Improving the QBO through surrogate-accelerated parameter optimization and vertical grid modification

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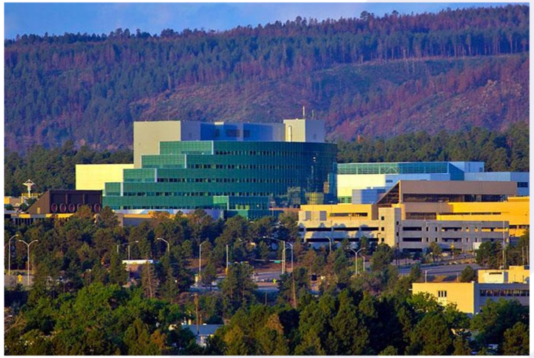

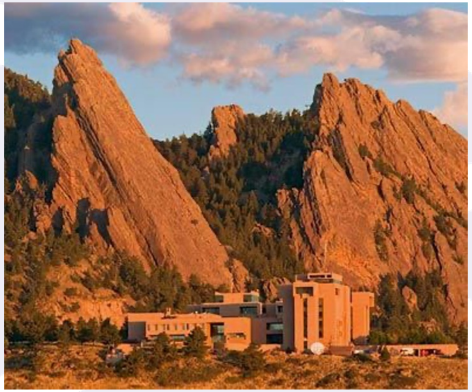

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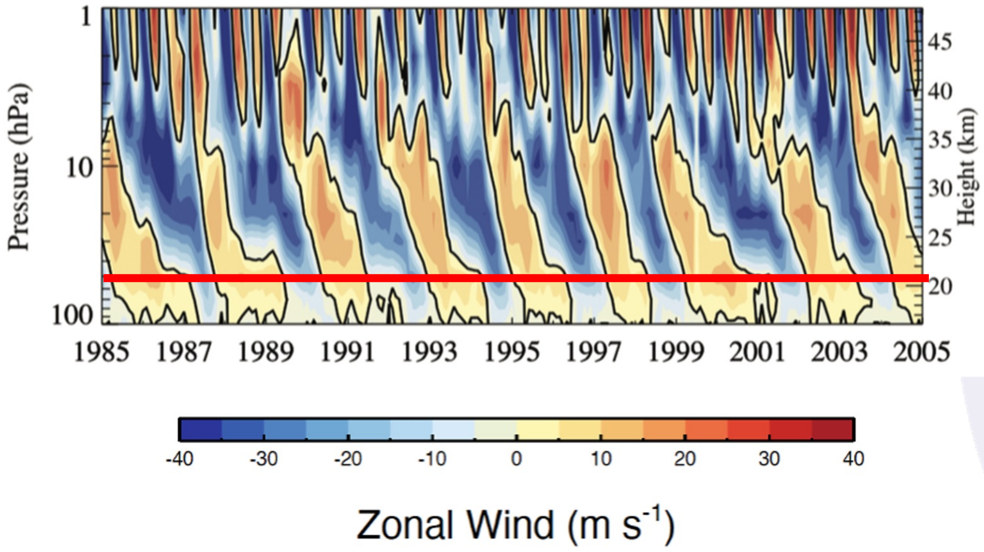
Science background

Observed (ERA-I) equatorial zonal winds



What is the QBO?

- Mode of variability in tropical stratosphere
- Identified by alternating phases of equatorial zonal mean easterly and westerly winds (period ~28 months)
- Wind extrema and shear zones migrate downward
- Driven primarily by momentum deposition from convection-generated gravity waves
- QBO impacts extratropical weather, tropical convective variability, and stratospheric tracers

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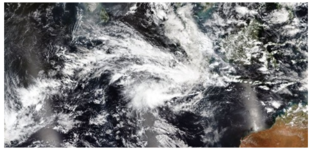
Science background

Accurate QBO representation in global climate models remains challenging.

Sufficient vertical resolution, especially near the tropopause and lower stratosphere, is required to capture vertical wave propagation, wave breaking, and momentum deposition that drives the QBO.



Tropical synoptic atmospheric waves must be adequately represented.

Convectively generated gravity waves must be adequately represented.

E3SM

15 of 30 CMIP6 models examined produce a QBO, but those that do fail to accurately capture QBO amplitude. **E3SMv2 and development E3SMv3 fail to produce a reasonable QBO.**

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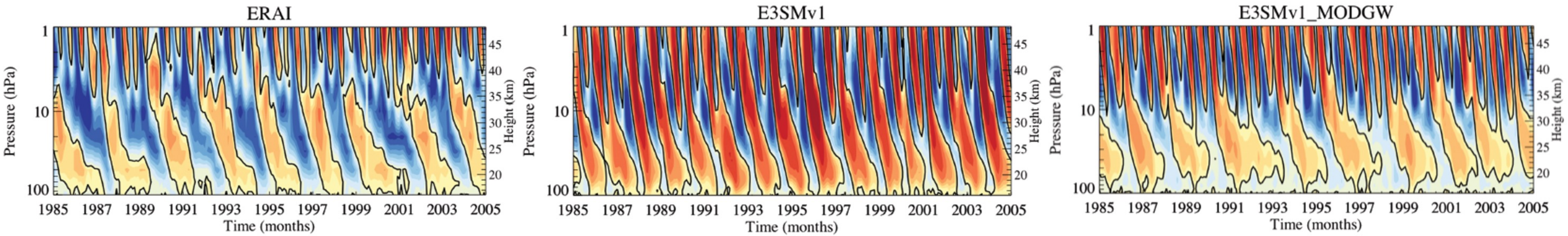
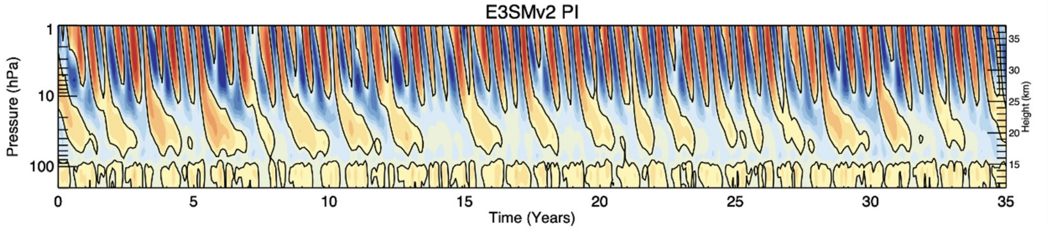
Statement of the problem

