Data Analysis and Modeling of Land-Atmosphere Interactions

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E3SM All Hands Webinar

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E³SM
Energy Exascale
Earth System Model

Motivation

Evaluation of climate models needs to go beyond the simple use of an individual variable (e.g., precipitation) to include relationships.

Challenges:

• What is the right approach to evaluate and determine the appropriate observation-based datasets for relationships?
• What are the observed relationships?

Three examples:
• Surface water balance over the Amazon Basin
• Snow-water equivalent over CONUS
• Morning soil moisture effect on afternoon rainfall

1. Surface water balance over the Amazon River Basin

E3SM Ocean Barrier layer discrepancy around the Amazon

Annual mean BLT bias:

- Ocean-only run (top), with Amazon discharge specified from observations, has larger BLT bias than the coupled run (bottom), with (apparently biased) Amazon discharge from the land model.

Top: ocean-only

Bottom: coupled

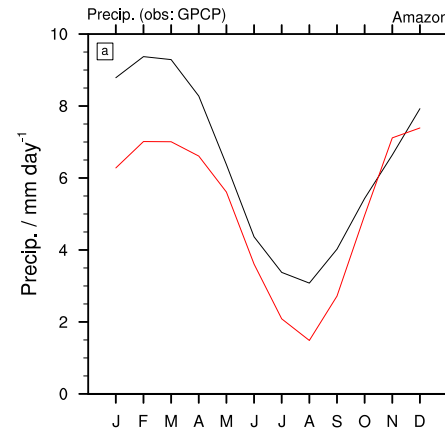- Is this just an ocean model problem? Or an issue with observations used in the forcing?
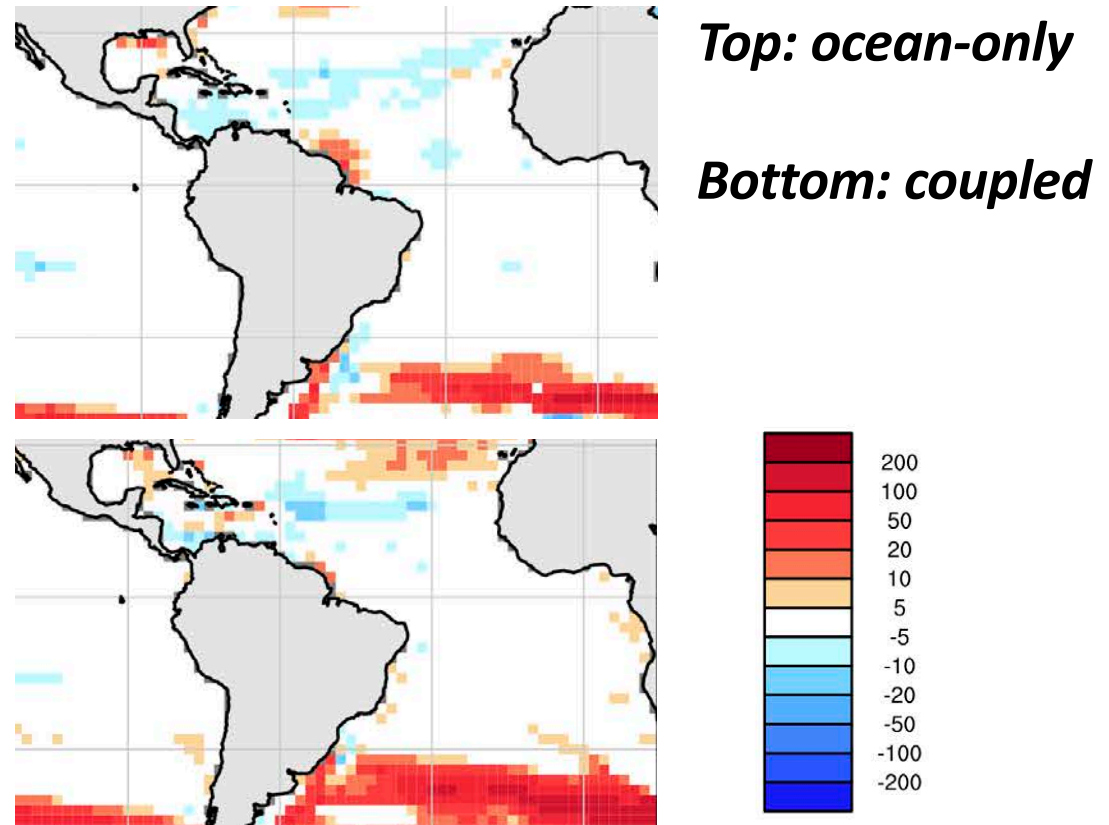
Reeves Eyre, Van Roekel, Zeng, Brunke, Golaz (2019)

E3SM Precipitation and runoff Biases
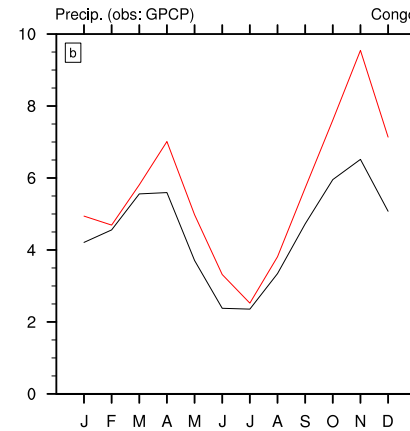
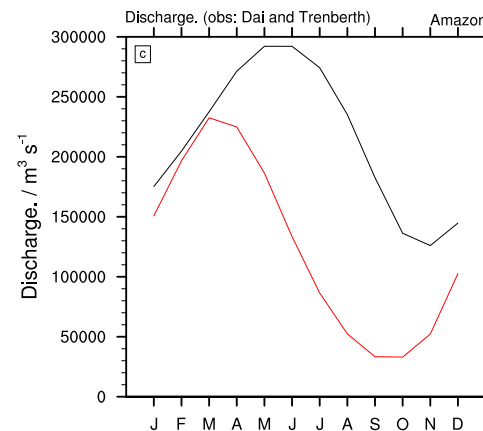***Red = E3SM, Black = obs.***

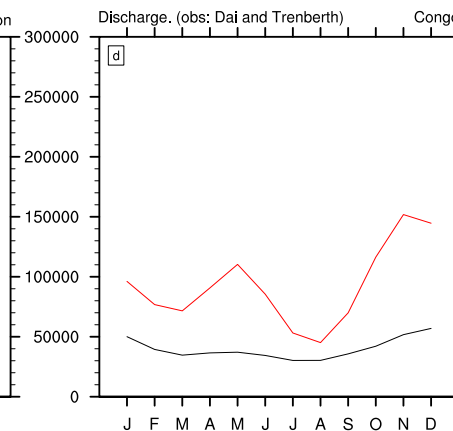**Amazon precip:**

Not enough

Correct phase

Congo precip:

A bit too much

Correct phase

Amazon discharge:

Not enough

Wrong phase!

Congo discharge:

Way too much!

Exaggerated seasonal cycle!

- Are these just atmosphere and land model problems? Or issues with the observations?

Terrestrial water budget:

$$P - E - R = dS/dt$$

Our Approach:

- **Test** water budget closure for different **combinations of individual data sets** over the Amazon River basin
- Use **ocean salinity** as an independent consistency check – exploiting the large and relatively well understood freshwater "plume" in the Atlantic.

Reeves Eyre et al. (to be submitted in March 2020)

Data

- Precipitation – 4 (GPCP, CMAP, ERA5, MERRA2)
- Evaporation – 3 (ERA5, MERRA2, GLEAM)
- Atmospheric convergence – 2 (ERA5, MERRA2)
  - This is an alternative to (P–E)
- Terrestrial water storage – 3 (JPL, GFZ, CSR)
  - Different retrievals using the same GRACE measurements
- River discharge – 1 (HyBAm)
  - Also use Dai et al. (2009) method to upscale gauging station to river mouth

Total number of closure "combinations": 30 (+3 ensemble means)

- Salinity – 3 (SMOS, SMAP, Aquarius)

