Characteristics of the stratospheric tropical circulation in DoE's Energy Exascale Earth System Model E3SMv2

Christiane Jablonowski[1], Lisa Nguyen[1], Doug Kinnison[2]
& the CLDERA project team at Sandia National Laboratories

1. University of Michigan, Department of Climate and Space Sciences and Engineering, Ann Arbor, MI
2. National Center for Atmospheric Research (NCAR)

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Phenomena, Simulations & Observations

Assessments of the E3SMv2 (stratospheric tropical) circulation with the focus on

- **Temperature:** Climatology and temperature tendencies
- **Specific humidity:** Climatology and the water vapor tape recorder in the tropics
- **Zonal wind:** Climatology and the Quasi-Biennial Oscillation (QBO) in the tropics

Coupled **historical simulations** following the **CMIP6** protocol with the DoE Energy Exascale Earth System Model versions v2 & v1 at a 1-degree resolution with 72 levels (model top at 0.1 hPa / 64 km)

- **E3SMv2** released in 2022, 5 members, not documented in CMIP6 publications, 1850-2014
- **E3SMv1** released in 2019, 5 members, 1850-2014 (164 years)
- **WACCM-CCMI-2022** (4-member ensemble, AMIP mode, 70-levels, top at 150 km, 1960-2018

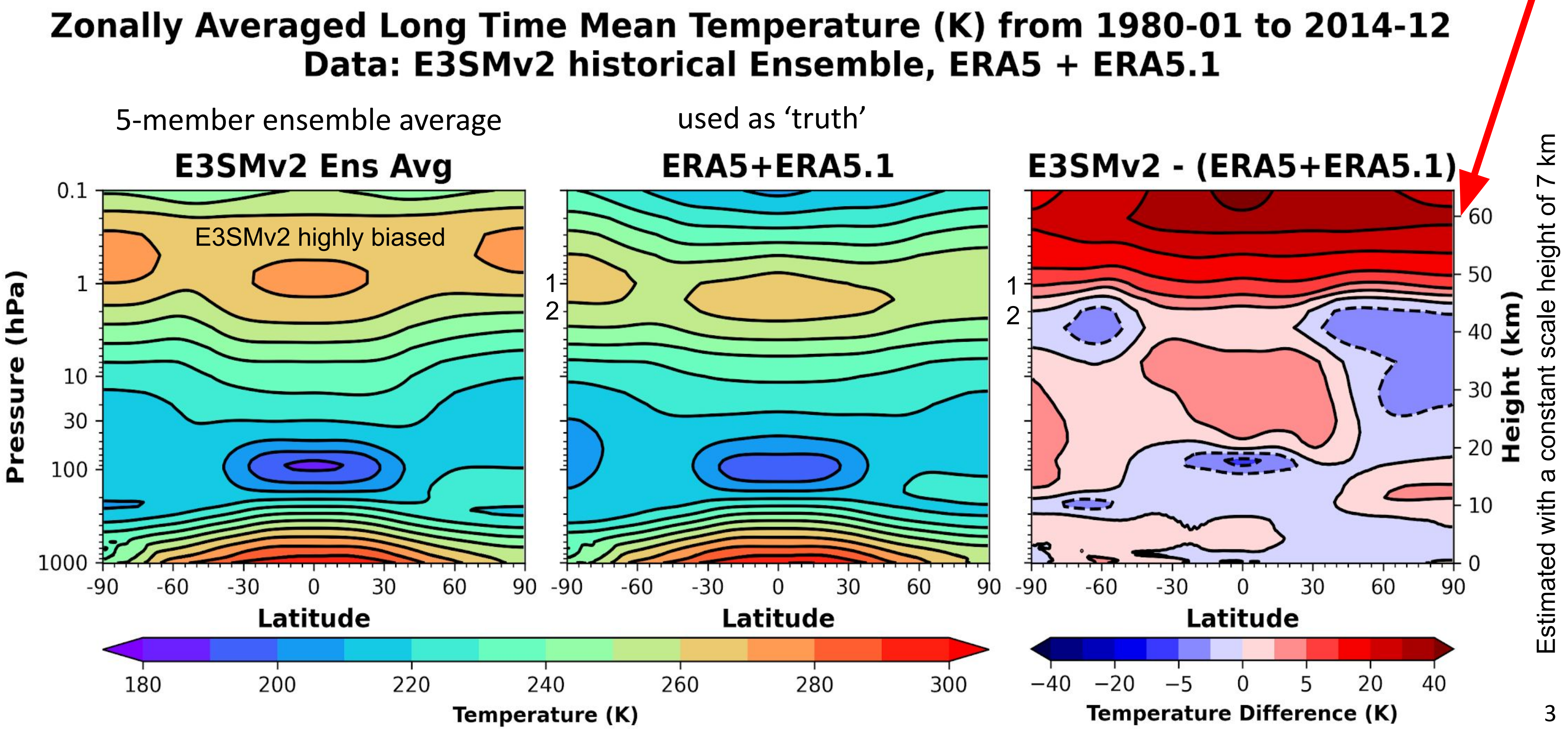
Observations

- ERA5/ERA5.1 reanalyses (zonal wind, temperature, specific humidity)
- SWOOSH satellite observations (water vapor, ozone)
- TRMM satellite observations (precipitation & tropical waves)

Goal of the talk: describe E3SMv2's stratosphere (missing from the CMIP6 literature)

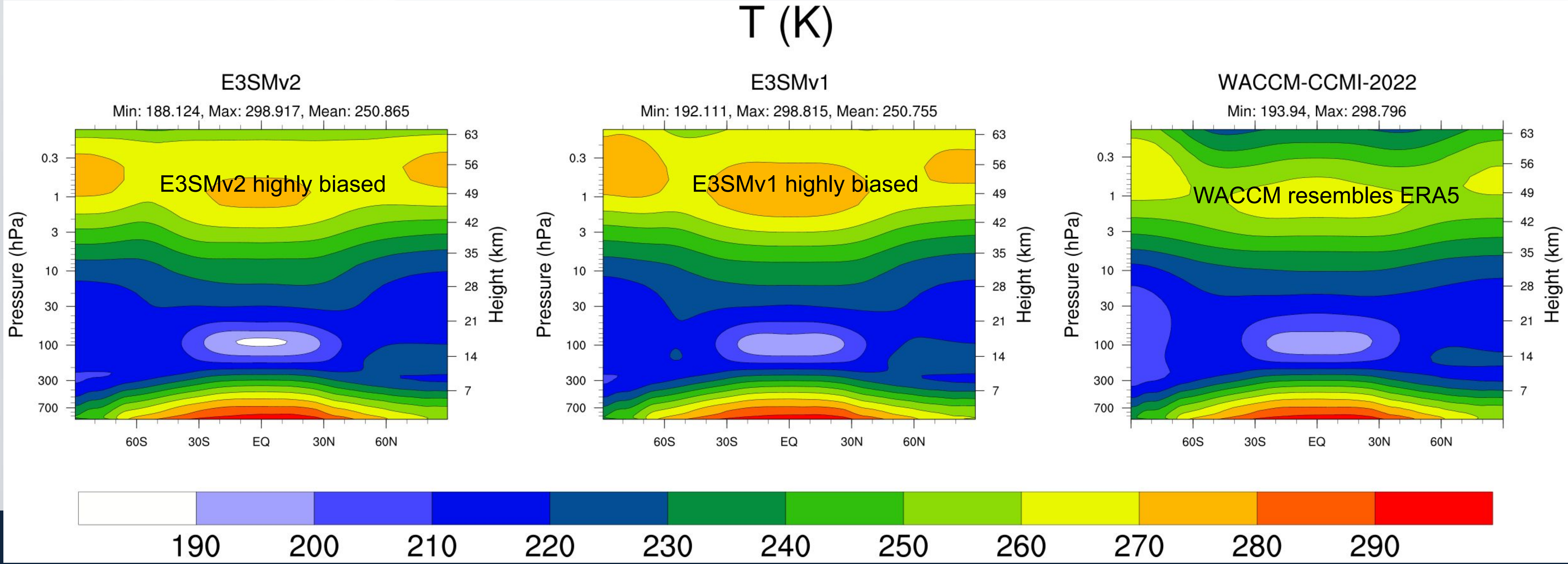
General Circulation: Physical Realism of the Temperature

- Very large E3SMv2 temperature biases in the upper stratosphere and mesosphere
- Use E3SMv2 data with extreme caution above 2 hPa (warm bias > 40 K)



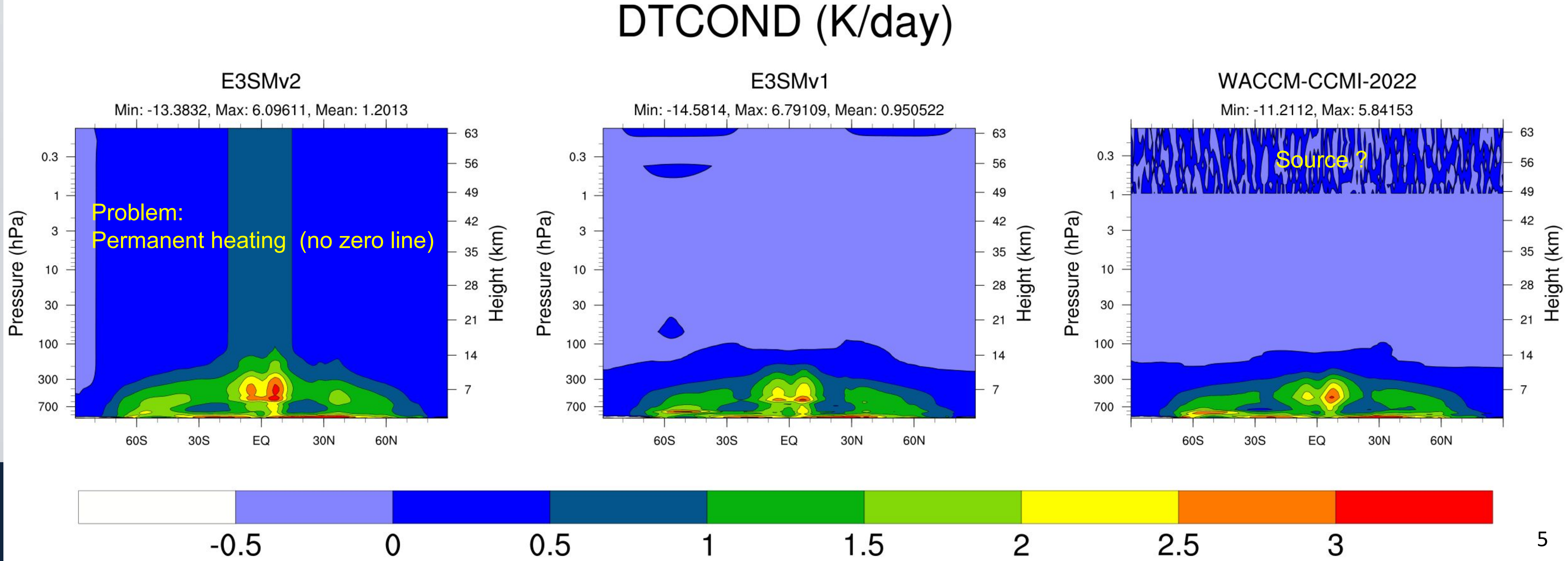
Temperature: Quick Comparison to WACCM-CCMI-2022

