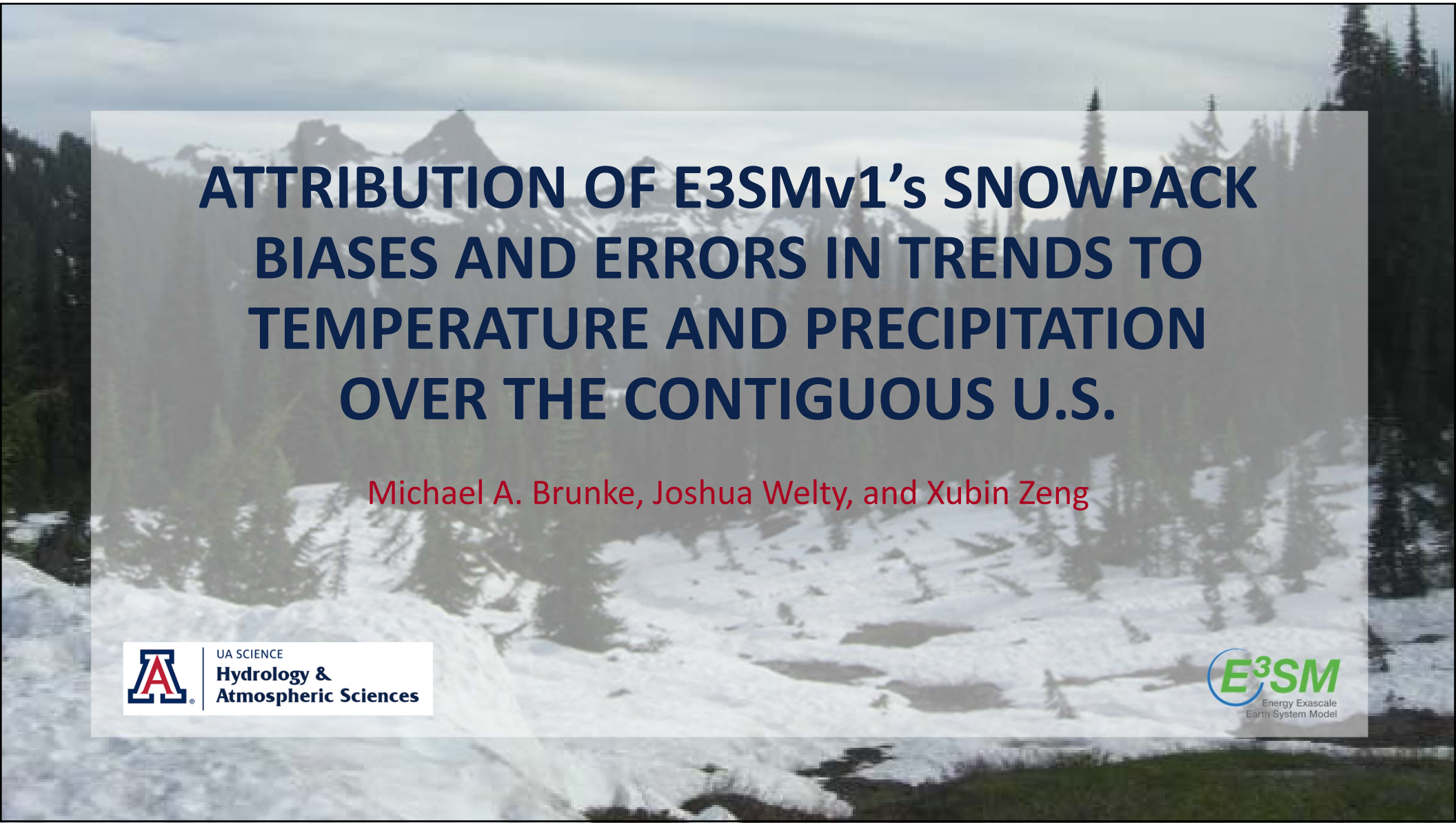

ATTRIBUTION OF E3SMv1's SNOWPACK BIASES AND ERRORS IN TRENDS TO TEMPERATURE AND PRECIPITATION OVER THE CONTIGUOUS U.S.