How well do data sets agree?
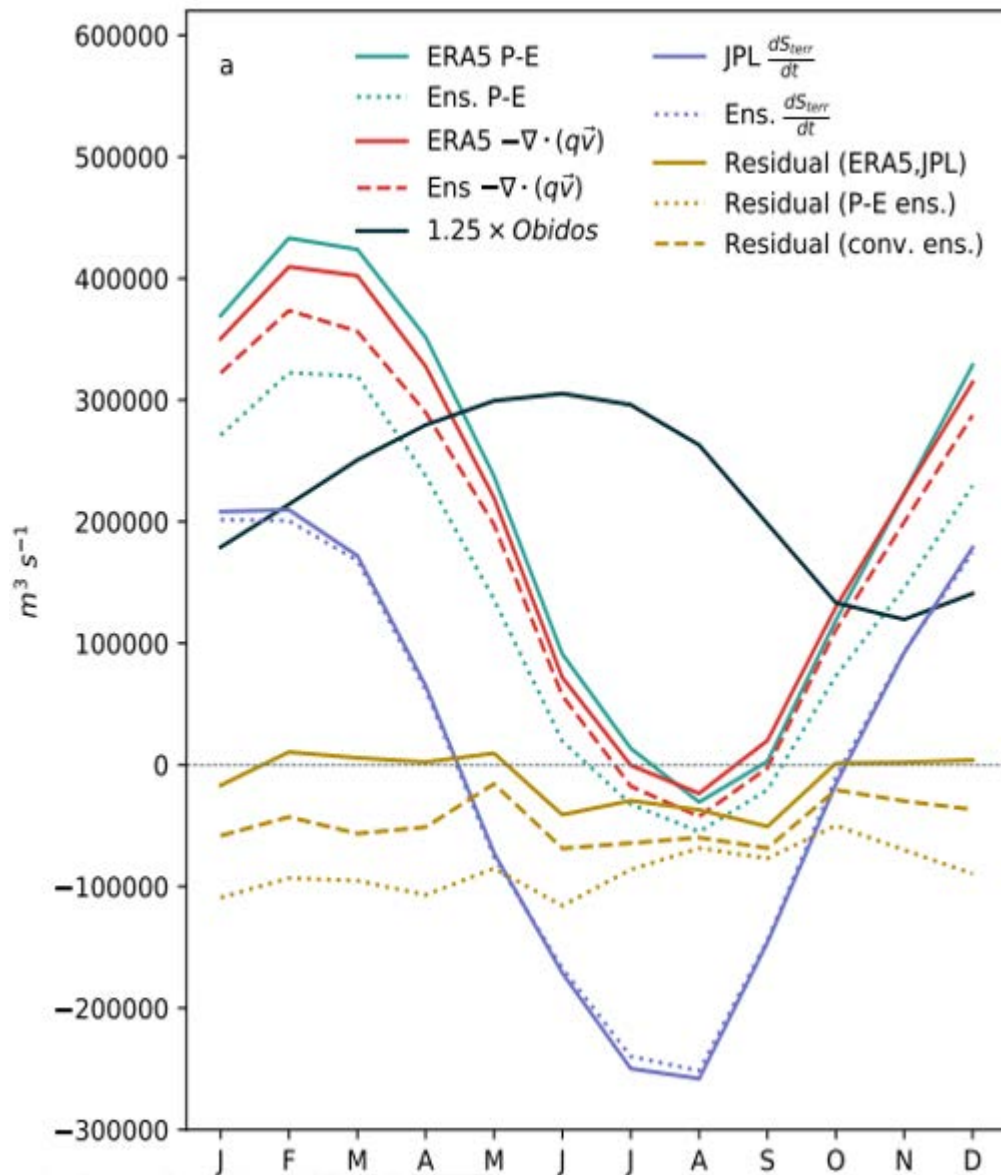
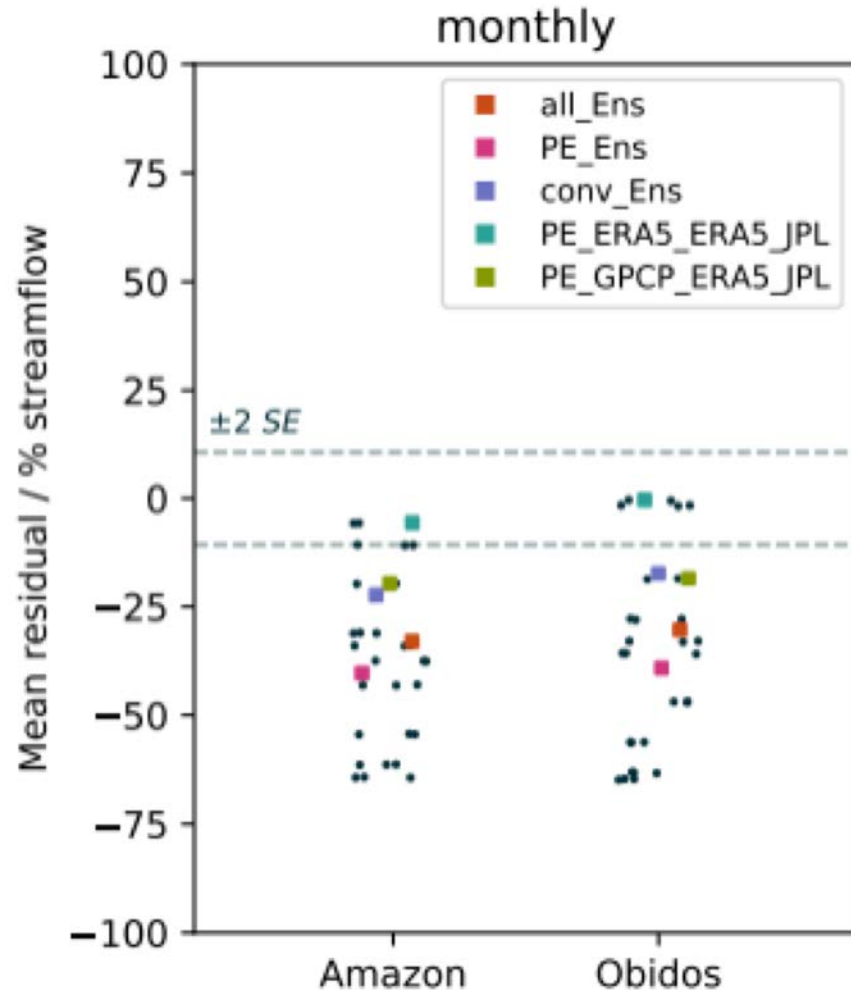
Three GRACE data agree with each other well

Residuals vary by ~50% of discharge, and ERA5 P and E give smallest residuals

Large difference in P-E between ensemble mean and ERA5

P-E differences come from both P and E (not shown)

Three salinity data sets have very similar seasonal cycles (not shown)

Can we close the water budget?

monthly

Mean residual / % streamflow

Legend:
- all_Ens
- PE_Ens
- conv_Ens
- PE_ERA5_ERA5_JPL
- PE_GPCP_ERA5_JPL

±2 SE

Amazon   Obidos

Amazon_closure.py   up to date with last commit: 202f5283f7371edba43aa76f6d351928a794f129
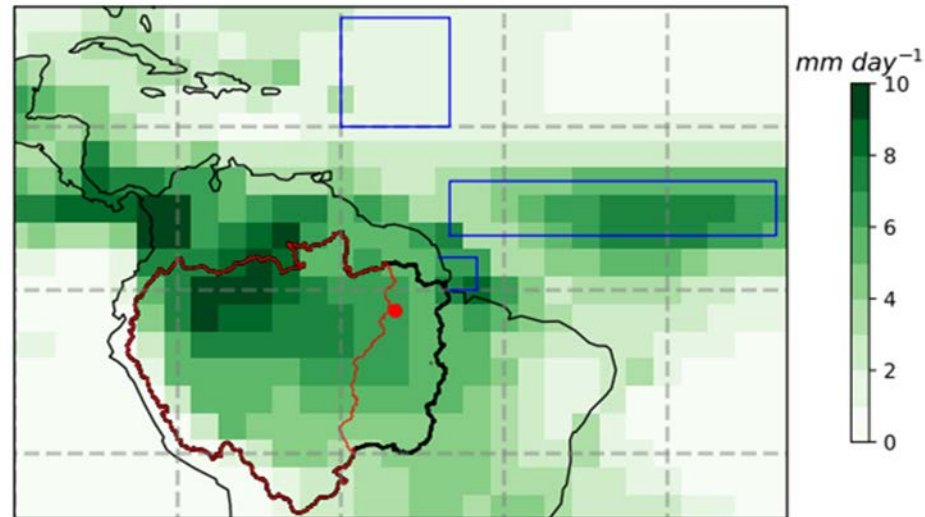
Each point is one combination of data sets:
some are "highlighted"

Only a few combinations close the water budget (within estimated uncertainty) – mostly with ERA5

Ensemble means do not close the budget

The better closure for "Obidos" than "Amazon" implies that the Dai et al. method may not give the correct seasonal cycle


$mm\ day^{-1}$

Óbidos gauge captures runoff from about 78% of the area of entire Amazon basin.
Dai et al. (2009):

$R_{Amazon} = 1.25 \times R_{obidos}$

since last commit: 0c875aa16fcc0f23714cf53c22f592e54573b70

Using salinity as a consistency check

Use ocean salinity near the river mouth (small blue box in inset) to test this idea