- Extreme warm T bias above 2 hPa already existed in E3SMv1
- WACCM-CCMI-2022 resembles ERA5 (previous slide)



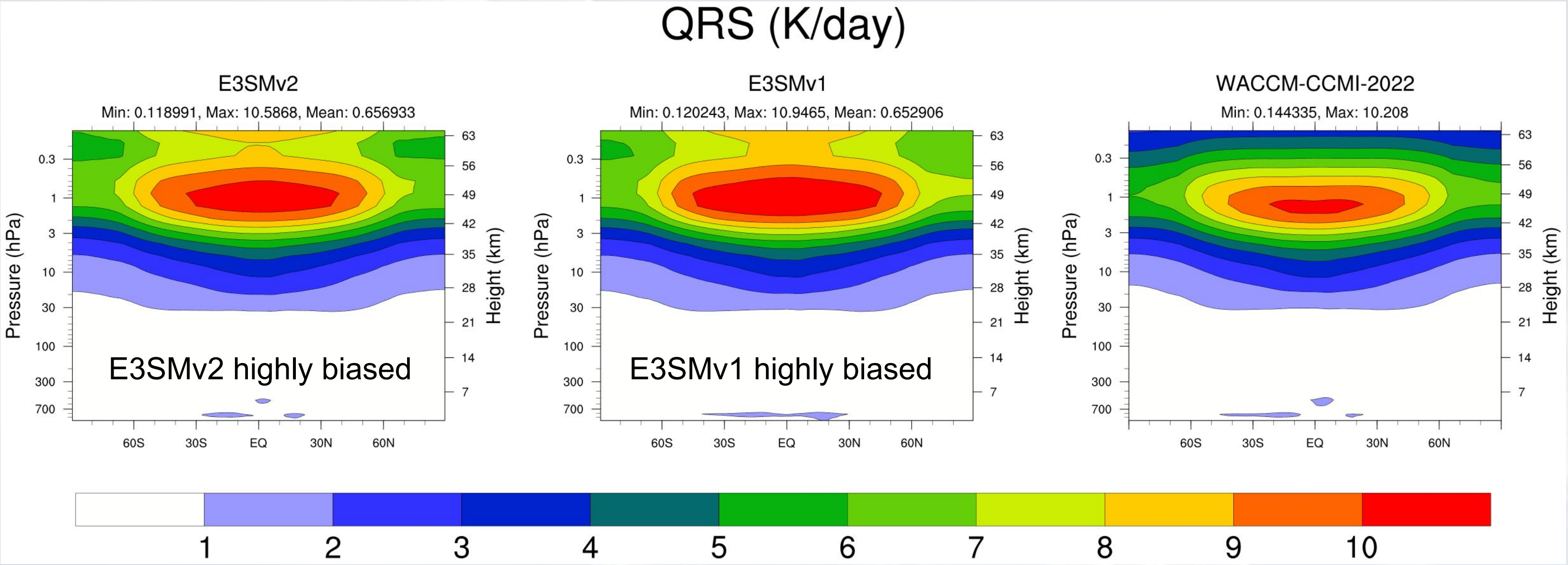
Possible Reasons for the E3SMv2 Warm Bias

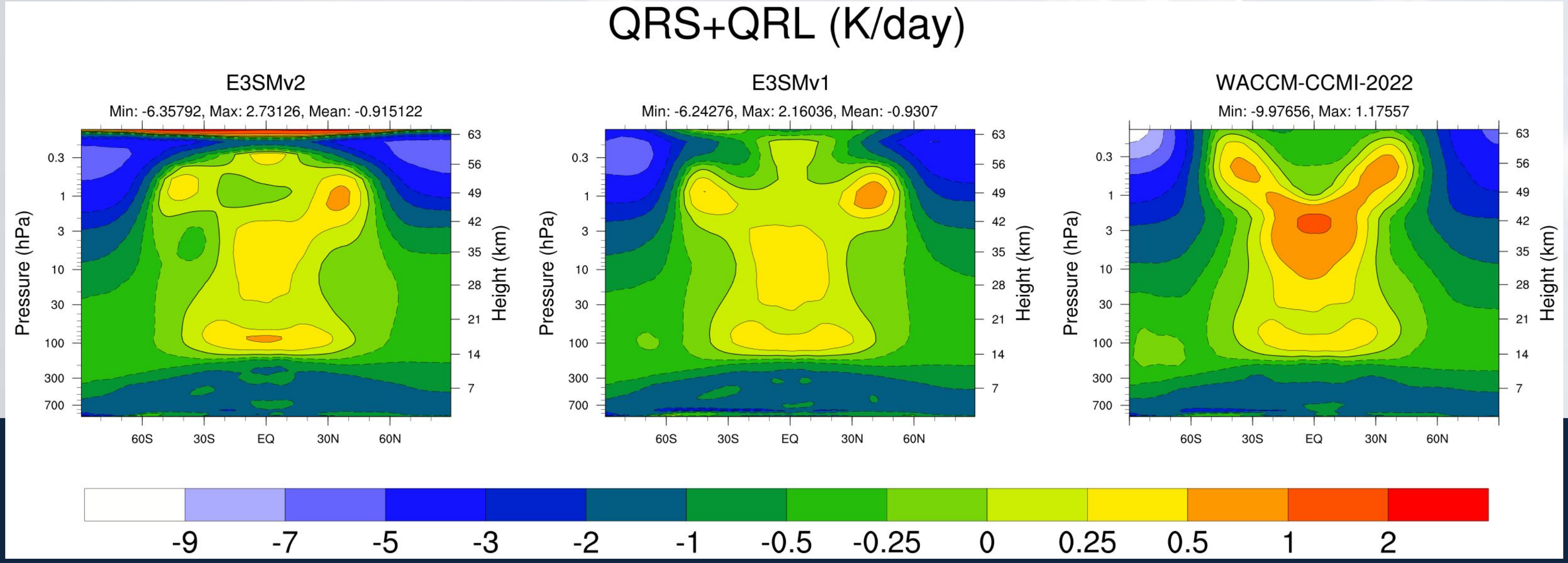
- DTCOND heating tendencies from moist processes (including convection) are suspicious in E3SM2
- Points to a problem in E3SMv2's CLUBB (PBL/shallow convection scheme) parameterization after consultation with Adam Herrington (NCAR)
- WACCM and E3SMv1 do not have the permanent heating problem in the stratosphere below 1 hPa



Possible Reasons for the E3SMv2 Warm Bias: Radiation

- Heating and cooling tendencies via shortwave (QRS) and longwave (QRL) radiation



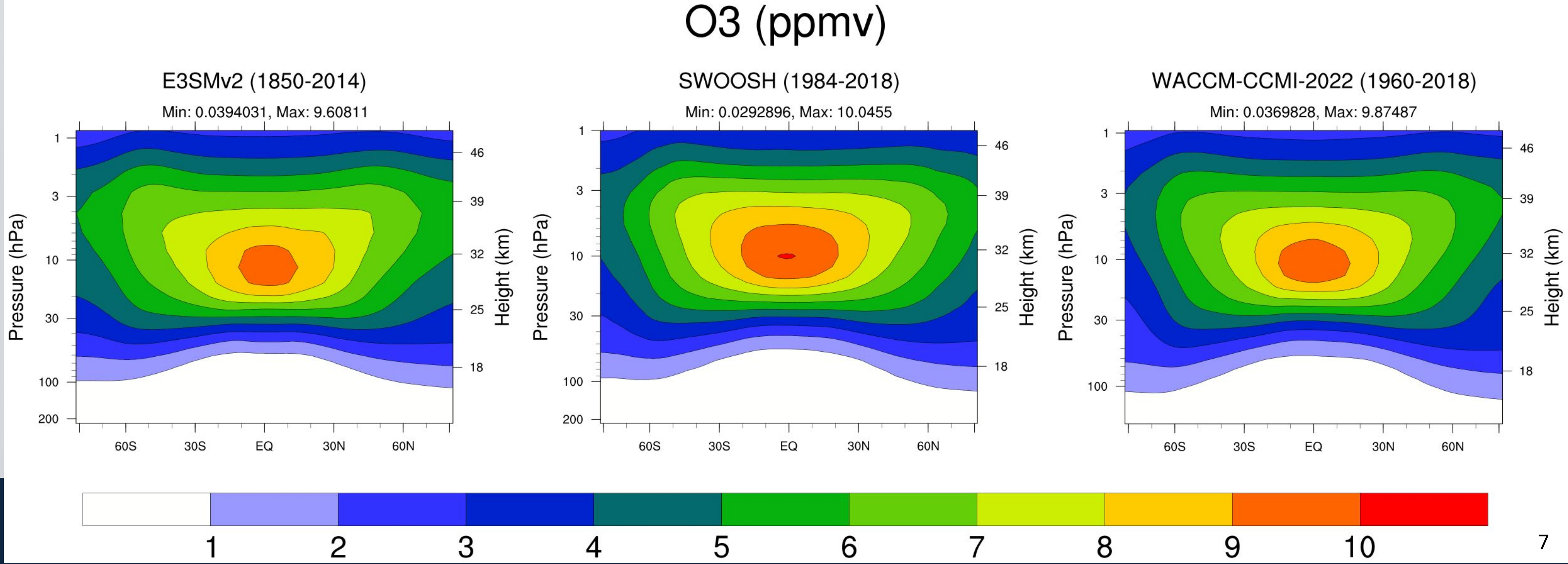


- In general: strong cancellation between QRS and QRL in the upper atmosphere
- Both QRS and QRL above 2 hPa are highly biased in E3SMv2/v1
- However, the E3SM biases are 'in sync' and strongly cancel each other when QRS+QRL is assessed (resembling WACCM-CCMI-2022)