Accurate representation of QBO amplitude and period in E3SM remains elusive.



effgw=0.4, CF=20
Richter et al., 2019

effgw=0.35, CF=12.5



effgw=0.1, CF=12.5
Golaz et al., 2022

- E3SMv2 tuning late in the development cycle could not achieve a similar QBO to E3SMv1_MODGW
- Updates to v2 deep convection scheme (dCAPE-ULL trigger) may have contributed to QBO changes

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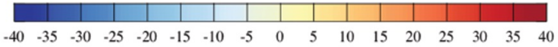
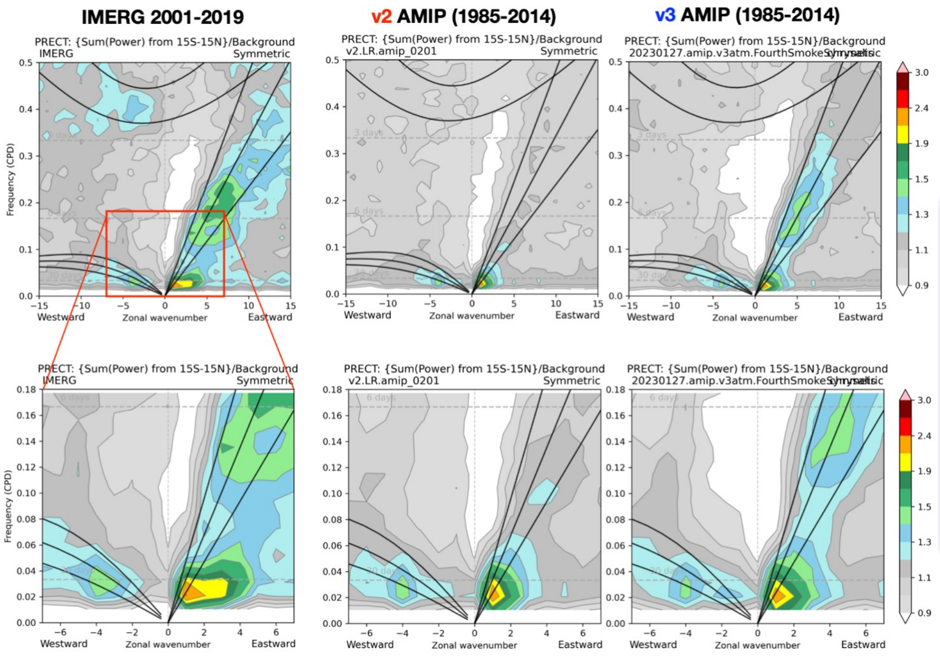


Zonal mean zonal wind @ Equator (m/s)

Task 1: Manual tuning of QBO in E3SMv3

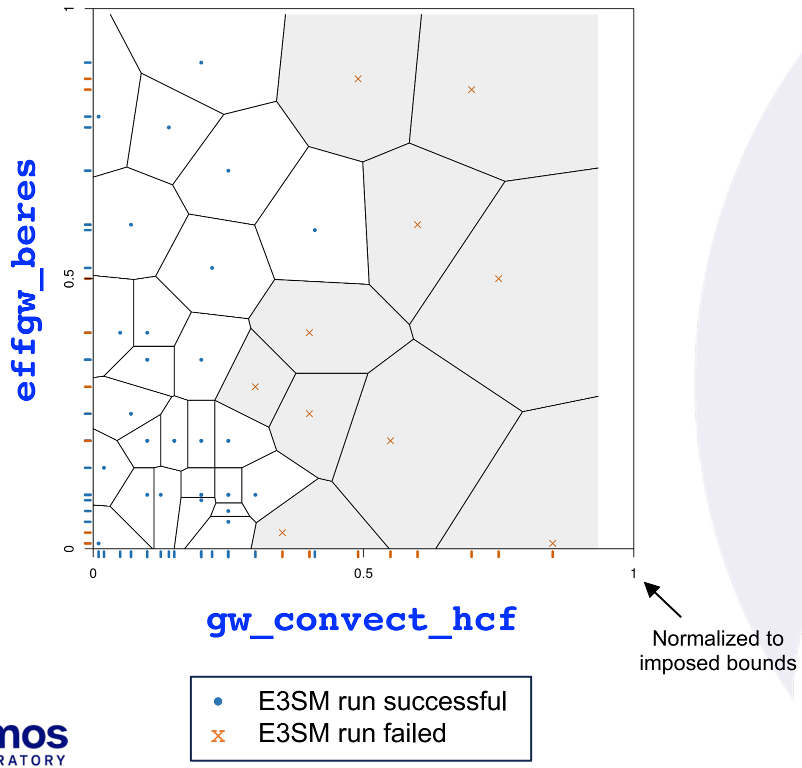
In development E3SMv3, convection has improved but the QBO remains problematic.



- Mesoscale Coherent Structure Parameterization (MCSP; Chen et al. 2021, 2023) in development E3SMv3, along with microphysics changes, has improved subseasonal tropical convection
- The E3SMv3-dev QBO remains weak
- "Manual" QBO tuning in E3SMv3-dev is much less successful than in previous development cycles
- Adequate representation of tropical convection is a **necessary but not sufficient condition** for an acceptable QBO
- Suggests that vertical grid resolution and gravity wave parameterization may be "weak links"

Task 2: Initial model calibration, leveraging manual tuning results

Manual QBO tuning is challenging; surrogate-accelerated parameter optimization can help.



