Atmosphere-Land-Ocean-Ice Interface Processes in E3SM

Xubin Zeng, Jack Reeves Eyre
Mike Brunke, Pieter Hazenberg

University of Arizona

In collaboration with PNNL, LANL, LBNL, ORNL, and LLNL scientists

16 August 2018

E3SM All-hands Science Talk

Energy Exascale
Earth System Model

THE UNIVERSITY
OF ARIZONA

Outline

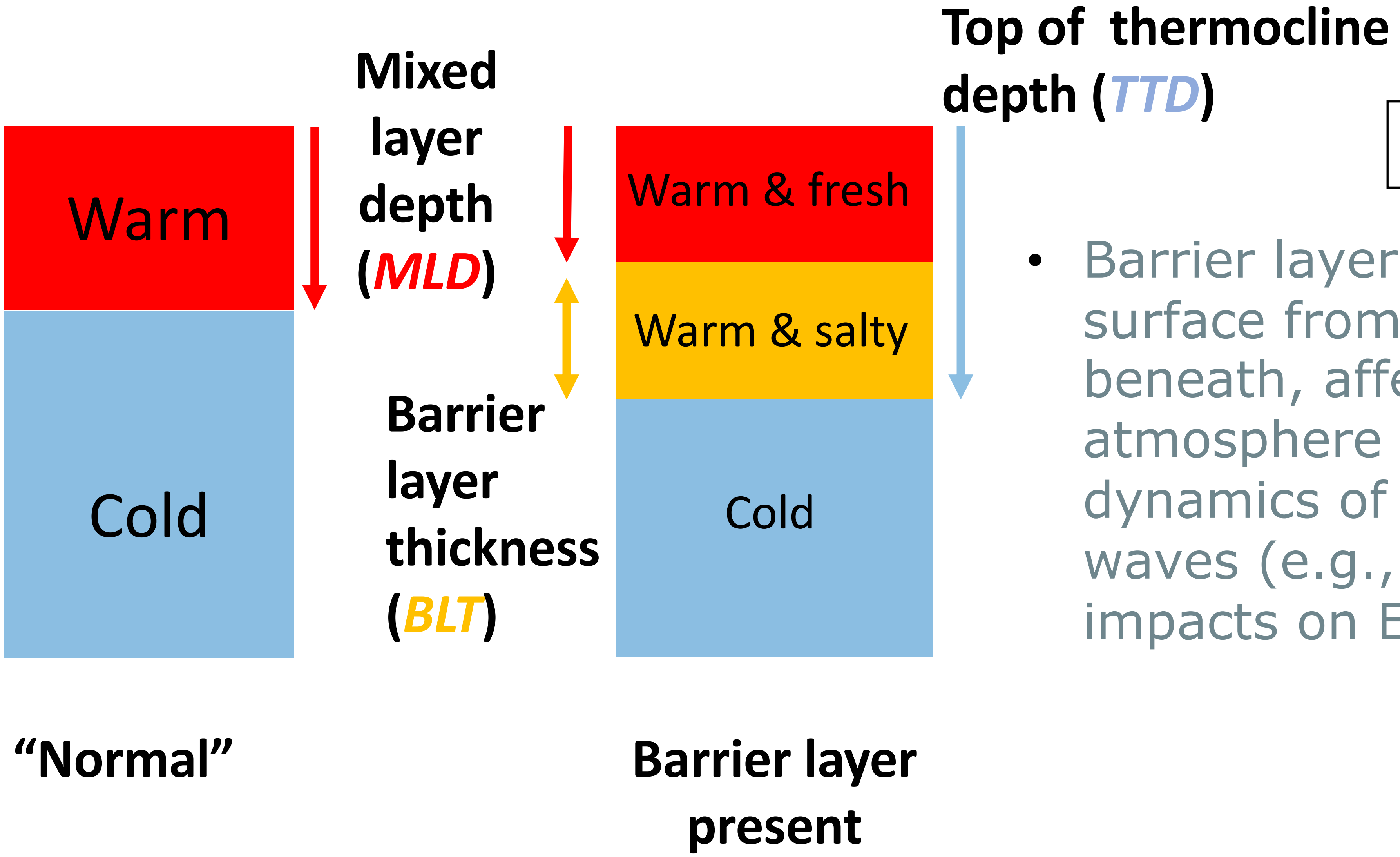
1. barrier layer in the ocean mixed layer
2. marine stratocumulus decks
3. ocean surface turbulence parameterization
4. land model parameterization and spinup time
5. Greenland temperature
6. soil moisture-precipitation interactions

"First light" image released from GOES-R (GOES-16)

Not covered in this presentation is our work related to the SciDAC Project on dynamics-physics coupling in E3SM, led by Hui Wan (PNNL) and Carol Woodward (LLNL).

Barrier layers in E3SM, and their relation to surface forcing

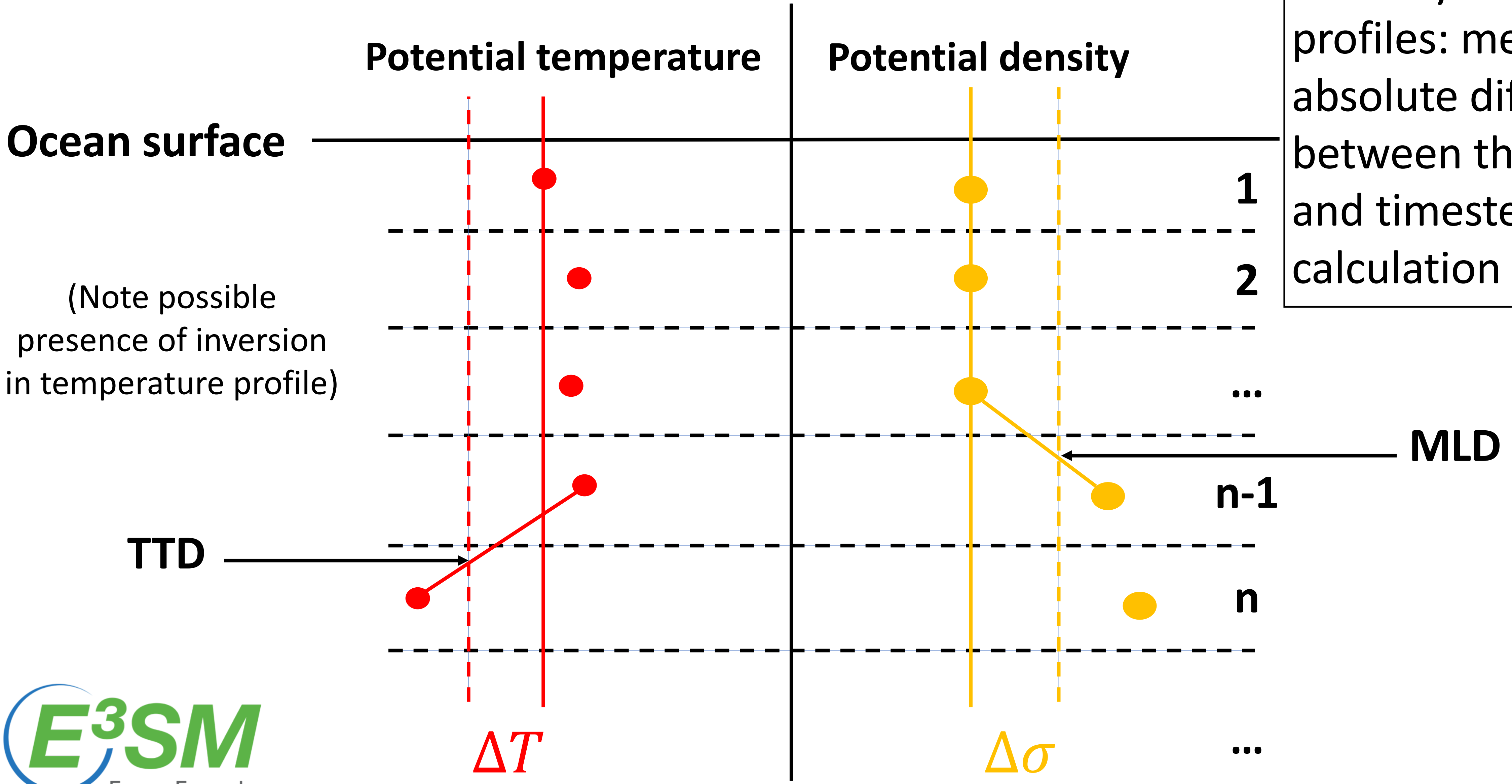
(Reeves Eyre, Van Roekel (LANL), Brunke and Zeng, 2018, to be submitted in September 2018)



BLT = TTD - MLD

- Barrier layers isolate ocean surface from cold waters beneath, affecting ocean-atmosphere heat exchange, and dynamics of sub-surface ocean waves (e.g., Kelvin waves; impacts on ENSO)

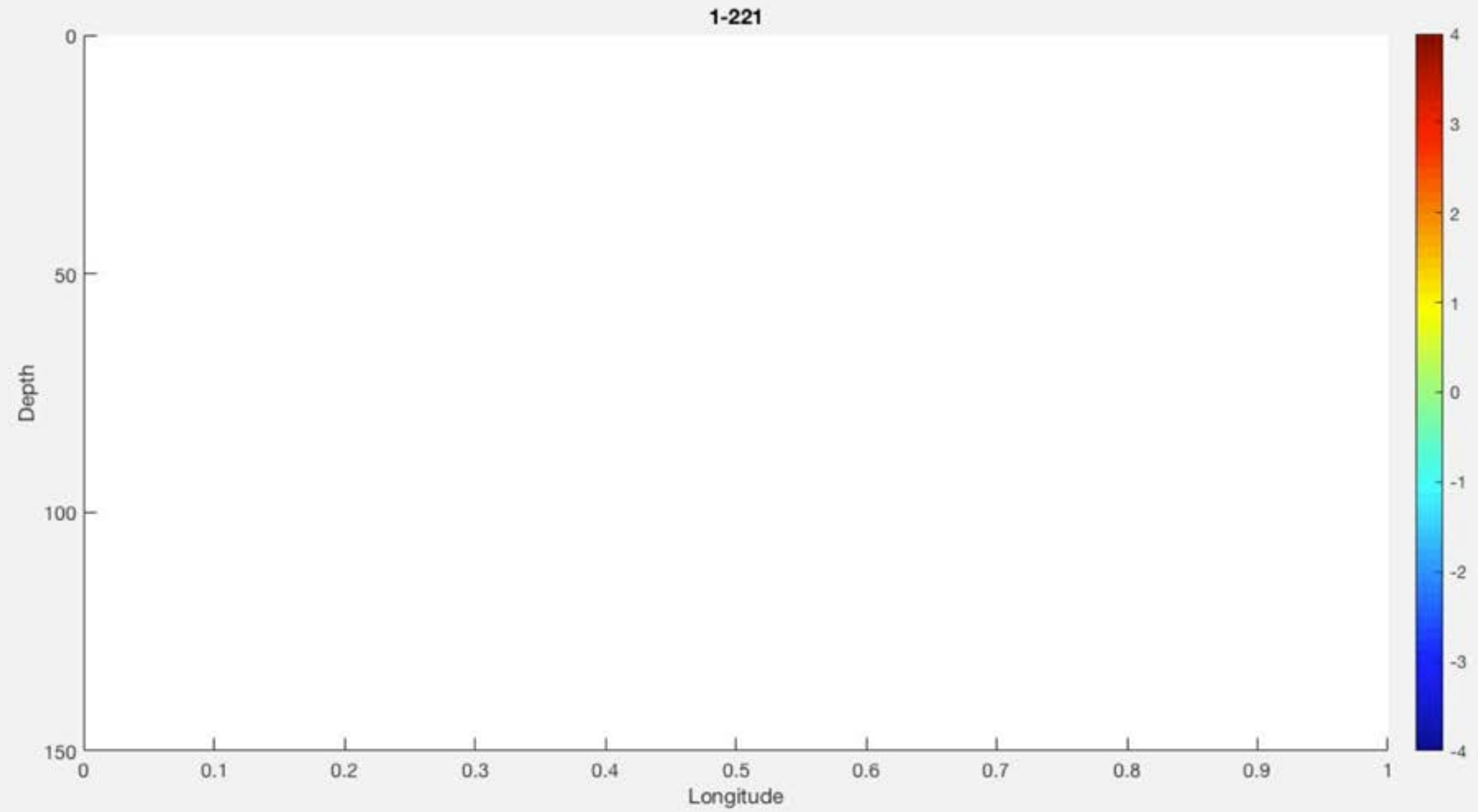
MLD and TTD calculation method



Performed on monthly mean profiles: mean absolute difference between this result and timestep-based calculation is ~ 4 m.

E3SM Energy Exascale Earth System Model

BLT and ENSO: equatorial cross section from ocean-sea ice case

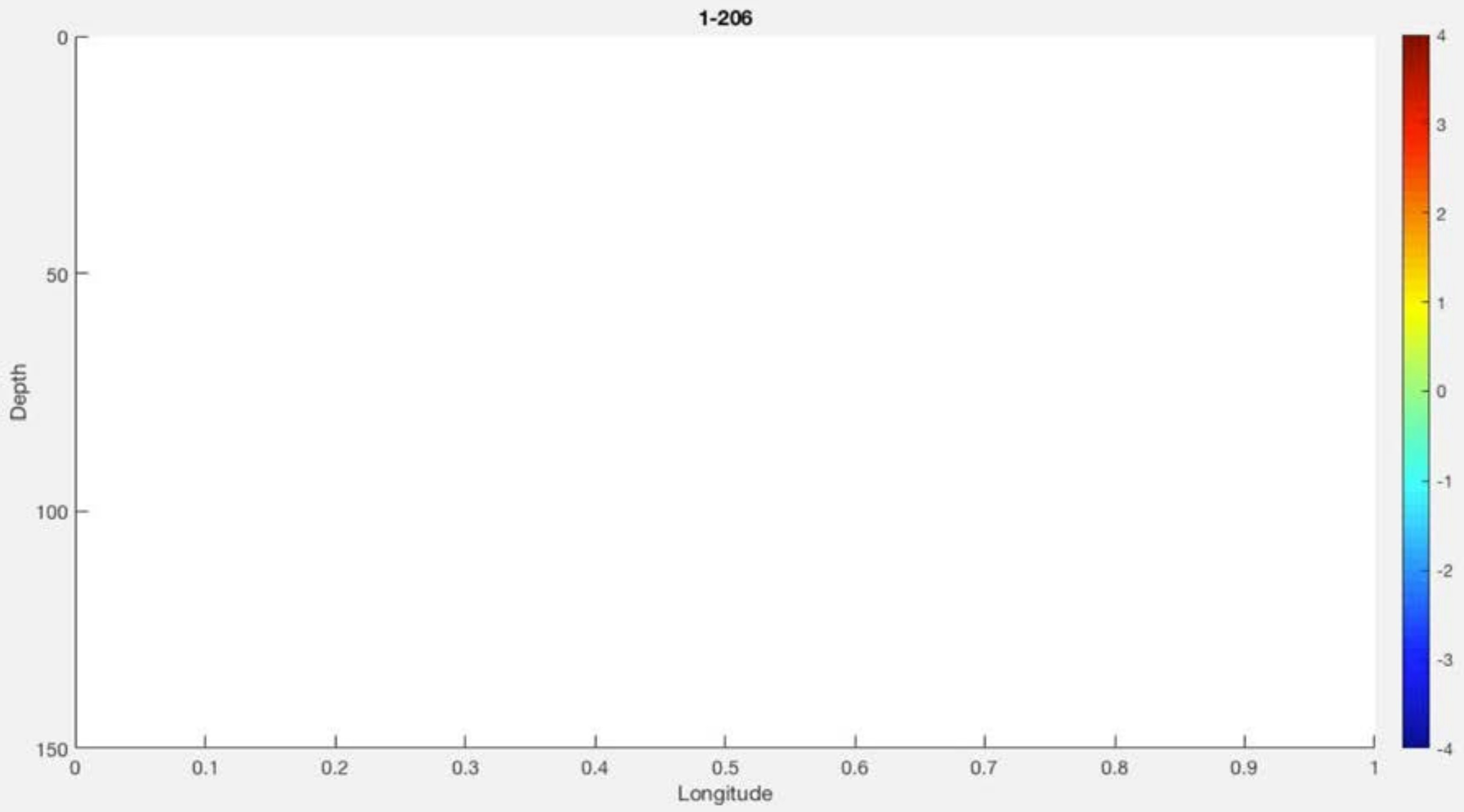


Note barrier layer between solid and dashed red lines.

