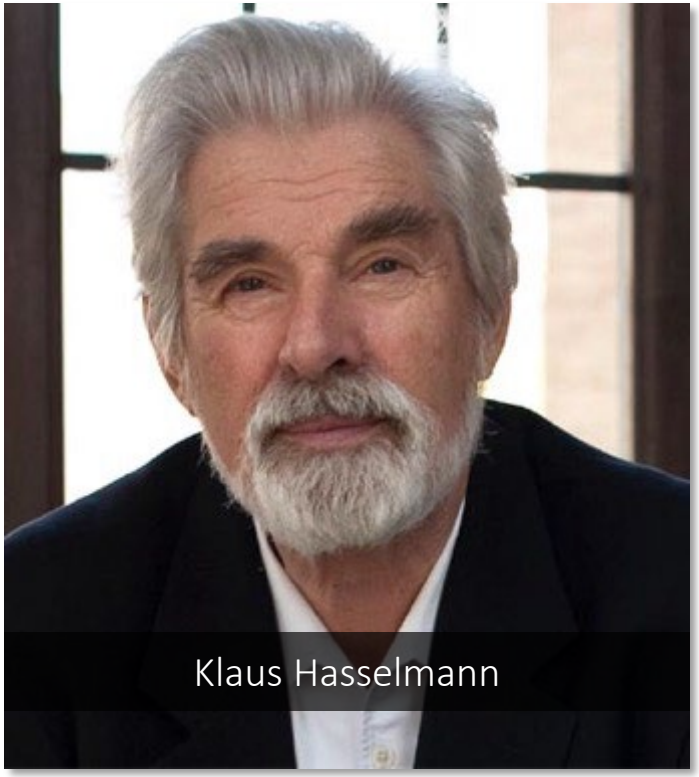


Figure 2.12 from IPCC AR6

What my talk will cover

- Recent advances
  - IPCC AR6
  - Seasonal cycle of tropospheric temperature
  - “Vertical fingerprinting”
- Outstanding challenges

Hasselmann: The power of patterns


Klaus Hasselmann

2021 Nobel Physics Prize

Awarded for developing:

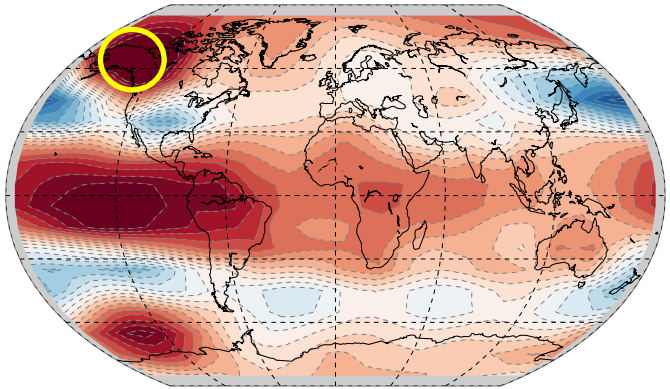
"…methods for identifying specific signals, fingerprints, that both natural phenomena and human activities imprint in the climate"

Using patterns to discriminate between human and natural effects on climate

Human fingerprint

Pattern amplitude

Natural climate variability



Pattern amplitude

Lower tropospheric temperature in CMIP5 models. From Santer et al., *Proceedings of the National Academy of Sciences*, 2019

Human influence on the seasonal cycle of tropospheric temperature: Santer et al., Science (2018)

RESEARCH ARTICLE

CLIMATE CHANGE

Human influence on the seasonal cycle of tropospheric temperature

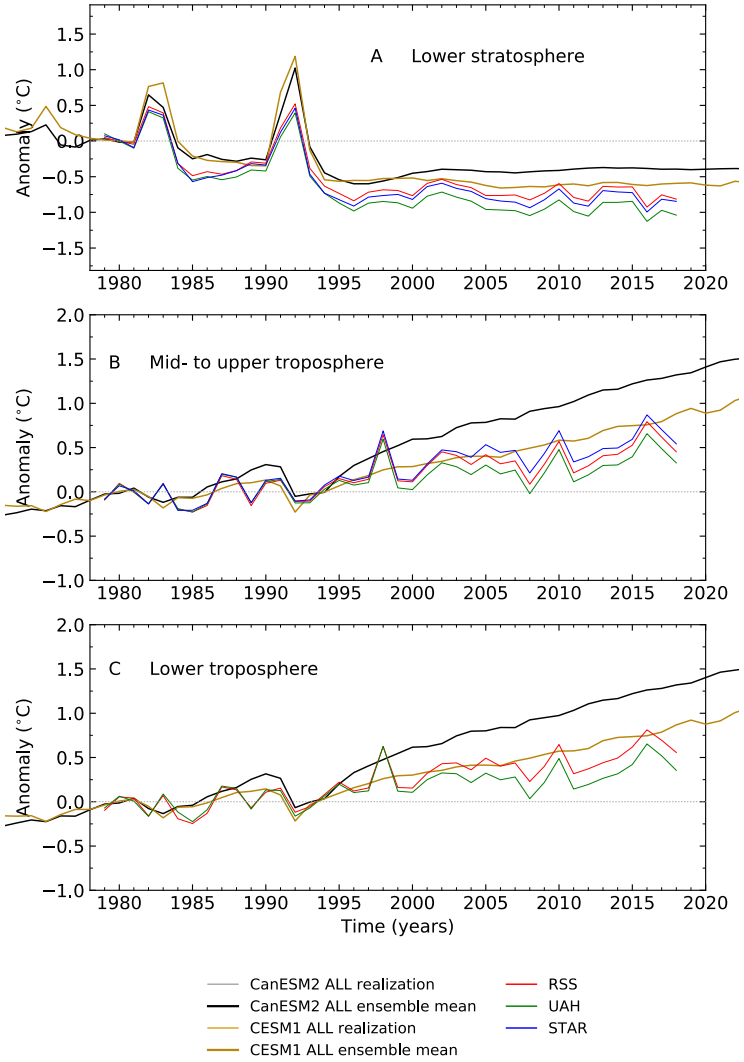
Benjamin D. Santer[1]*, Stephen Po-Chedley[1], Mark D. Zelinka[1], Ivana Cvijanovic[1], Céline Bonfils[1], Paul J. Durack[1], Qiang Fu[2], Jeffrey Kiehl[3], Carl Mears[4], Jeffrey Painter[1], Giuliana Pallotta[1], Susan Solomon[5], Frank J. Wentz[4], Cheng-Zhi Zou[6]

We provide scientific evidence that a human-caused signal in the seasonal cycle of tropospheric temperature has emerged from the background noise of natural variability. Satellite data and the anthropogenic "fingerprint" predicted by climate models show common large-scale changes in geographical patterns of seasonal cycle amplitude. These common features include increases in amplitude at mid-latitudes in both hemispheres, amplitude decreases at high latitudes in the Southern Hemisphere, and small changes in the tropics. Simple physical mechanisms explain these features. The model fingerprint of seasonal cycle changes is identifiable with high statistical confidence in five out of six satellite temperature datasets. Our results suggest that attribution studies with the changing seasonal cycle provide powerful evidence for a significant human effect on Earth's climate.

Human influence on the seasonal cycle of tropospheric temperature: Santer et al., J. Climate (2022)

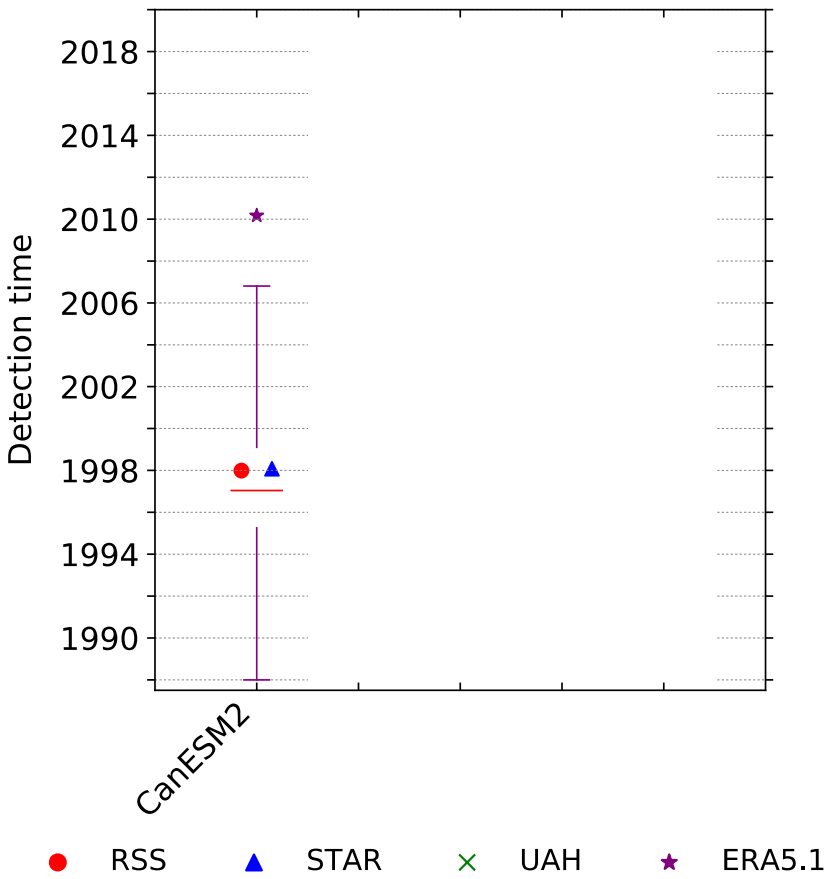
Robust Anthropogenic Signal Identified in the Seasonal Cycle of Tropospheric Temperature