- An initial batch of 20+ "manually-tuned" QBO parameter sets was attempted, with limited success
- Surrogate-based calibration studies are ongoing to more fully explore parameter space
- Focus is on…
  effgw_beres: efficiency with which convection generates gravity waves
  gw_convect_hcf: ratio of convective cells within a model grid cell
  hdepth: scaling factor to adjust the heating depth predicted by deep convection

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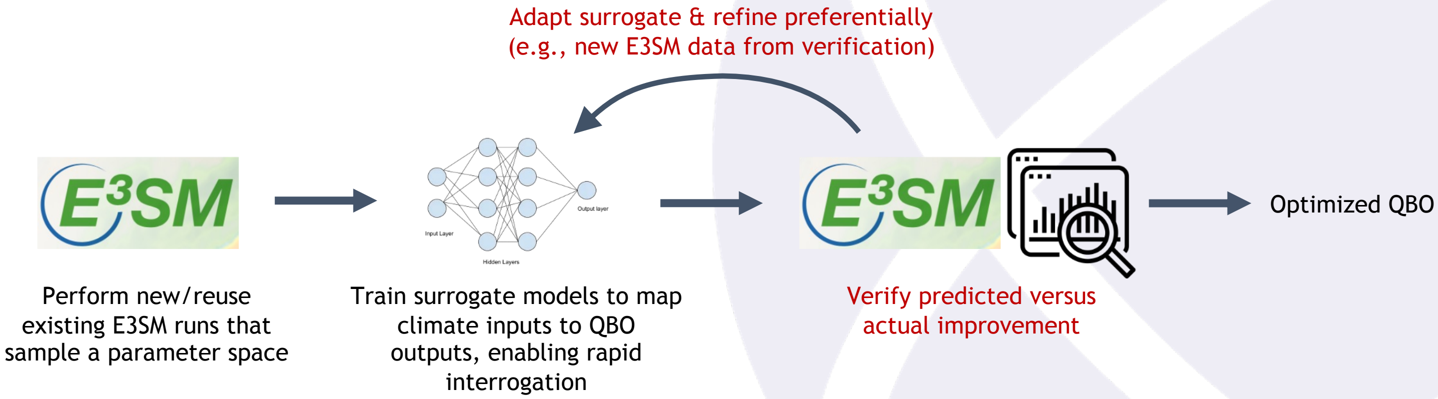
Task 3: Surrogate modeling for UQ analysis, parameter optimization

Developed workflows demonstrate dimensionality reduction, surrogate construction, and Bayesian inference on test data set.

- A surrogate modeling capability is being developed for mapping climate parameter inputs into QBO “quantities of interest” (e.g. period, amplitude), enabling forward or inverse UQ analysis based on E3SM simulations



Task 4: QBO sensitivity to vertical grid

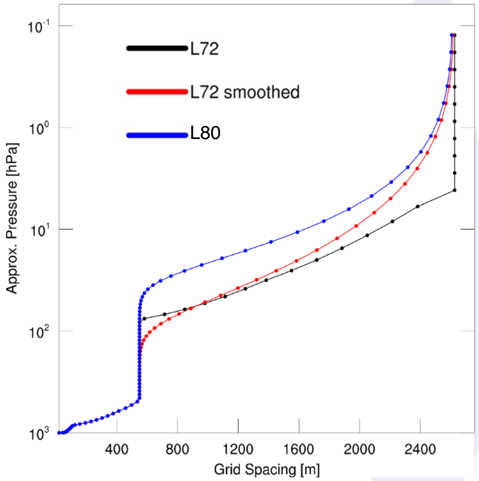
E3SMv2 tests suggest QBO improves with targeted vertical grid smoothing or added levels.

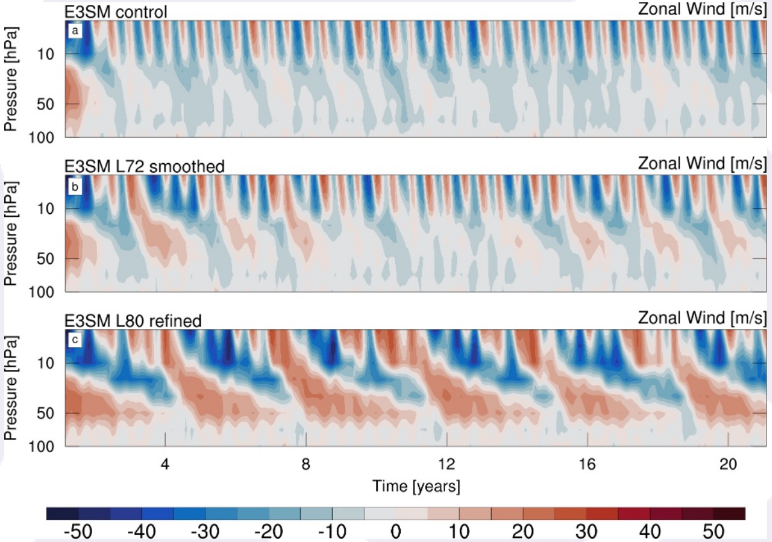
L72-smth

- Abrupt coarsening of vertical grid resolution in default L72 is smoothed
- With smoothing: Modest improvement in QBO amplitude and period

L80

- Free-tropospheric vertical grid resolution is extended further into lower stratosphere; 5-6% added cost*
- QBO amplitude is dramatically improved, period not yet correct





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An 80-level configuration of E3SMv3