Water budget estimates of discharge have higher correlation with salinity than either Obidos discharge
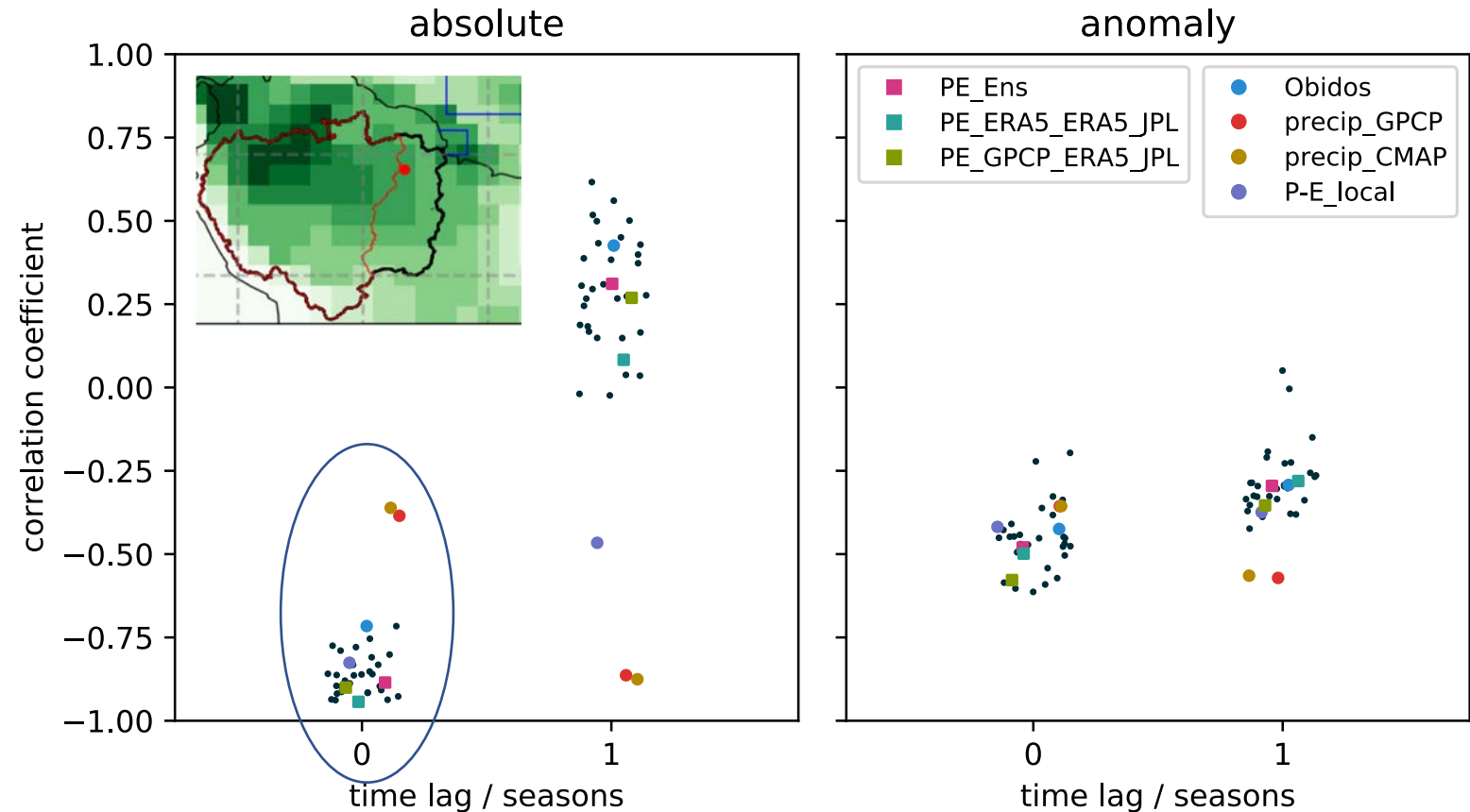

Amazon_correlation_scatter_seasonal.py   up to date with last commit: 250a43576fecab55b7d9c7c8550493907796db00

Note – we expect negative correlations: more freshwater discharge means lower salinity

Application: variability of the Amazon plume

Correlation between ocean salinity and Amazon River discharge

We see quite different lag correlations depending on the discharge estimate
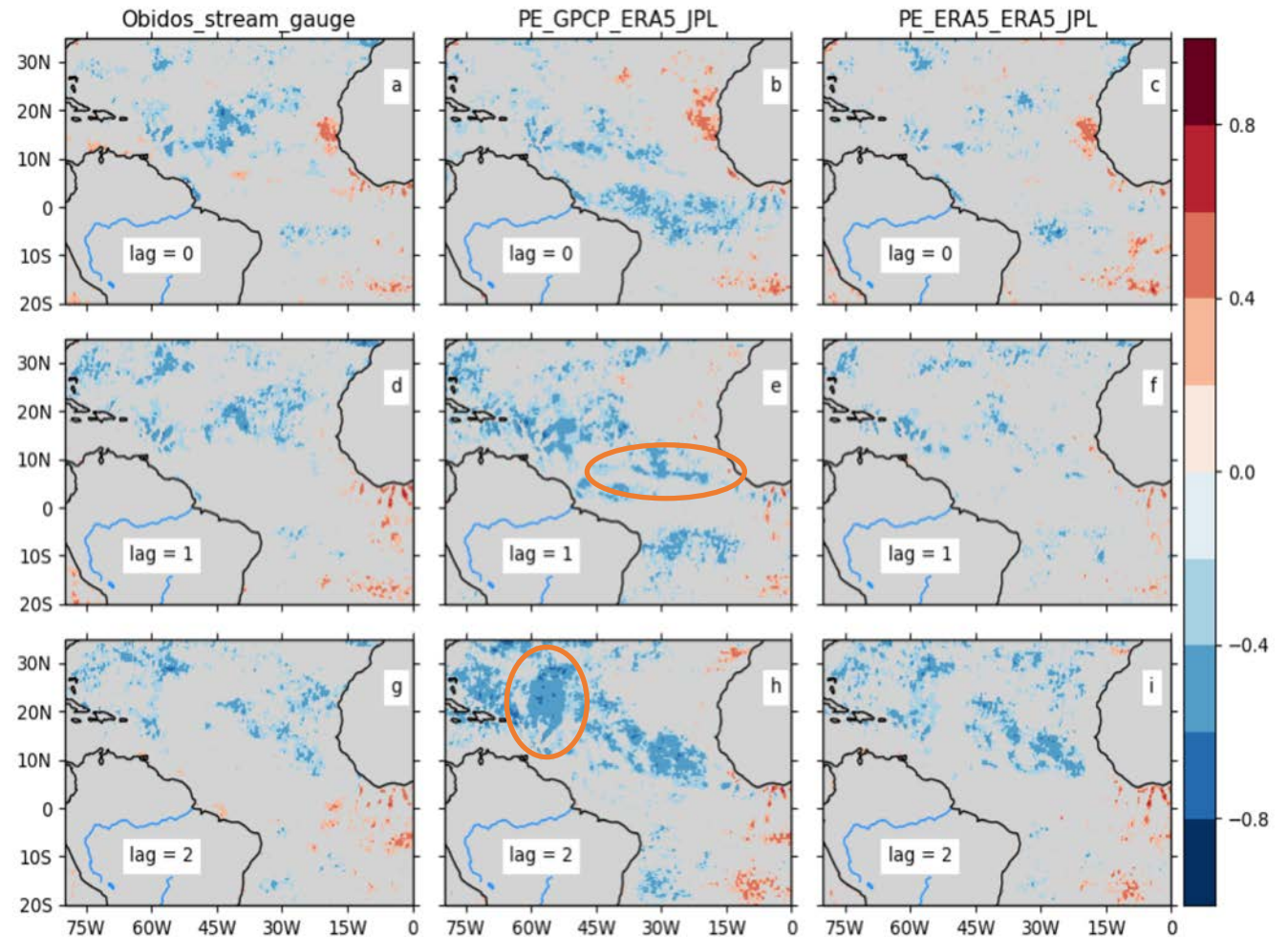
2. Snow-Water Equivalent over CONUS

Importance:

Snowpack is a major component in land-atmosphere interactions.

Challenge:

Global snow-water equivalent (SWE) observation-based data have relatively poor quality: re-analysis, land data assimilation (GLDAS), satellite passive microwave (e.g., AMSR-E), and merged products

Our Approach:

We spent three years to develop the UA daily 4 km SWE and snow depth dataset over CONUS from Oct 1981- present (Broxton et al. 2016; Dawson et al. 2017; Zeng et al. 2018)

UA Daily 4 km SWE and snow depth dataset

Schneider Meadows SNOTEL site in Oregon

a) Input data:

- (USDA/CA DWR) SNOTEL SWE/snow depth sites, NWS COOP snow depth sites,

- PRISM daily 4 km precipitation and temperature data

b) Main ideas in data assimilation

- Point-area interpolation (Broxton et al. 2016; Editor's highlight)

- A new snow density model to combine SWE and snow depth measurements (Dawson et al. 2017)
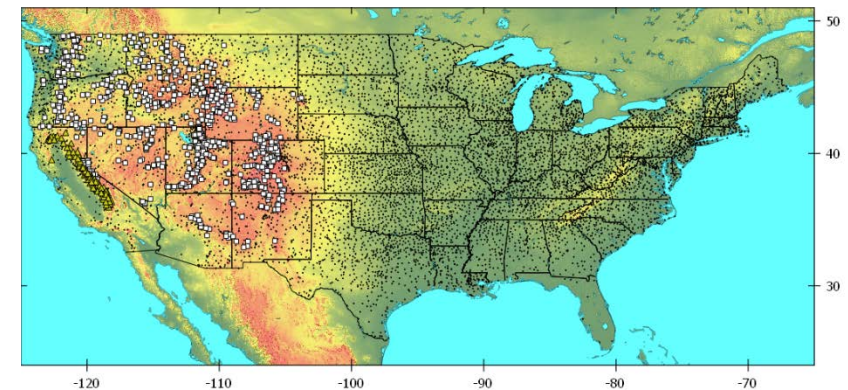

c) Passed four rigorous tests:

- Point-point interpolation test

- Point-pixel interpolation test

- Evaluation using the JPL ASO airborne lidar data in CA and CO

- Evaluation using the independent snow cover data

d) Passed independent test by another group

- Using NOAA airborne Gamma radiation SWE measurements

NWS Boston COOP Program

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E. Cho, J. Jacobs, and C. Vuyovich (Dec 2019) used 40-year airborne Gamma radiation SWE record to evaluate satellite (SSMI/S), merged (GlobSnow), and UA SWE products, and concluded in Abstract:

"UA SWE has much better agreement with gamma SWE in all land cover types and snow classes" and