BENJAMIN D. SANTER,[a,b] STEPHEN PO-CHEDLEY,[a] NICOLE FELDL,[c] JOHN C. FYFE,[d] QIANG FU,[e] SUSAN SOLOMON,[f] MARK ENGLAND,[c] KEITH B. RODGERS,[g,h] MALTE F. STUECKER,[i] CARL MEARS,[j] CHENG-ZHI ZOU,[k] CÉLINE J. W. BONFILS,[a] GIULIANA PALLOTTA,[a] MARK D. ZELINKA,[a] NAN ROSENBLOOM,[l] AND JIM EDWARDS[l]



- Large Initial Condition Ensembles are valuable for estimating:
  - Signal and noise in models with different forcing, ECS
  - Internal variability in OBS
  - Uncertainty in fingerprint detection time

Fingerprint detection time for seasonal cycle of tropospheric temperature

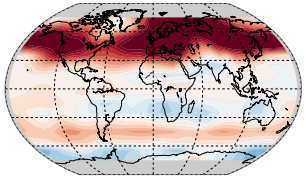


- Robust detection of seasonal cycle fingerprint in LEs and satellite data
- Why?

Fingerprints and noise in the seasonal cycle of tropospheric temperature

CESM1 CESM2 CanESM2 CanESM5 MIROC6

Fingerprint



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Summary of seasonal cycle work

- Fingerprints of human-caused seasonal cycle changes statistically identifiable in 239 of 240 Large Ensemble realizations
- Fingerprint identification unlikely to be biased by model underestimates of observed multidecadal internal variability
- Fingerprint patterns are spatially dissimilar to smaller-scale patterns of internal variability associated with the AMO and ENSO
- Basic physical processes drive common patterns of forced seasonal cycle changes in observations and the five LEs:
  - GHG-induced tropical expansion, lapse-rate changes, land surface drying, sea ice decrease

What my talk will cover

- Recent advances
  - IPCC AR6 and Steiner et al. (2020)
  - Seasonal cycle of tropospheric temperature
  - “Vertical fingerprinting”
- Outstanding challenges

Manabe: Using models to understand the real-world climate system

2021 Nobel Physics Prize

Awarded for:

"…the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

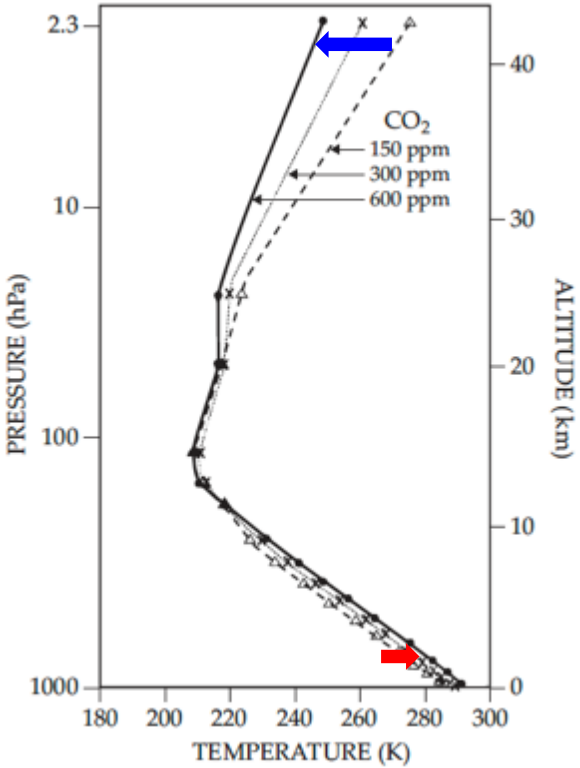
Manabe and Wetherald, 1967

Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity

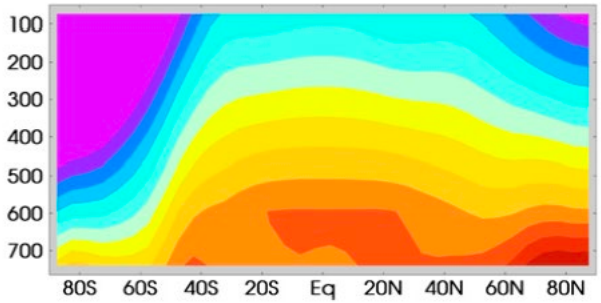
SYUKURO MANABE AND RICHARD T. WETHERLAND

Geophysical Fluid Dynamics Laboratory, ESSA, Washington, D.C.

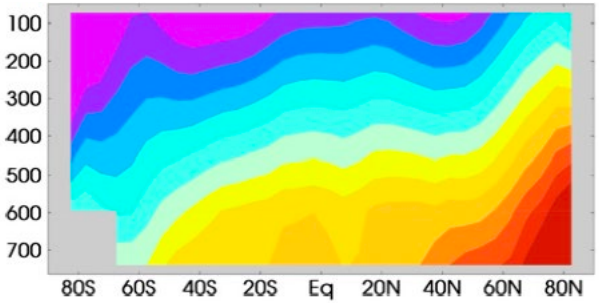
(Manuscript received 2 November1966)



CMIP5 models



MSU (Remote Sensing Systems)



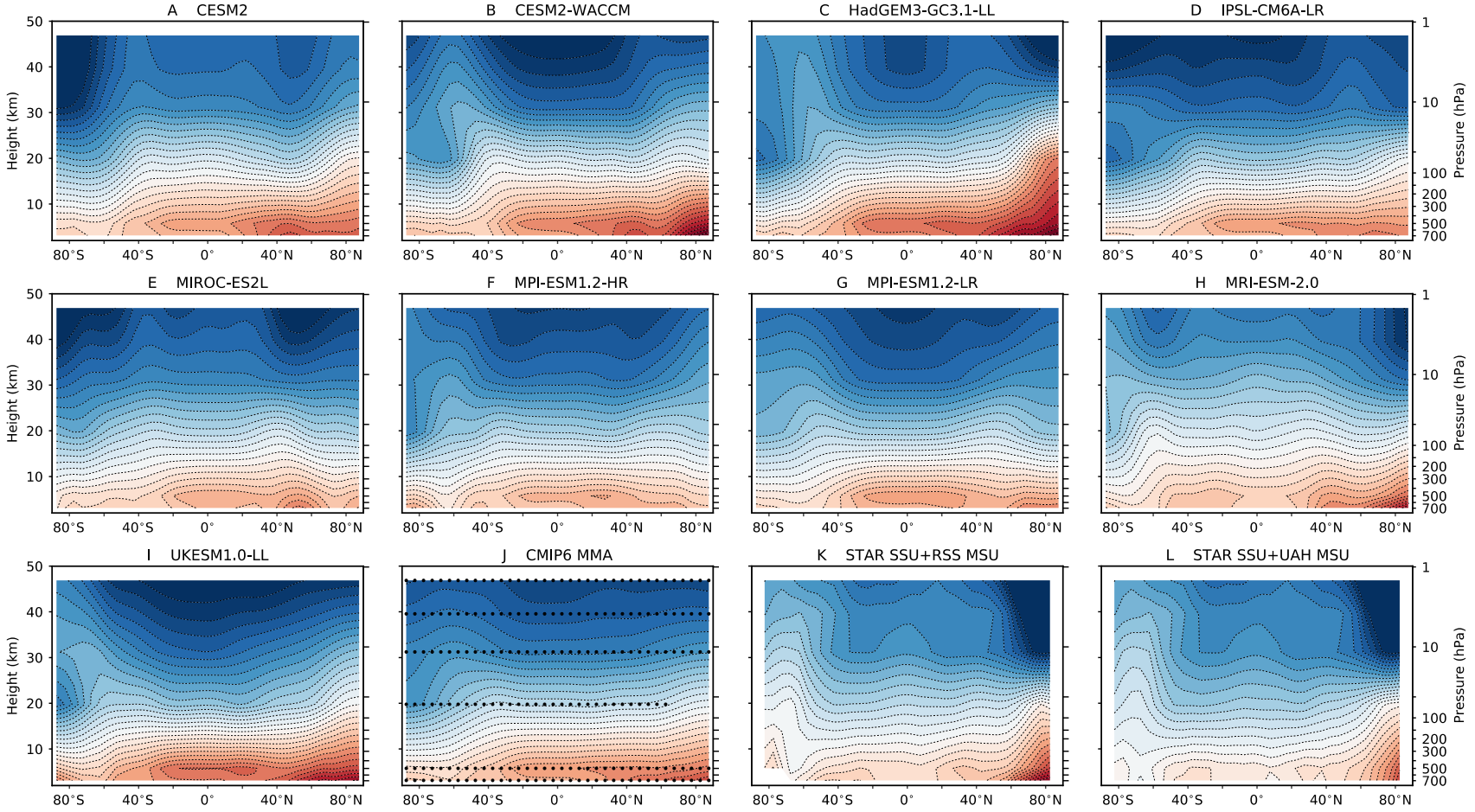
Human and natural influences on the changing thermal structure of the atmosphere