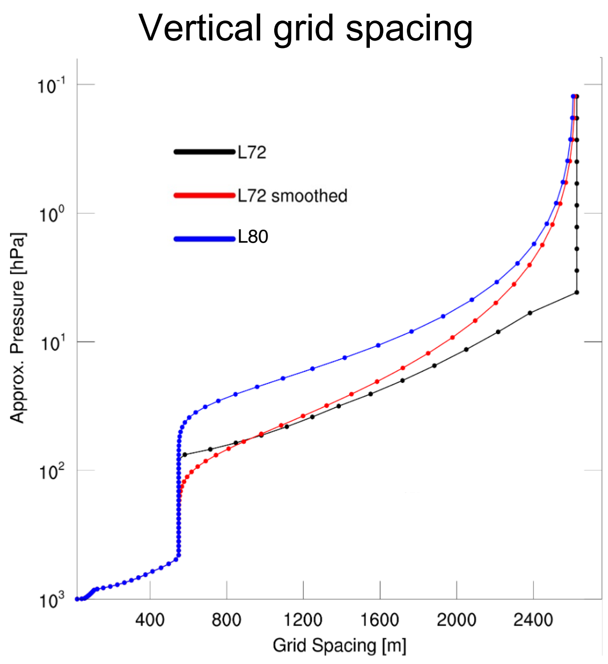
Experiment details:

- Compare **v3alpha02-hist** with 72 levels vs. 80 levels
- L80: 8 layers added to lower stratosphere only
- All other parameter values identical
- Timing/cost: ~5-6% slower*
- Full E3SM diagnostics output:

  20230629.v3alpha02.amip.chrysalis.L72

  20230629.v3alpha02.amip.chrysalis.L80

  Model-model difference



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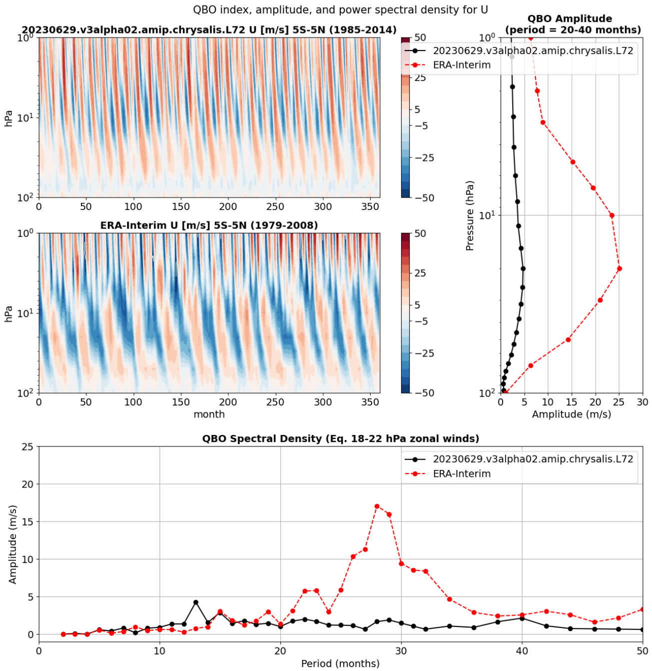
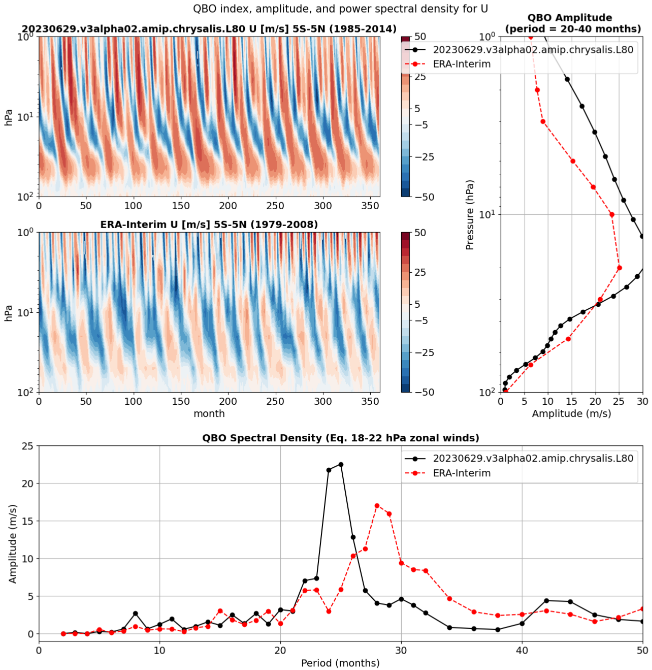
More on 80-level configuration of E3SMv3

Adding 8 layers to the lower stratosphere dramatically improves QBO characteristics in E3SMv3.

v3alpha02, L72



v3alpha02, L80



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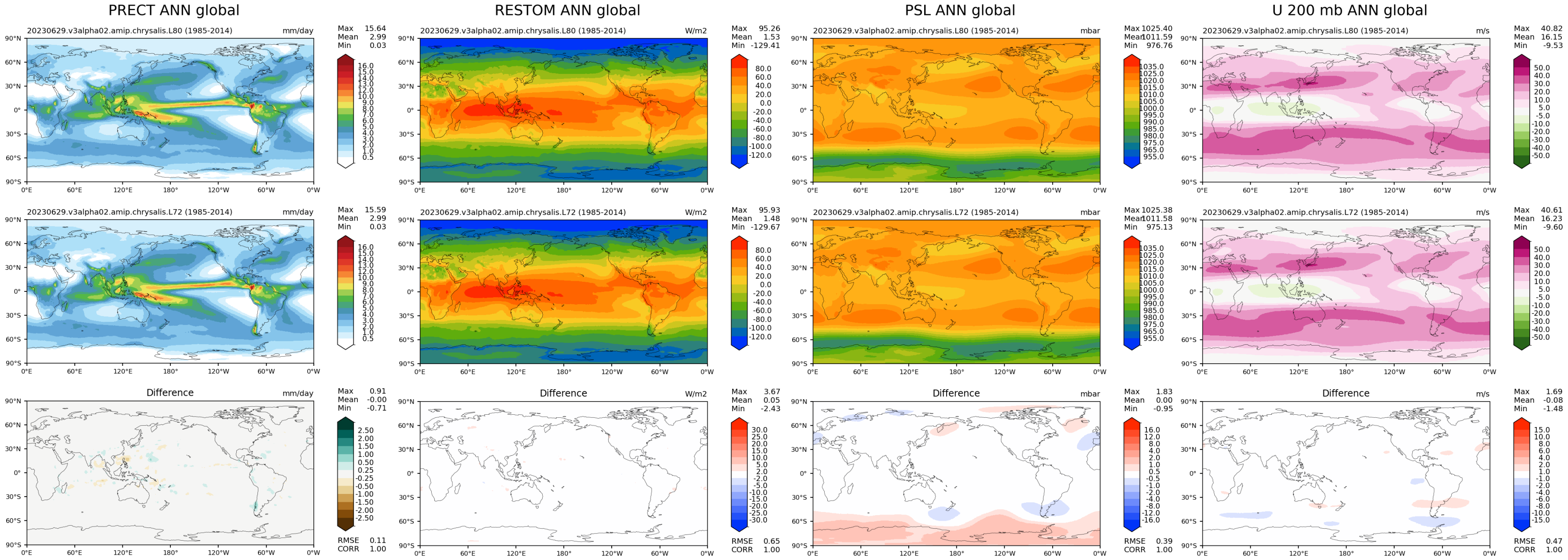
More on 80-level configuration of E3SMv3