zero line

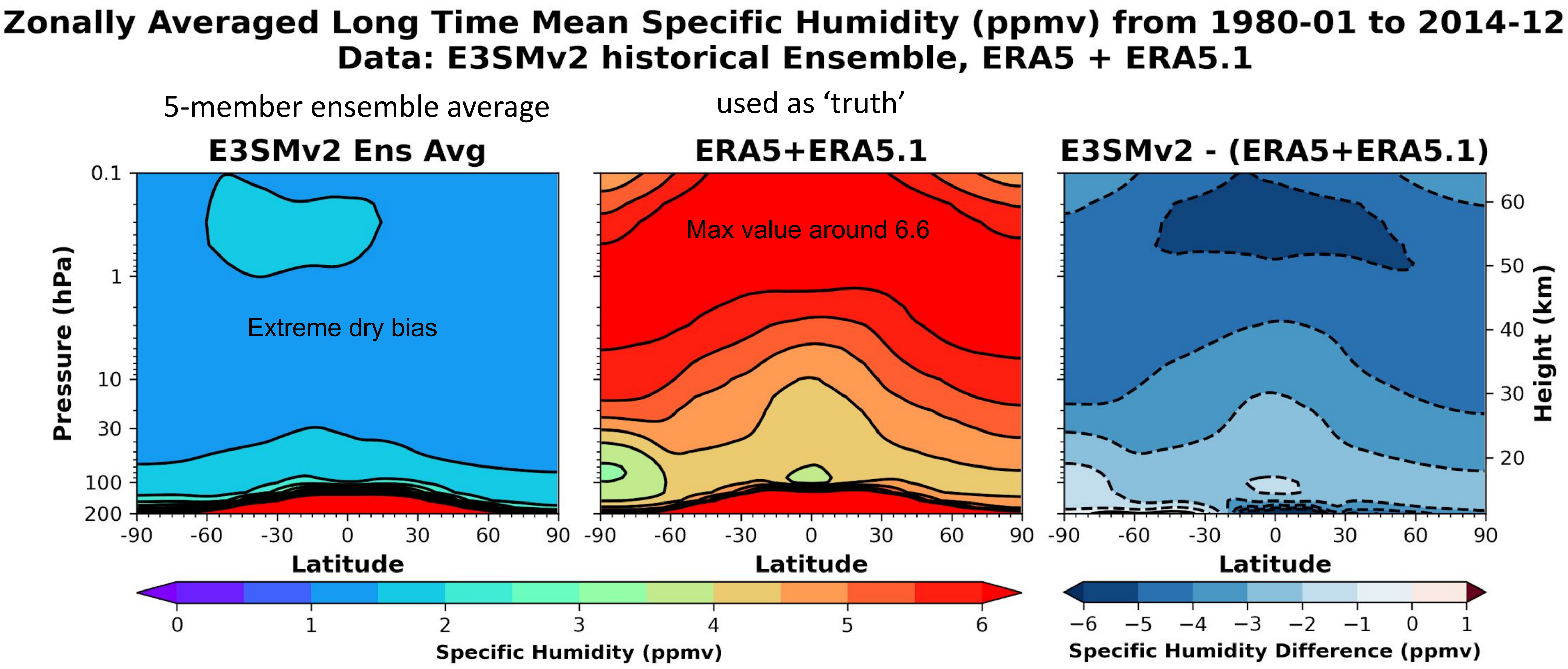
Possible Reasons for the E3SMv2 Warm Bias: Ozone

- Majority of the shortwave solar heating in the stratosphere is caused by the ozone (O3) production
- O3 in E3SMv2 unlikely source of the warm bias above 2 hPa
- O3 in E3SMv2 somewhat reduced in comparison to SWOOSH satellite observations (1994-2018)



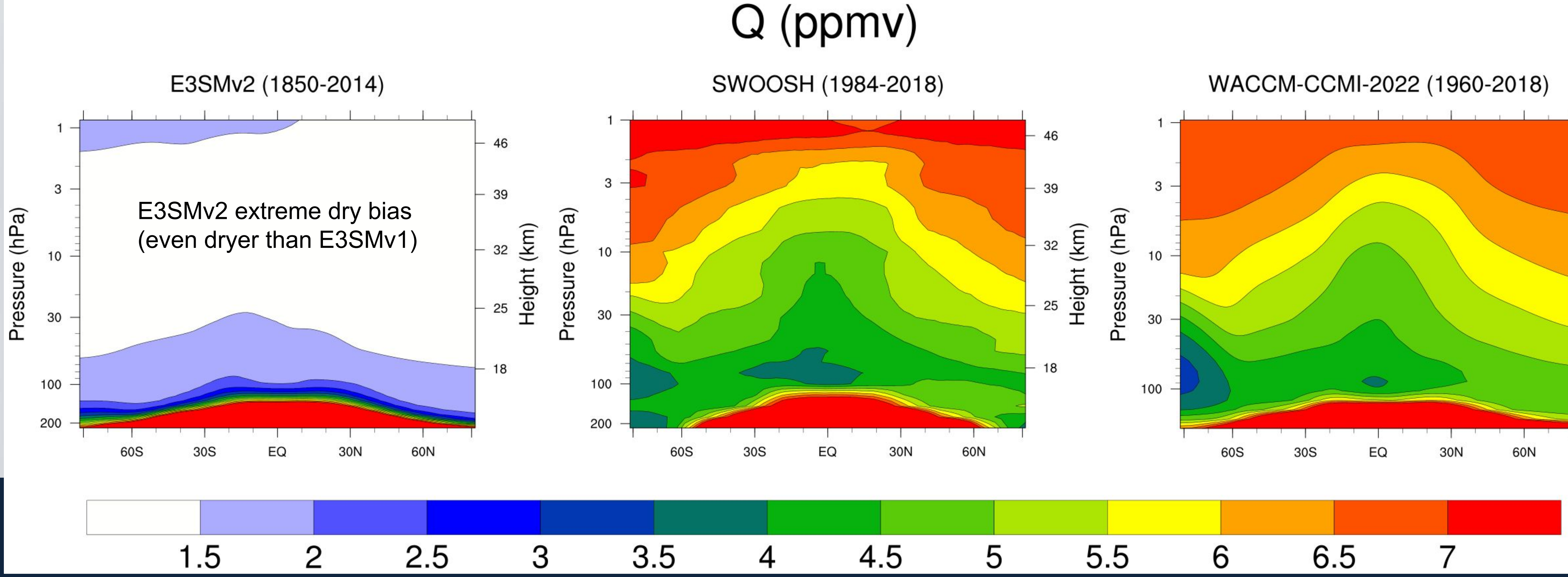
Physical Realism: Specific Humidity in the Middle Atmosphere

- Very large E3SMv2 humidity deficit in the stratosphere & mesosphere, E3SMv2 is too dry
- Use with caution, can trigger biases in other processes such as chemistry reactions that rely on the presence of moisture (important of SO2 to sulphate transition after Mt. Pinatubo eruption)



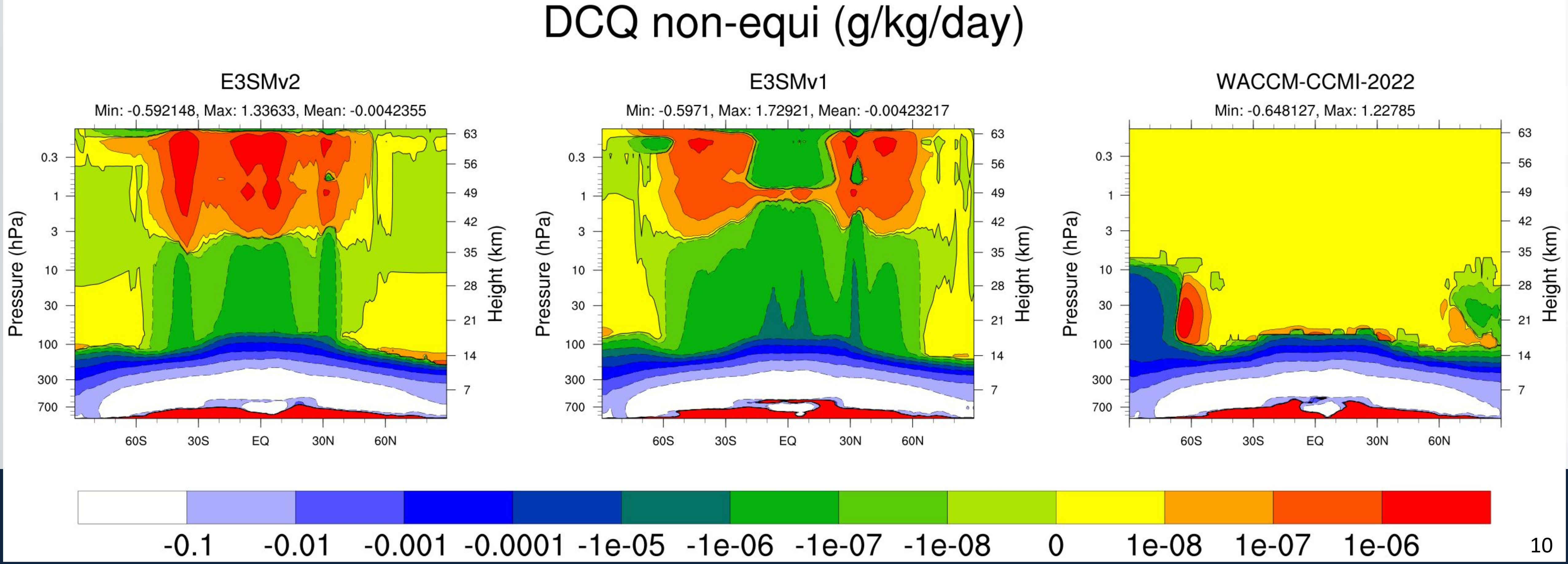
Specific humidity: Quick Comparison to WACCM-CCMI-2022