Benjamin D. Santer[a,1], Jeffrey F. Painter[a], Céline Bonfils[a], Carl A. Mears[b], Susan Solomon[c], Tom M. L. Wigley[d,e], Peter J. Gleckler[a], Gavin A. Schmidt[f], Charles Doutriaux[a], Nathan P. Gillett[g], Karl E. Taylor[a], Peter W. Thorne[h], and Frank J. Wentz[b]

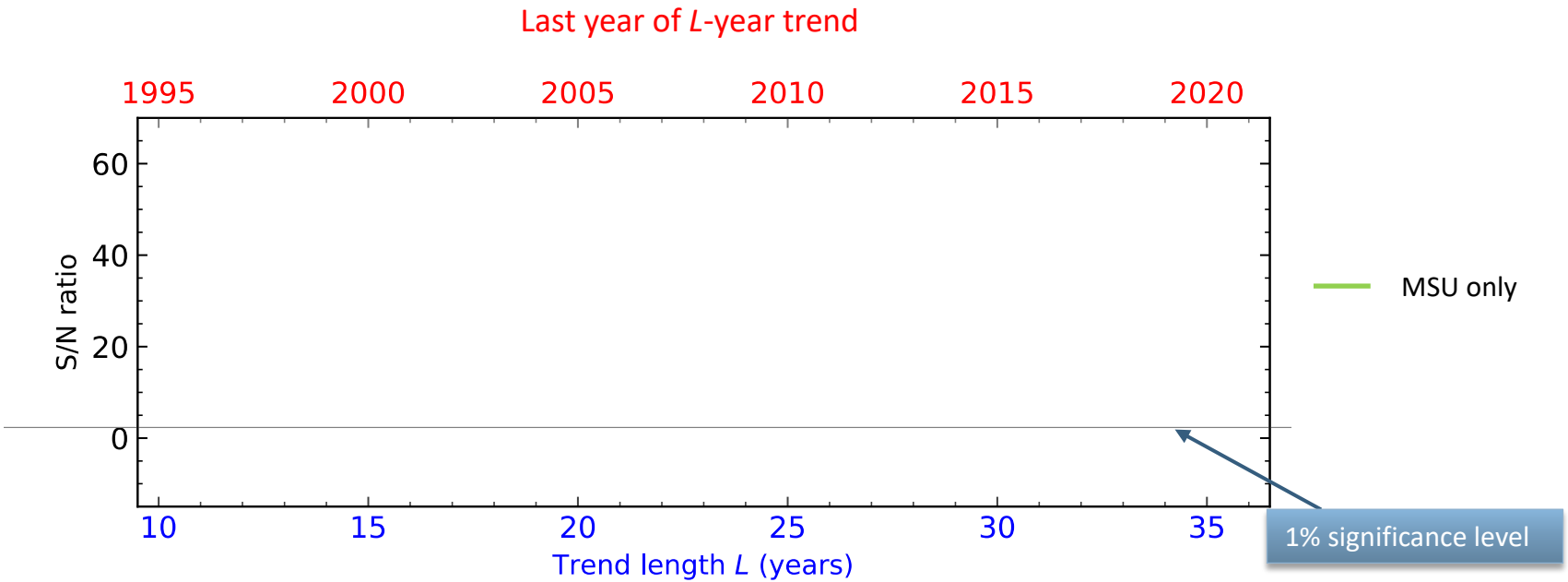
[a]Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, CA 94550; [b]Remote Sensing Systems, Santa Rosa, CA 95401; [c]Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139; [d]National Center for Atmospheric Research, Boulder, CO 80307; [e]School of Earth and Environmental Sciences, University of Adelaide, Adelaide, SA 5005, Australia; [f]National Aeronautics and Space Administration/Goddard Institute for Space Studies, New York, NY 10025; [g]Canadian Centre for Climate Modelling and Analysis, Environment Canada, Victoria, BC, Canada V8W 2Y2; and [h]Nansen Environmental and Remote Sensing Center, N-5006 Bergen, Norway

- Previous “vertical fingerprint” studies with MSU/AMSU satellite data
- Fingerprint: lower troposphere to ca. 20-25 km above the surface
- Missed mid- to upper stratosphere

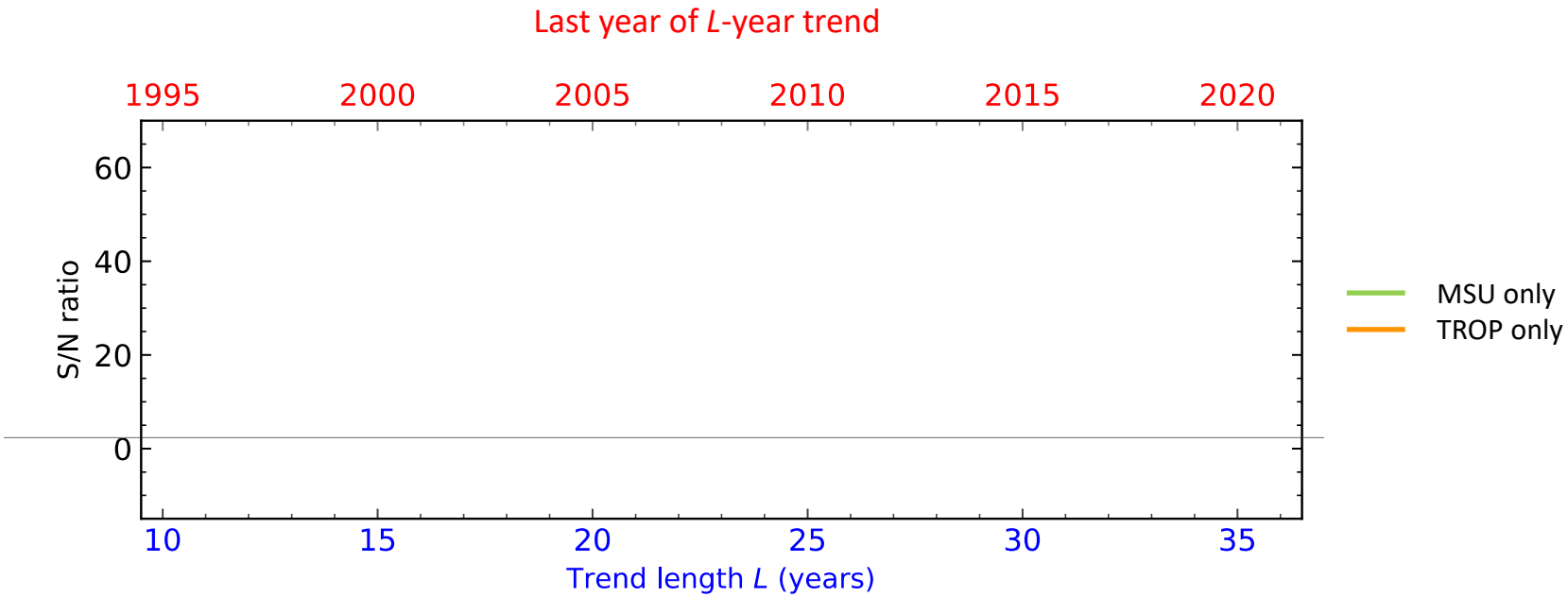
Trends in Satellite and CMIP6 SSU and MSU Temperature (1986-2021)