"The results demonstrate the reliability of the UA SWE products…"
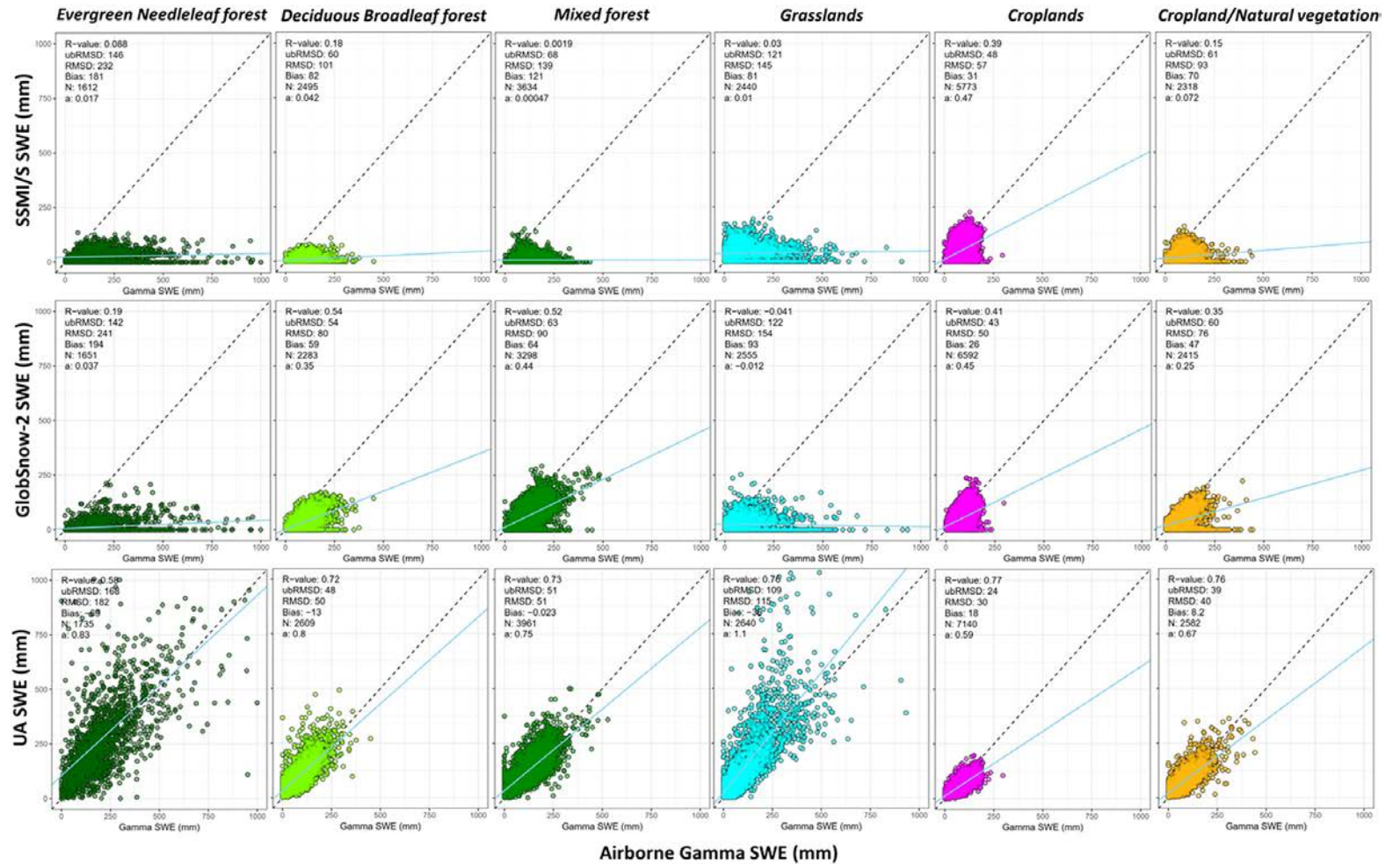
Question: Do point measurements at SNOTEL represent the snowpack decline across the whole western U.S.?

The trends of annual maximum snow mass are very similar at government sites and co-located 4 km grids:
- their median trends are -2.8 and -2.9 mm/year,

These results do not represent those using all snowy grids of western U.S. above 5000 ft (or 1500 m) in elevation:
- median trend is -0.5 mm/year
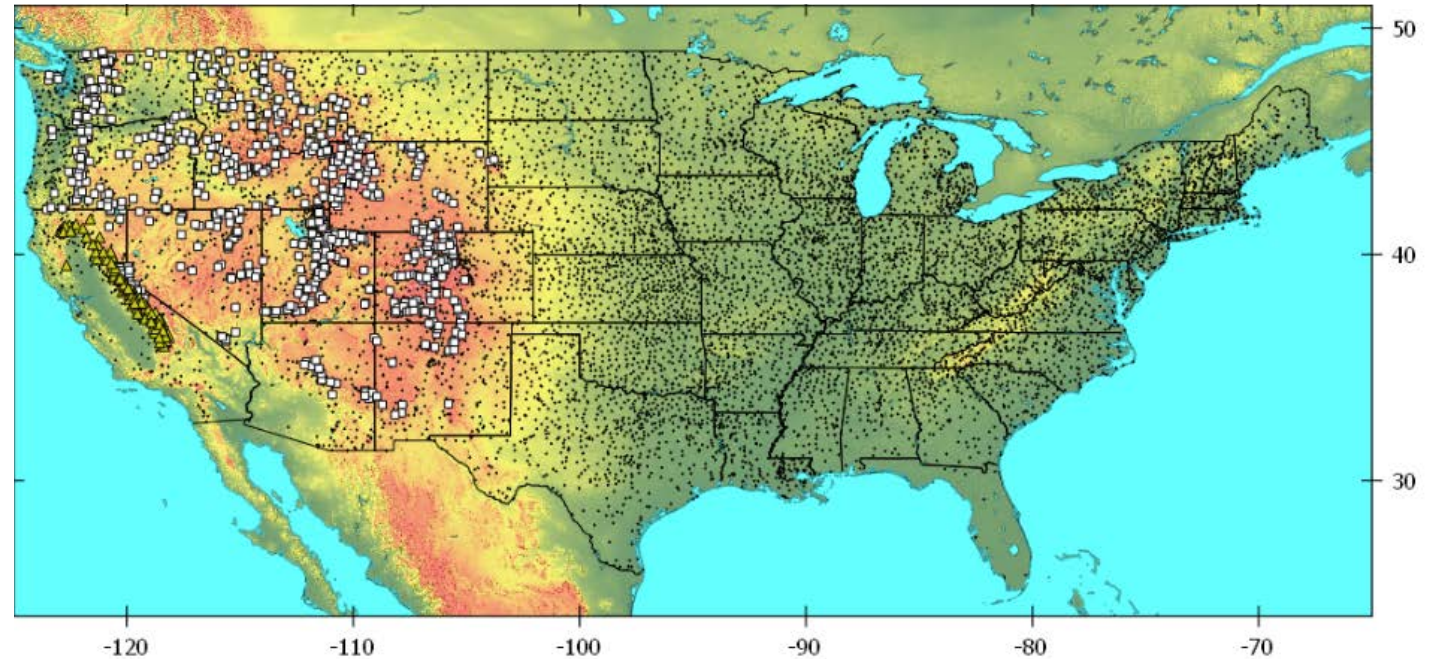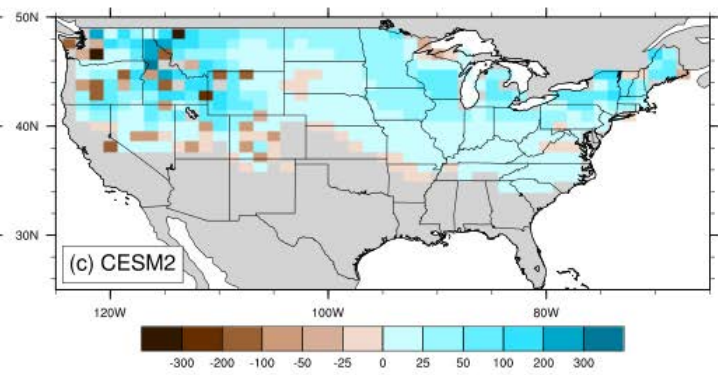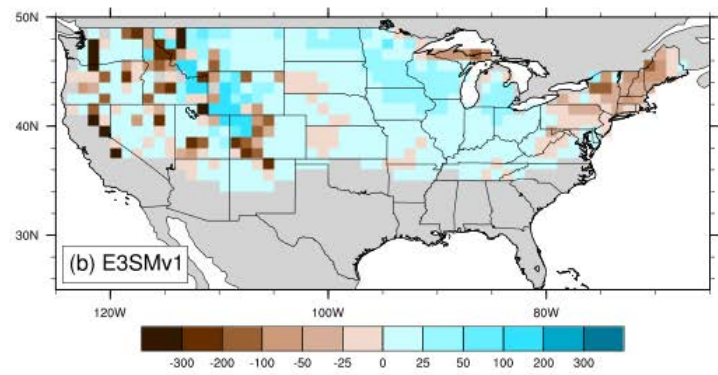
Evaluation of AMIP runs of CMIP6 models in the U.S.