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UA SCIENCE
Hydrology & Atmospheric Sciences

E3SM
Energy Exascale Earth System Model

INTRODUCTION

- Snow changes the surface energy and water balance.
- The accurate simulation of snow in Earth system models is important.
- Recent research has shown that:
  - The largest uncertainty to snowpack simulation come from model forcing.
  - Observed SWE is related to both temperature AND precipitation

Therefore, we ask:

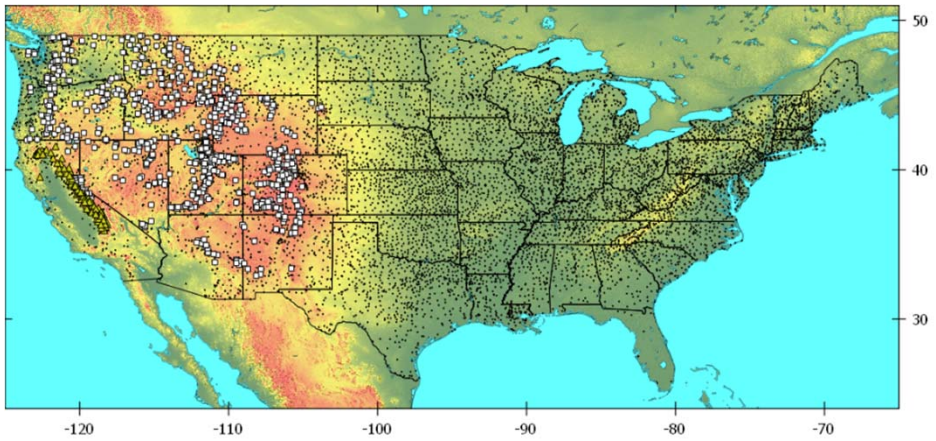
- **How much of the errors in simulated snowpack in E3SMv1 are due to simulated temperature and precipitation?**

METHODS

OBS DATA

- 4-km gridded daily SWE for CONUS by The University of Arizona (UA):
  - Derived from SNOTEL and COOP measurements constrained by PRISM.
  - Rigorously tested:
    - Point-to-point interpolations,
    - Point-to-pixel interpolations,
    - Evaluation against independent snow cover extent data,
    - Evaluation against independent airborne lidar measurements, and
    - Independent evaluation to NOAA airborne gamma radiation SWE measurements.
- PRISM 4-km temperature and precipitation

The SNOTEL (open circles) and COOP (dots) stations used to develop the UA snow product (Broxton et al., 2016).



Our analysis is based on water year (WY) *t* defined from the October of year *t* – 1 to September of year *t* for WY 1985-2015.

We focus on evaluating the effect of snow season (October-March) **mean temperature (T)** and **accumulated precipitation (P)** on March **mean snow water equivalent (SWE).**

METHODS

E3SMv1 SIMULATIONS ANALYZED

- AMIP (prescribed SST) ensemble
- Historical (fully-coupled atmosphere-ocean-land-sea ice) ensemble

ATTRIBUTION METHODOLOGY

We evaluate E3SMv1's biases and trends in SWE, T, and P. We also attribute model errors to those in T and P in three regions: the Western CONUS (W-CONUS), Central CONUS (C-CONUS), and Eastern CONUS (E-CONUS).

SWE errors to T and P errors through a multi-linear regression of the T and P errors normalized by the interannual variability in such errors:

$$\varepsilon_{\mathrm{SWE}}(x,y,t) = A_\varepsilon \frac{\varepsilon_T}{\sigma_t(\varepsilon_T)} + B_\varepsilon \frac{\varepsilon_P}{\sigma_t(\varepsilon_P)} + C_\varepsilon$$

$A_\varepsilon, B_\varepsilon, C_\varepsilon$ = regression coefficients

ε_T = temperature error

ε_P = precipitation error

$\sigma_t(\varepsilon_T), \sigma_t(\varepsilon_P)$ = standard deviation of errors

Similarly, errors in SWE trends are attributed T and P trend errors by a multi-linear regression of the normalized T and P trend errors such that:

$$\Delta\tau_{\mathrm{SWE}}(x,y) = A_{\Delta\tau} \frac{\Delta\tau_T}{\sigma_{xy}(\Delta\tau_T)} + B_{\Delta\tau} \frac{\Delta\tau_P}{\sigma_{xy}(\Delta\tau_P)} + C_{\Delta\tau}$$