Early assessment of L72 vs. L80 <u>tropospheric climate</u> shows no degradation with L80.

L80

L72

Diff



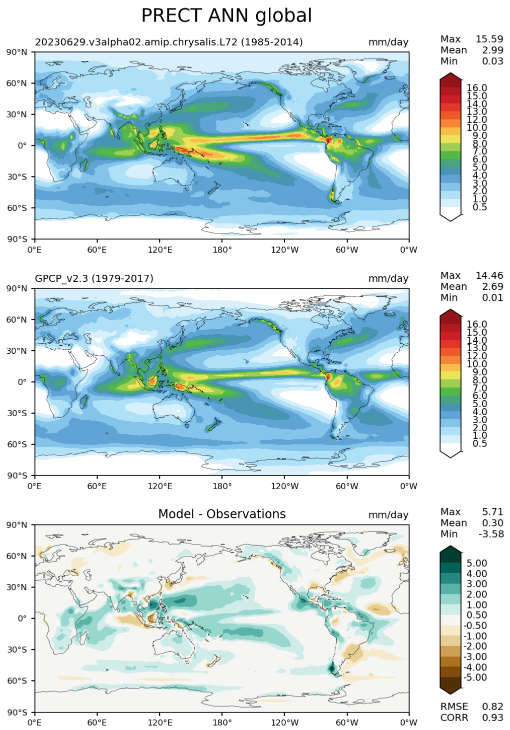
More on 80-level configuration of E3SMv3

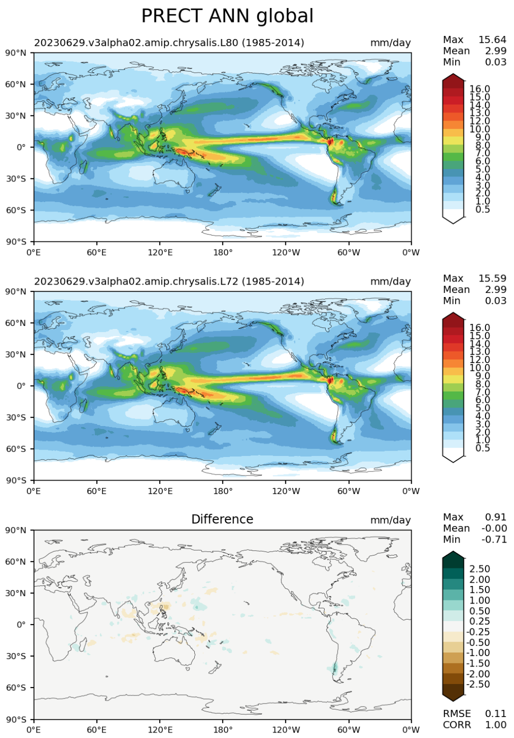
L80-L72 tropospheric climate differences are negligible compared to L72-observations differences.

L72

GPCP

L72–GPCP





L80

L72

L80–L72

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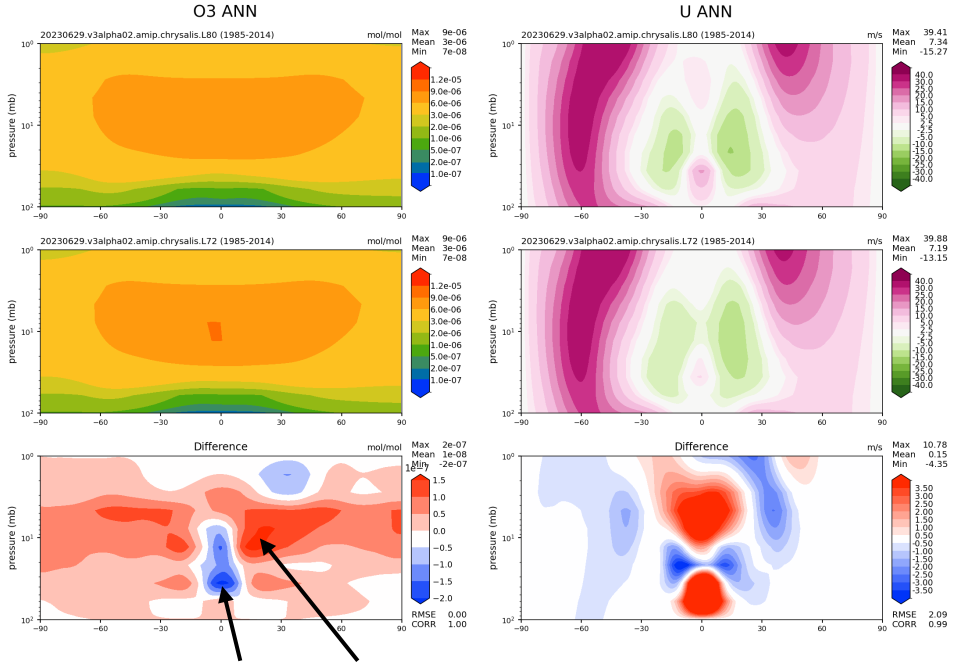
More on 80-level configuration of E3SMv3

Early assessment of stratosphere between L72 and L80 shows some differences, as expected.