Note also salinity front in west to central Pacific.

Shading = T′ Black contours = S Red solid line = TTD Red dashed line = MLD

BLT and ENSO: equatorial cross section from coupled case

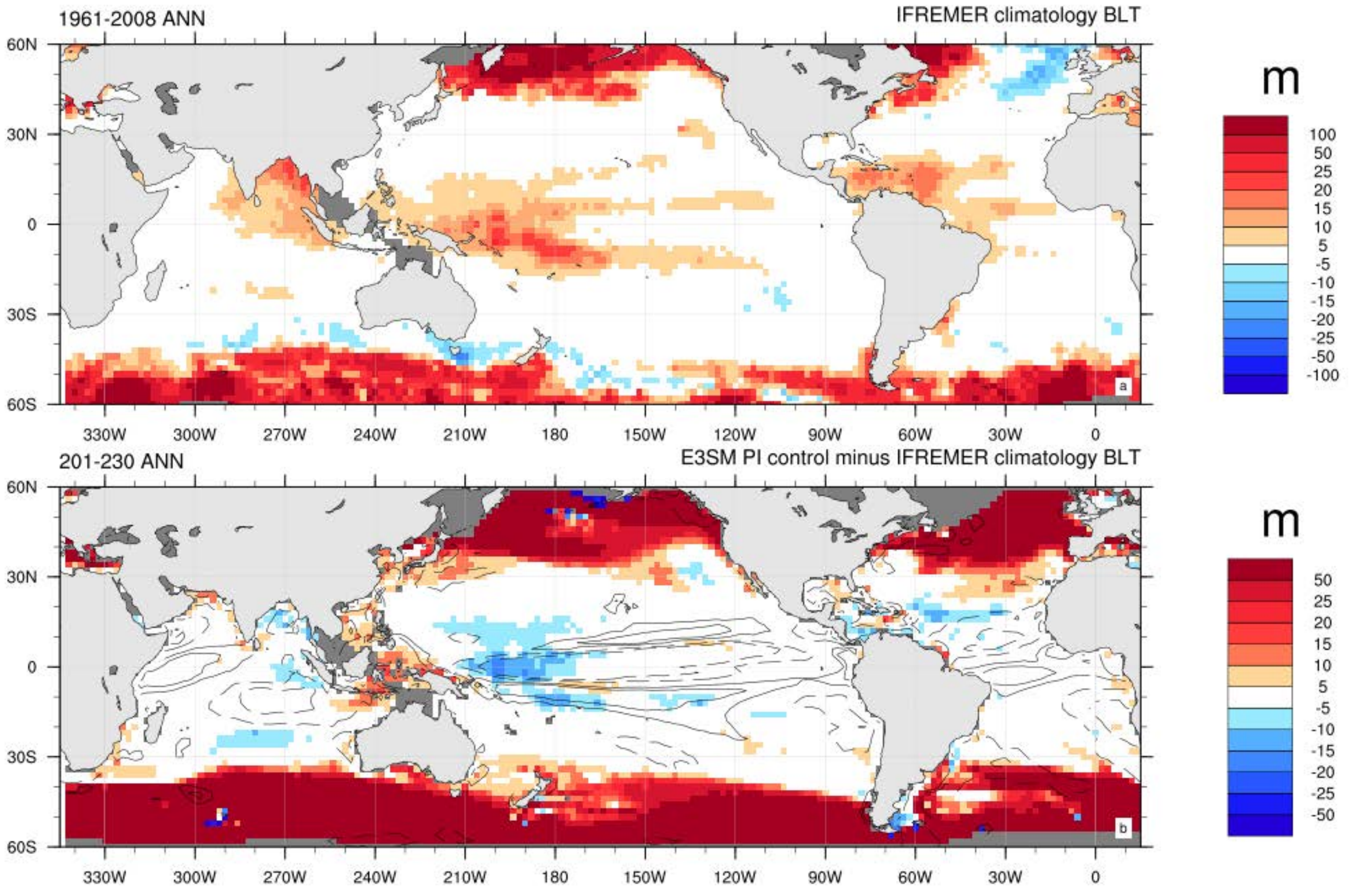


Barrier layer and salinity front limited to far west Pacific and Maritime Continent.

Shading = T′ Black contours = S Red solid line = TTD Red dashed line = MLD

How well does E3SM simulate barrier layers?

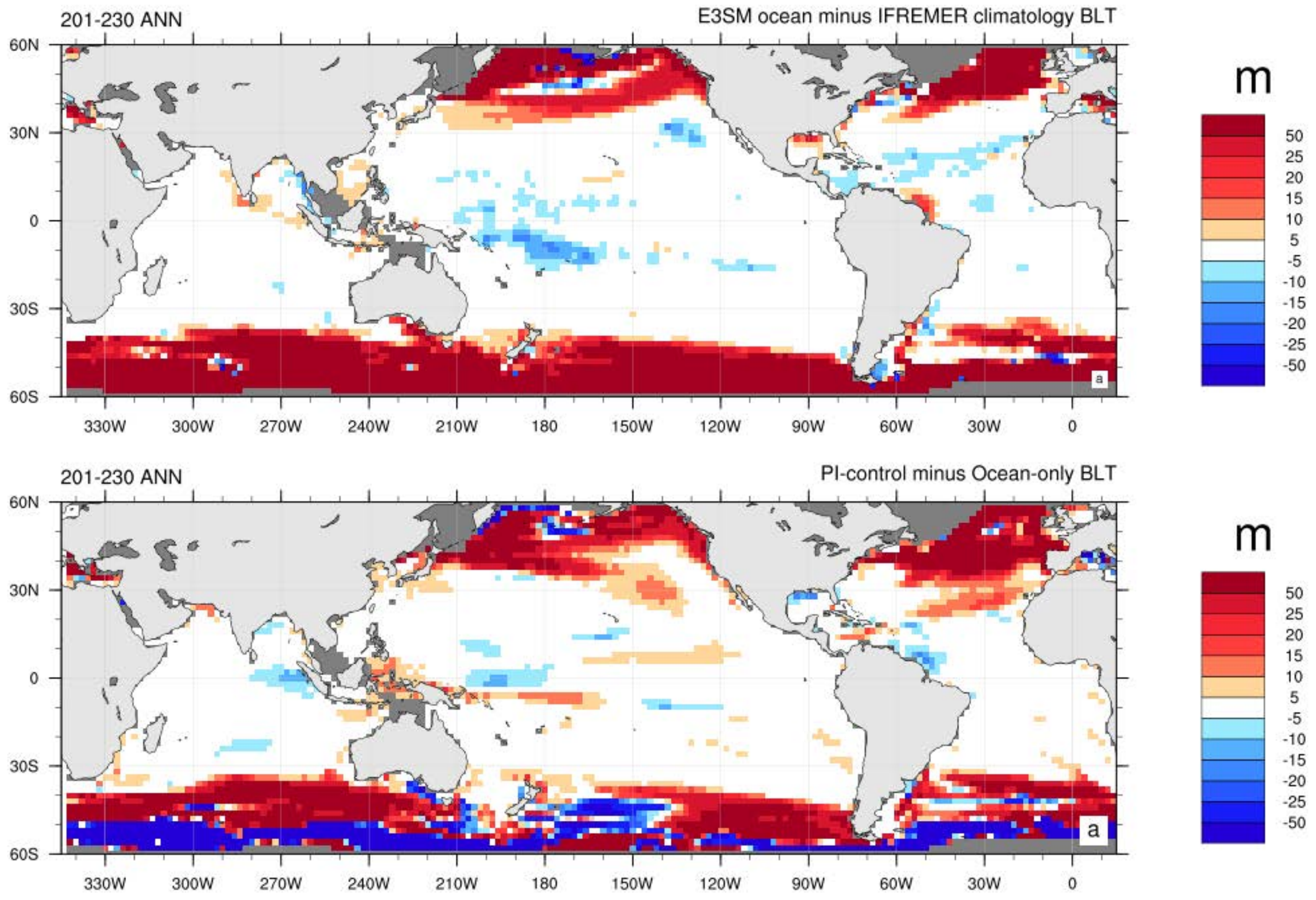
- Correct general pattern.
- BL too thin in tropics (except around Maritime Continent).
- BL too thick and too extensive in high and mid-latitudes.
- Possible relationship with (P-E) biases in tropics (contour lines in bottom panel).



Top: observed annual mean BLT. Bottom: E3SM BLT bias.

How much BLT bias is contributed by the ocean model?

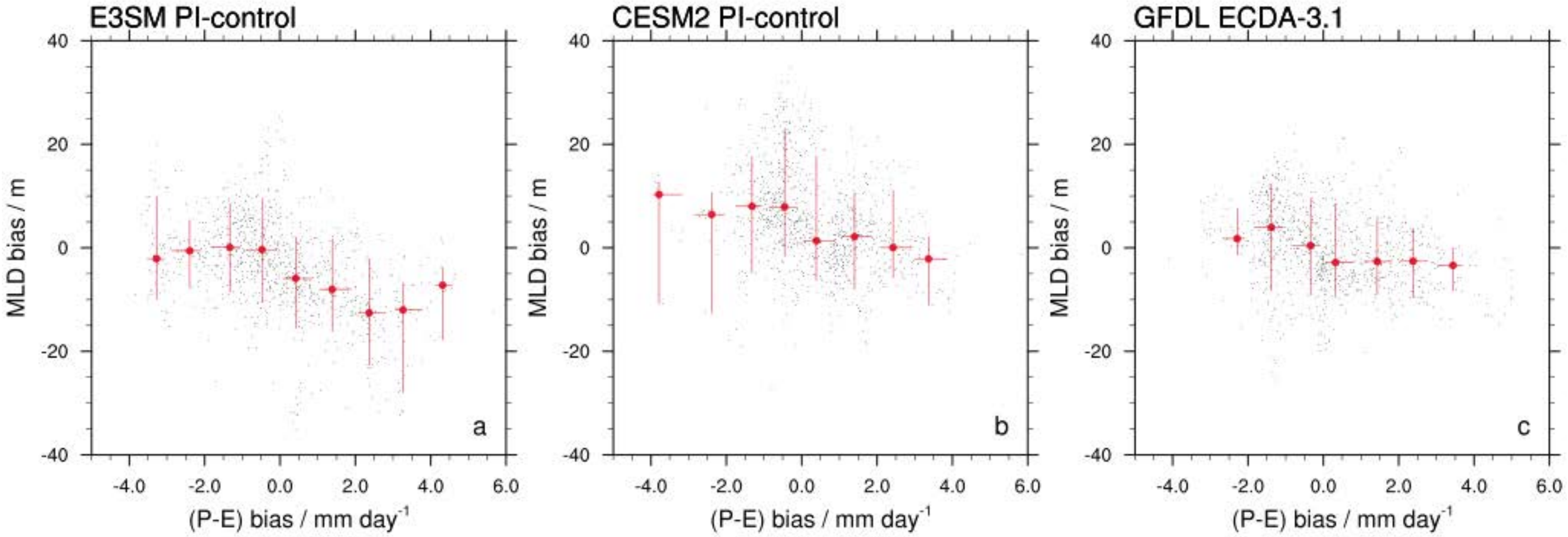
- Top plot shows ocean model contribution – relatively small in tropics (except South Pacific Convergence Zone).
- Bottom plot shows component likely caused by atmosphere and land model biases, or coupled interactions.



Annual mean BLT: (top) E3SM ocean-sea ice minus obs.; (bottom) E3SM coupled minus ocean-sea ice run

What does the atmosphere model contribute in the tropics?

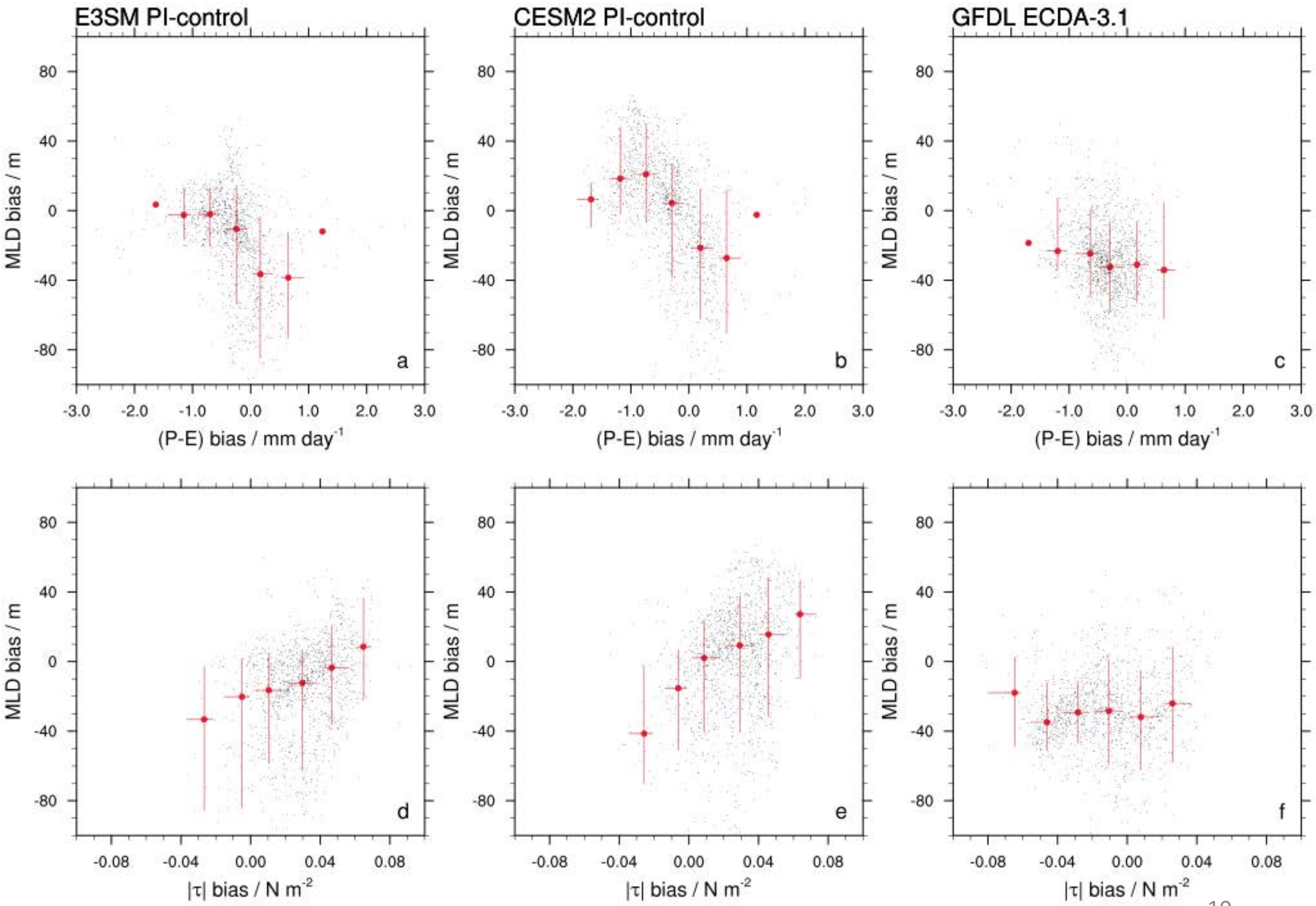
- In the tropics, differences (previous slide) are partially explained by effects of (P-E) biases on MLD. Because the ocean model doesn't "add" much bias, this is carried over to coupled model MLD biases:



Black dots: grid points where observed annual BLT > 5 m. Red points: bin medians, 10th and 90th percentiles.