- Extreme dry bias in the stratosphere worsened in E3SMv2
- WACCM-CCMI-2022 specific humidity (Q) climatology (1960-2018) resembles ERA5 (previous slide, 1980-2014) and SWOOSH satellite observations (1984-2018)



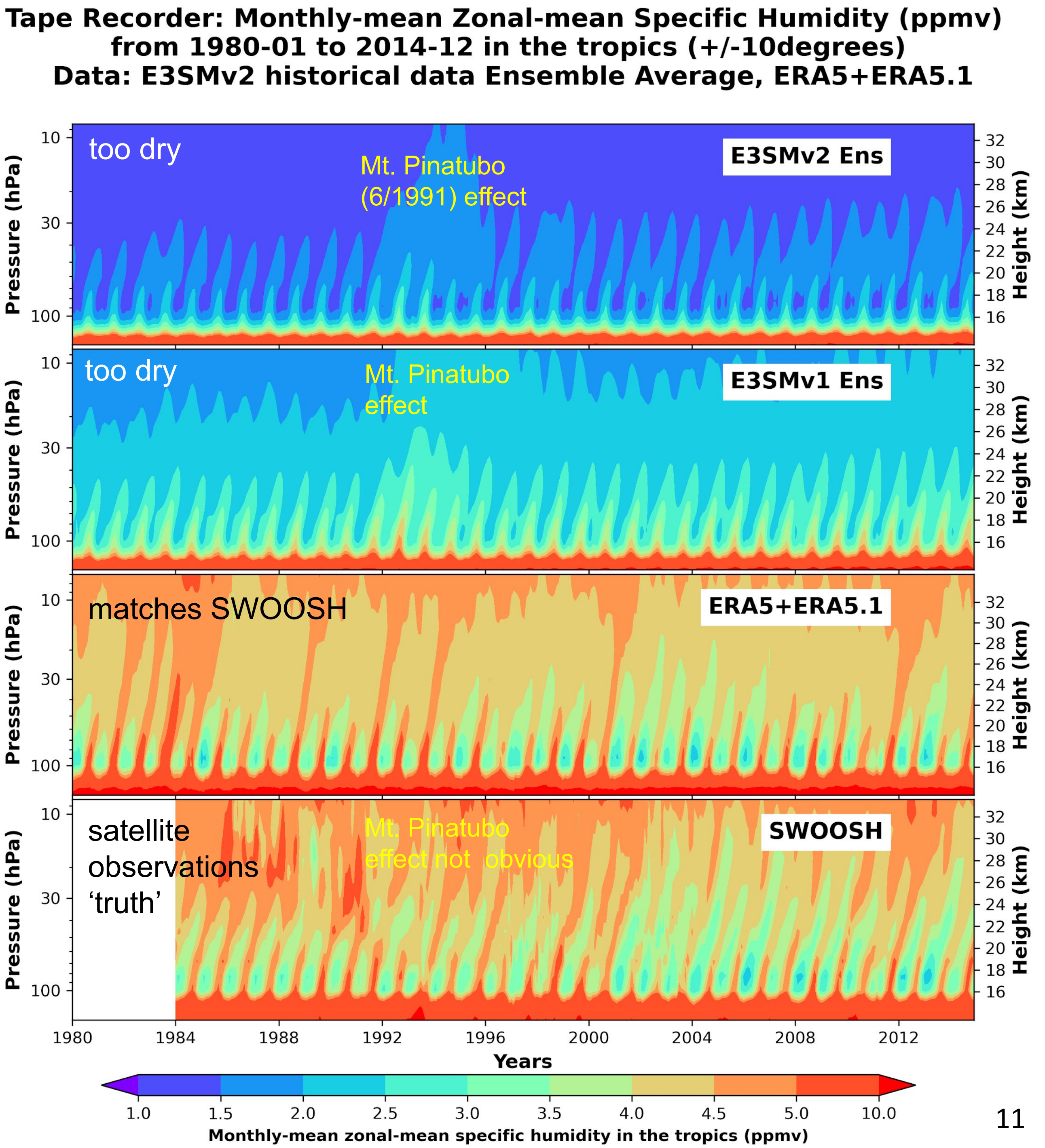
Possible Reasons for the E3SMv2 dry bias

- DCQ: Q tendency due to moist processes are suspicious in E3SM2/v1, permanent drying 80-3 hPa
- Maybe related to the E3SM's CLUBB (PBL/shallow convection scheme) scheme?
- WACCM: no permanent drying tendency between 80-3 hPa, WACCM's Q resembles observations



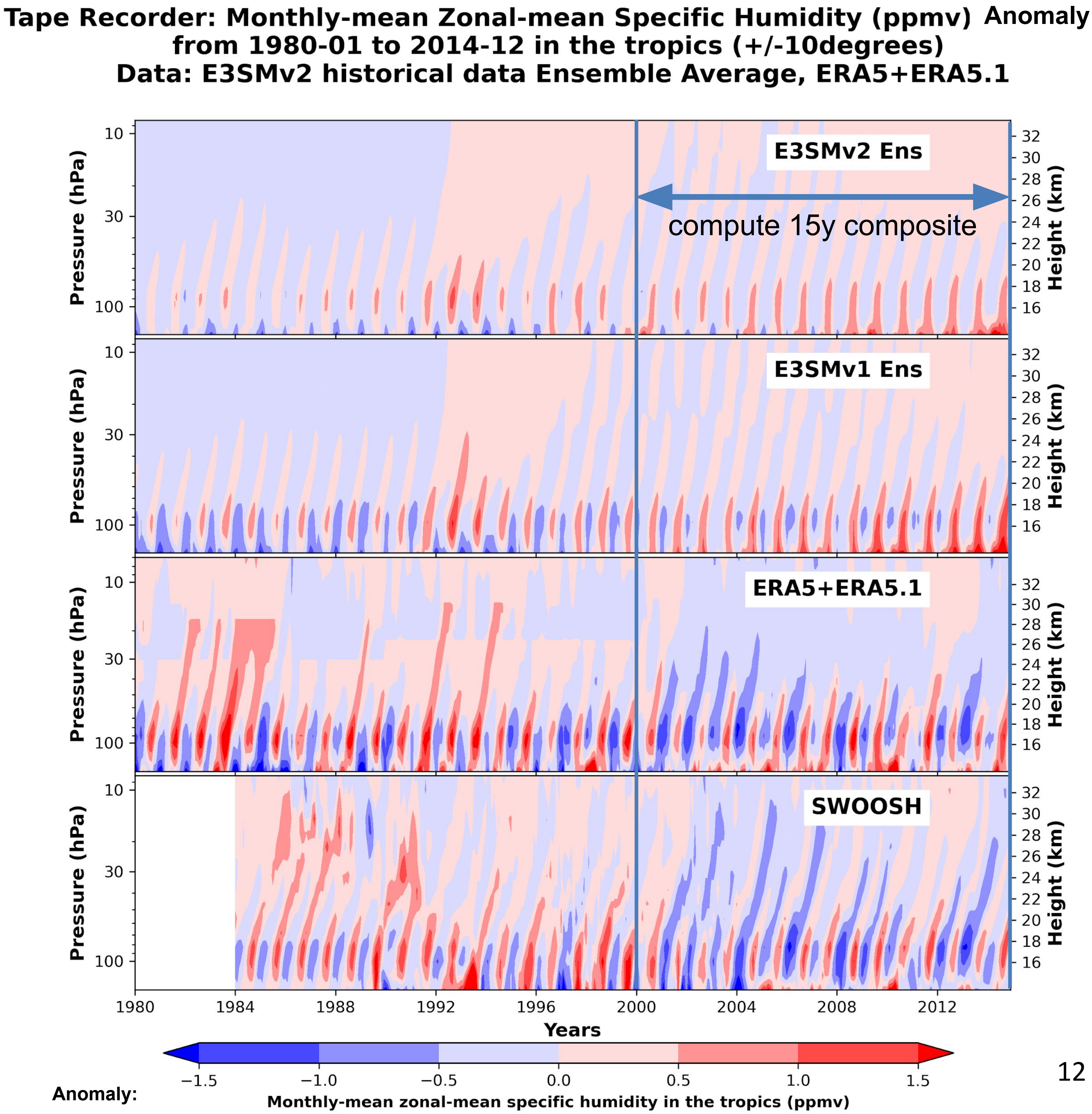
Tropical Water Vapor Tape Recorder

- E3SMv2 increases the large moisture deficit of E3SMv1 further
- Tape recorder signals in E3SMv2/v1 emphasize positive anomalies instead of negative anomalies
- Vertical transport in E3SM does not reach high enough
- ERA5 and SWOOSH satellite observations agree well, this highlights the E3SMv2 and v1 biases