$A_{\Delta\tau}, B_{\Delta\tau}, C_{\Delta\tau}$ = regression coefficients

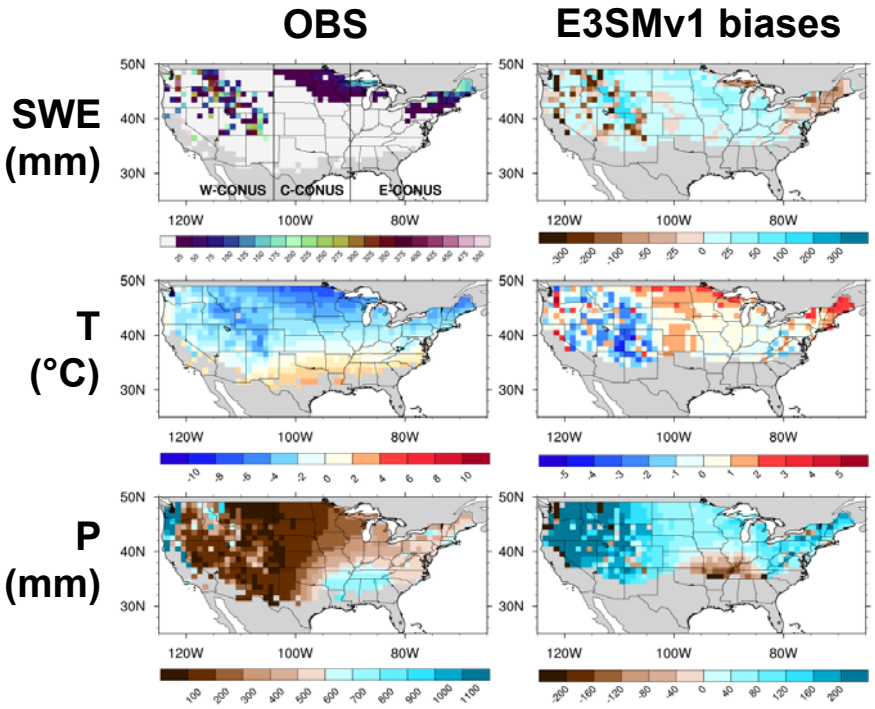
$\Delta\tau_T$= temperature trend error

$\Delta\tau_P$= precipitation trend error

$\sigma_{xy}(\Delta\tau_T), \sigma_{xy}(\Delta\tau_P)$ = std. dev. of trend errors

RESULTS

ERRORS IN SWE AND THEIR ATTRIBUTION TO T AND P ERRORS



(left column from top to bottom) Mean SWE, T, and P in OBS. (right column) SWE, T, and P biases in E3SMv1.

- The highest biases are located in the W-CONUS.

Mean multi-linear regression coefficients of the normalized T and P errors (mm)

Region	T coef.	P coef.
W-CONUS, elevation < 1500 m	-0.42	0.31
W-CONUS, elevation ≥ 1500 m	-0.48	0.30
C-CONUS	-0.45	0.19
E-CONUS	-0.46	0.18

|T coefficients| > |P coefficients|:

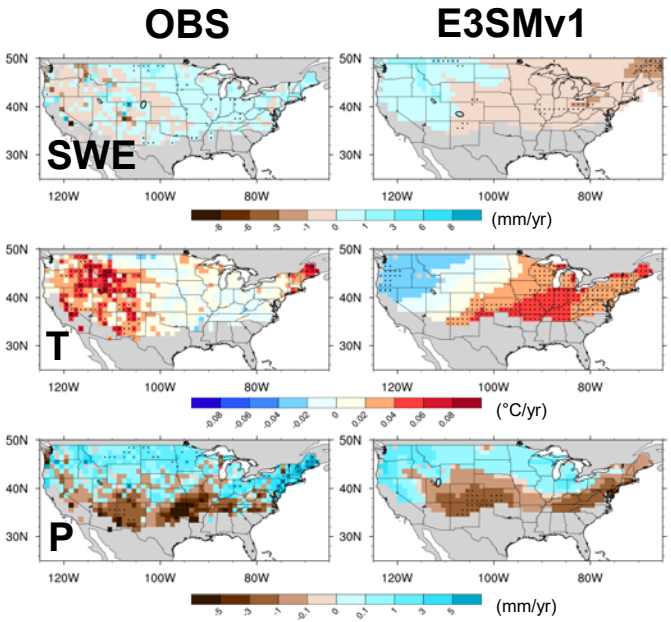
- **SWE errors are attributed more to T errors than P errors.**

P coefficients smaller in the C-CONUS and E-CONUS:

- SWE errors are less attributed to P errors there.

RESULTS

TRENDS AND ATTRIBUTION OF SWE ERRORS TO T AND P



(from top to bottom) Mean SWE, T, and P trends in OBS (left column) and in the E3SMv1 AMIP simulations (right column).

- OBS T trends are the most positive over the W-CONUS.
- E3SMv1 T trends are negative over the NW CONUS and positive towards the East.
  - Positive trend SWE trends in the W-CONUS and negative SWE trends in the other regions.

Multi-linear regression coefficients of the normalized T and P errors in trends (mm/yr)

Region	T coef.	P coef.
W-CONUS, elevation < 1500 m	-0.21	0.04
W-CONUS, elevation ≥ 1500 m	-0.14	1.42
C-CONUS	-0.04	0.12
E-CONUS	0.18	0.11