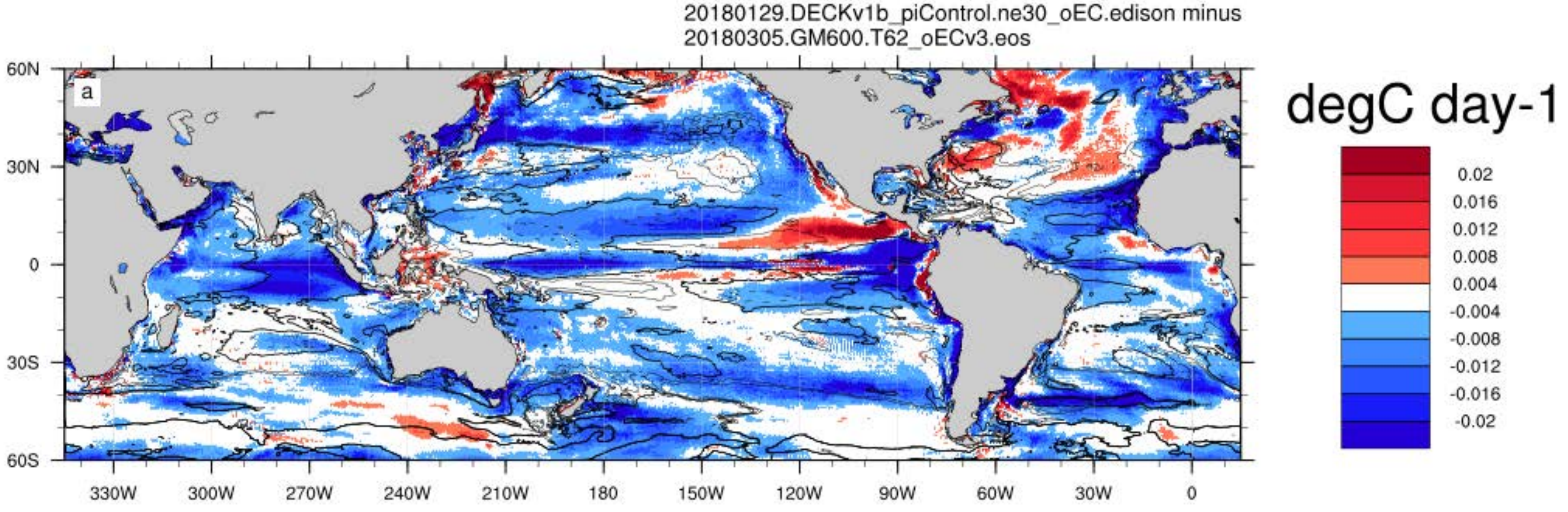
What does the atmosphere model contribute in mid-latitudes?

- In higher latitudes (figure shows the Southern Ocean), (P-E) biases (top row) have an effect on MLD, but wind stress biases(bottom row) are important too.



Do BLT biases change the "insulation" effect?

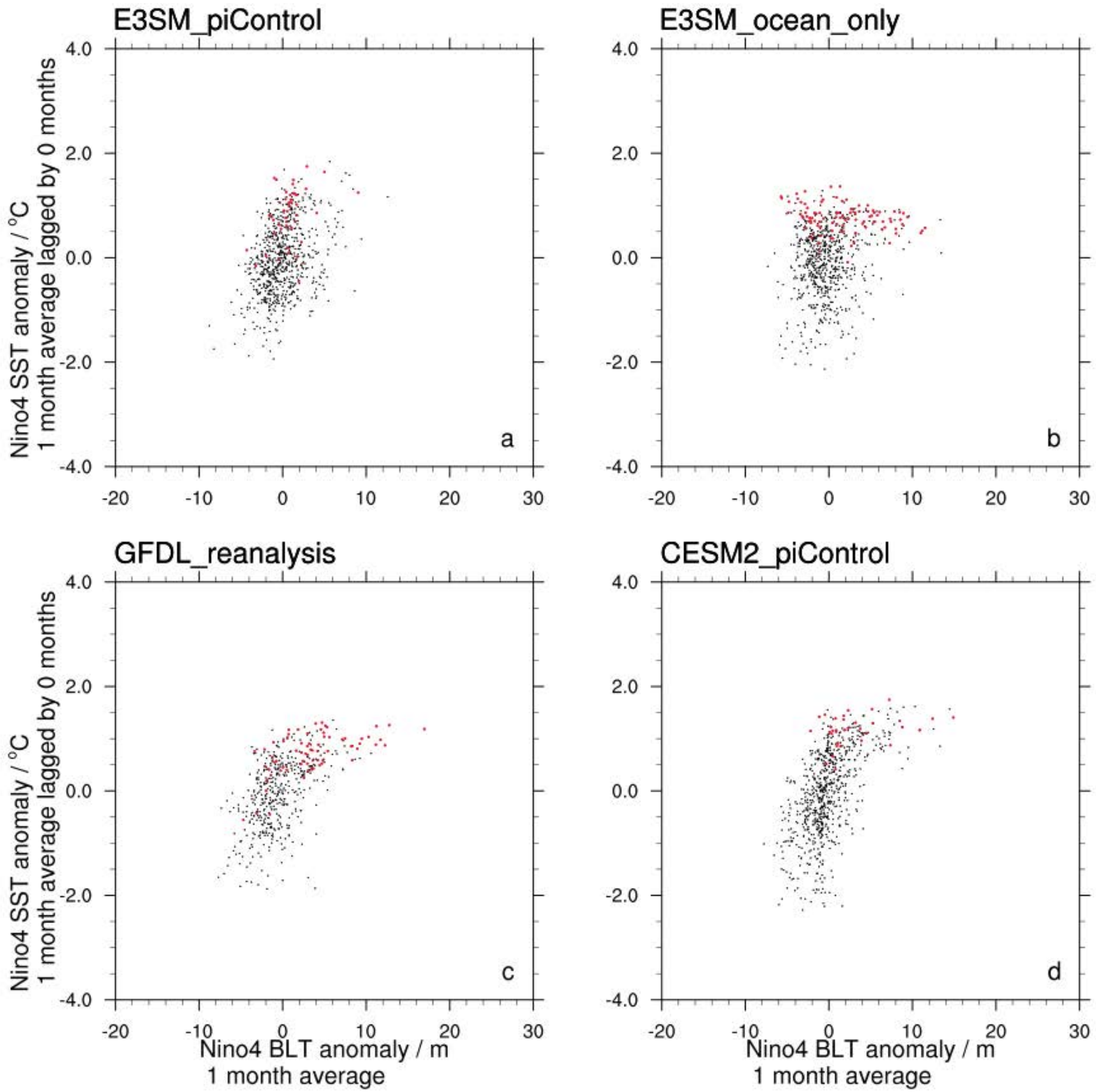
- Where BL too thick, less entrainment cooling (i.e., less negative temperature tendency). Where BL too thin, more entrainment cooling (i.e., more negative temperature tendency).



Difference (E3SM coupled minus ocean-sea ice run) in vertical mixing contribution to temperature tendency of layer above TTD (shading) and difference in BLT (contour lines; positive = solid, negative = dashed, thicker contour = 0).

Do BLT biases affect SST?

- In GFDL reanalysis, CESM2 and E3SM ocean-sea ice case, Niño4 region has occasional thick BLs, occurring at the same time as positive SST anomalies.
- In E3SM coupled run, BLT anomalies have smaller variance. BLs rarely get thick enough to cut off entrainment cooling?
- Possible contribution to negative SST bias in equatorial Pacific: Need model experiments to verify.



Scatter plots of monthly BLT anomaly vs. monthly SST anomaly in the Niño4 region. Red dots have monthly zonal wind stress anomaly greater than +0.015 N m^{-2}.

Conclusions

- In E3SM coupled run, barrier layers are generally too thin over tropics, while in mid-latitudes, they are too thick and extend too far equatorward.
- In some tropical regions – notably west Pacific – BL biases are dominated by atmosphere model biases and coupled interactions. In mid-latitudes, the ocean model also makes a large contribution.
- The atmosphere model bias of most importance for tropical BLs seems to be (P-E), while in mid-latitudes, (P-E) and wind stress biases both contribute.
- BL biases affect model representation of cold water entrainment from below the thermocline, especially in the tropics.
- BL biases related to model SST variability, possibly through the effect on cold water entrainment. This may be a sign of BL bias influence on SST bias, though further work required to establish this.

Outline

1. barrier layer in the ocean mixed layer
2. marine stratocumulus decks
3. ocean surface turbulence parameterization
4. land model parameterization and spinup time
5. Greenland temperature
6. soil moisture-precipitation interactions

"First light" image released from GOES-R (GOES-16)

Model spread in Sc remains large in spite of focused studies and field campaigns

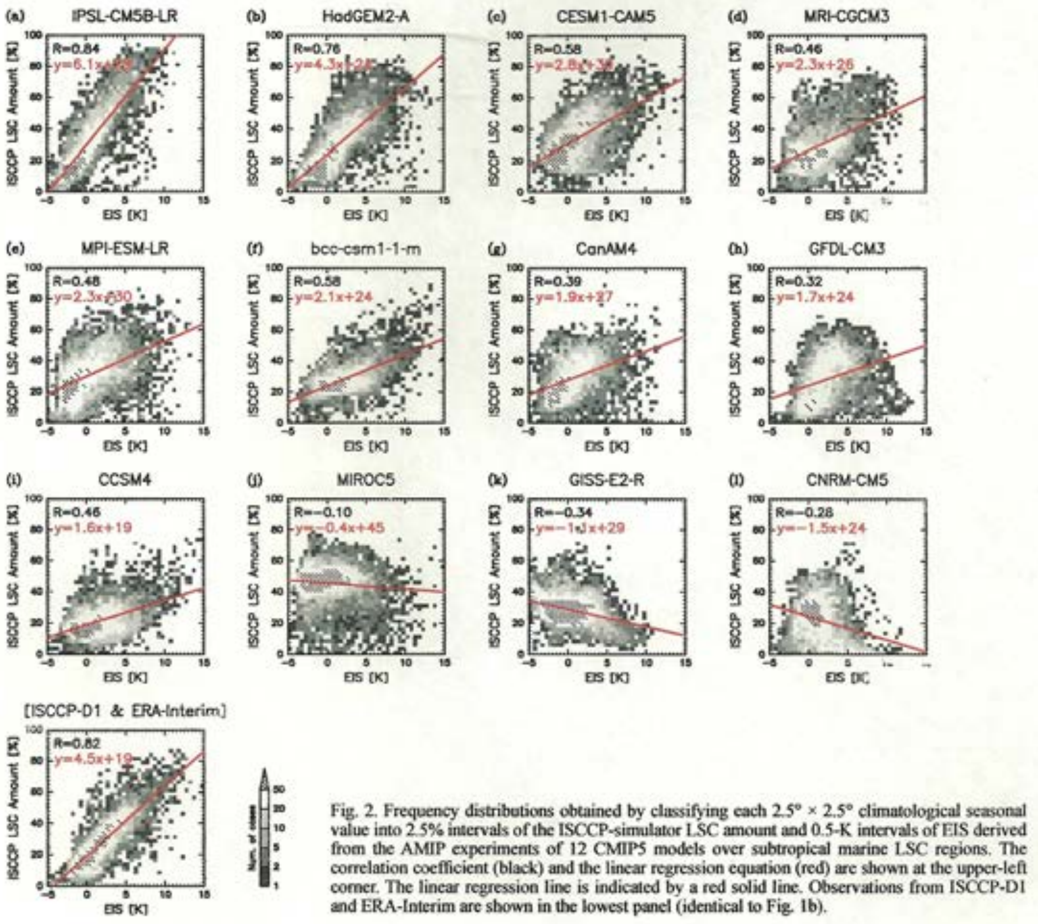
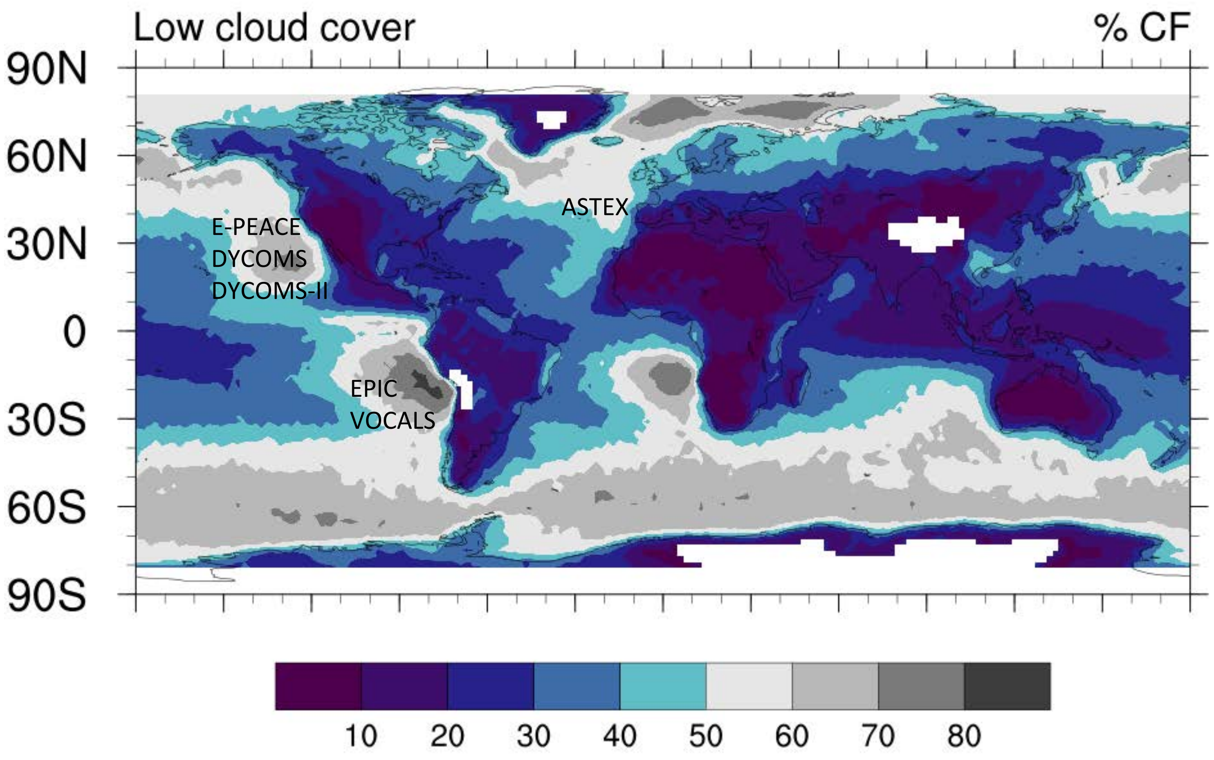
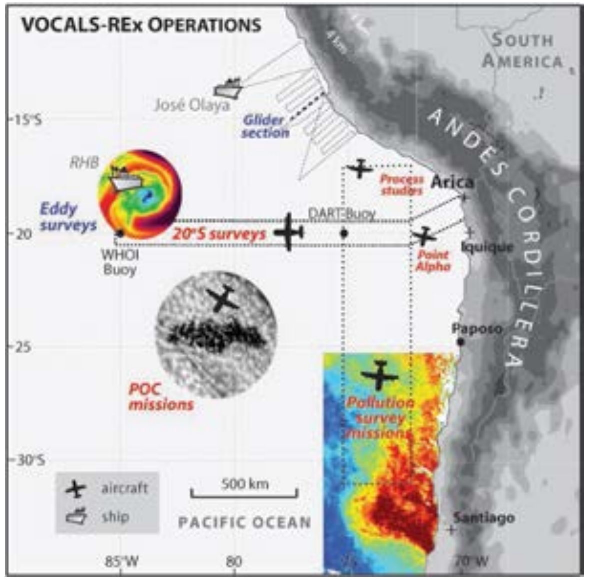