UA
March SWE (mm)

(Model – UA) March SWE Bias (mm)

Overall E3SMv1 simulates SWE slightly better over CONUS than other three models.
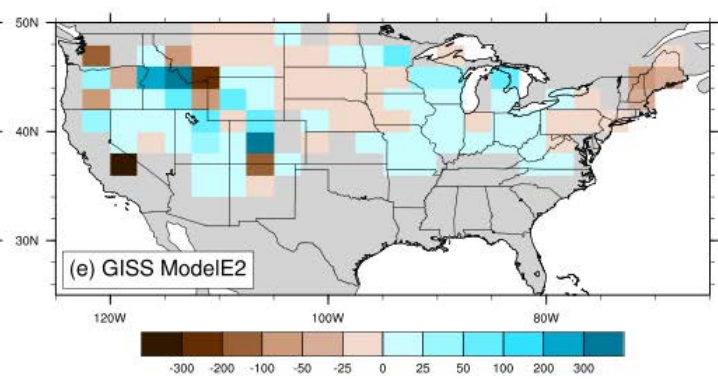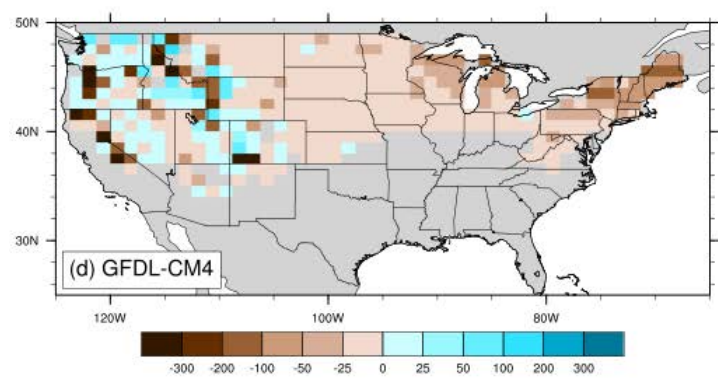
CESM2 produces too much SWE over CONUS.

Brunke et al. (to be submitted in April 2020)

March SWE trend (mm/yr)
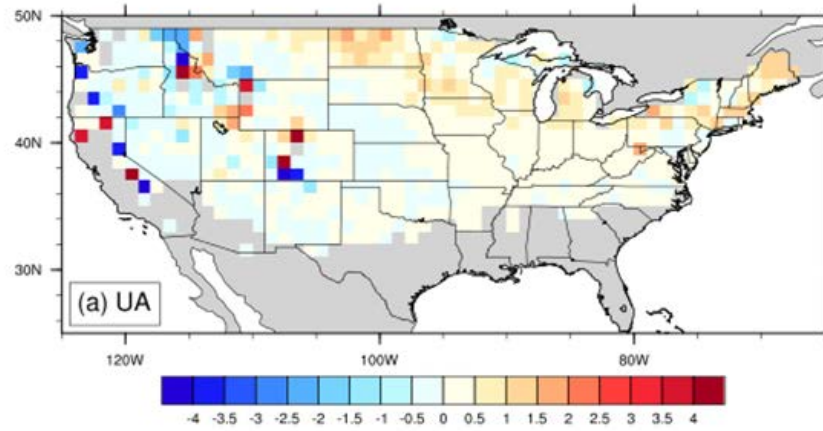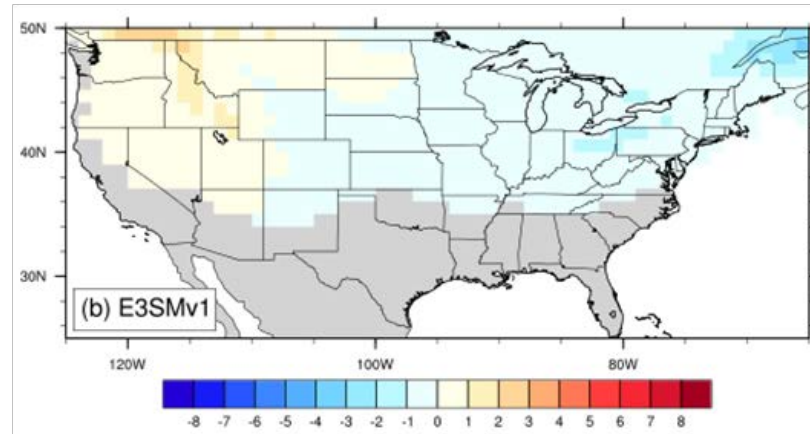
UA

March SWE trends (mm/yr)

Both E3SMv1 and GFDL-CM4 miss the observed SWE trend near the West Coast

Challenge:
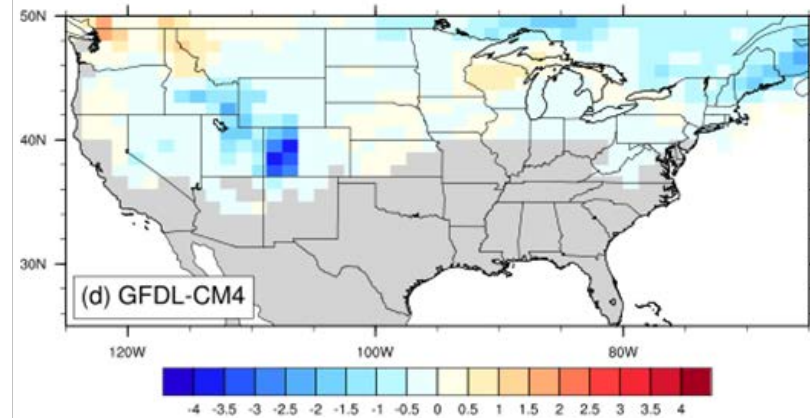How do we gain any insights on model's performance?

E3SMv1
(with a different color bar)

GFDL-CM4

Oct.-March mean temp. relation. R²
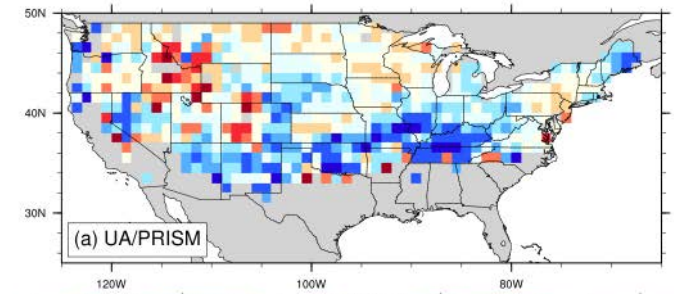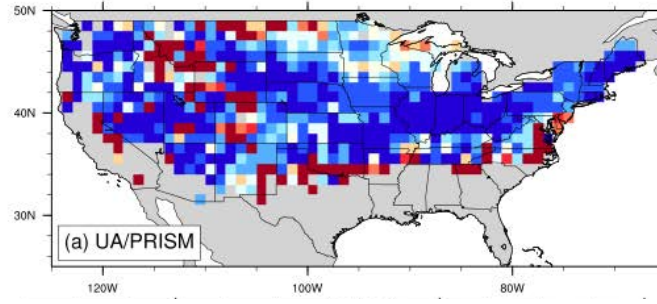
$$SWE = aT + b$$

Oct.-Mar. accum precip. relation. R²

$$SWE = aP + b$$

Multi-linear relationship R²

$$SWE = a_T T + a_P P + b$$
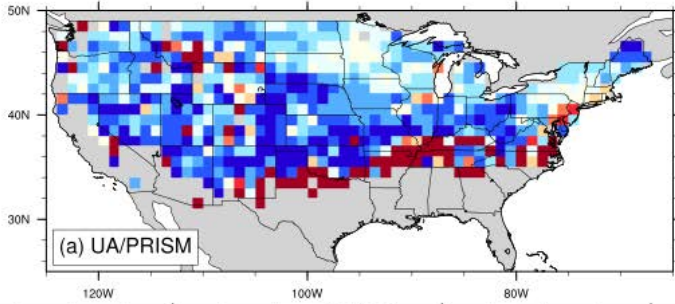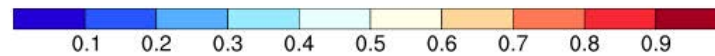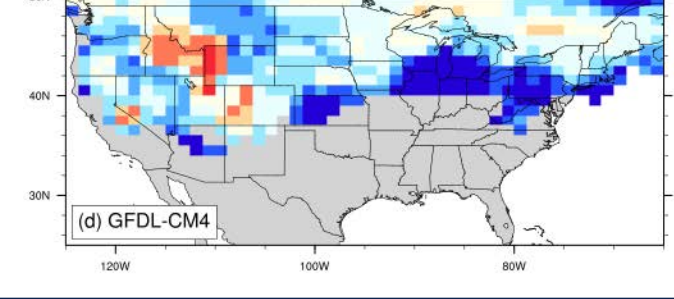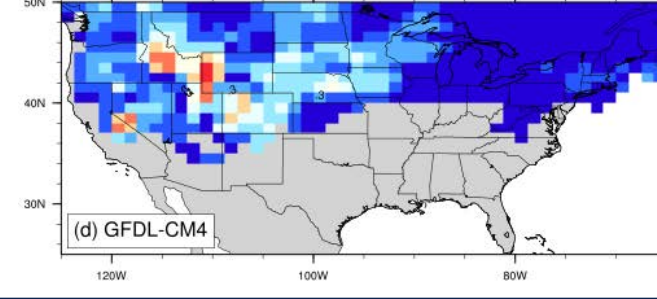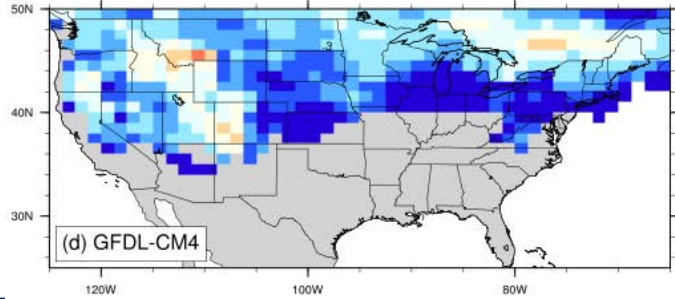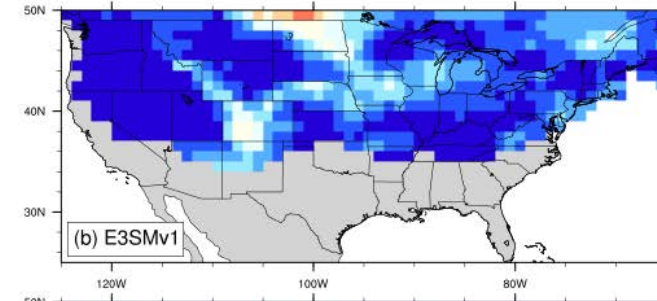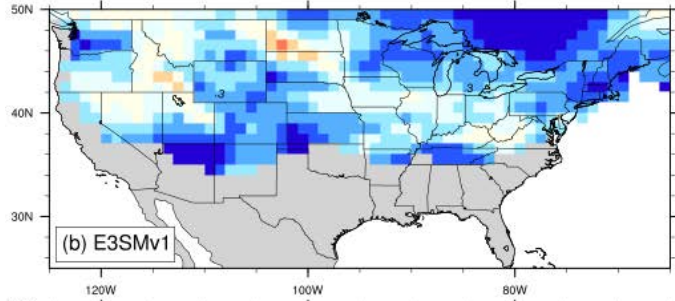
OBS: SWE has a strong correlation with P (particularly over mountains), and has a weaker relation with T