Signal-to-noise of different atmospheric layers: CMIP6



Signal-to-noise of different atmospheric layers: CMIP6



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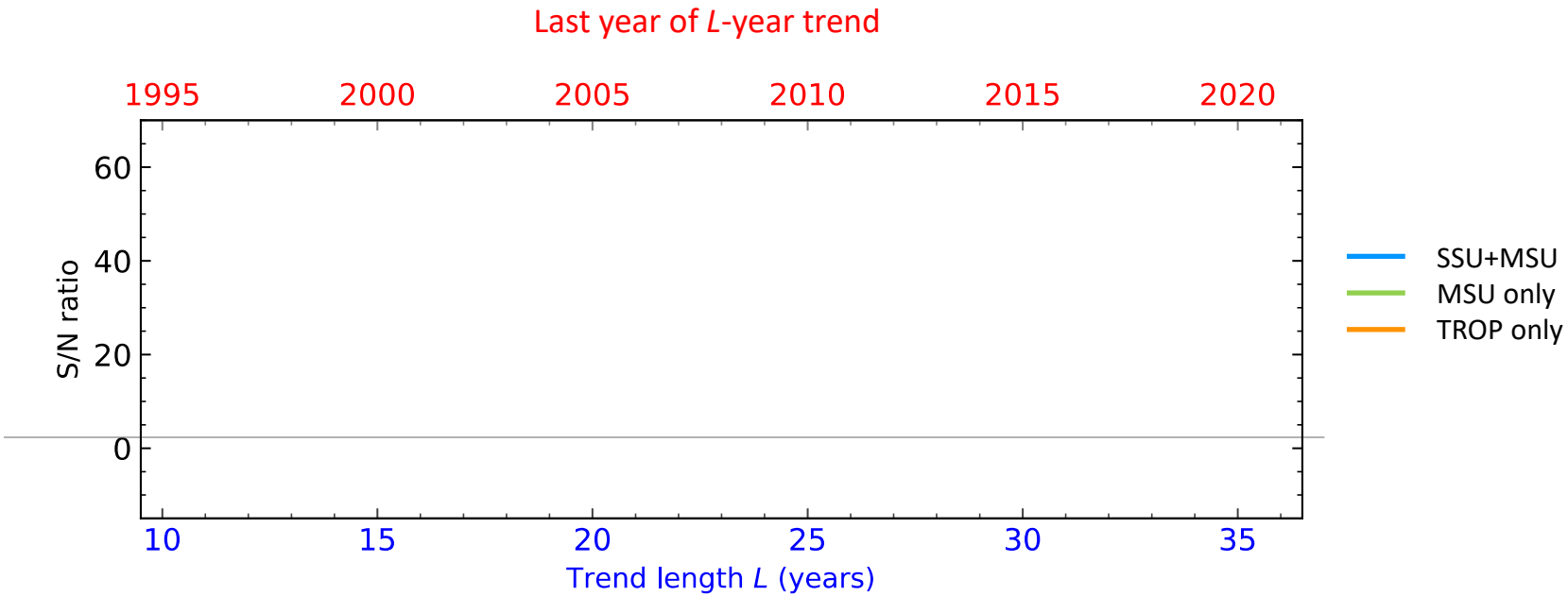
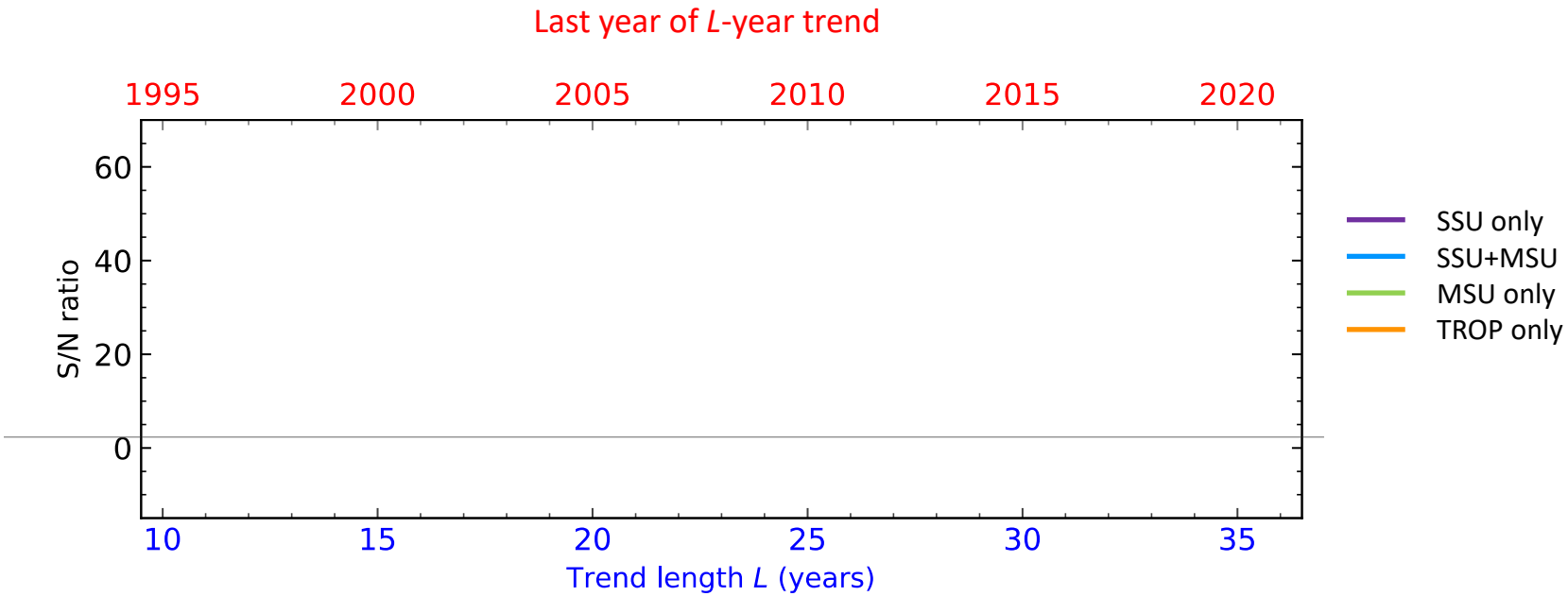
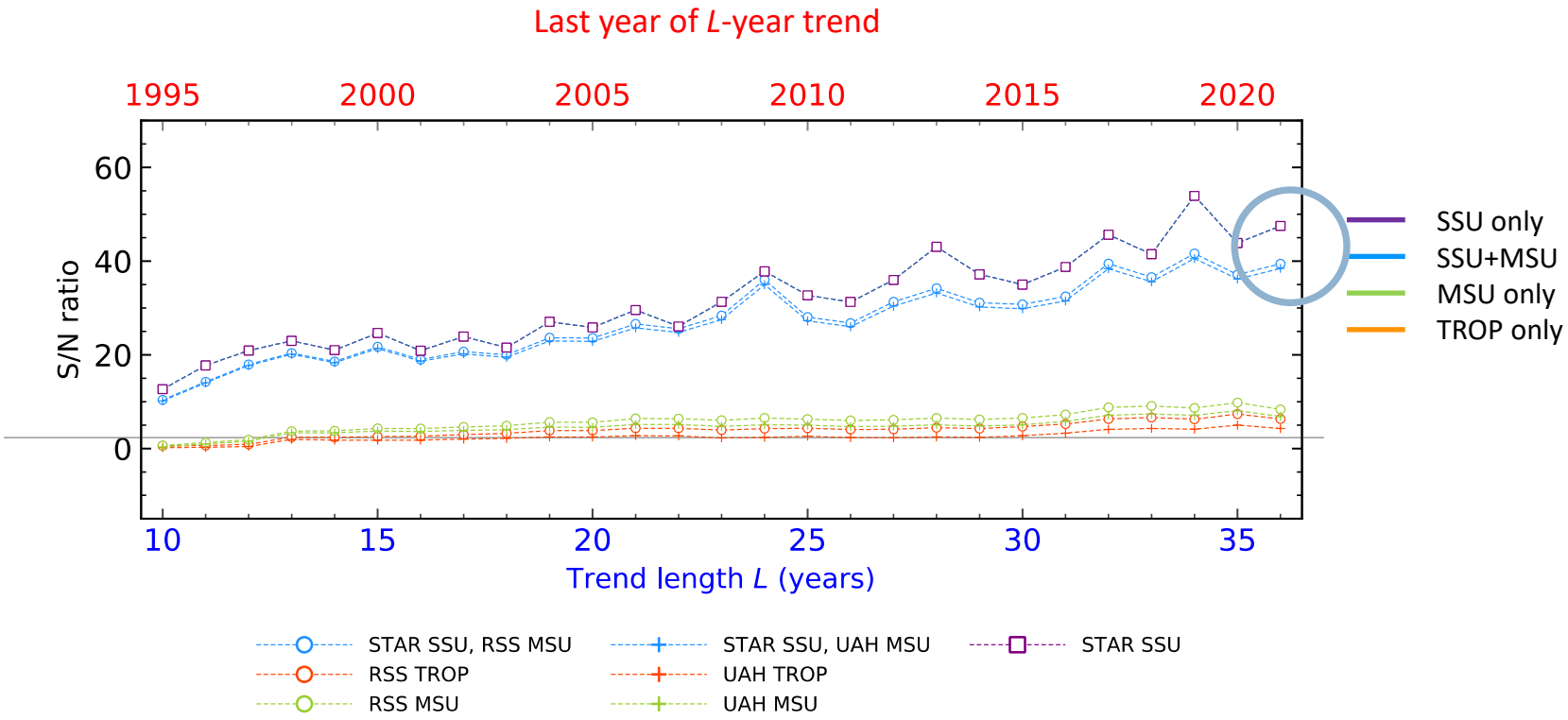


Signal-to-noise of different atmospheric layers: CMIP6



Signal-to-noise of different atmospheric layers: OBS



Summary of “vertical fingerprint” work

- Including the large (>1-2°C) mid- to upper stratospheric cooling over 1986 to 2021 enhances detectability of a human-caused fingerprint in atmospheric temperature
- Signal-to-noise (S/N) ratios > 38 in satellite temperature data
- S/N ratios exceed values obtained with other aspects of observed climate change
- Vertical structure of atmospheric temperature provides one of the clearest signatures of human effects on global climate

What my talk will cover

- Recent advances
  - IPCC AR6 and Steiner et al. (2020)
  - Seasonal cycle of tropospheric temperature
  - “Vertical fingerprinting”
- Outstanding challenges

Results from a recent Journal of Climate paper (Santer et al., 2021)