Fig. 2. Frequency distributions obtained by classifying each 2.5° × 2.5° climatological seasonal value into 2.5% intervals of the ISCCP-simulator LSC amount and 0.5-K intervals of EIS derived from the AMIP experiments of 12 CMIP5 models over subtropical marine LSC regions. The correlation coefficient (black) and the linear regression equation (red) are shown at the upper-left corner. The linear regression line is indicated by a red solid line. Observations from ISCCP-D1 and ERA-Interim are shown in the lowest panel (identical to Fig. 1b).

(Koshiro et al. 2018)



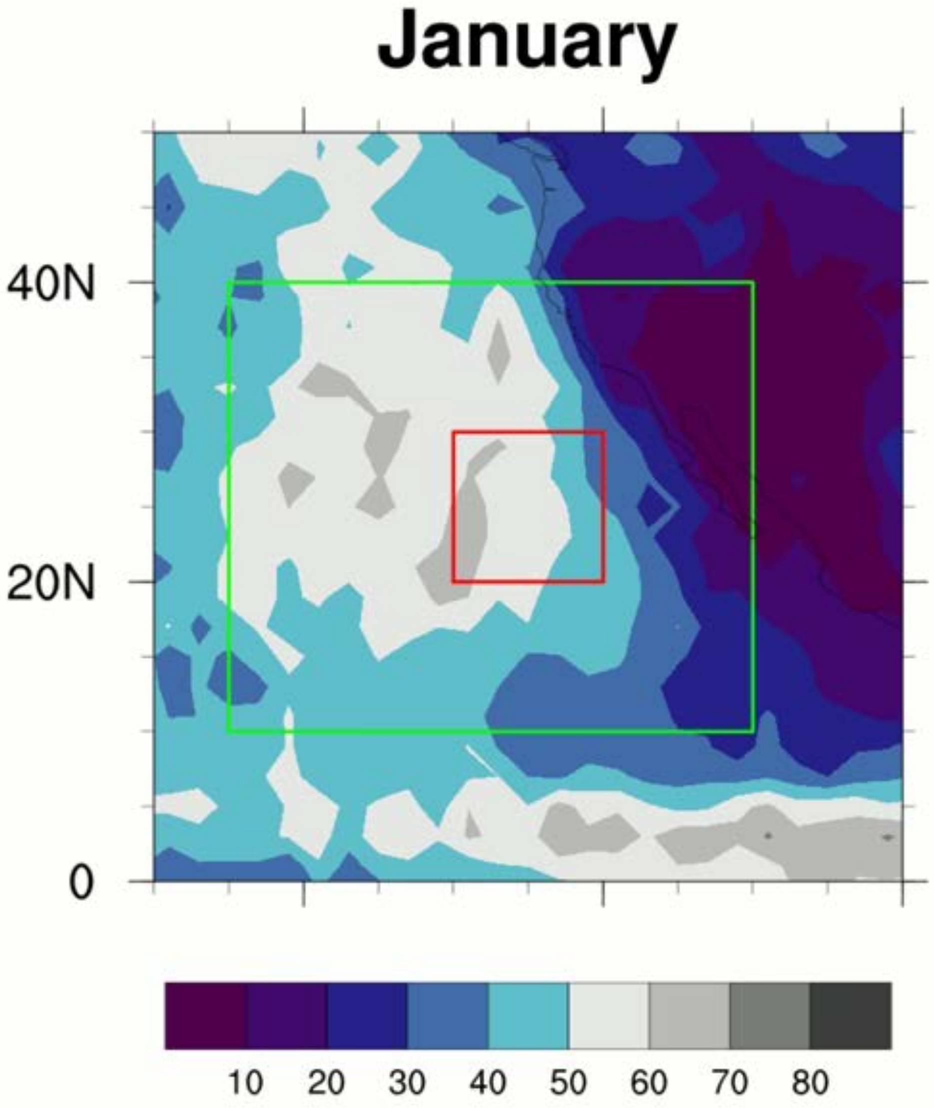


(Mechoso et al. 2014)

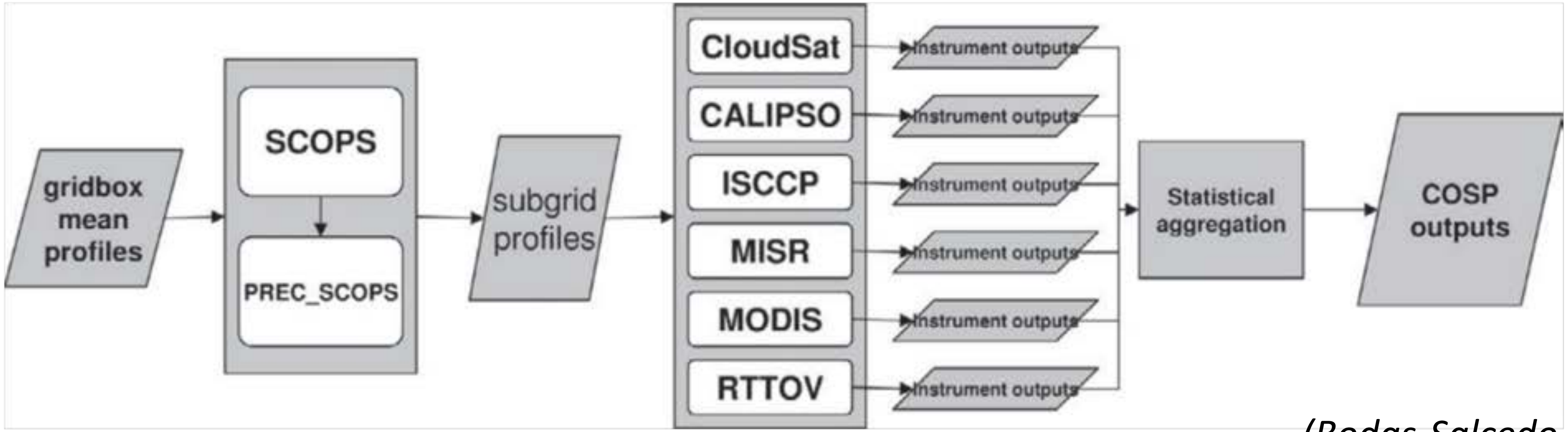
Re-thinking the evaluation of stratocumulus decks

- We ask:
  - What is the best way to evaluate the models in order to provide new insights for model physics improvement?
  - What are the new insights that such improved model evaluations provide?
- We consider extended regions (green box) vs. the classic core regions (red box).

Brunke et al. 2018, submitted to *JGR-Atmospheres*
DOE collaborator: Phil Rasch (PNNL)



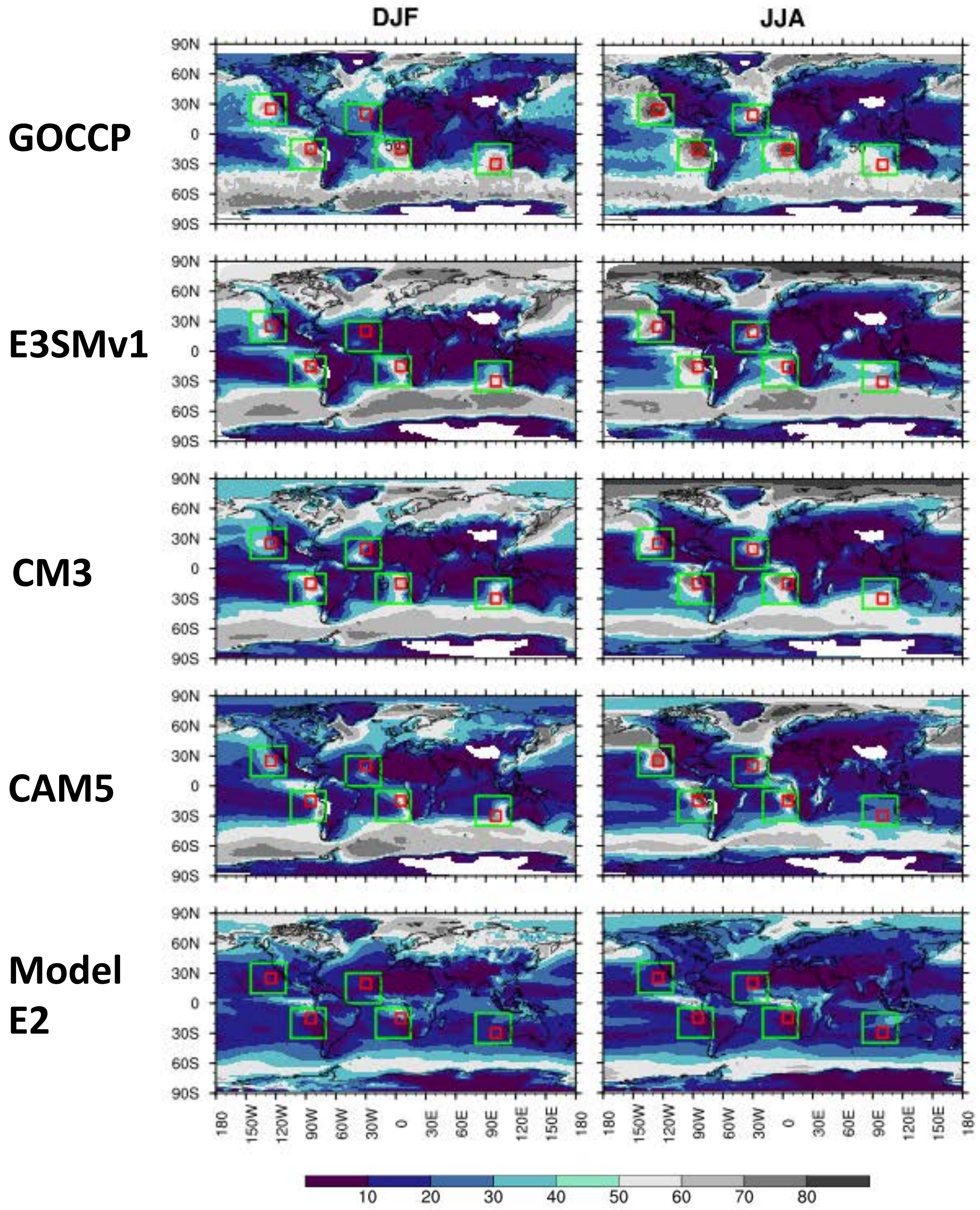
Methodology



(Bodas-Salcedo et al. 2011)

FIG. 1. **COSP schematic.**

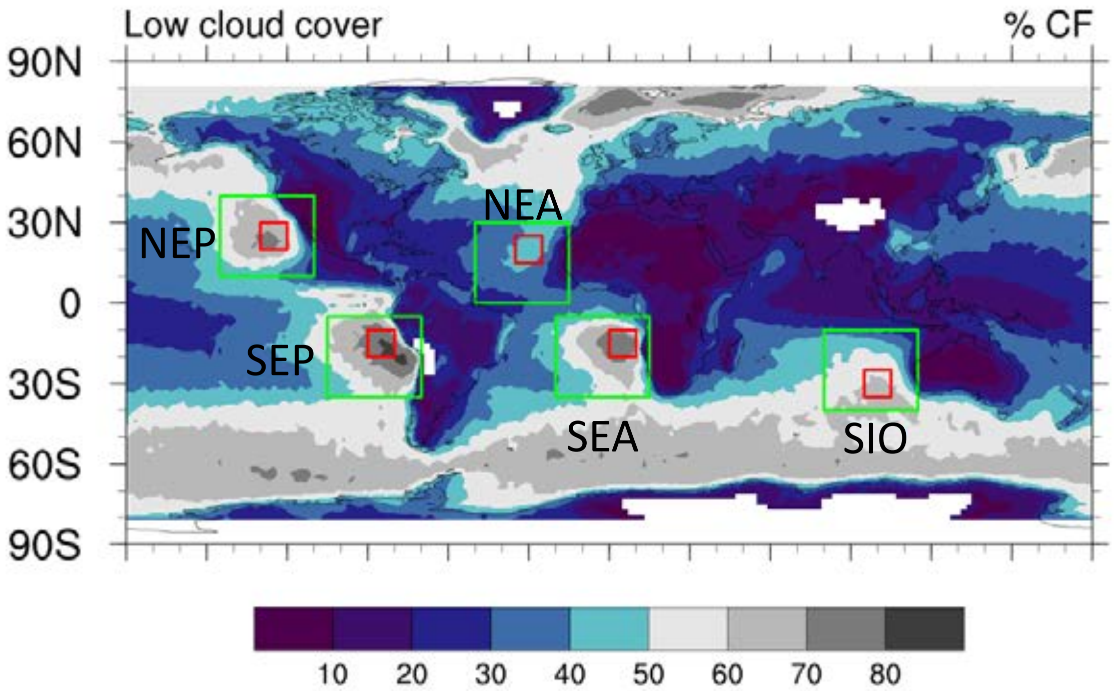
- Compare E3SMv1 Sc decks to those produced by other U.S. models (CESM1-CAM5, GFDL CM3, and GISS ModelE2).
- "Apples-to-apples" comparison of COSP output with CALIPSO-GOCCP monthly mean LCC.
- Observed lower tropospheric stability (LTS) = θ(700 hPa) – θ(1000 hPa) from ERA-Interim