E3SM: SWE has a weak correlation with P and has a stronger correlation with T

For OBS and models, using T and P yields much higher correlation than using T or P alone

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Temp. sensitivity indices　　　　**Precip. sensitivity indices**

$$SWE = a_T T + a_P P + b$$

$$S_X = a_X \sigma_X, X = T, P$$

(a) UA/PRISM

(a) UA/PRISM

Obs

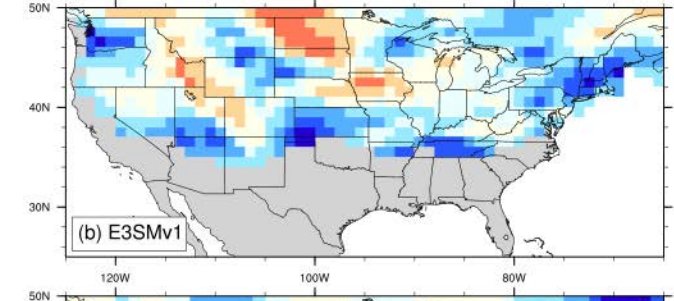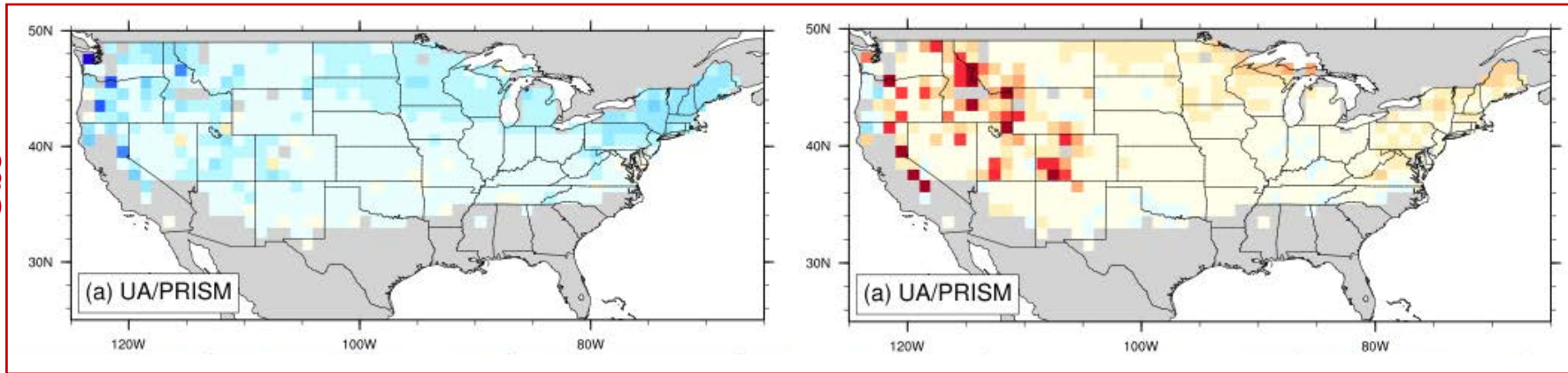Observed sensitivity to precip > that of temperature over W CONUS highest elevations.

(b) E3SMv1
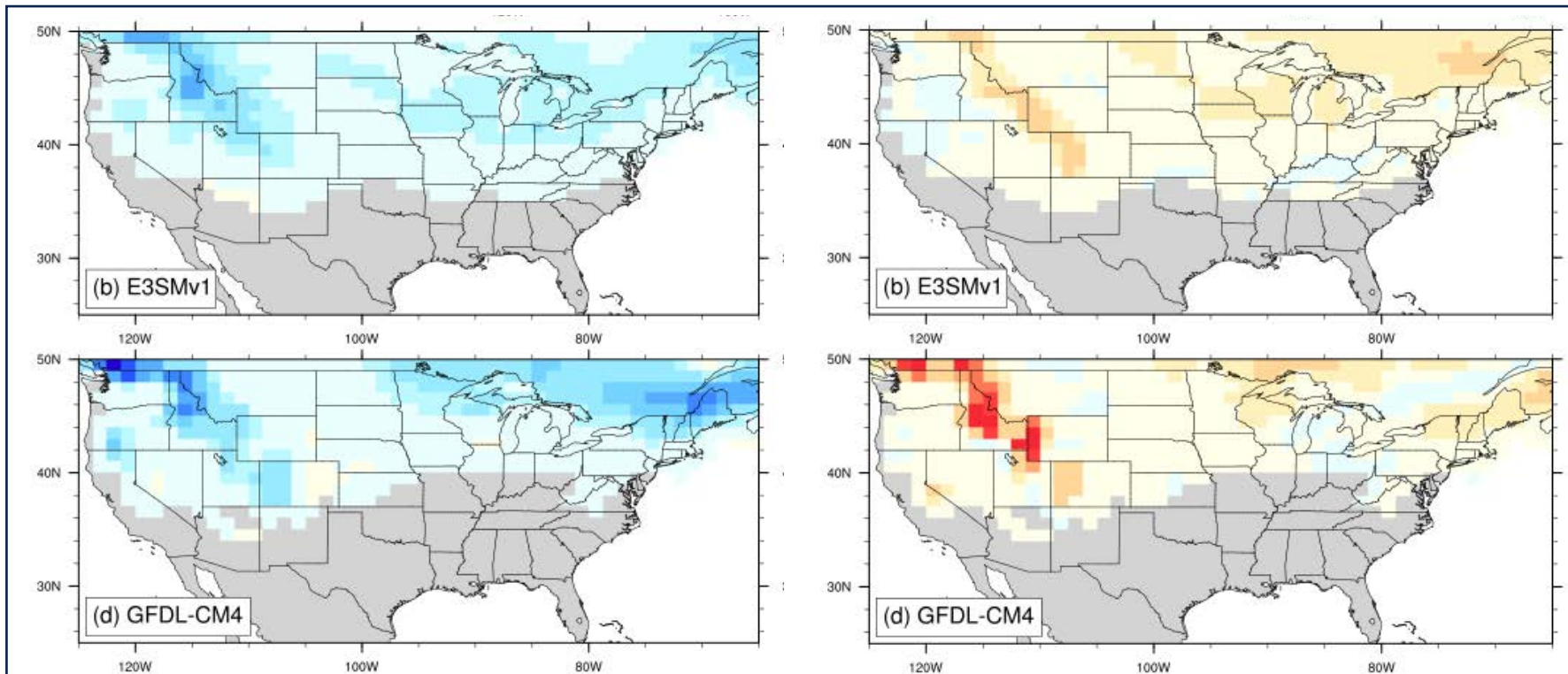
(b) E3SMv1

Models

E3SMv1 precip. sensitivity < observed precip. sensitivity.

(d) GFDL-CM4

(d) GFDL-CM4

Models miss greater sensitivity to temperature and precipitation over coastal mountains.