Using Climate Model Simulations to Constrain Observations

BENJAMIN D. SANTER,[a] STEPHEN PO-CHEDLEY,[a] CARL MEARS,[b] JOHN C. FYFE,[c] NATHAN GILLETT,[c] QIANG FU,[d] JEFFREY F. PAINTER,[a] SUSAN SOLOMON,[e] ANDREA K. STEINER,[f] FRANK J. WENTZ,[b] MARK D. ZELINKA,[a] AND CHENG-ZHI ZOU[g]

[a] *Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, California*
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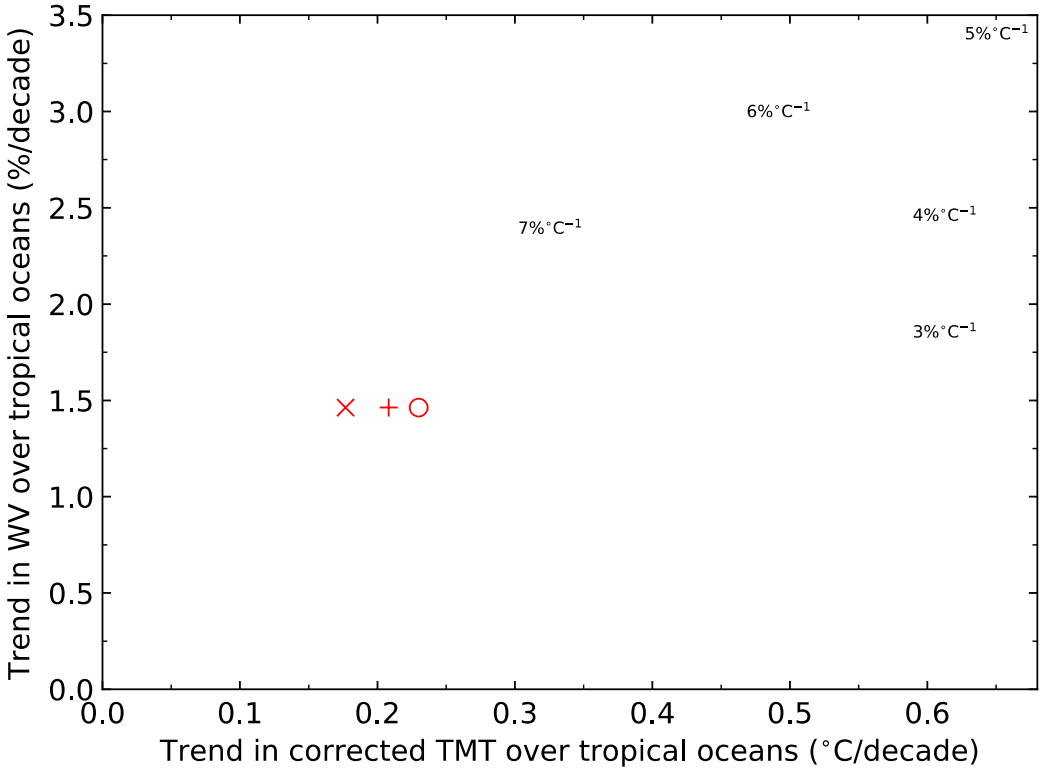
[c] *Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, British Columbia, Canada*
[d] *Department of Atmospheric Sciences, University of Washington, Seattle, Washington*
[e] *Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts*
[f] *Wegener Center for Climate and Global Change, University of Graz, Graz, Austria*
[g] *Center for Satellite Applications and Research, NOAA/NESDIS, Camp Springs, Maryland*

Trends in tropical tropospheric temperature and moisture (1988-2019)



Climate models

- CMIP5 (CanESM2 LE)
- CMIP5 (CESM1 LE)
- CMIP5 (26 other models)
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- CMIP6 (CESM2 LE)
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Observations

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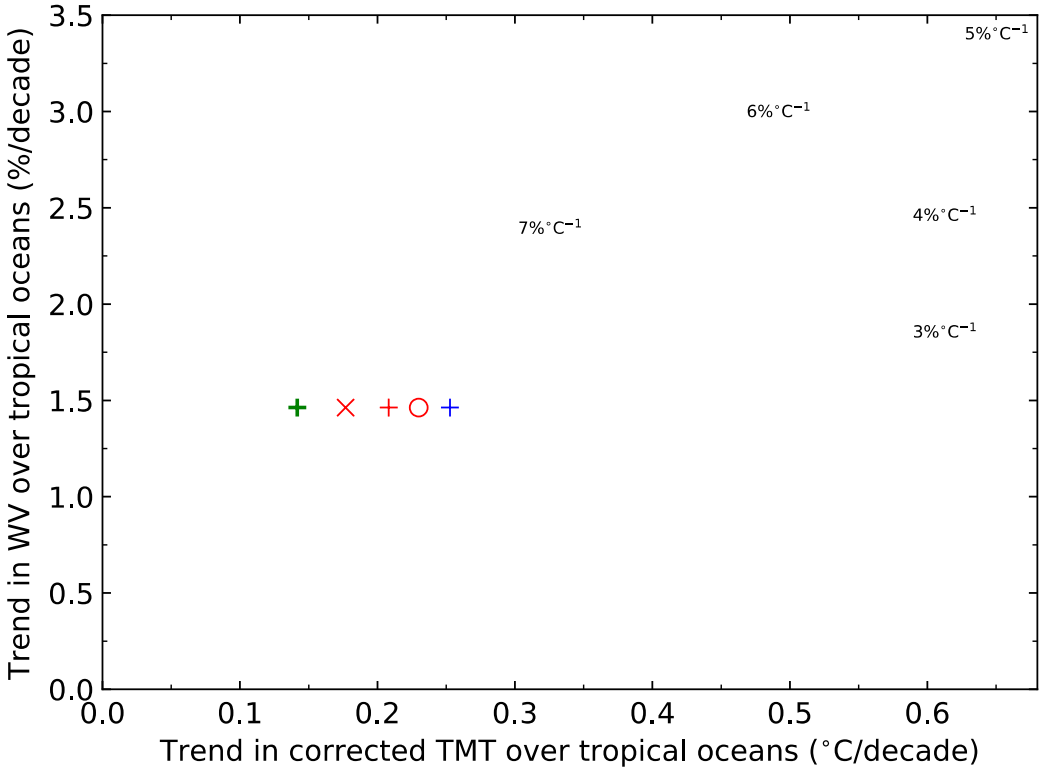

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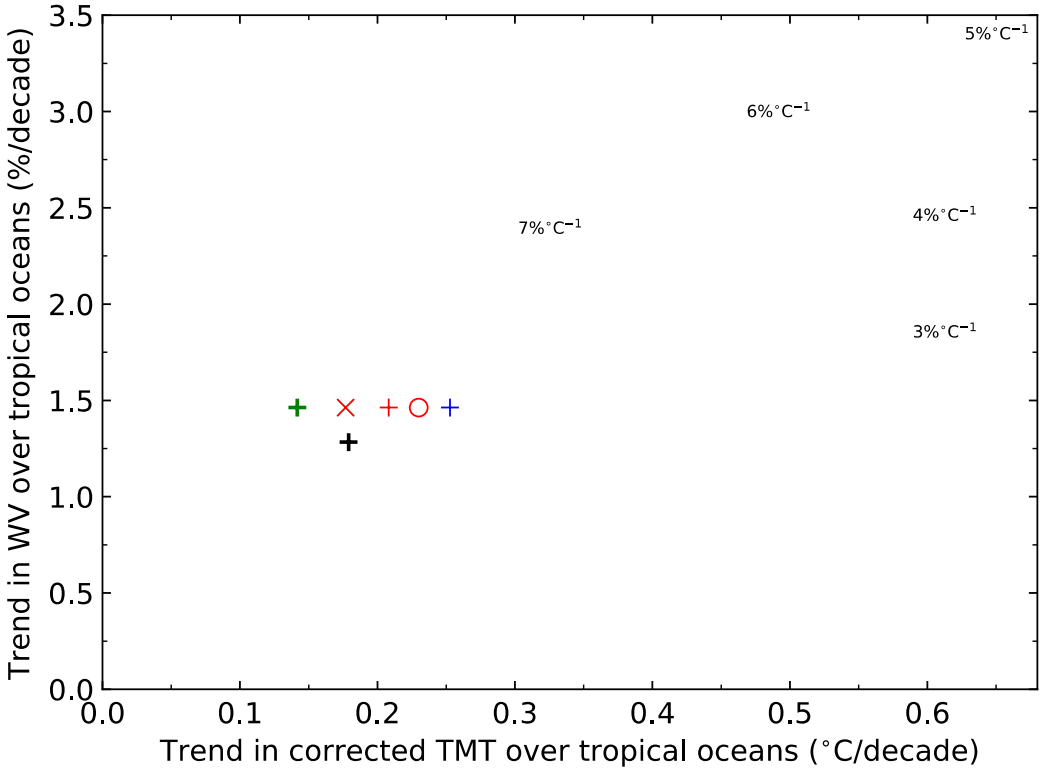