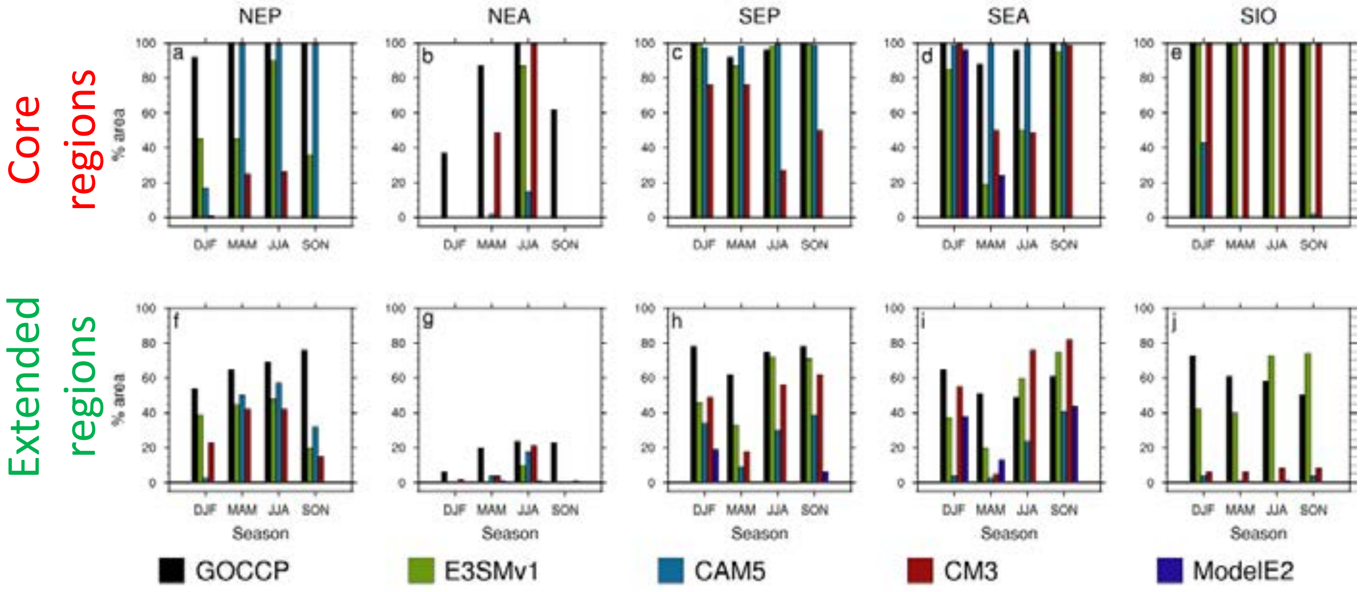


Seasonal mean LCC

- E3SMv1 and CM3 stratocumulus decks are displaced away from the coasts.
- CAM5 decks are restricted to near-shore.
- ModelE2 produces too little cloud cover globally.

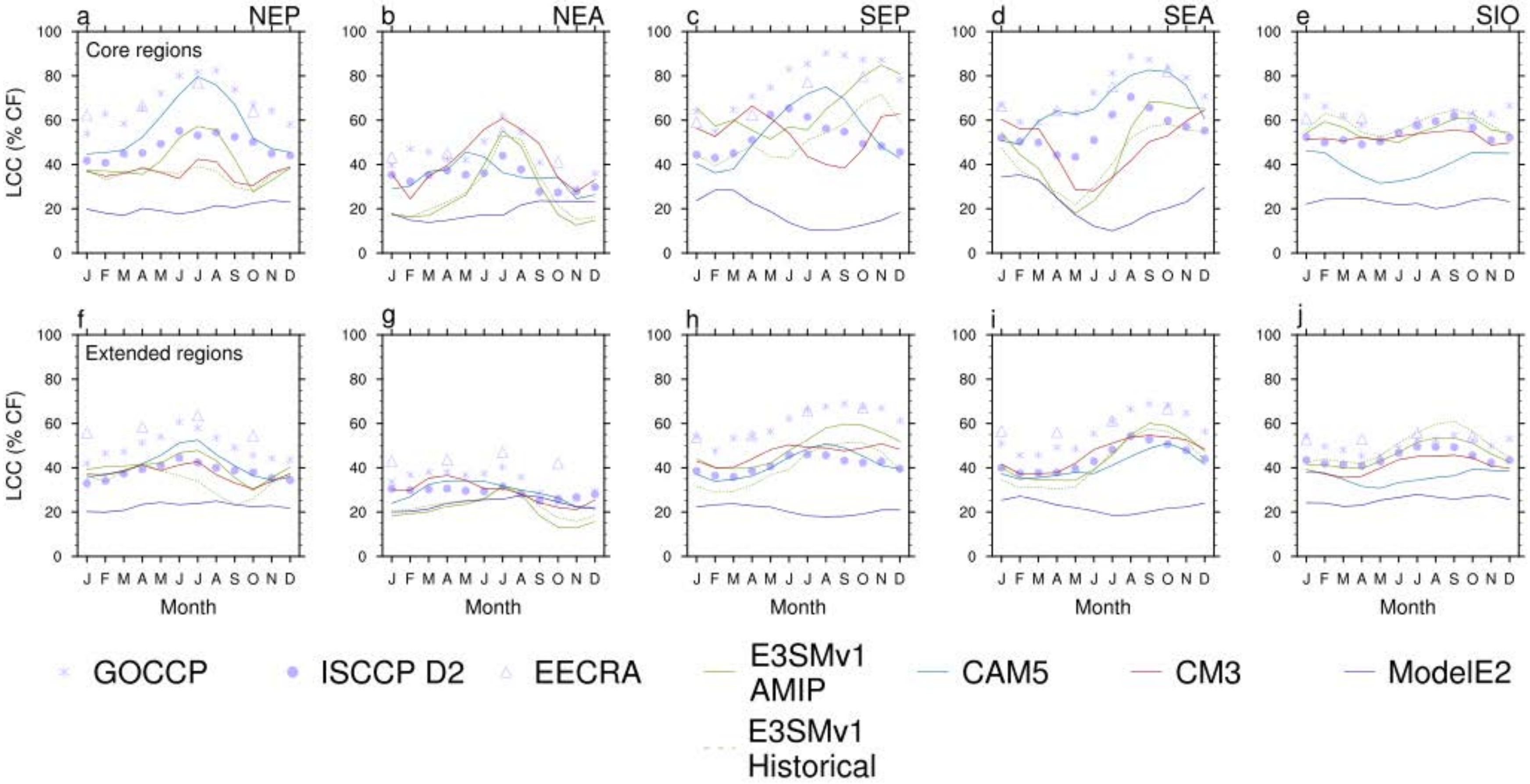
LCC > 45% over the extended regions vs. over the core regions





- Core regions: large spread in the model-simulated % coverage of LCC > 45% CF, models less consistent with CALIPSO-GOCCP in some regions for some seasons.
- Extended regions: smaller spread in model coverage of LCC > 45% CF, models more consistent with CALIPSO-GOCCP.

Mean annual cycle over the extended regions vs. over the core regions



- Model and observational mean annual cycle spread is reduced in the extended regeions.
- Models are also more consistent with the reduced observational spread over the extended regions.

LCC-LTS relationships over the extended regions vs. over the core regions

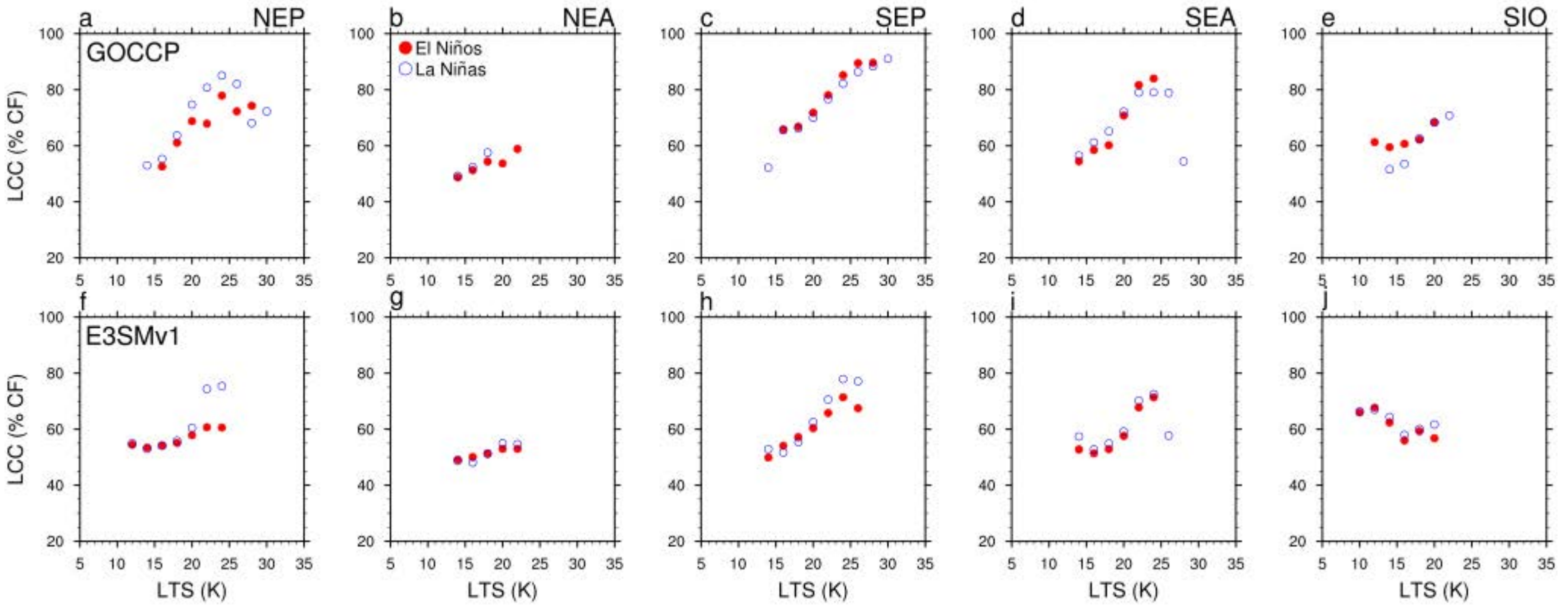
- In the core regions:
  - GOCCP LCC-LTS regression slope over the core regions is slightly lower than that of previous studies.
  - E3SMv1's relationship compares well to GOCCP.
  - Relationship as low as 0.36 in CM3, negative in some regions.
- In the LCC45+ decks:
  - Relationships are lower.
  - E3SMv1's relationship compares better to GOCCP.

All region regression slopes (% CF K^{-1})	Core regions	LCC45+ decks
CALIPSO-GOCCP	4.03	2.44
E3SMv1	3.41	1.37
CESM1-CAM5	3.44	0.36
GFDL CM3	0.36	0.96

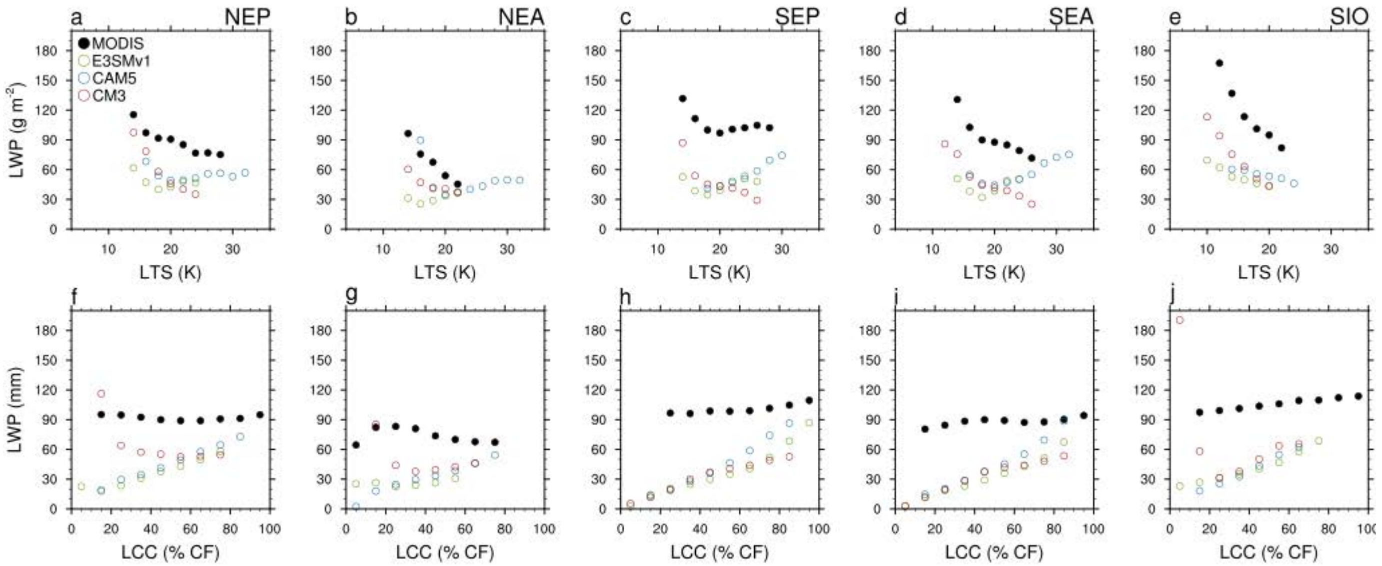
LCC45+ Deck: grids in the extended region with LCC > 45%

The effect of ENSO on the LCC-LTS relationship

- The LTS range where low clouds exist is somewhat sensitive to ENSO in GOCCP.
- E3SMv1 and the other models produce low clouds over similar LTS ranges no matter the ENSO phase.

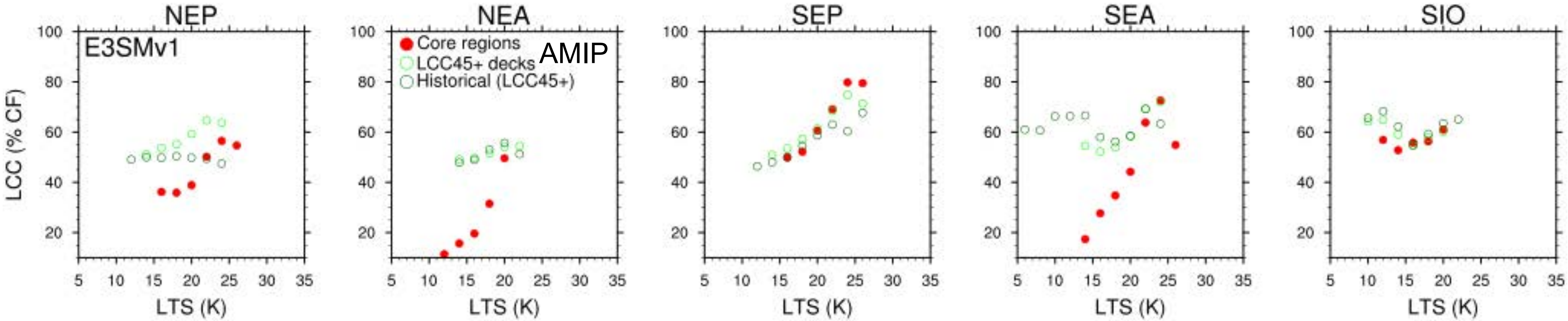


Is LWP realistically simulated?