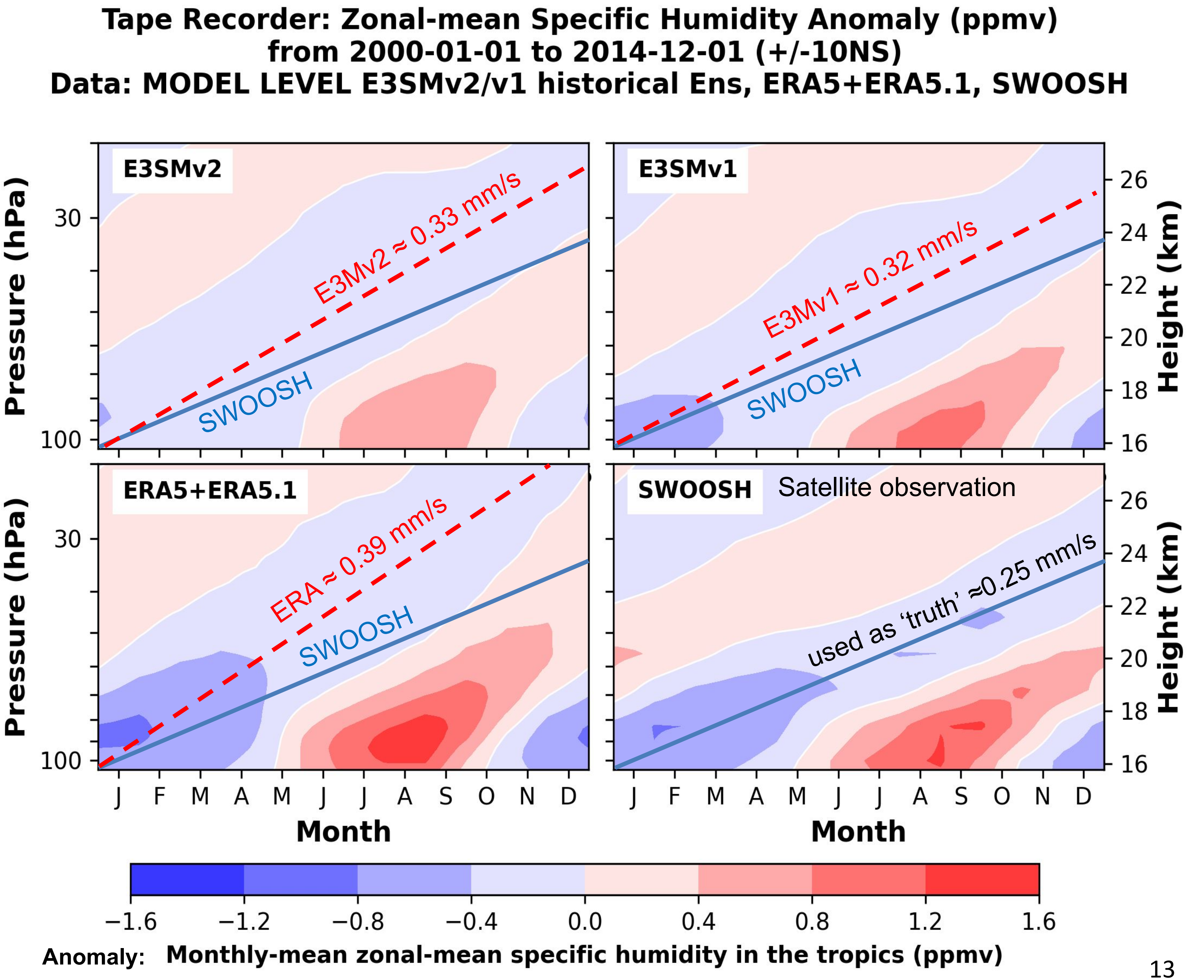
Tropical Water Vapor Tape Recorder Anomaly

- Specific humidity climatology (individual 34-year mean) removed to highlight the vertical propagation of the anomalies
- E3SMv2 increases the E3SMv1 biases further (diminished amplitudes further, weaker upward transport)
- Allows assessments of the average updraft speed (Brewer-Dobson)



Tape Recorder 15y Composites: Anomaly

- E3SMv2/v1 & ERA5 average vertical transport speeds are faster than SWOOSH: blue line used as ‘truth’
- Fast speed is typical bias for many climate models & reanalyses
- Points to deficits in the modeled Brewer-Dobson circulation (residual



Tape Recorder: Comparison to WACCM

- Systematic dry bias in the stratosphere is not present in NCAR's WACCM model
- Water vapor composites (10 years) from coupled historical CMIP6 simulations, see Gettelman et al. (2019):
  - color indicates WACCM
  - white contours are overlaid water vapor satellite observations (MLS/SWOOSH): good agreement

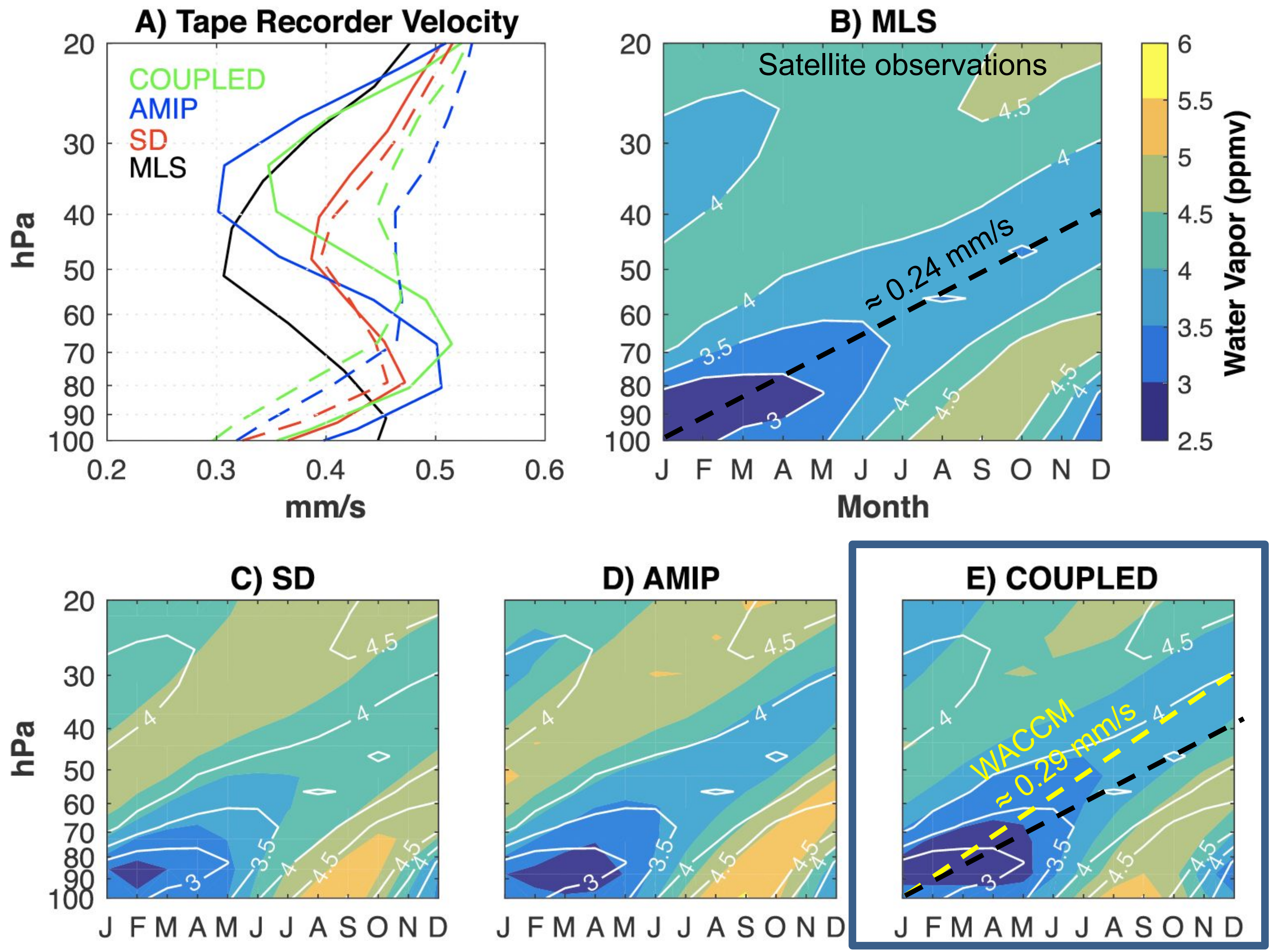
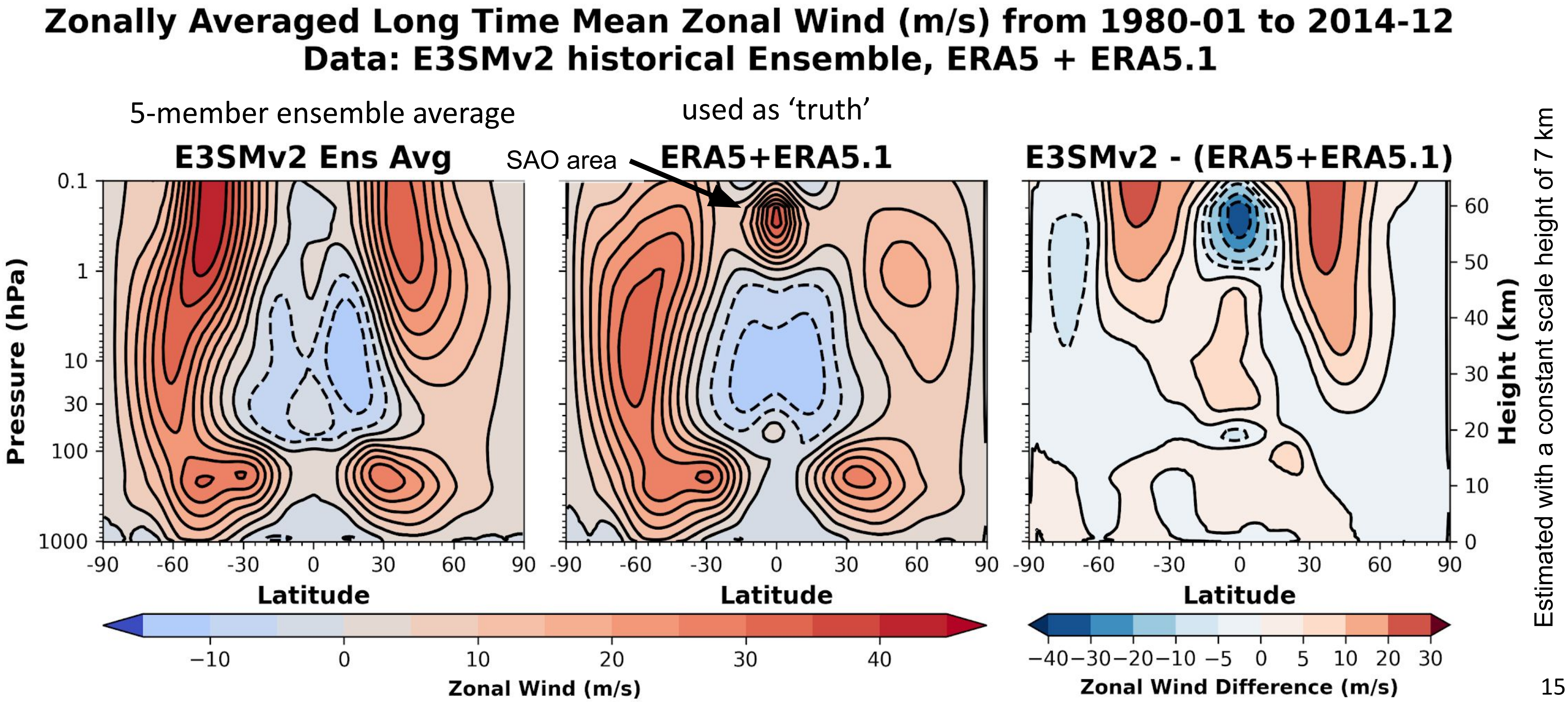