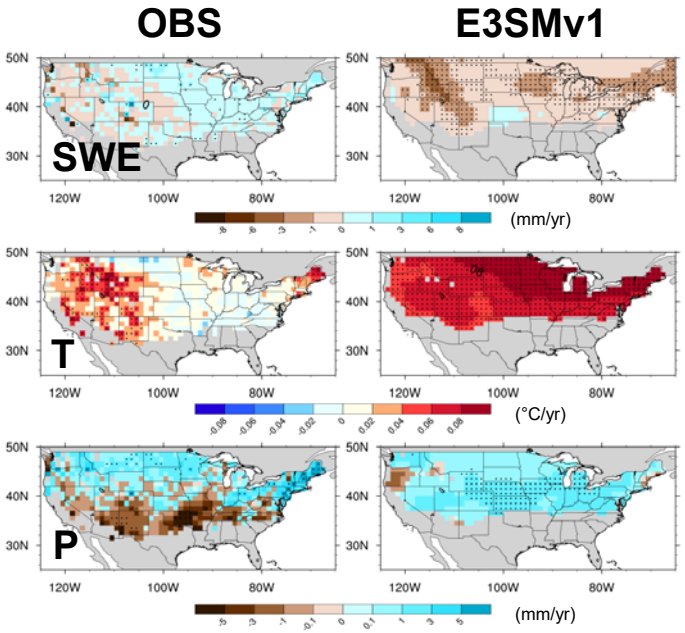
In the W-CONUS:

- |T coefficient|>|P coefficient| for elevations<1500 m.
- |P coefficient|>|T coefficient| for elevations≥1500 m.

- **SWE trends are attributed more to T trends at lower elevations and more to P trends at higher elevations.**

RESULTS

TRENDS AND ATTRIBUTION OF SWE ERRORS TO T AND P IN THE HISTORICAL SIMULATIONS



(from top to bottom) Mean SWE, T, and P trends in OBS (left column) and in the E3SMv1 historical simulations (right column).

SWE, T, and P trends differ from the AMIP ensemble:

- SWE trends are generally negative corresponding to the T trends everywhere.
- P trends are positive over most of the CONUS.

Multi-linear regression coefficients of the normalized T and P errors in trends (mm/yr)

Region	T coef.	P coef.
W-CONUS, elevation < 1500 m	-0.35	0.18
W-CONUS, elevation ≥ 1500 m	-0.15	1.47
C-CONUS	-0.48	0.28
E-CONUS	-0.05	0.55

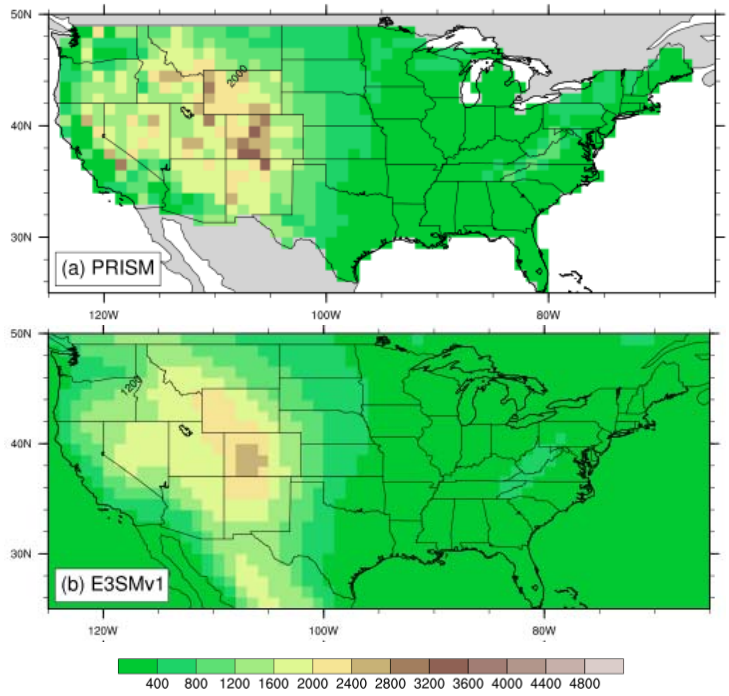
- **SWE trends are more strongly attributed to T and P trend errors in the historical runs.**
- Since the same atmosphere and land models are used in both the AMIP and historical simulations, the difference in trend errors are due to the change in interannual variability introduced by the ocean model coupling.

CONCLUSIONS

SWE errors and errors in trends in E3SMv1* are attributed to T and P by performing multi-linear regressions:

- **SWE errors are attributed more to T errors than P errors.**
- **Errors in SWE trends are attributed more to T trend errors for lower elevations and to P trend errors at higher elevations.**
- **Higher attributions to T and P trend errors are found in the historical simulations.**
- Problems with the representation of the land surface may also contribute:
  - For example, the elevation of the high terrain of the W-CONUS is not well represented in E3SMv1.
- Improvement in the simulation of SWE must come from advances in the representation of the land surface along with better simulation of T and P.

*Other U.S. models (CESM2, GFDL-CM4, and GISS ModelE2.1) produce similar results.



The surface elevation (m) used in (a) UA/PRISM degraded to 1° × 1° and (b) E3SMv1.