- MODIS LWP decreases with LTS.
  - Model LWP lower than MODIS; E3SMv1 and CAM5 LWP is constant or increases with LTS.
- MODIS LWP nearly constant across LCCs.
  - Model LWP is too sensitive to LCC.

Is there a difference between E3SMv1's AMIP and historical (A-O coupled) runs?



- E3SMv1 historical LCC is similarly simulated to AMIP run in every LCC45+ deck except NEP.

Summary

- What is the best way to evaluate the models in order to provide new insights for model physics improvement?
  - Model spread is reduced when considering the extended regions or LCC45+ decks
  - Despite the displacement of the Sc deck, E3SMv1 produces a reasonably good stratocumulus deck.
  - Models' displacement of Sc deck is likely caused by the interaction between model physics and large-scale dynamics.

- What are the new insights that such improved model evaluations provide?
  - LTS range from E3SMv1 and the other U.S. models are insensitive to ENSO – likely caused by errors in the large-scale dynamics
  - Model LWP is lower than MODIS, less sensitive to LTS than MODIS; much more strongly dependent on LCC than MODIS – likely caused by model physics errors
  - LCC45+ decks are similarly simulated by the historical runs versus in the AMIP runs except in the NEP.

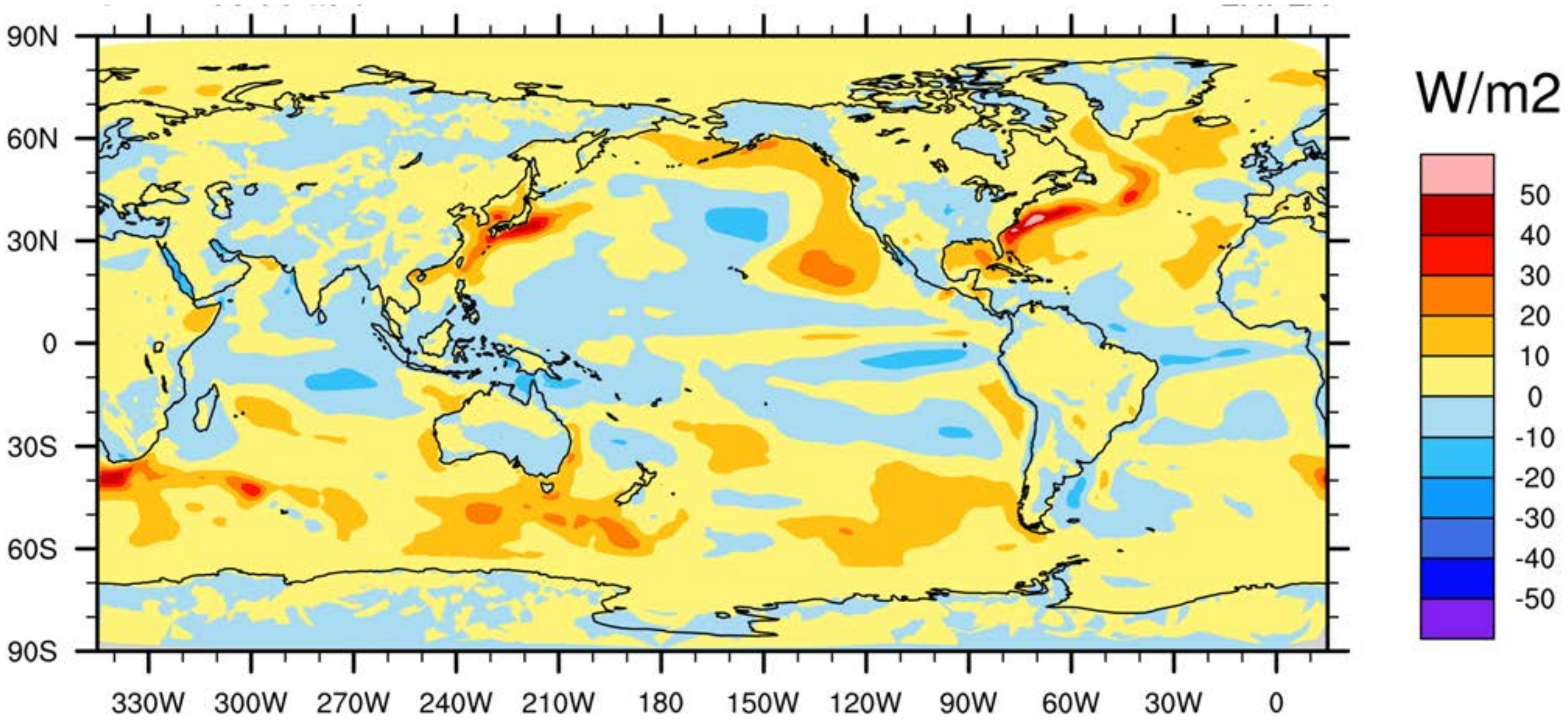
Outline

1. barrier layer in the ocean mixed layer
2. marine stratocumulus decks
3. ocean surface turbulence parameterization
4. land model parameterization and spinup time
5. Greenland temperature
6. soil moisture-precipitation interactions

"First light" image released from GOES-R (GOES-16)

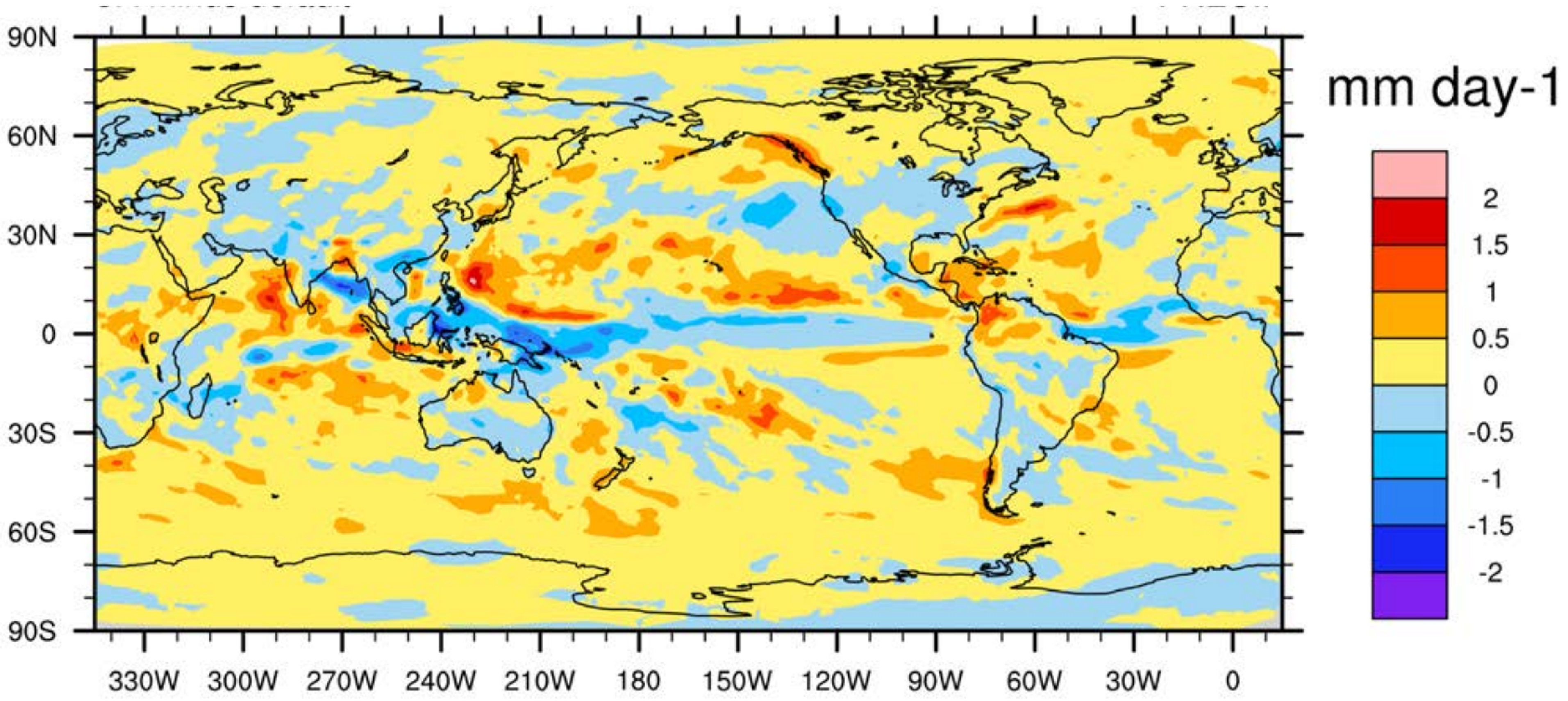
Turbulence over the ocean surface: implementing an alternative flux algorithm

In collaboration with Po-Lun Ma (PNNL), we have implemented the Zeng et al. (1998) method of calculating fluxes over ocean surface.



Difference (UA minus control) in 5-year annual mean latent heat flux.

Initial assessment suggests changes in hydrologic cycle, surface winds and net heat flux at surface and TOA (so might require re-tuning E3SM for use in long coupled model runs). This will be an E3SM V2 effort.



Difference (UA minus control) in 5-year annual mean precip. rate.

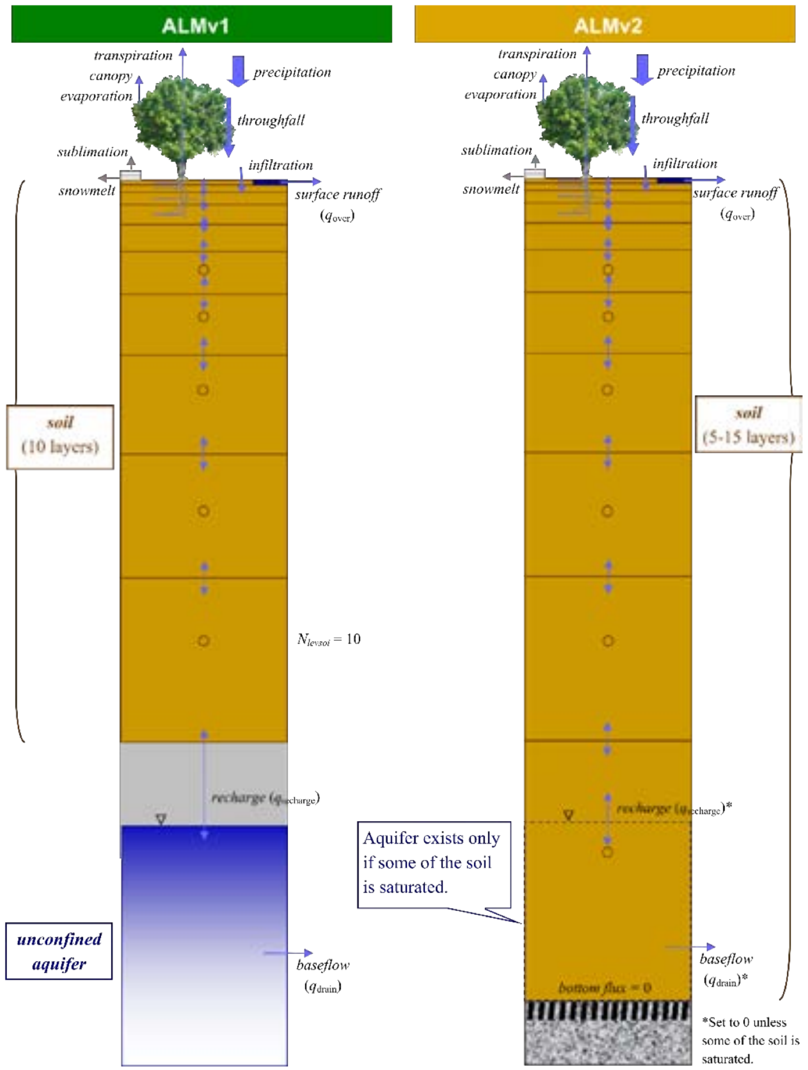
Outline

1. barrier layer in the ocean mixed layer
2. marine stratocumulus decks
3. ocean surface turbulence parameterization
4. land model parameterization and spinup time
5. Greenland temperature
6. soil moisture-precipitation interactions

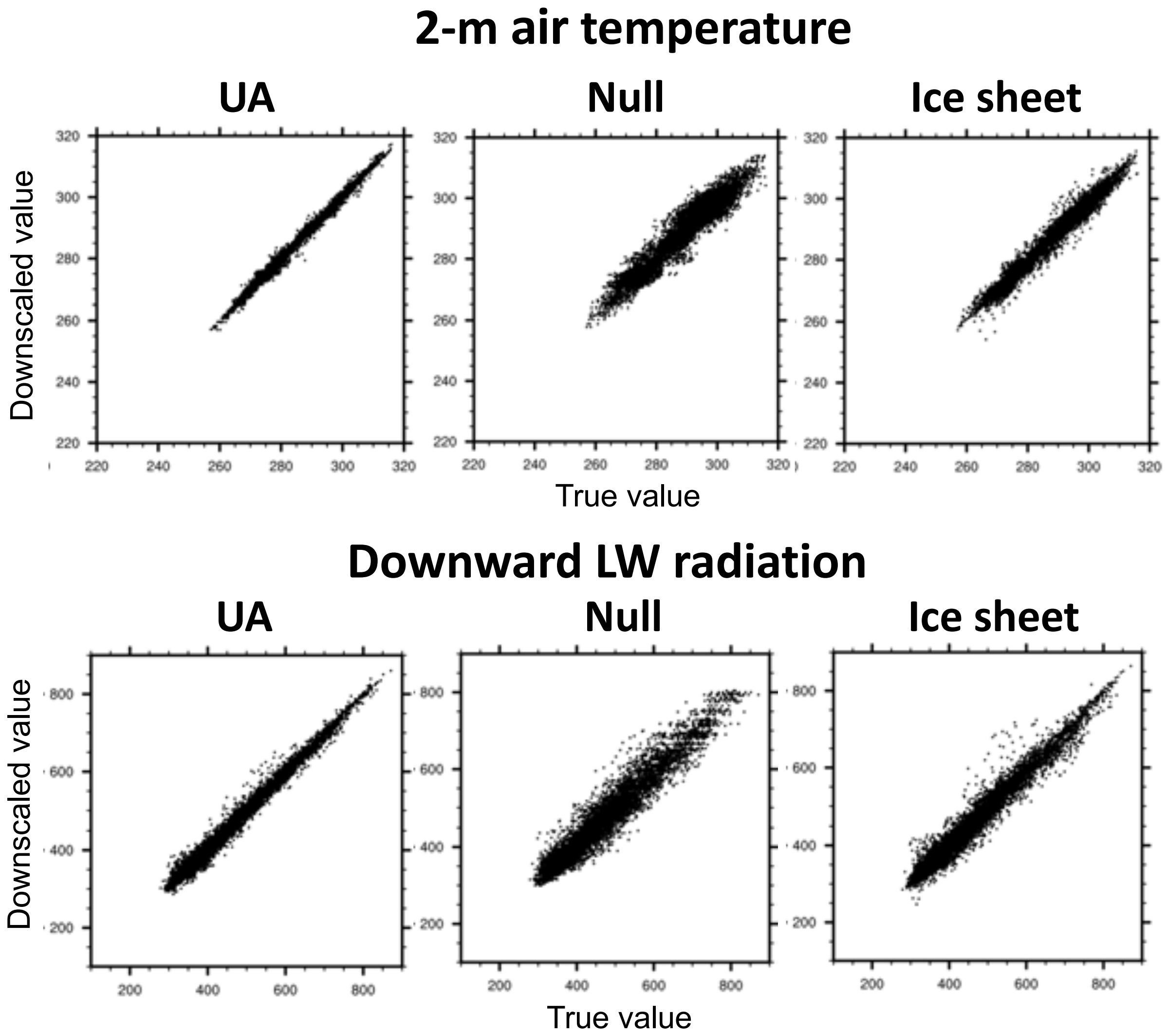
"First light" image released from GOES-R (GOES-16)

Supporting the implementation of elevation classes in ELM V2

- Prepared variable soil thickness over elevation classes (collaborators: Bill Riley and Gautam Bisht at LBNL).
- Developed the downscaling method from atmospheric grid to subgrid elevation classes for air temperature and humidity, downward radiation, and surface pressure (collaborators: Teklu Tesfa (PNNL) and Peter Thornton (ORNL)



Evaluating downscaling methods



- We test downscaling methods using the 7-km GEOS-5 nature run over North America for July 15, 2006 at 18Z.
- Up to 10 elevation classes are determined from the high resolution GEOS-5 grid for 1° x 1° mean grid cells.
- The downscaled values on the elevation classes for the currently-used ice sheet and our methods are compared to the null hypothesis of using the grid cell mean.