L80

L72

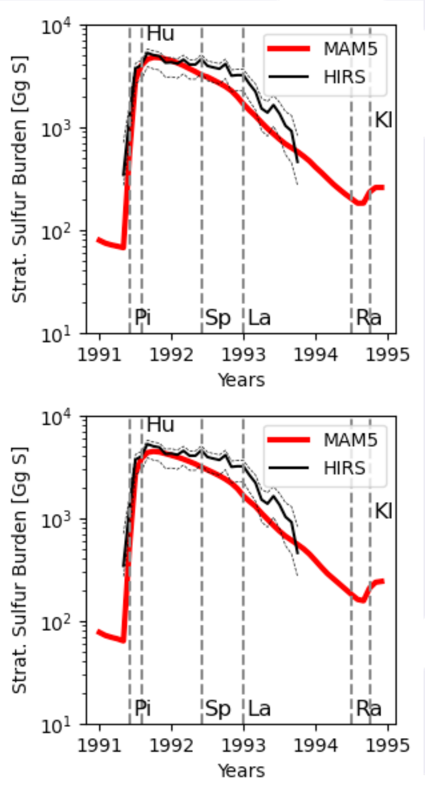
L80–L72



–7%

+2%

Stratospheric sulfur burden



L72

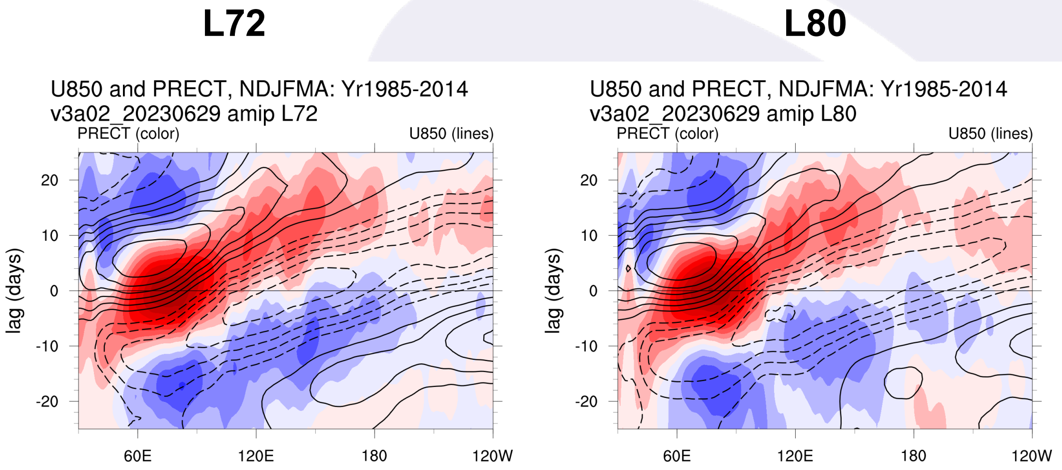
L80

More on 80-level configuration of E3SMv3

Other notes:

- MJO is <u>slightly</u> weaker, as expected given L80's preference for QBO westerly phase
- Have not yet examined diurnal cycle
- Have not yet examined other modes of variability

Lag correlation: PRECT & U850 with MJO index



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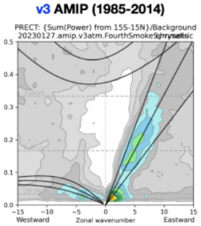
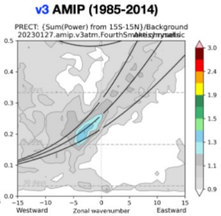
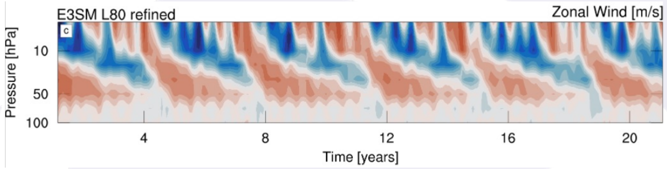
Summary and future work

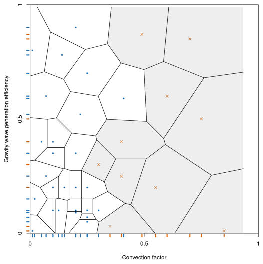




Despite improved tropical convective variability in E3SMv3 (L72), the QBO remains weak



Targeted addition of 8 levels in lower stratosphere (and/or grid smoothing) improves QBO at modest cost



Manual QBO tuning for E3SMv3 (L72) had limited success. Surrogate-accelerated parameter optimization is a more objective, efficient, and informative approach.

Next: More evaluation of E3SMv3 L80, begin using surrogate-E3SM interfacing to optimize QBO in L80

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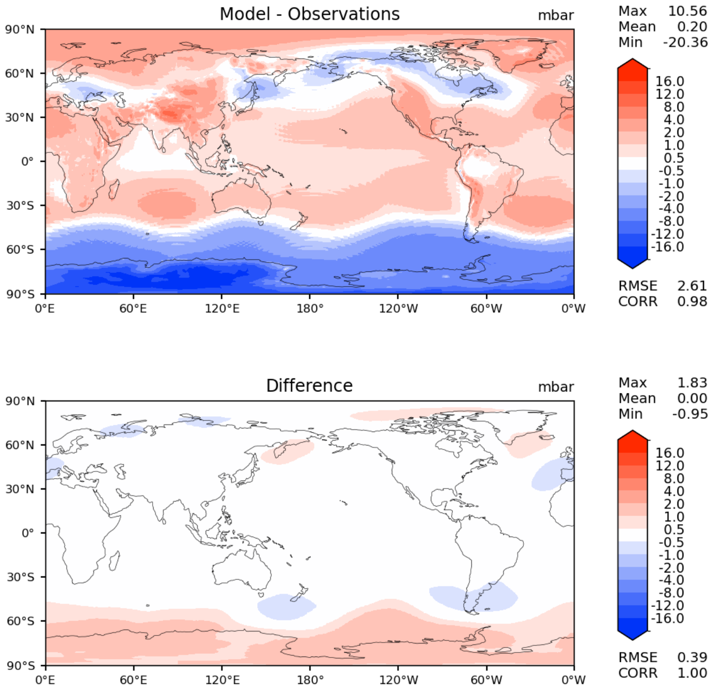
Supplemental figures

Low Antarctic PSL difference pattern is reduced in L80, but U850 is mostly unchanged.