Figure 4. (a) Tape recorder velocity (mm/s) averaged over 2005–2014 from MLS satellite observations (black), specified dynamics WACCM-SD (red), specified SST WACCM6 (AMIP-blue), and coupled WACCM6 run (COUPLED-green). WACCM6 solid lines, WACCM4 dashed lines. (b) Composite MLS water vapor annual cycle showing the "tape recorder" of low and high water vapor being advected in the vertical circulation of the stratosphere. (c–e) Composite water vapor annual cycles (contour shading) with MLS annual cycle (white contours). (c) Specified dynamics WACCM6 (SD), (d) free running specified SST WACCM6 (AMIP) and (e) coupled CESM2-WACCM6 historical run (COUPLED).

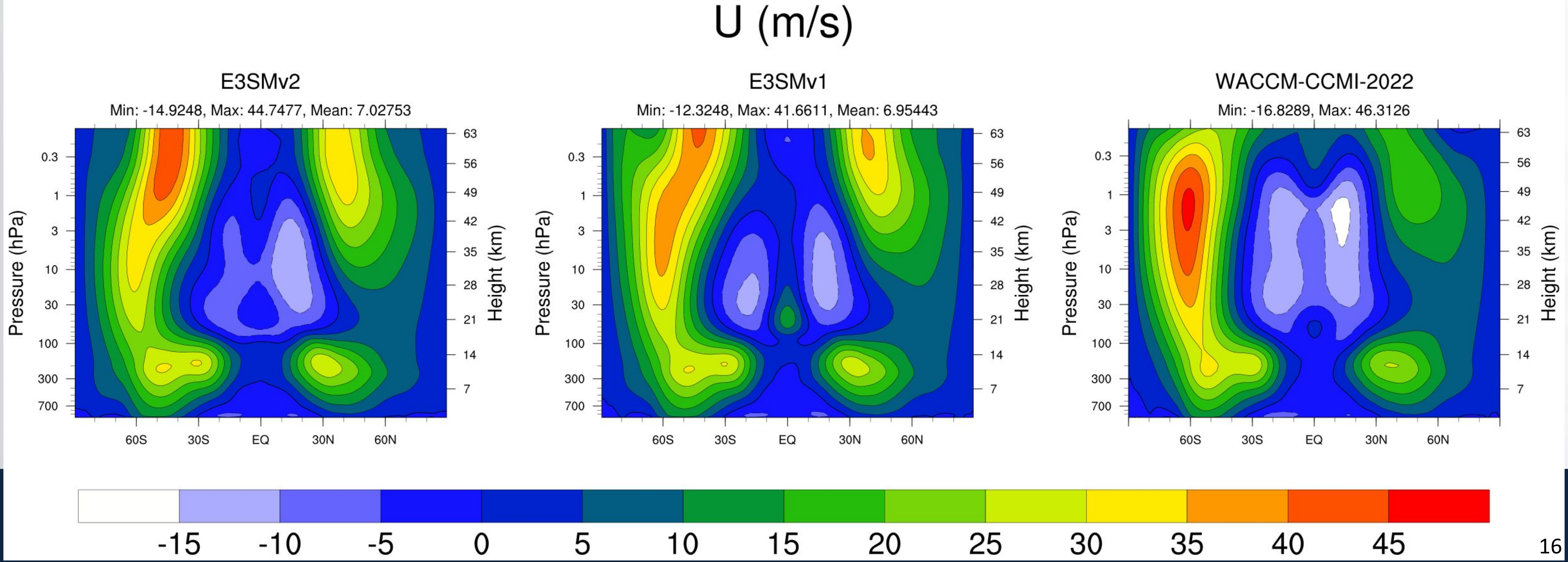
General Circulation: Physical Realism of the Zonal Wind

- Large E3SMv2 zonal wind biases upwards of 2 hPa, following the T biases
- High biases in polar jet regions & midlatitudes upwards of 30 hPa, mesosphere unreliable



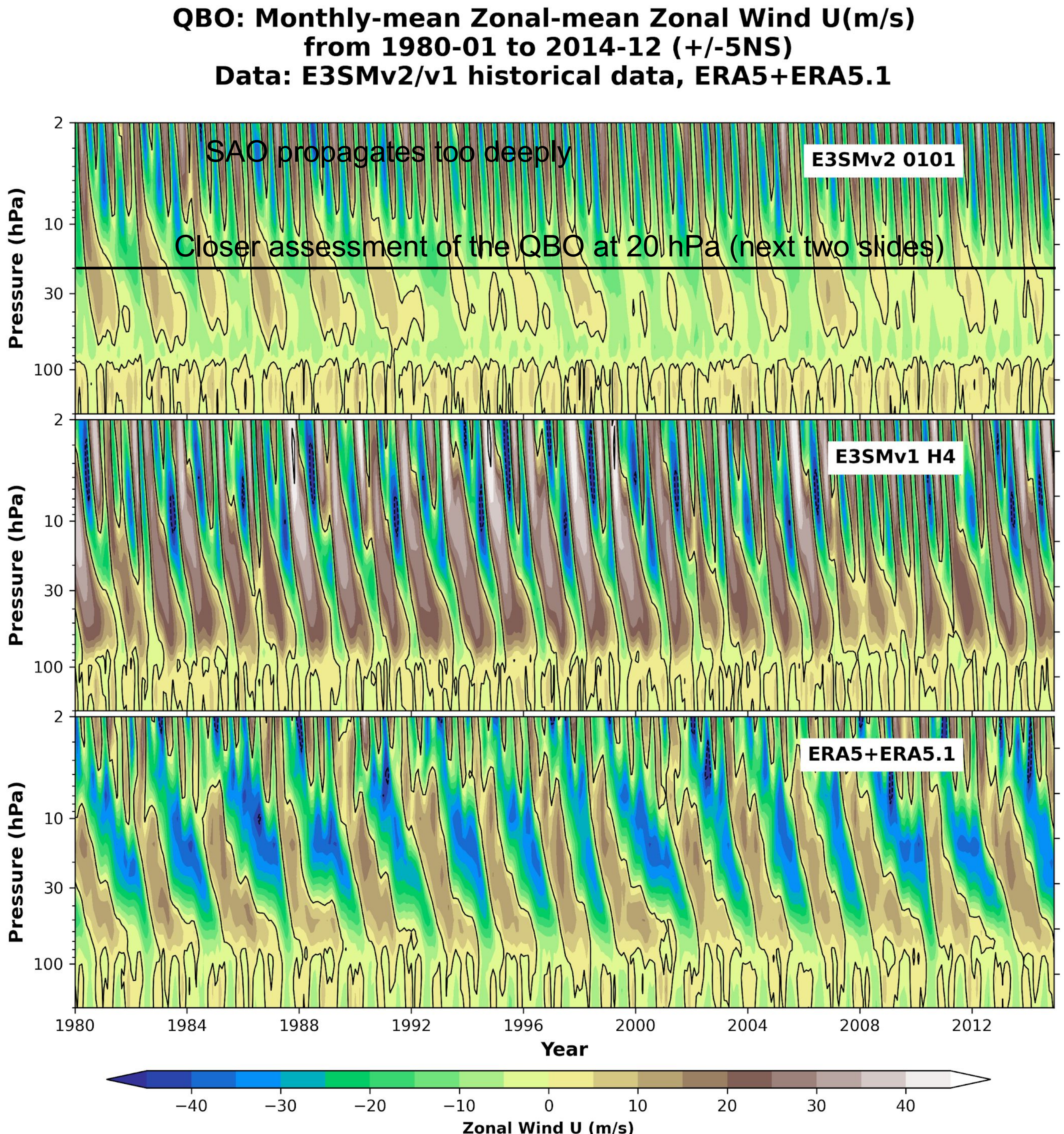
Zonal Wind: Quick Comparison to WACCM-CCMI-2022

- Zonal wind (U) biases in the E3SMv2 and E3SMv1 climatologies (1850-2014) are similar
- WACCM-CCMI-2022 zonal wind climatology (1960-2018) resembles ERA5 (previous slide, 1980-2014), although misses the SAO signal in the lower tropical mesosphere