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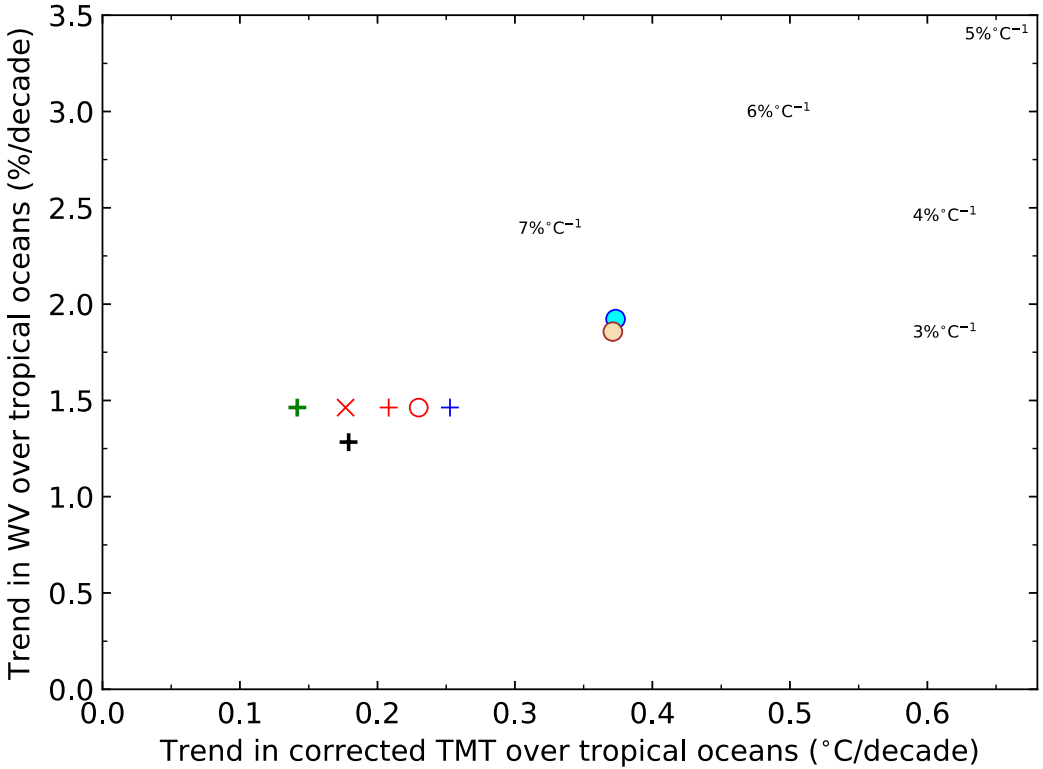

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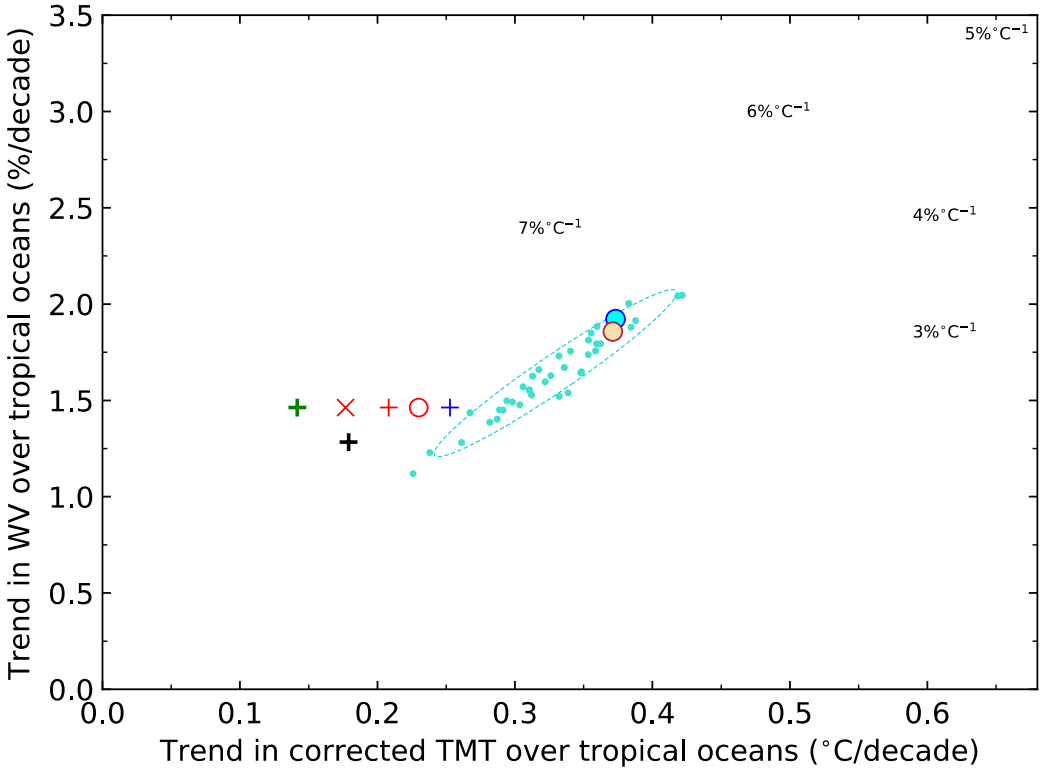

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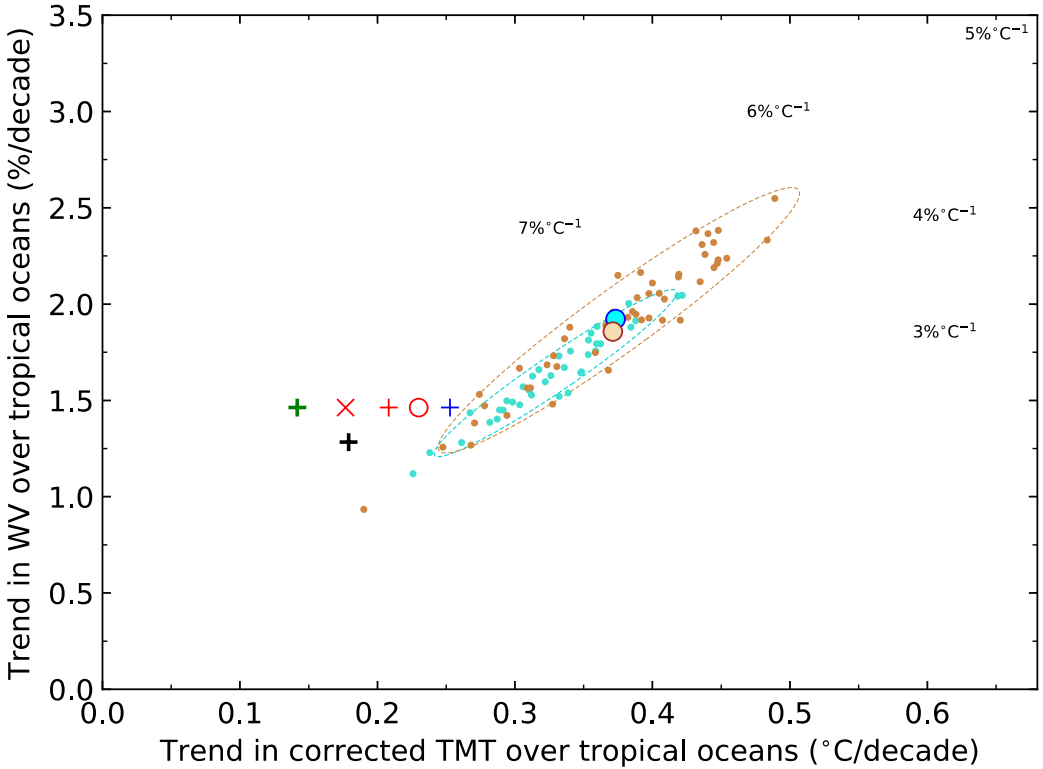

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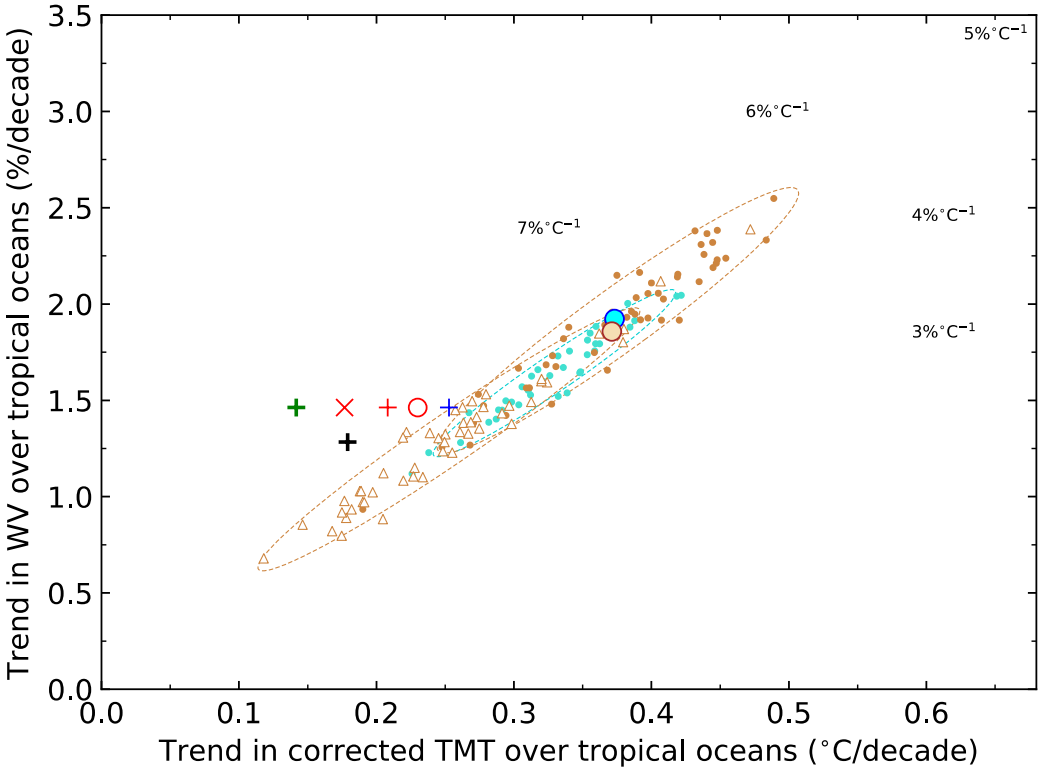