Annual mean PSL

L72–ERA5

L80–L72



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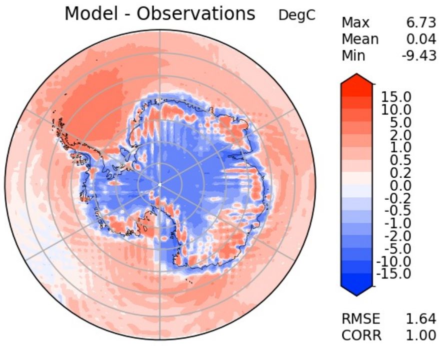
Supplemental figures

- **L80 reduces polar surface temperature differences compared to ERA5**

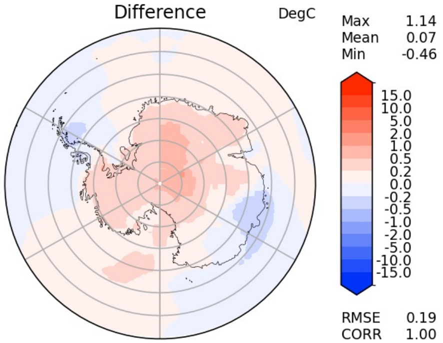
- **Some reduction in difference also seen in Arctic region**

Annual mean TREFHT

L72–ERA5



L80–L72



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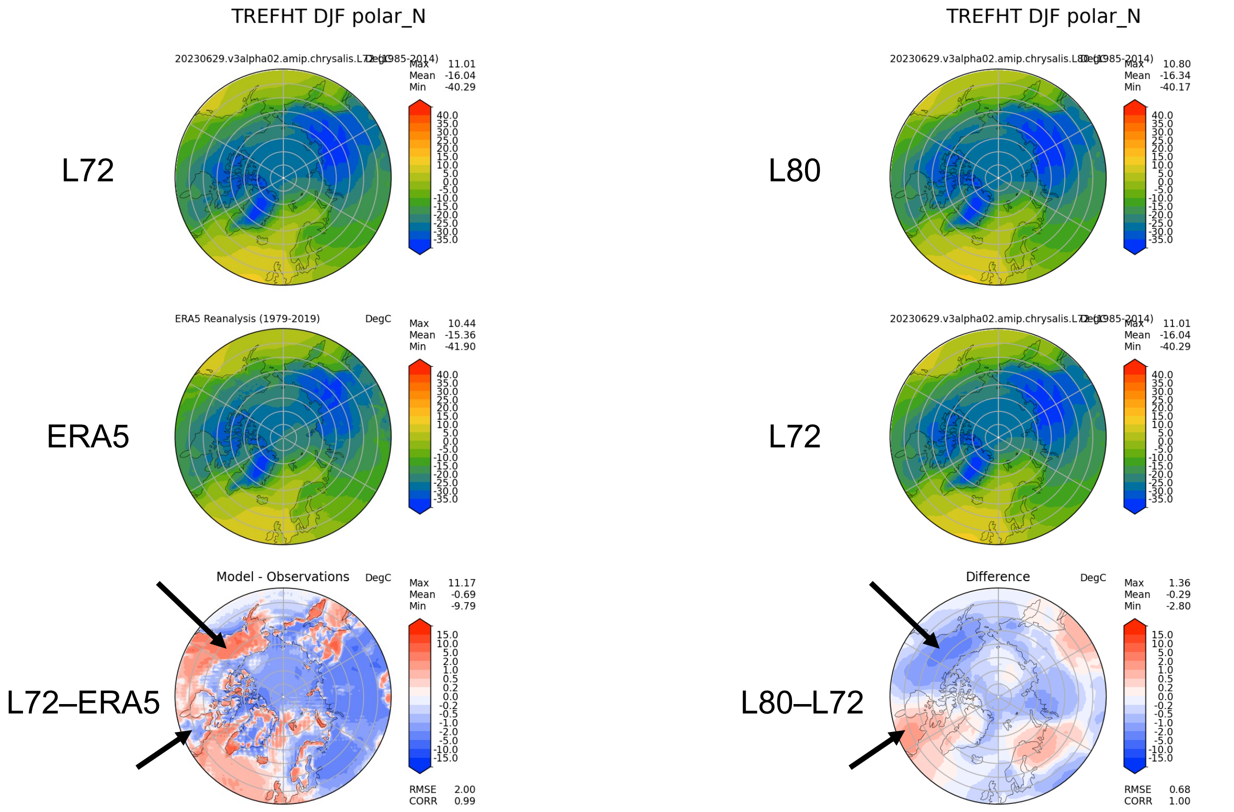
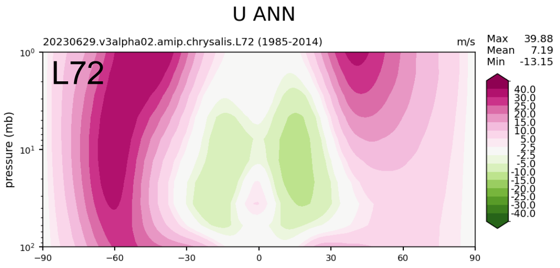
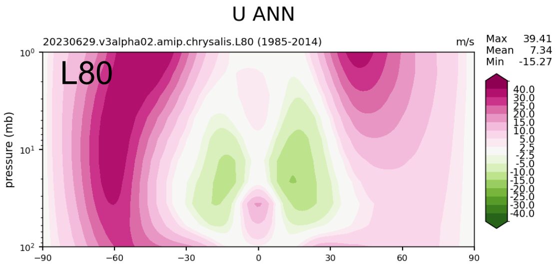
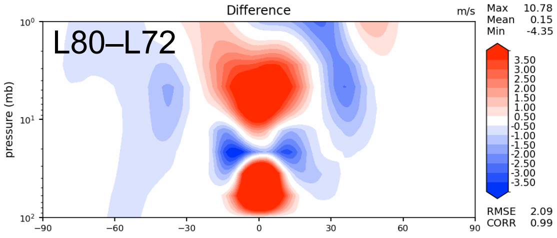
Supplemental figures