-100 -80 -60 -40 -20 0 20 40 60 80 100
mm SWE

Comparison of March SWE trends from AMIP runs versus coupled runs

March SWE trend (mm/yr)

UA

CMIP6 coupled runs
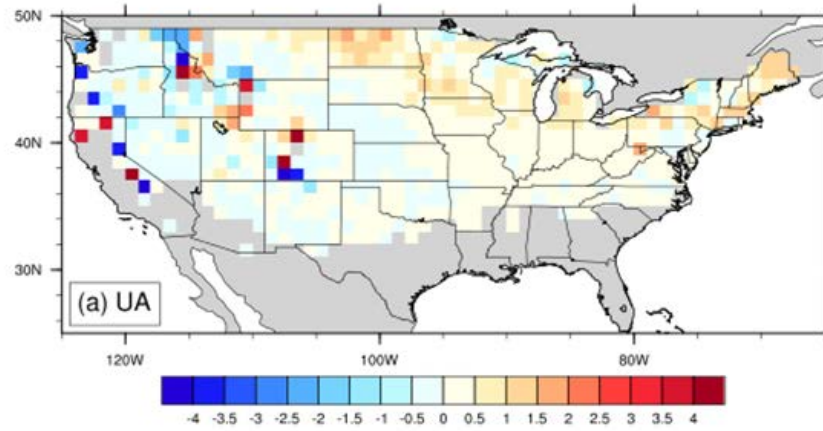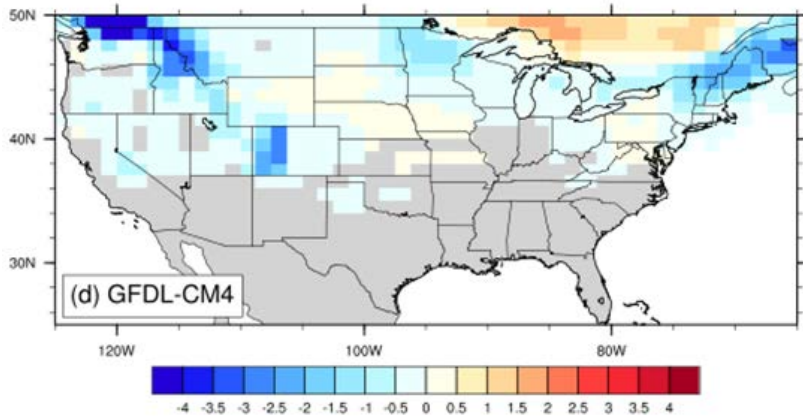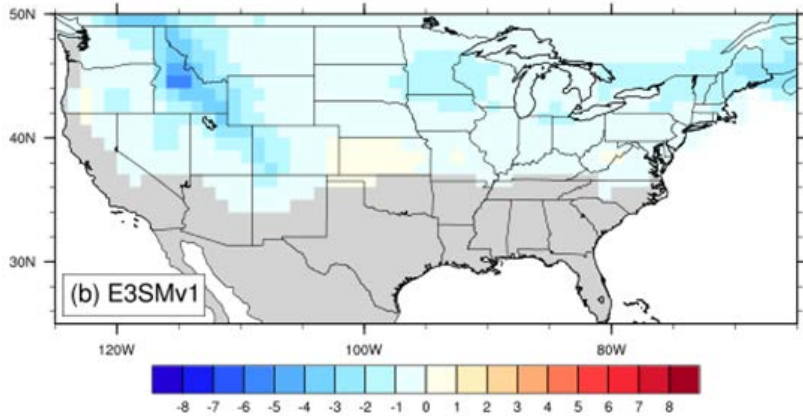
E3SMv1 AMIP run (with a different color bar)
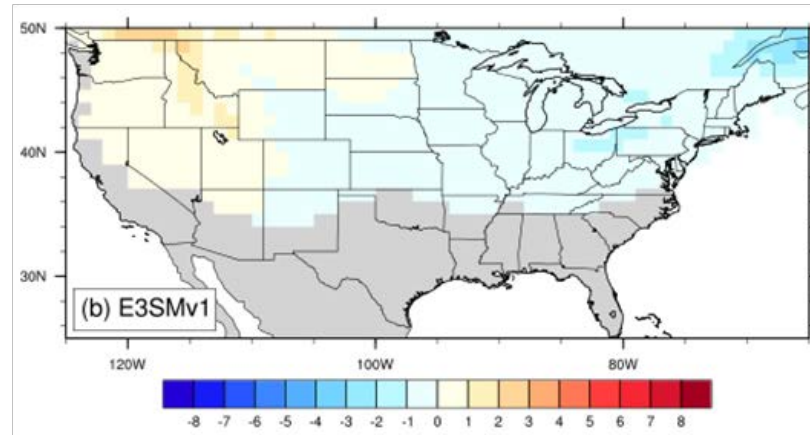
GFDL-CM4 AMIP run
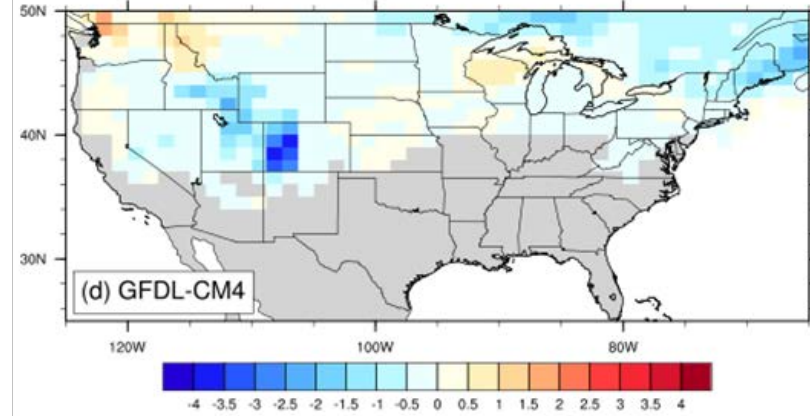
3. Morning soil moisture effect on afternoon rainfall
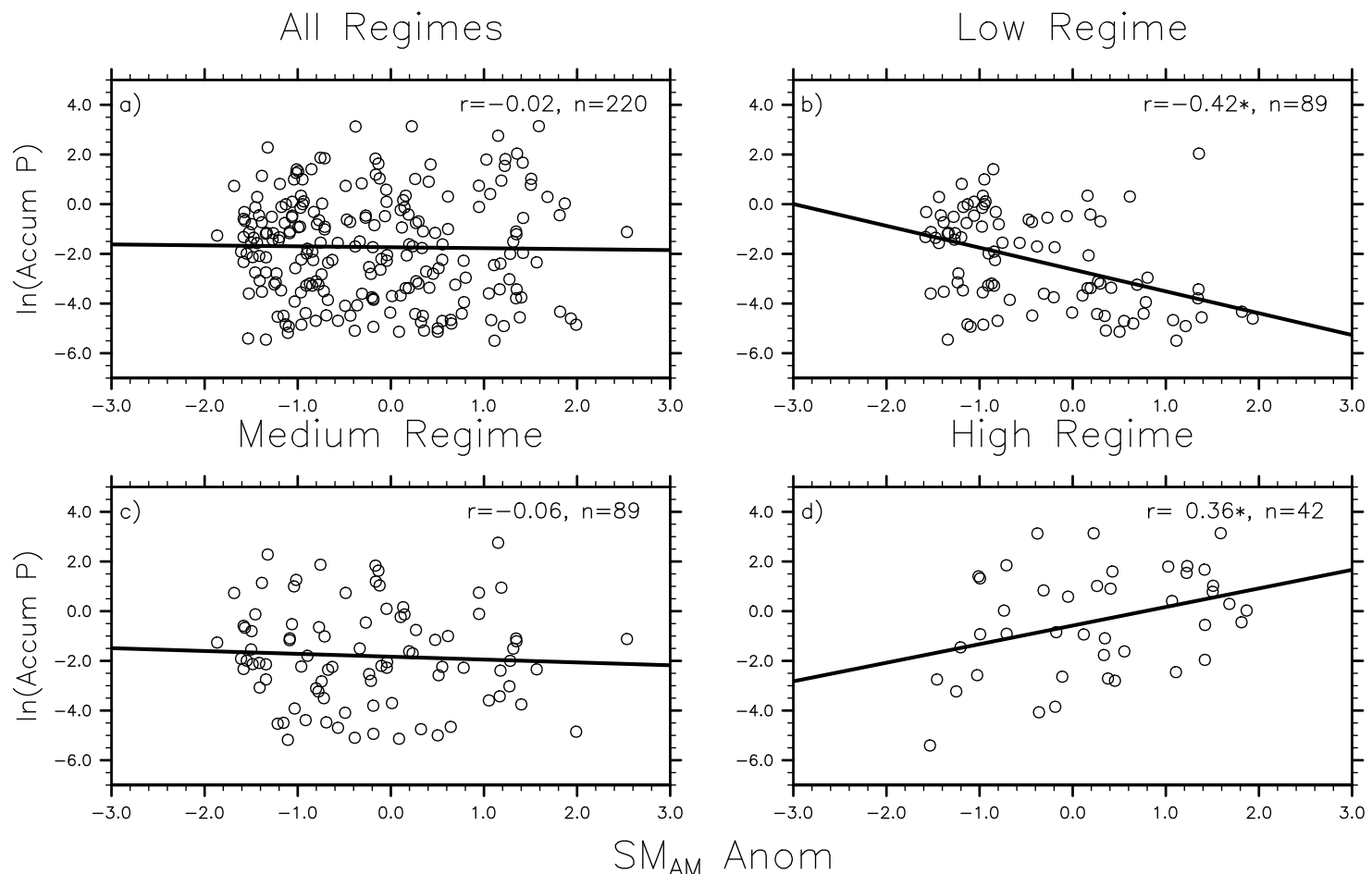
Figure 2. Relationship between the logarithm of precipitation accumulations (mm) from 1100–2300 CST and antecedent standardized soil moisture anomalies from 0700–1100 CST over stations across the SGP domain for a) all APEs, b) low dynamic regime APEs, c) medium regime APEs, and d) high regime APEs. Correlation coefficients (r) significant at $p < 0.05$ are marked with an asterisk, and n refers to the number of days.