Preliminary testing of UA downscaling on the ice sheet elevation classes

- ELM already has elevation classes for grid cells encompassing ice sheets when MPAS-Land Ice is active.
  - To produce more accurate surface mass balance required for the ice sheet model.
- The same downscaling will be used on the ice sheets as for the non-ice covered topographic units.
- UA (modified) downscaling generally produces similar differences in surface temperature between active elevation classes.

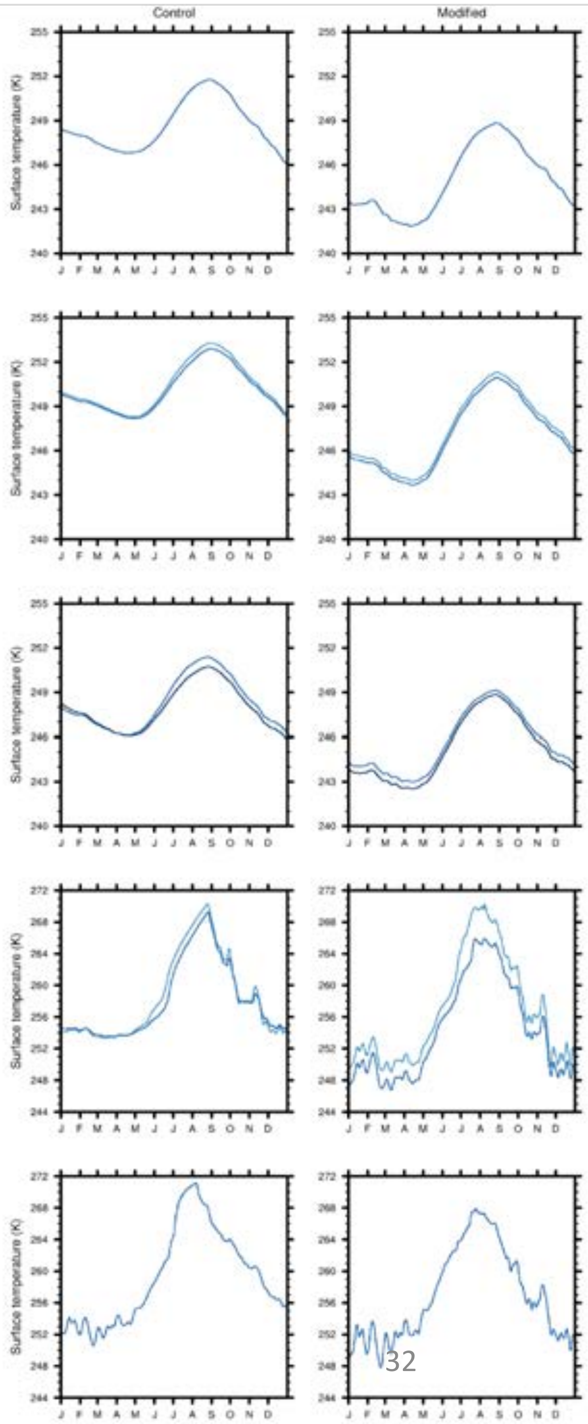
(75.1°N, 42.3°W)

(75°N, 30°W)

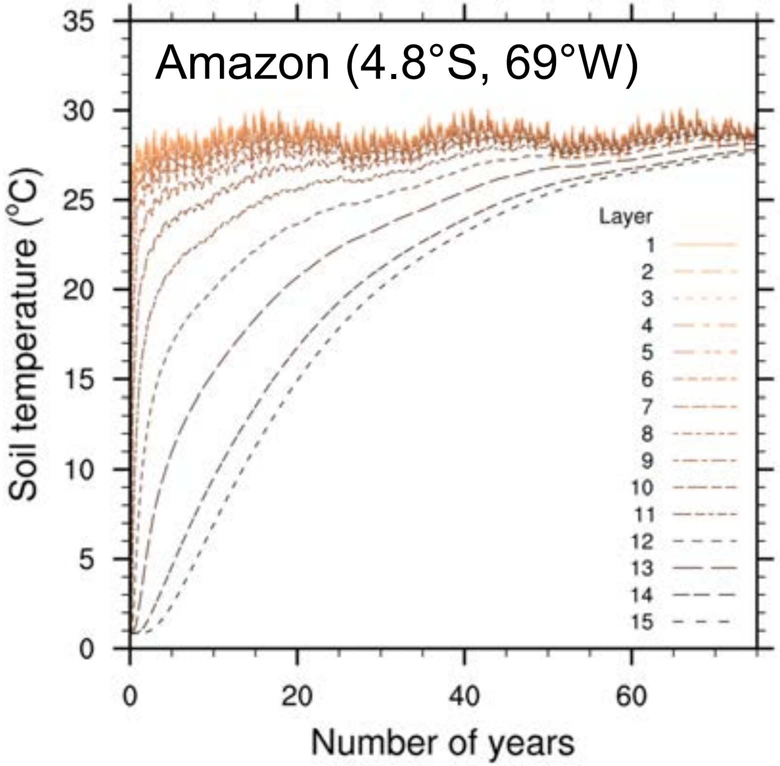
(72.6°N, 38.5°W)

(66°N, 44.5°W)

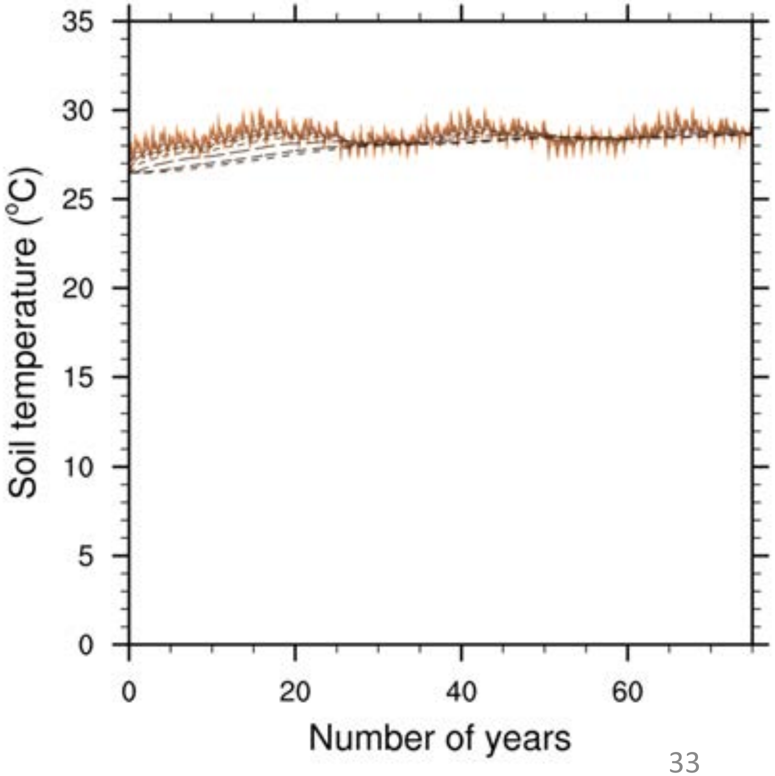
(63.1°N, 44.8°W)



Spin-up with variable soil thickness



- Soil temperature spin up much longer than 50 years with variable soil thickness at locations with deeper soil.
- The current cold start temperature starts out with constant near-freezing temperature which is unrealistic.



- A viable option is to change the cold start temperature to something more reasonable: e.g., the annual average 2-m air temperature.

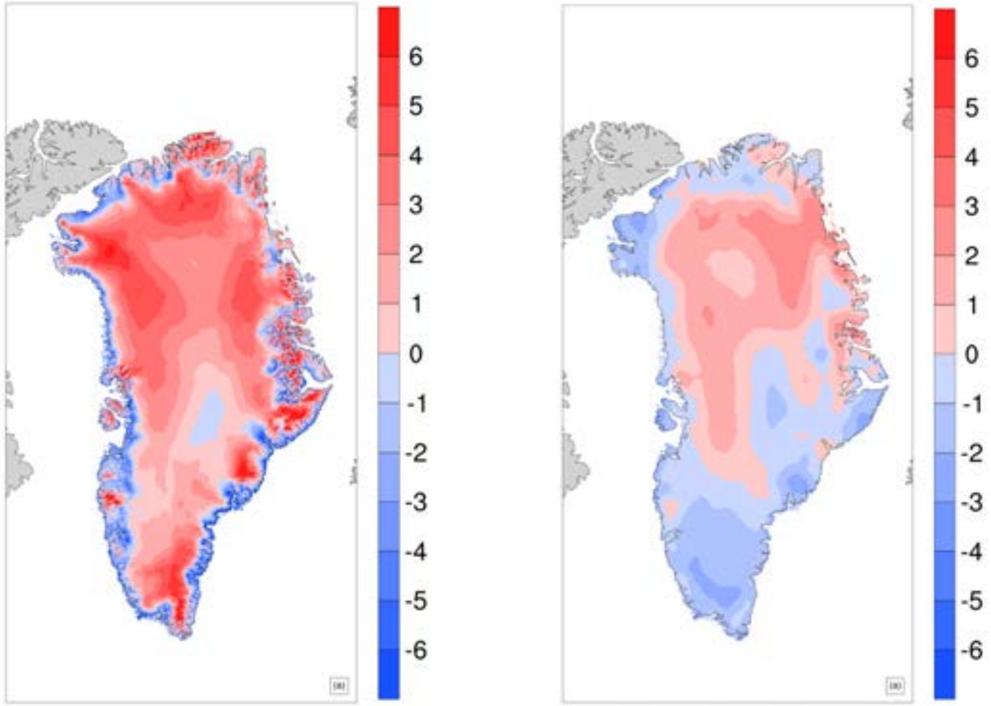
Outline

1. barrier layer in the ocean mixed layer
2. marine stratocumulus decks
3. ocean surface turbulence parameterization
4. land model parameterization and spinup time
5. Greenland temperature
6. soil moisture-precipitation interactions

"First light" image released from GOES-R (GOES-16)

Greenland Near-Surface Air Temperature

Based on earlier work (Reeves Eyre and Zeng, 2017, *The Cryosphere*; *UA released a news story:* https://uanews.arizona.edu/story/analysis-figure-out-how-fast-greenland-melting), we use GISTEMP and MERRA2 to assess E3SM.



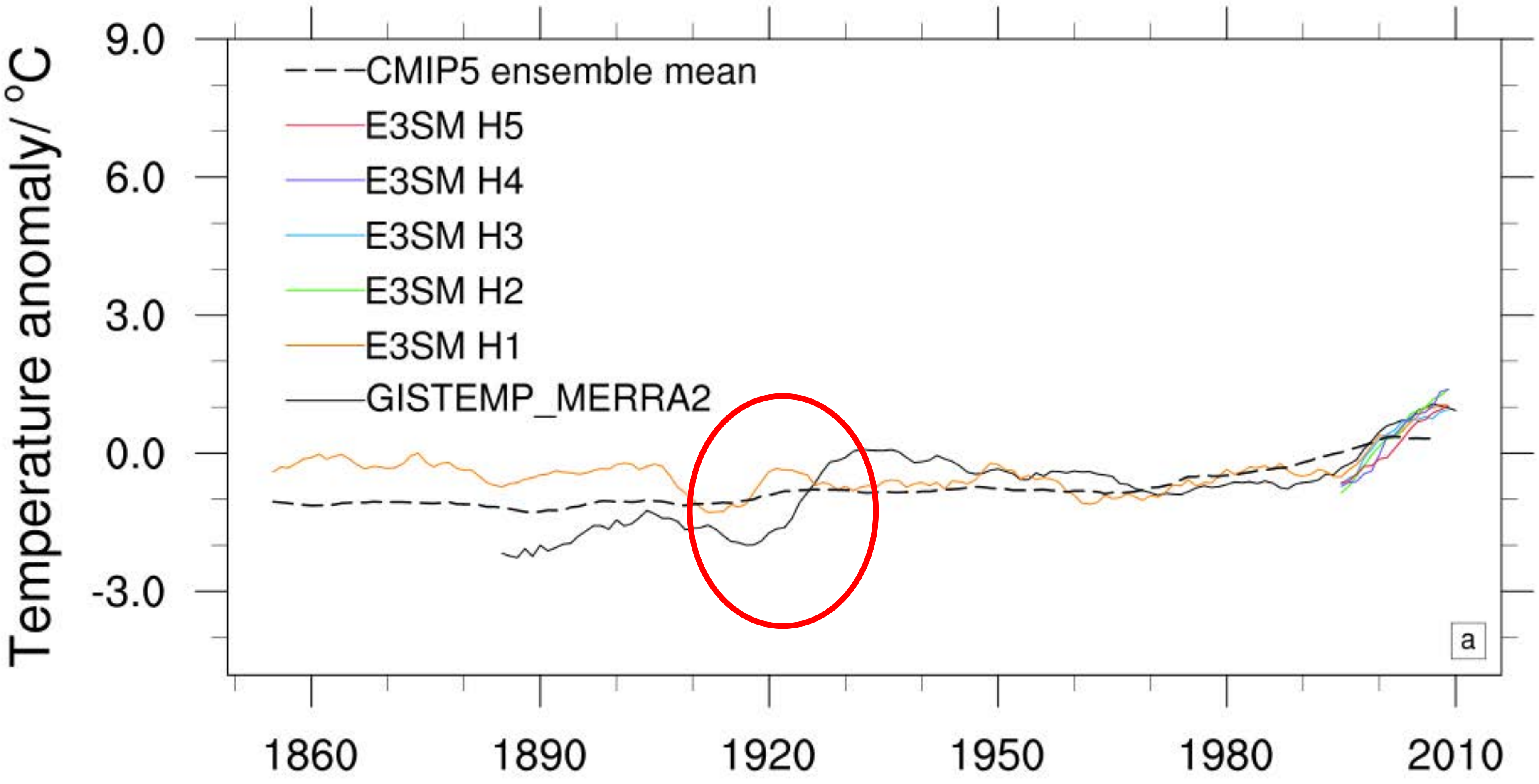
Note that care must be taken when comparing high resolution (e.g., ~10 km) regional climate models with lower resolution global climate models: the results can depend strongly on the upscaling/ downscaling approach taken.