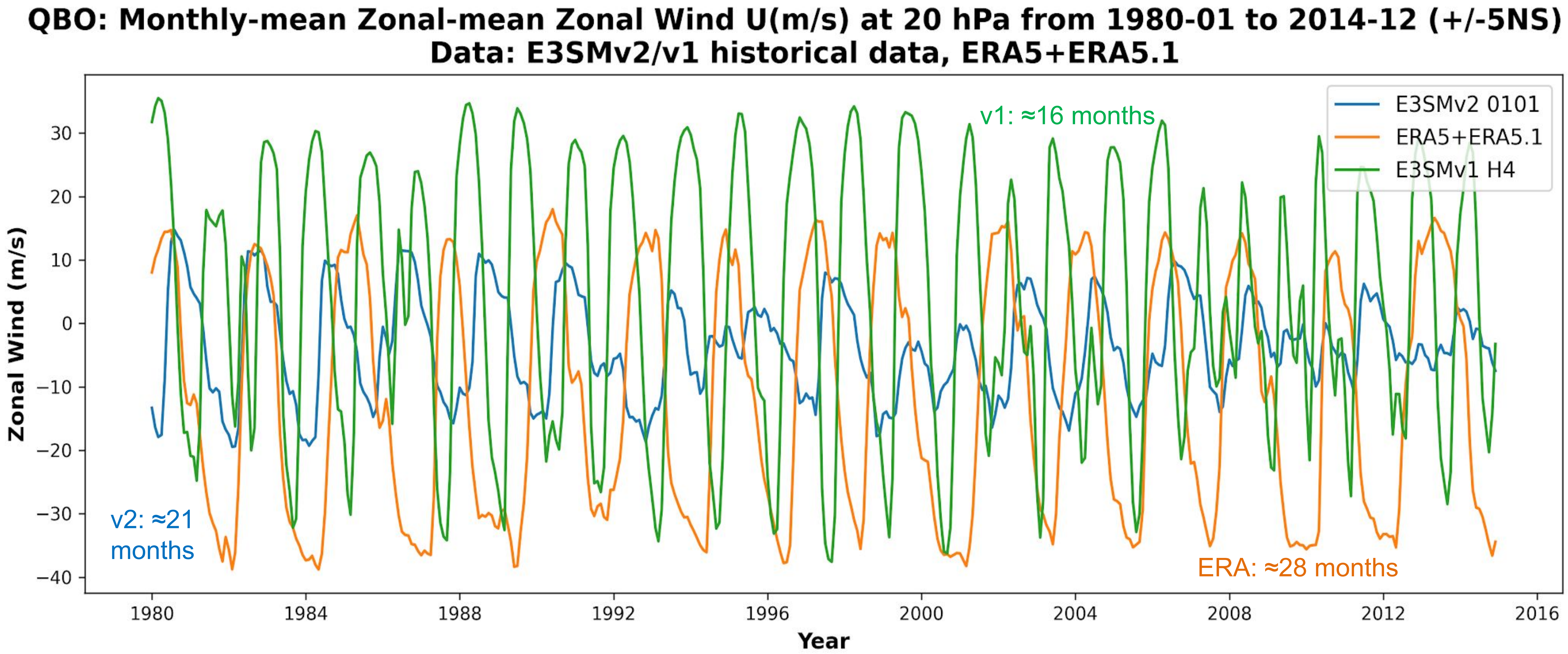
QBO: Time series

- Single ensemble members shown (averaging not possible, not synchronized)
- E3SMv2 degrades the v1 QBO amplitude of the easterlies, but damps overactive v1 westerlies
- QBO period somewhat longer in E3SMv2 than E3SMv1 (21 versus 16 months), but difficult to assess in E3SMv2 (some cycles are almost skipped)
- Semi-annual oscillation (SAO) reaches down to 10-20 hPa in E3SMv2 and interferes with QBO

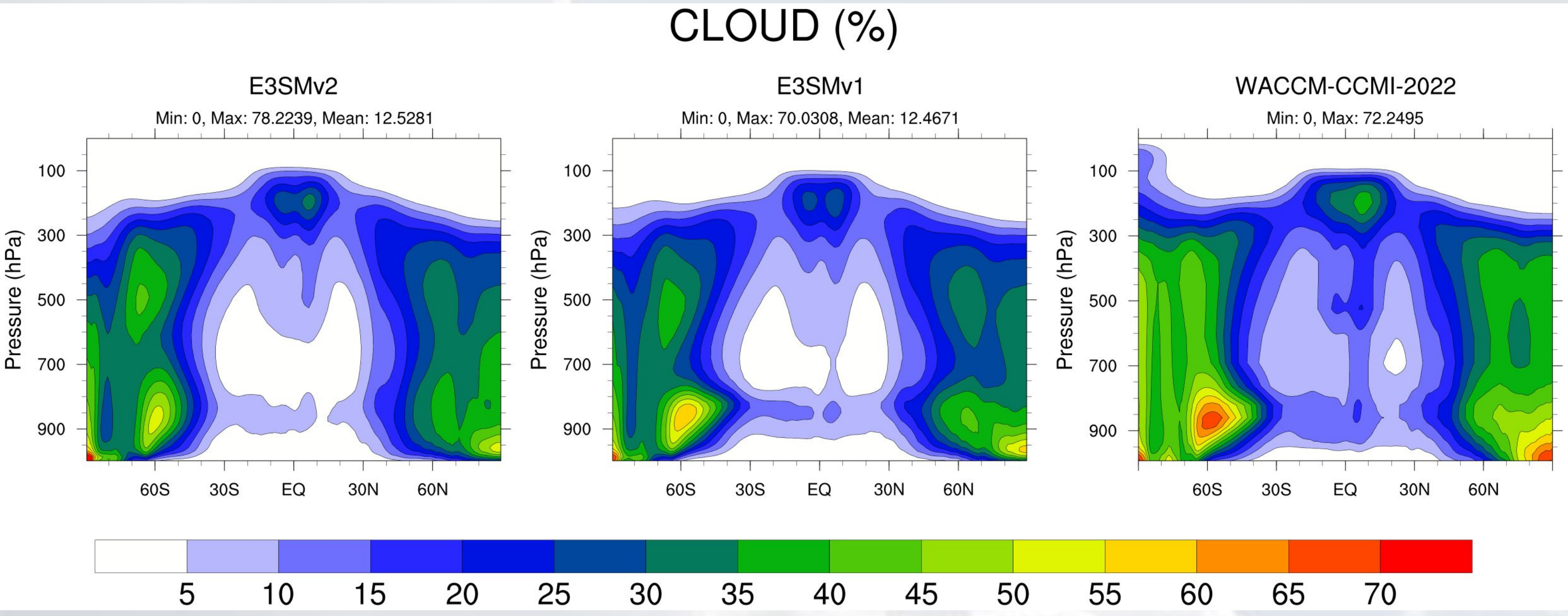


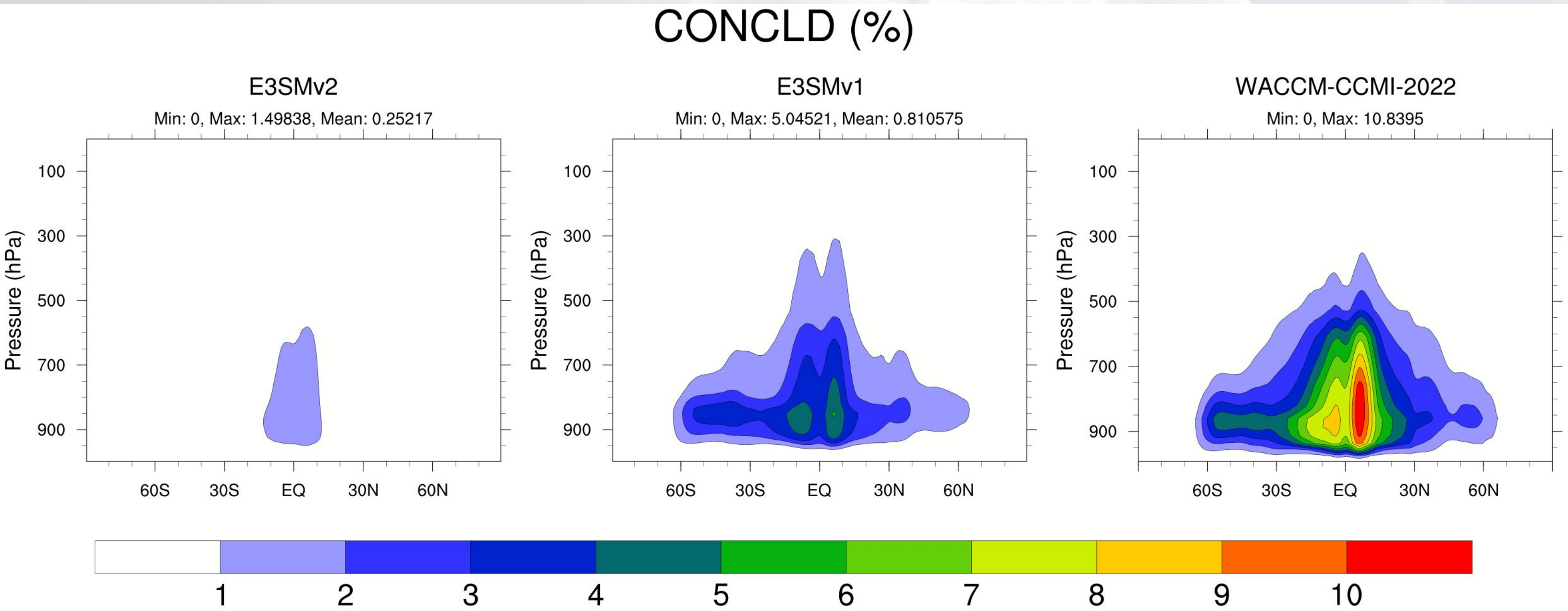
QBO: Zonal Wind Amplitude Analysis at 20 hPa

- E3SMv2's amplitude is a **factor of at least 2 too small,** mostly due to **very weak easterlies**
- E3SMv1's **westerlies too strong,** easterlies ok, with regular ≈16-month period (too fast)
- Very irregular QBO period in E3SMv2, about 21 instead of 28 months (ERA5) on average