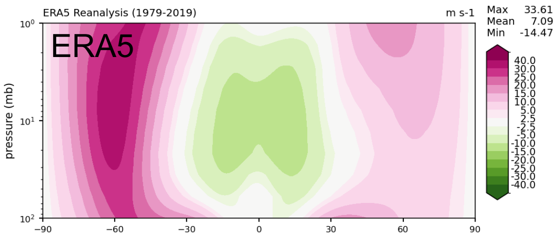


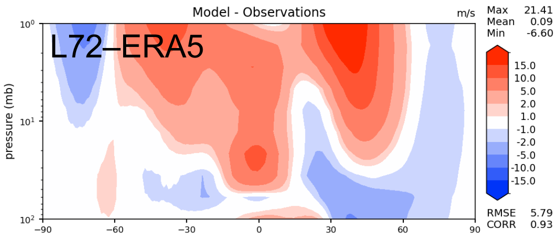
Supplemental figures



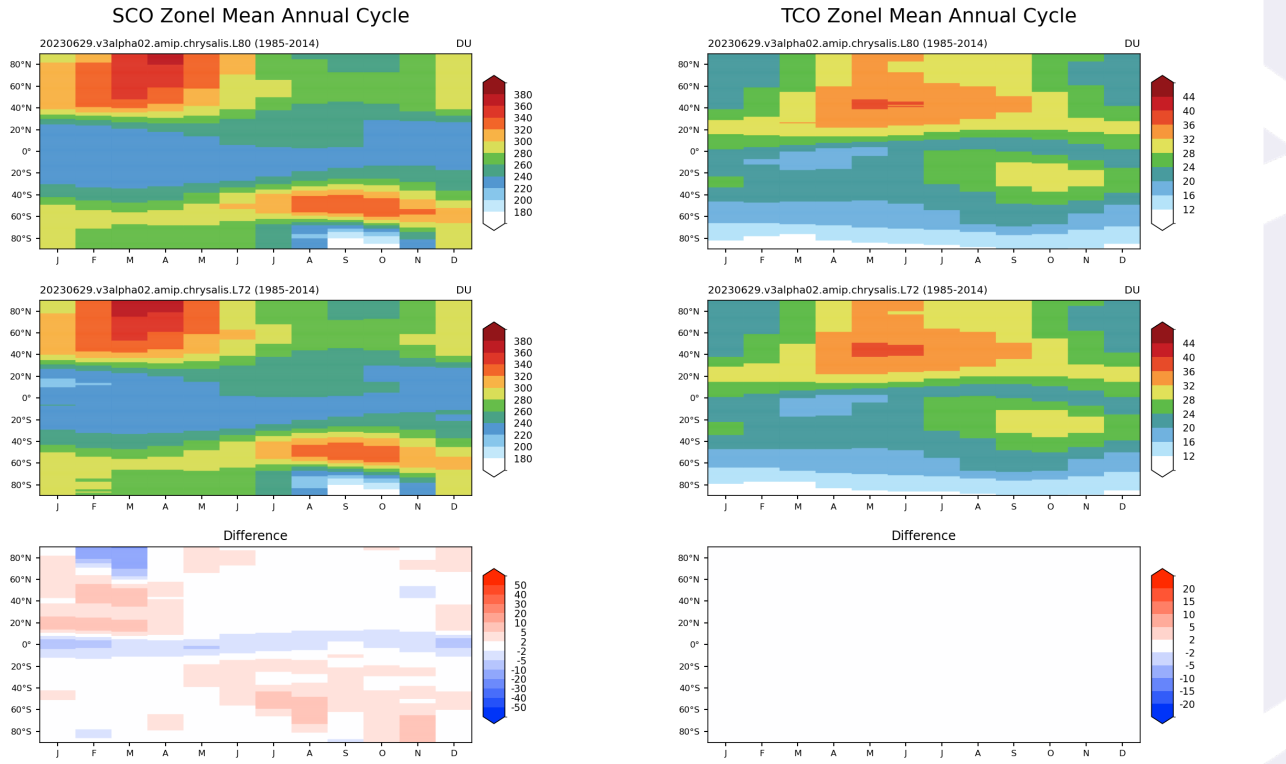








Supplemental figures



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Model physics changes, E3SMv1 → E3SMv2

- Structural changes to ZM deep convection scheme ("dCAPE-ULL trigger")
  - Dynamic CAPE (dCAPE): *CAPE generation driven by empirical large-scale parameterization of the dynamical triggering processes, including large-scale upward motion and warm and moist advection in the low levels – **addresses too frequent, too light precipitation problem** by reducing strong surface heating control on model convective initiation*
  - Unrestricted Launch Level (ULL): *Removes the constraint that convection always has its root within the boundary layer as often assumed in deep convection schemes -- **improves precipitation diurnal cycle***
- Significant tuning of CLUBB: 23 input parameters values changed
- Moderate tuning of ZM: 5 input parameter values changed
- Moderate tuning of MG2: 4 input parameter values changed
- Additional changes to nucleate (`so4_sz_thresh_icenuc`), microp/aero (`microp_aero_wsubmin`), aerosol (`seasalt_emis_scale`), dust (`dus_emis_fact`), linoz (`linoz_psc_t`), gravity wave drag (`gw_convect_hcf`, `effgw_beres`, and `effgw_oro`)