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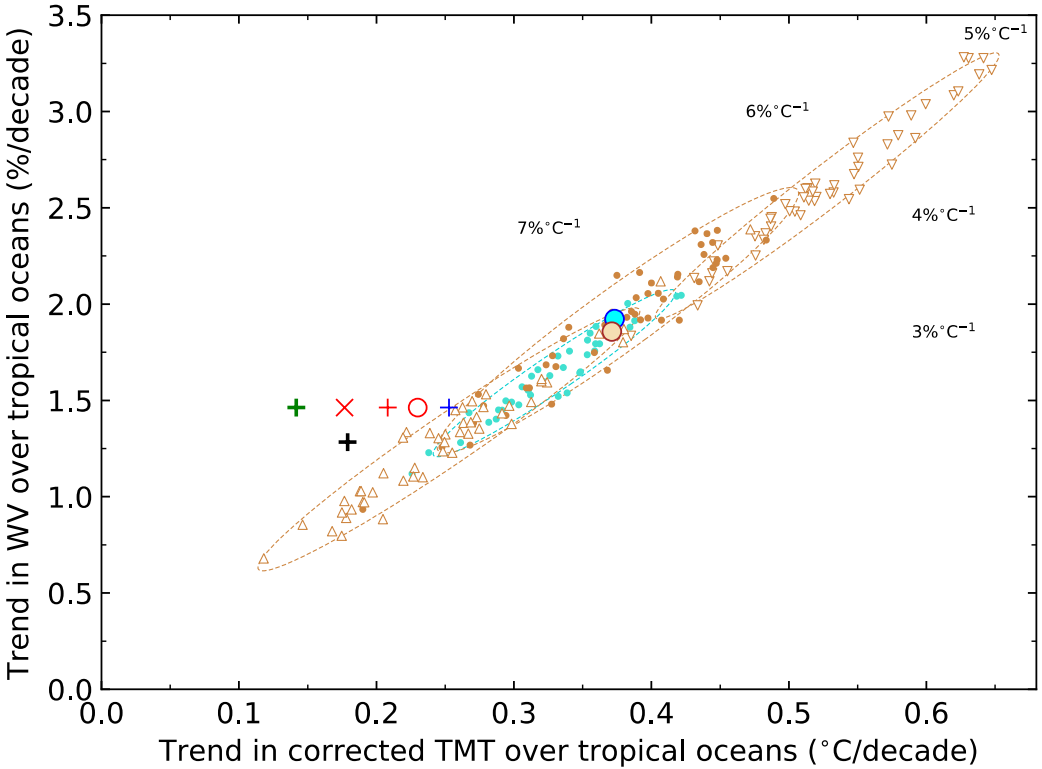

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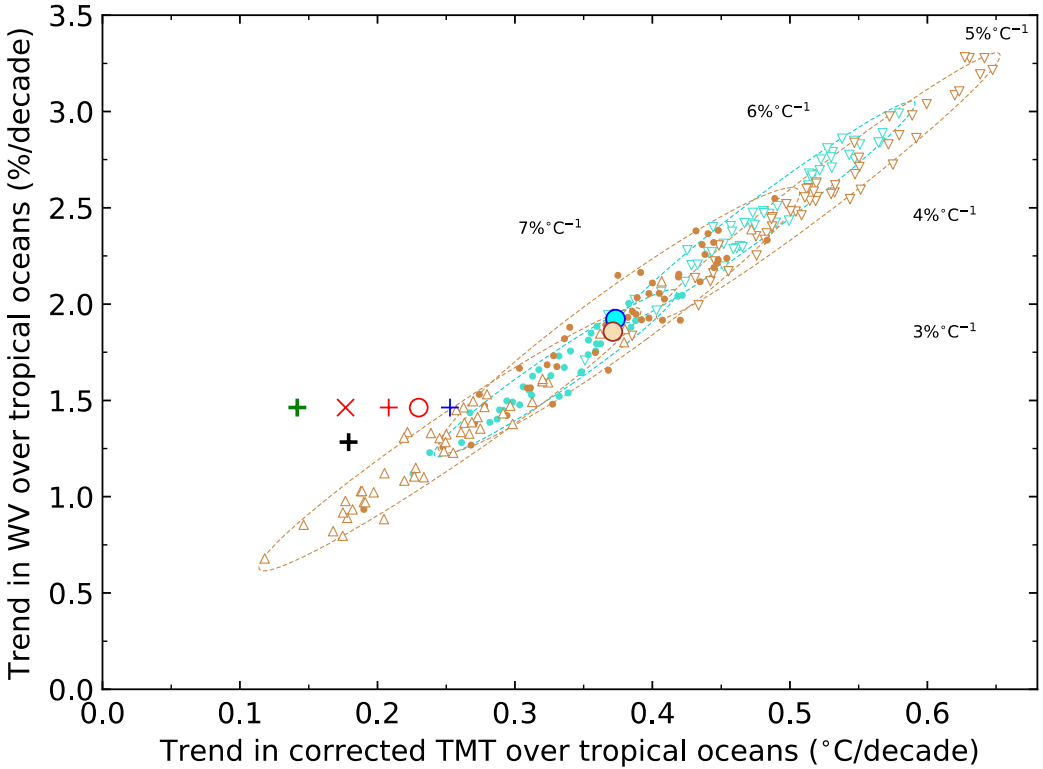

Climate models

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CMIP5 (CESM1 LE)	**4.1**
CMIP5 (26 other models)	
CMIP5 MMA	
CMIP6 (CanESM5 LE)	**5.64**
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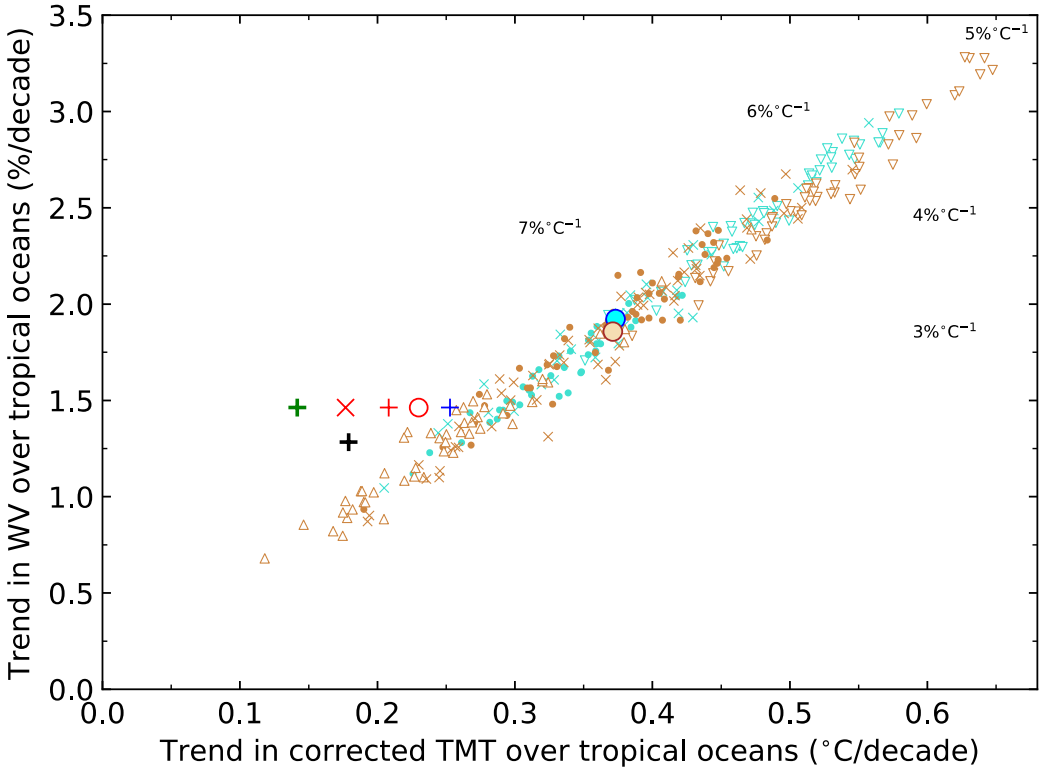
Trends in tropical tropospheric temperature and moisture (1988-2019)