Annual mean temperature bias relative to elevation corrected GISTEMP+MERRA2: (left) naïve downscaling of E3SM; (right) elevation correction applied to E3SM too.

Long term temperature variability in E3SM

Similar long term variability in second half of 20th century.

Will be interesting to see if other historical runs have similar warming in 1910s/1920s.

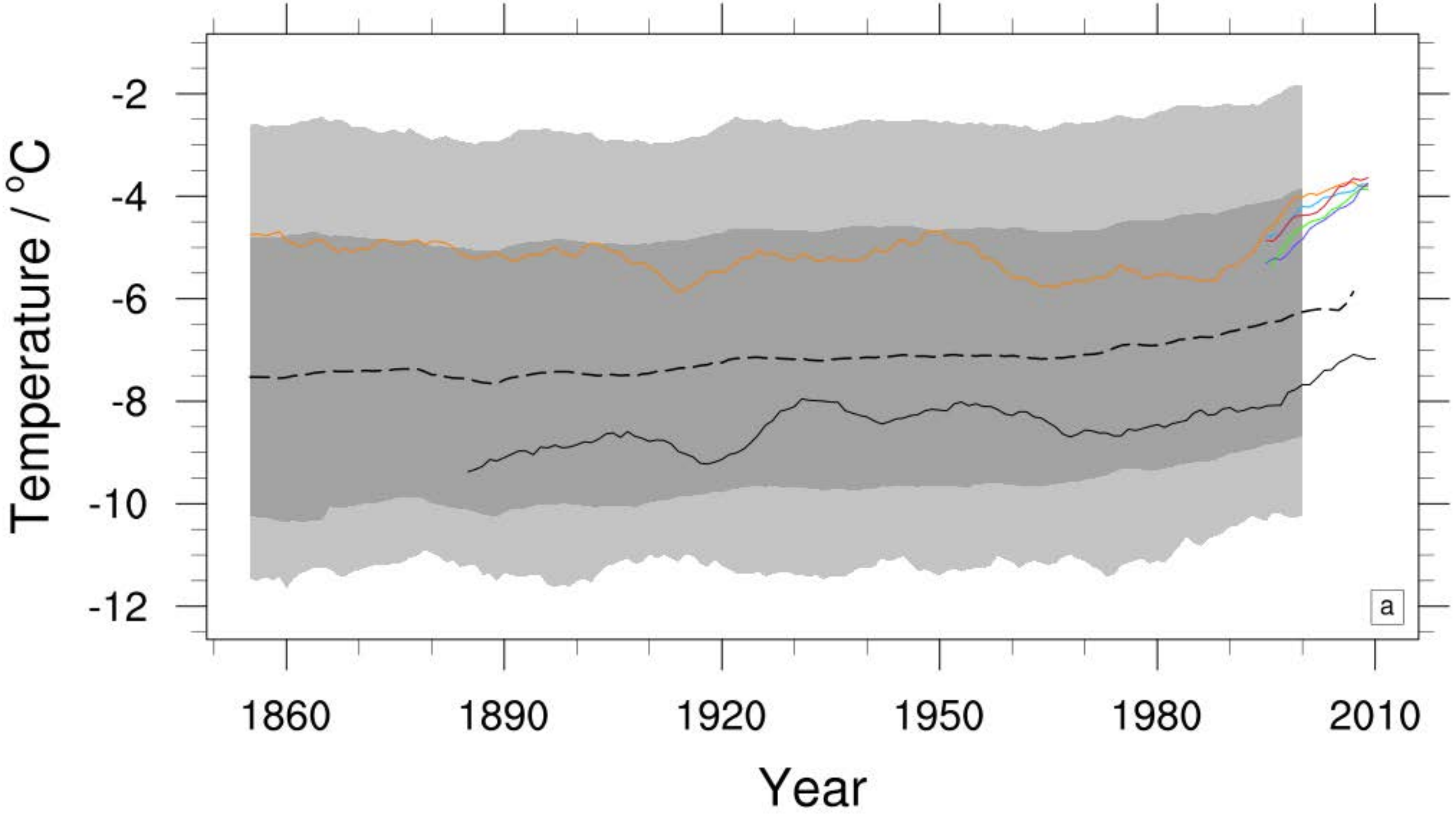


Annual mean, areal average temperature anomaly (with 11-year smoothing): full time series of E3SM H1, last 25 years of H2-H5.

Long term temperature variability in E3SM

E3SM towards the warm end of CMIP5 spread.

Spread among different historical runs is small compared to CMIP5 spread.

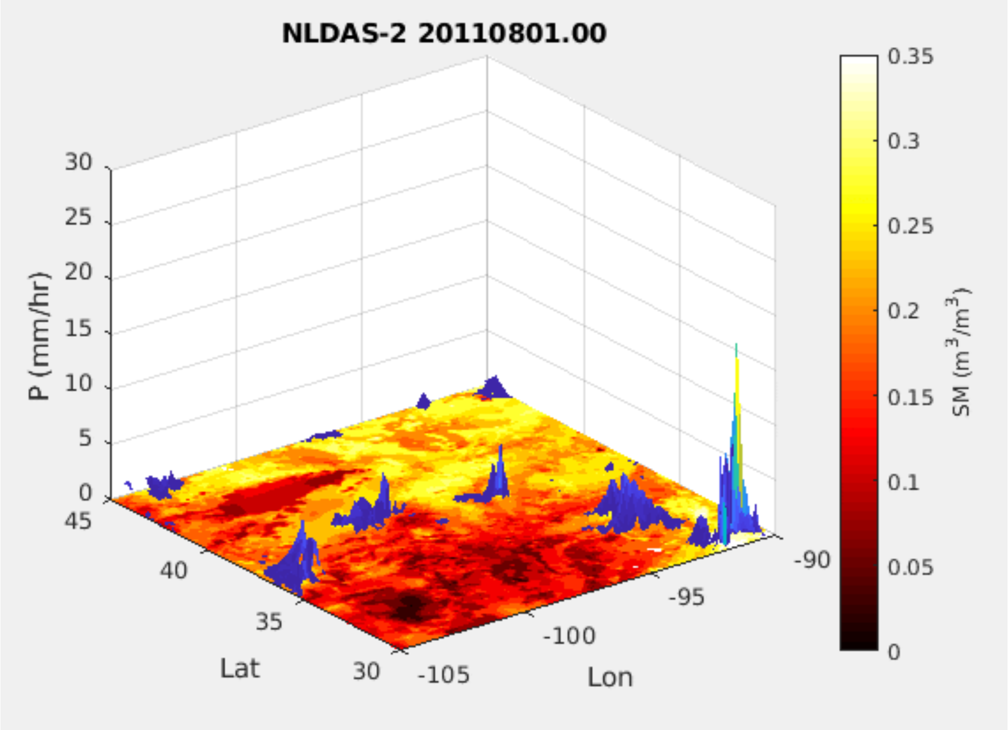


JJA mean, areal average temperature (with 11-year smoothing): full time series of E3SM H1, last 25 years of H2-H5. Shading represents spread of CMIP5 models (min, max and +/- 1 S.D.).

Outline

1. barrier layer in the ocean mixed layer
2. marine stratocumulus decks
3. ocean surface turbulence parameterization
4. land model parameterization and spinup time
5. Greenland temperature
6. soil moisture-precipitation interactions

"First light" image released from GOES-R (GOES-16)



NLDAS-2 SM and P
Aug. 1-10, 2011

Does soil moisture affect warm season precipitation over the SGP?

Reference: Welty and Zeng (2018)
https://uanews.arizona.edu/story/does-rain-follow-plow?utm_source=uanow&utm_medium=email&utm_campaign=

THE UNIVERSITY OF ARIZONA

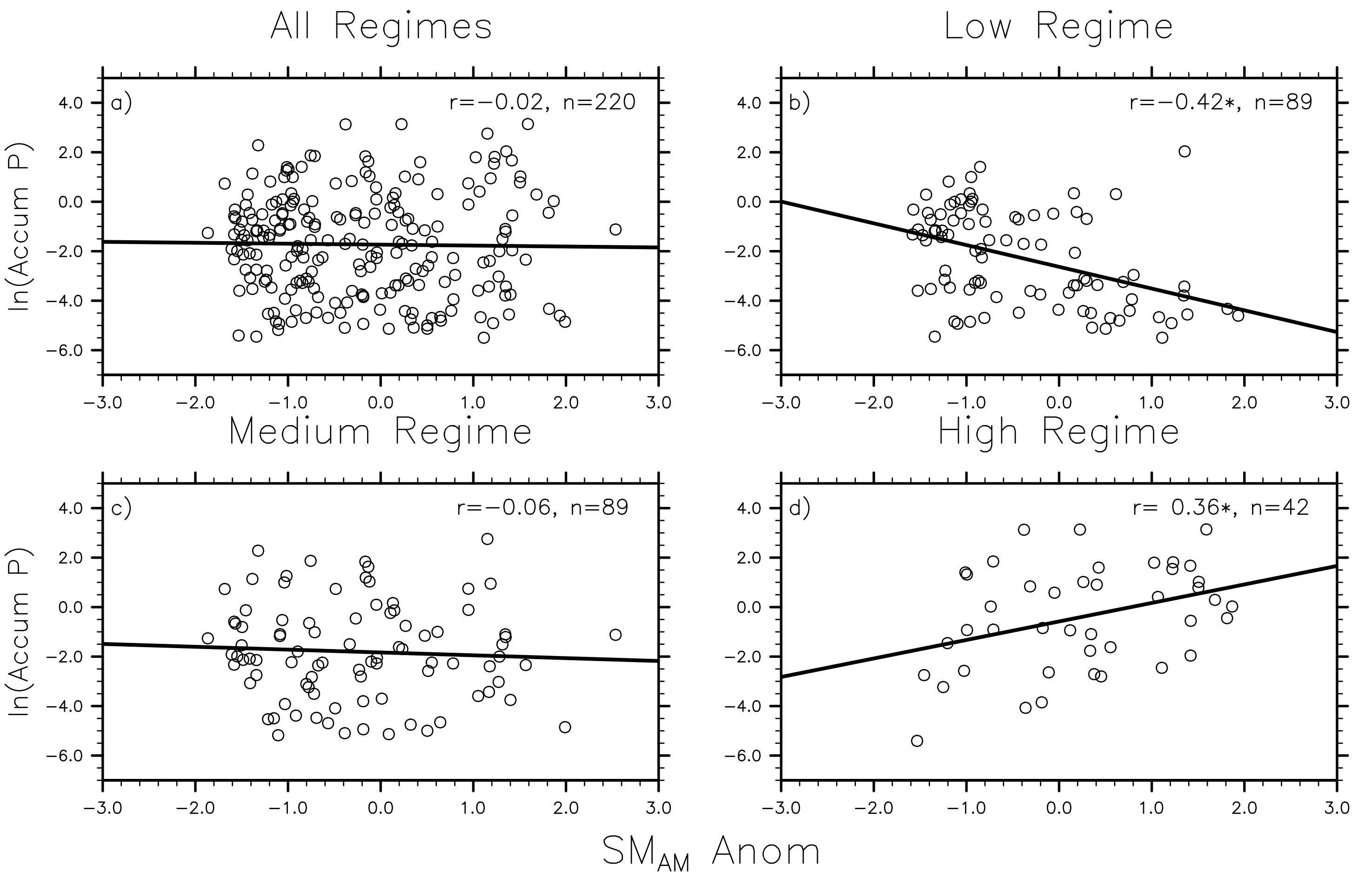


Figure 2. Relationship between the logarithm of precipitation accumulations (mm) from 1100–2300 CST and antecedent standardized soil moisture anomalies from 0700–1100 CST over stations across the SGP domain for a) all APEs, b) low dynamic regime APEs, c) medium regime APEs, and d) high regime APEs. Correlation coefficients (r) significant at $p < 0.05$ are marked with an asterisk, and n refers to the number of days.

SM-P Correlations under Different Dynamic Regimes

- Negative (positive) correlation between seasonal standardized anomaly of morning SM with afternoon P accumulation under low (high) regime
- When all afternoon P days taken as a whole, no statistically significant relationship between SM and P

Physical Pathways

- Under low regime:
  - positive correlations for soil T, 2m T, 2m Q, CAPE, and PBLHd/LCLd
  - negative correlation for SM
- Under high regime:
  - positive correlation for EF, SM

Table 1
Relationship Between Variables and Accumulated Precipitation Across Regimes

P vs.	All	Low	Medium	High
Morning SM Anomaly	−0.02	−0.42*	−0.06	0.36*
Morning SM	0.11	−0.21	0.09	0.34*
Soil T	0.21*	0.38*	0.25*	−0.01
Q	0.27*	0.39*	0.23*	0.08
RH	0.04	−0.02	0.06	0.02
T	0.20*	0.33*	0.17*	0.04
Net Radiation	0.09	0.16	−0.05	0.15
CTP	−0.07	0.13	0.04	−0.23
HI_{low}	−0.04	−0.23*	−0.10	0.16
CAPE	0.21*	0.30*	0.16	0.07
PBLHd/LCLd	0.14*	0.31*	0.09	−0.03
EF	0.08	−0.07	−0.02	0.36*

Note. Correlation coefficients between the logarithm of precipitation accumulations (mm) from 1100–2300 CST and various quantities for APEs for all, low, medium, and high dynamic regimes. The meaning of variables is provided in the text. CAPE, CTP, and HI_{low} are computed from the ~0600 CST sounding, and the PBLHd and LCLd are calculated as the respective differences between ~0600 and ~1200 CST soundings (to capture the diurnal growth of each). Other variables are averaged from 0700–1100 CST. Correlation coefficients significant ($p < 0.05$) are marked with an asterisk.

*CTP: Convective Triggering Potential
*HI_{low}: Low-level Humidity Index

THE UNIVERSITY OF ARIZONA

Conclusions

1. barrier layer in the ocean mixed layer
   - Provided earlier
2. marine stratocumulus decks
   - Provided earlier
3. ocean surface turbulence parameterization
   - Ready for further testing in E3SM V2
4. land model parameterization and spinup time
   - Variable soil thickness is ready for E3SM V2;
   - downscaling for elevation classes are ready for further testing in E3SM V2;
   - suggest a simple approach for land model spinup
5. Greenland temperature
   - E3SM is able to produce the multi-decadal T variability, but it is 4°C too warm
6. soil moisture-precipitation interactions
   - Basis for future global data analysis and model evaluation on precipitation diurnal cycle