Welty and Zeng (2018)
UA News Release on 8/8/2018: Does rain follow the plow?
DOE Office of Science web site: University research highlight

SM-P Correlations under Different Dynamic Regimes (from NASA MERRA2)

- 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

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ARM CLIMATE RESEARCH FACILITY

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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

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For each regime, compute afternoon rainfall frequency over wetter soil minus that over drier soil:

- Positive differences: occurrence more likely over wetter soils
- Negative differences: occurrence more likely over drier soils

Afternoon rainfall tends to occur over wetter soils under low (L) moisture convergence conditions.

Afternoon rainfall tends to occur over drier soils under high (H) moisture convergence conditions.

Results over ARM SGP are not representative of global results.

Welty et al. (to be submitted in March 2020)
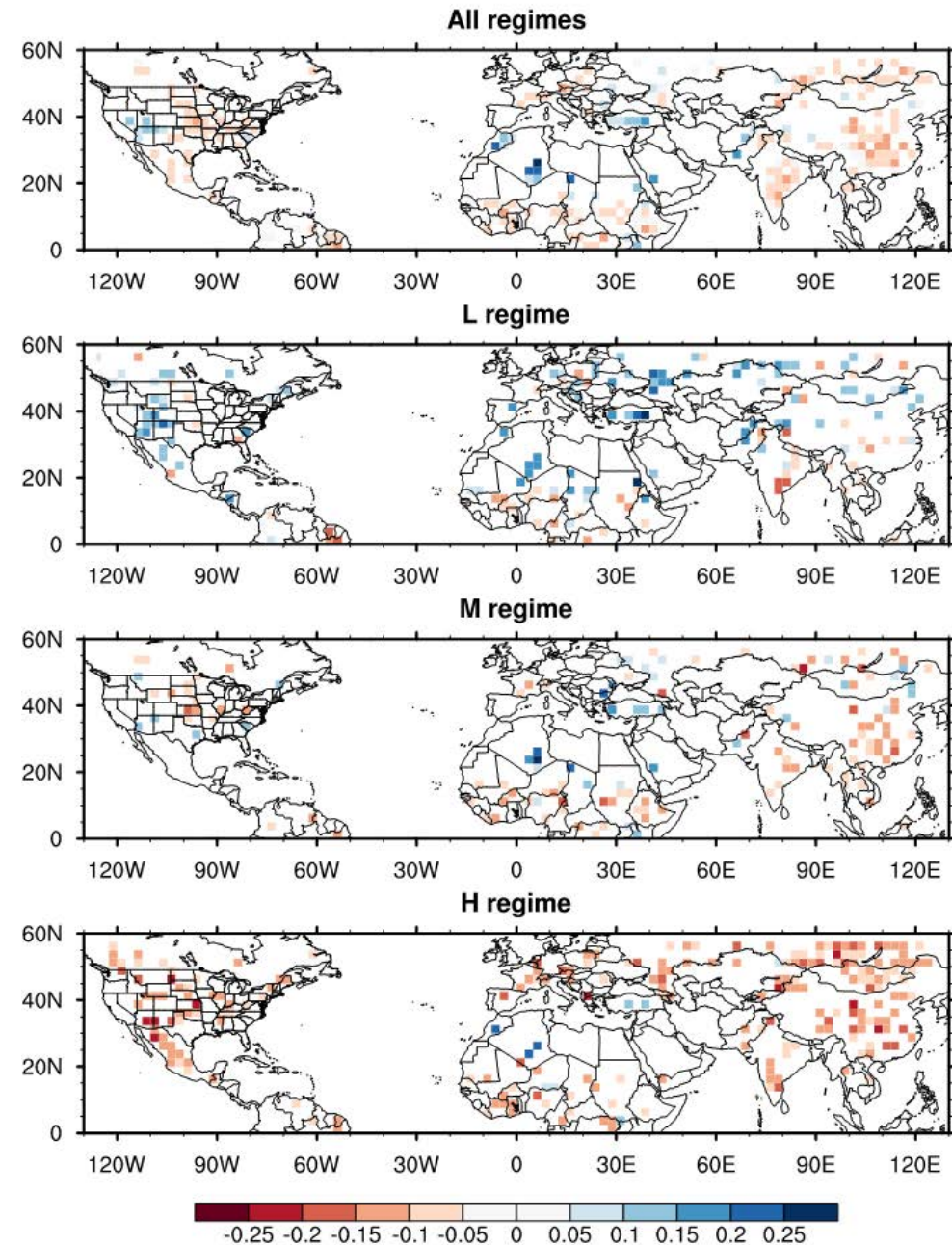
# Investigating other variable relationships with afternoon rainfall

Conditional probability difference of afternoon rainfall over positive and negative anomalies of each indicated variable over CONUS for all regime days.

Afternoon rainfall tends to occur over warmer surface (using surface or air T) and primarily over higher specific humidity

Results depend on location for soil moisture, evaporative fraction, and relative humidity

We are currently analyzing global model representation of afternoon rainfall processes (e.g., E3SM)
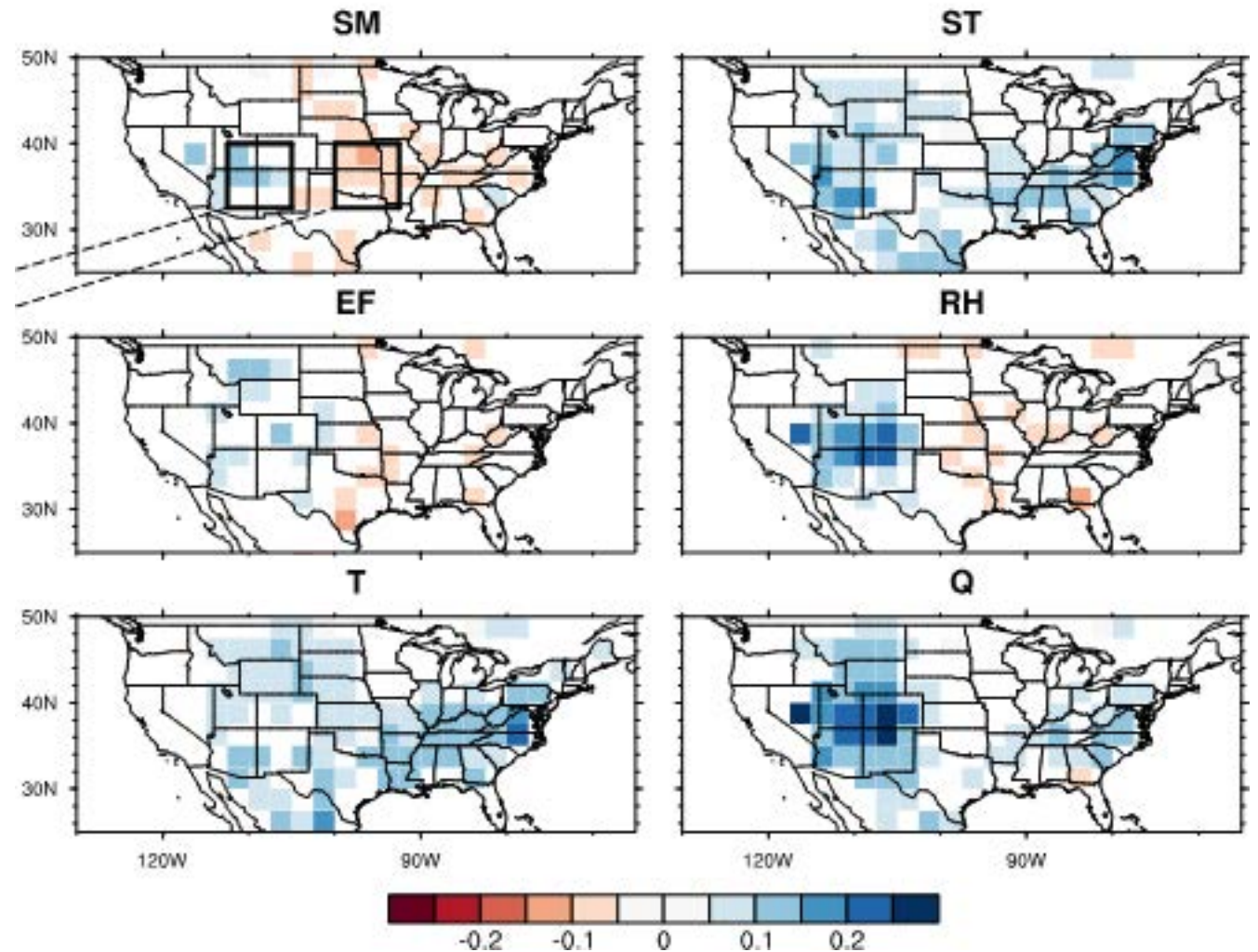
Conclusions

1. Surface water balance over the Amazon Basin
   - Only a few combinations of data sets allow water budget closure: ensemble mean P and E do not
   - Using scaled Obidos discharge to represent Amazon discharge appears to give correct long term mean but incorrect seasonal cycle
   - Using water budget estimates of discharge should be considered for oceanographic studies of the tropical Atlantic using climate models (including E3SM)

2. Snow-water equivalent (SWE) over CONUS
   - Developed a high-quality daily 4km SWE data over CONUS
   - Observed SWE shows more sensitivity to P (particularly over mountains) than T
   - Models (including E3SM) show more sensitivity to T than P, <u>which has implications on future SWE projection</u>
   - Models miss greater sensitivity to T and P over coastal mountains.

3. Morning soil moisture effect on afternoon rainfall
   - Afternoon rainfall in summer over Northern Hemisphere tends to occur over wetter soils under low moisture convergence conditions.
   - It tends to occur over drier soils under high moisture convergence conditions.
   - It tends to occur over warmer surface (using surface or air T)