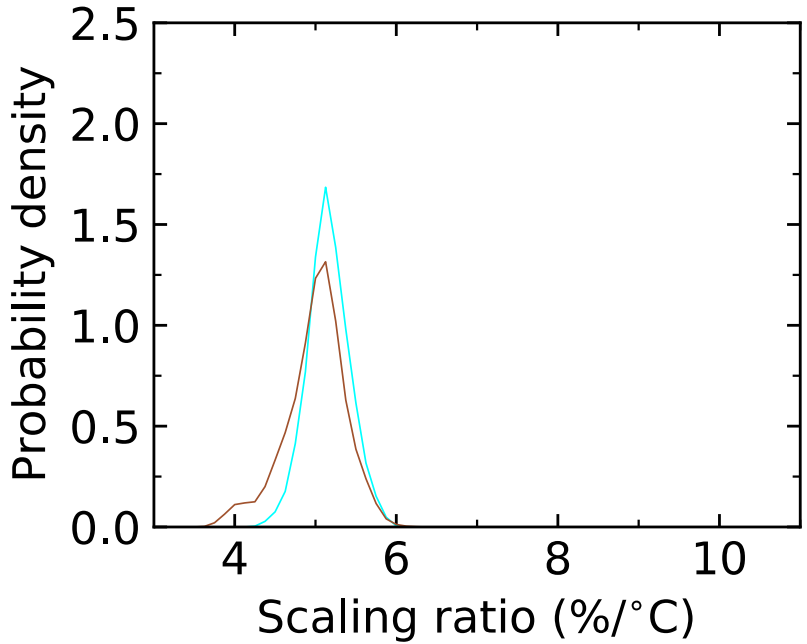
Climate models

- CMIP5 (CanESM2 LE)
- CMIP5 (CESM1 LE)
- CMIP5 (26 other models)
- CMIP5 MMA
- CMIP6 (CanESM5 LE)
- CMIP6 (CESM2 LE)
- CMIP6 (MIROC6 LE)
- CMIP6 (20 other models)
- CMIP6 MMA

Observations

- RSS (baseline)
- RSS (AMSU merge)
- RSS (MSU merge)
- STAR
- UAH
- ERA5.1

Ratio between trends in tropical tropospheric temperature and moisture



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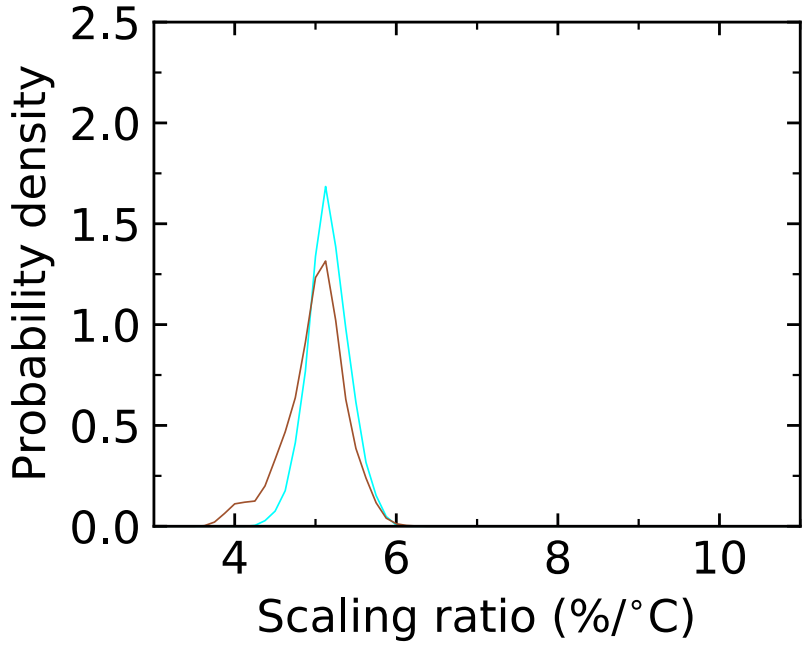

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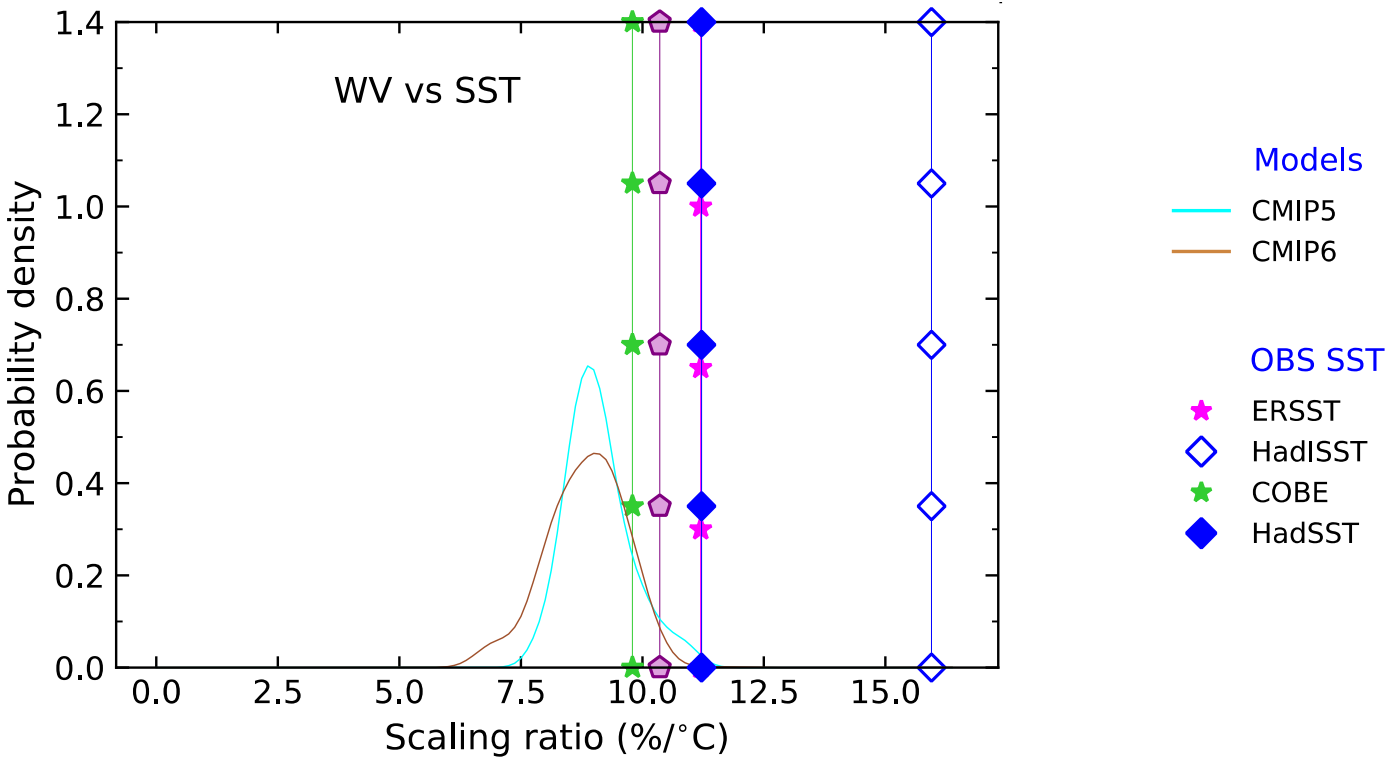
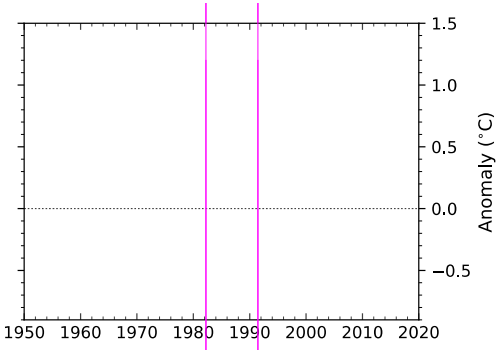
SST also yields systematic differences between model and observed tropical scaling ratios



Summary of work on covariability of temperature and water vapor

- In models, ratio $R_{\{WV:TMT\}}$ between tropical tropospheric temperature trends and tropical moisture trends is tightly constrained
  - $R_{\{WV:TMT\}}$ insensitive to model differences in vintage, ECS, historical external forcings, and multidecadal internal variability
- Observed $R_{\{WV:TMT\}}$ values vary by a factor of 2 and significantly exceed model results
- Differences between simulated and observed $R_{\{WV:TMT\}}$ values may reflect:
  - Systematic low bias in observed TMT trends (not enough warming)
  - High bias in observed WV trend from SSMI (too much moistening)

EXTRA SLIDES



CESM2 AMO

Do models underestimate observed internal variability on multidecadal timescales?