Possible Reasons for QBO Differences: Convection / Waves

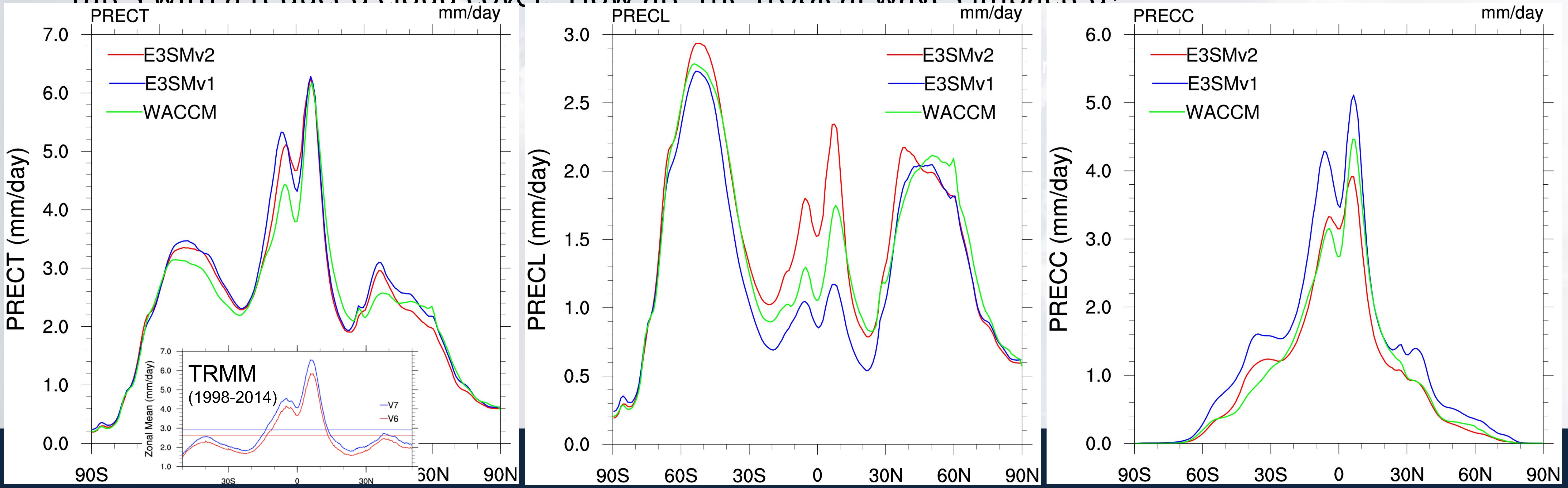




- Convection can act as trigger of waves
- Cloud cover (CLOUD) is reduced in E3SMv2 in comparison to E3SMv1 and WACCM-CCMI-2022
- Convective cloud cover (CONCLD) is greatly reduced in E3SMv2
- What are implications for the the total (PRECT), large-scale (PRECL) and convective (PRECC) precipitation rates? See next slide

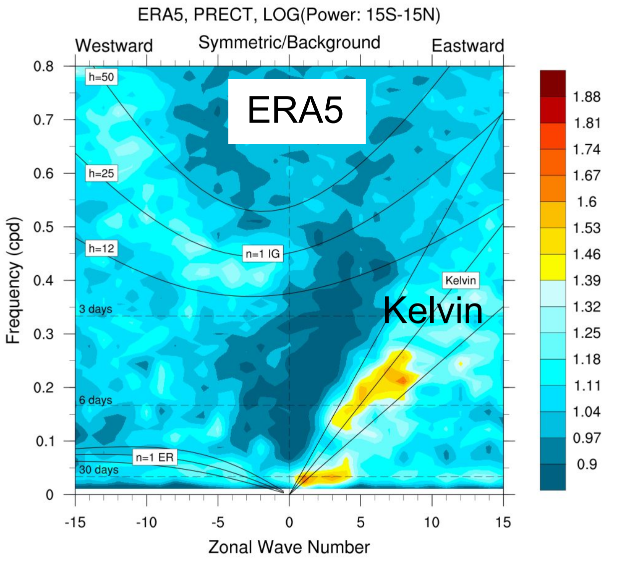
Possible Reasons for QBO Differences: Convection / Waves

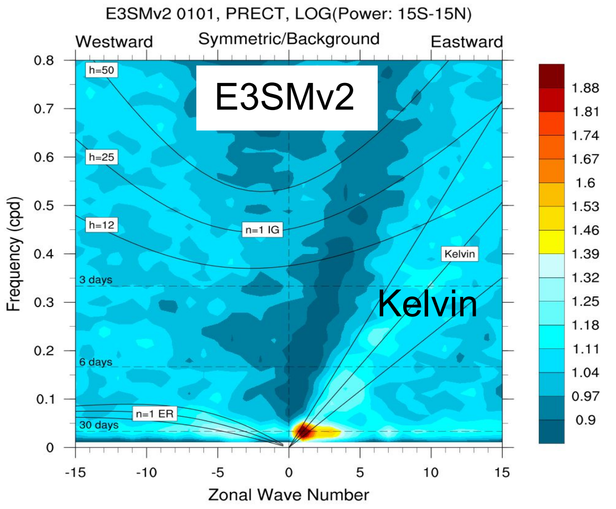
- Surprinsingly: Despite the big cloud cover differences inE3SMv2, total precipitation rate (PRECT) in E3SMv2 is approx. identical to E3SMv1, very similar to WACCM
- Compensating effects in E3SMv2: PRECL (large-scale) increased and PRECC (convection) reduced
- Hypothesis: it must rain more vigorously (more heavy rain) in E3SMv2 to get identical precipitation rates with a reduced cloud cover. How are the tropical waves impacted?

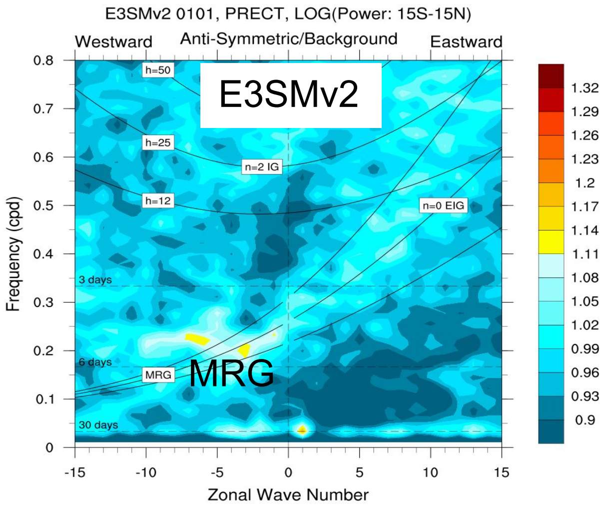


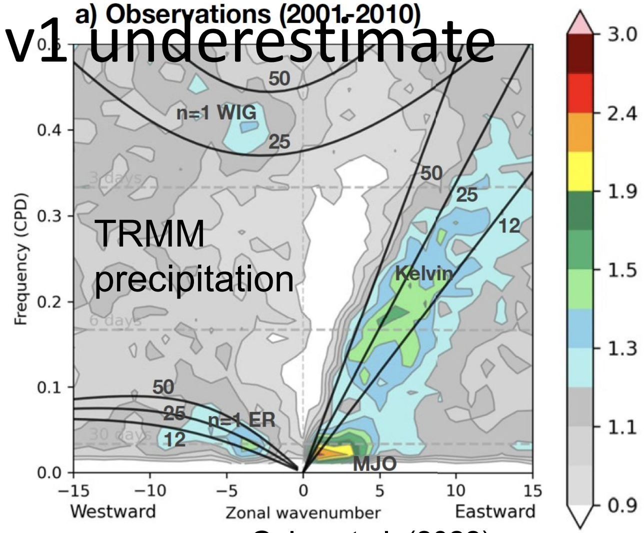
QBO: Tropical Wave Analyses (15S-15N)

- Initial assessment: wavenumber-freque[…] of the total 3hr-mea[…] rates
- **E3SMv1 generates m[…] tropical wave activit[…]** likely contributing to
- But: both E3SMv2 & v1 underestimate the Kelvin wave activity observed via TRMM satellite observations
- E3SM's gravity wave

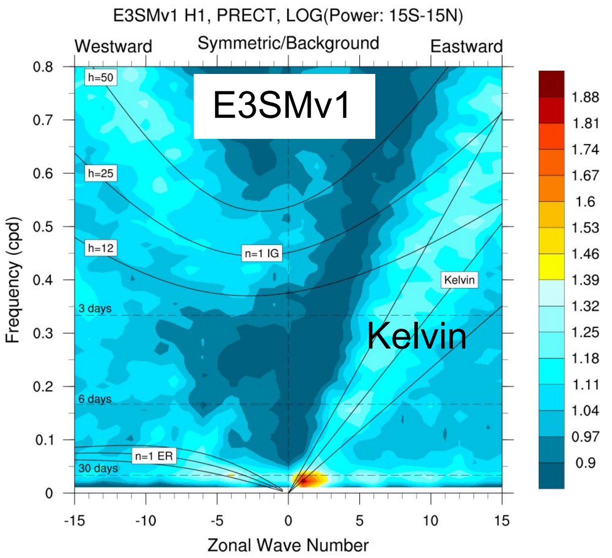


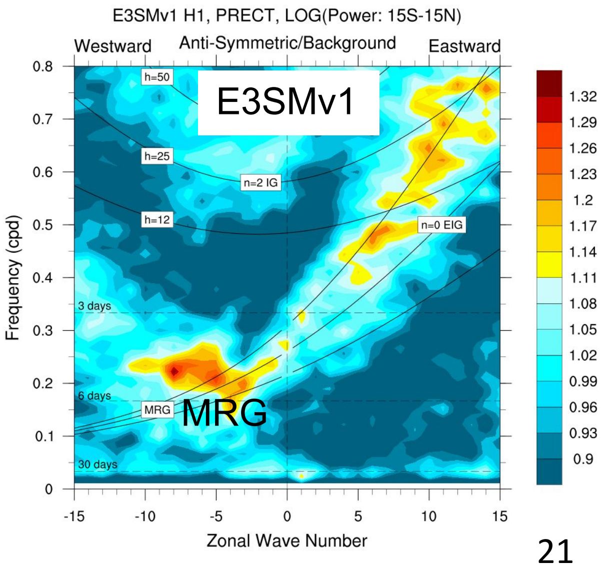






source: Golaz et al. (2022)





Conclusions and Outlook

- Work supports the DoE Sandia National Laboratories' CLDERA project focused on climate attribution (https://www.sandia.gov/cldera/)
- Presentation provides a brief glimpse at the realism of E3SMv2's CMIP6 historical simulations, E3SMv2/v1 data typically missing in CMIP6 papers (late data release)
- Comparisons to ERA5, WACCM and observations reveal large biases in E3SMv2's stratosphere and mesosphere
- E3SMv2's temperature and zonal wind data (above 2 hPa) & upper-level specific humidity data need to be used with extreme caution
- E3SMv2's tape recorder signal is suppressed, average updraft speed too quick
- QBO signal in E3SMv2 is of low quality, small amplitude, irregular period, too quick
- Analysis to come: variability assessments using the E3SMv2 large ensemble, process-level understanding of the E3SMv2 biases, tropical wave analysis / TEM

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