High-resolution WRF-based Downscaling of Earth System Model Projections for Energy Applications across CONUS

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1. Introduction

- Spatial and temporal resolutions of the global-scale Earth system models (**ESMs**) (e.g., **~100 km and daily** for **spatiotemporal resolutions**) **are too coarse for regional energy studies**.
- **Employ a dynamical downscaling** method using **Weather Research Forecasting (WRF)** model to create **unbiased, physically-consistent, high-resolution** historical and future projections tailored for energy applications across the contiguous United States (**CONUS**).
- **Data product: Version 2** (Note: Version 1 used MPI-ESM1-2-HR for WRF downscaling)

Product	Spatial and Temporal Resolution	Spatial Coverage	Data Period	Input for WRF downscaling
4-km Reanalysis	4-km and hourly	CONUS	2000-2021	ERA5
Historical projection	4-km and hourly	CONUS	2000-2014	Bias-corrected ESM (Xu et al., 2021)
Future projection (SSP126)	4-km and hourly	CONUS	2015-2060	Bias-corrected ESM (Xu et al., 2021)
Future projection (SSP245)	4-km and hourly	CONUS	2015-2060	Bias-corrected ESM (Xu et al., 2021)

2. WRF Configuration

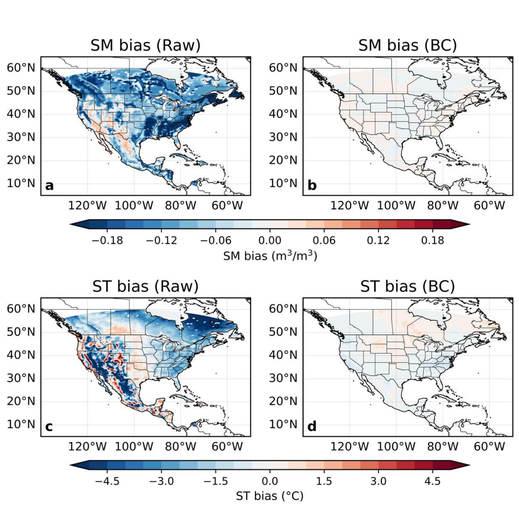
Selection of WRF physics (Yang et al., 2025a, 2025b, 2026):

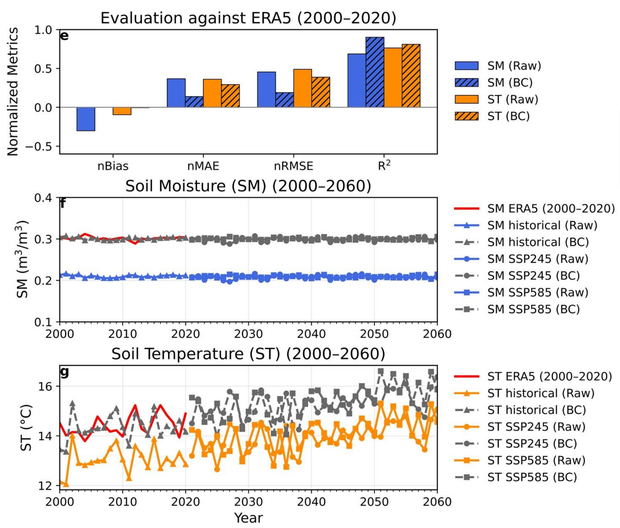
- **Microphysics:** Thompson
- **Cumulus scheme:** Tiedtke (1st domain only)
- **Short-wave/long-wave radiation:** RRTMG
- **PBL:** MYNN PBL
- **Coupled subgrid-scale clouds from PBL scheme to radiation scheme:** on
- **LSM:** Noah LSM.

Unique components:

- ✓ **High-resolution:** 4-km grid spacing, 60 vertical layers
- ✓ **Convection-allowing** simulation
- ✓ **Physically consistent** simulation
- ✓ **Various meteorological variables:** more than 50 2D/3D variables for solar, wind, hydro, and extreme weather (e.g., heatwave/coldwave, extreme precipitation/drought, severe snow/blizzard events, severe hail events/potential lightening conditions, etc.) applications.

3. Bias-correction (BC) of Soil Initial States

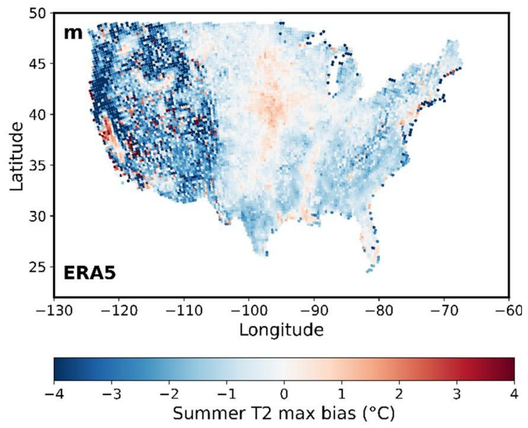




- We have found that **biased soil moisture (SM) and soil temperature (ST)** from global-scale ESMs significantly **distort the surface heat flux balance**, leading to biases in atmospheric variables during WRF dynamical downscaling.

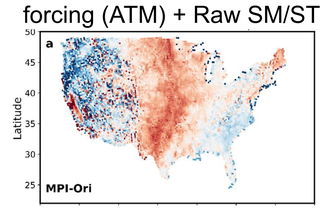
4. Numerical Experiment Results (T2 Extremes at 28-km Resolution)

Summer bias of downscaled ERA5 at 28-km grid (2000-2014)



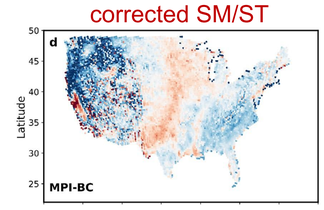
Variable: daily-max 2-m air temperature (T2)
Observation: PRISM

Case 1: Raw atmospheric forcing (ATM) + Raw SM/ST



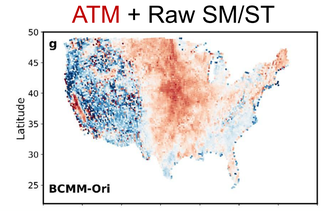
Strongly biased daily-max T2

Case 2: Raw ATM + Bias-corrected SM/ST



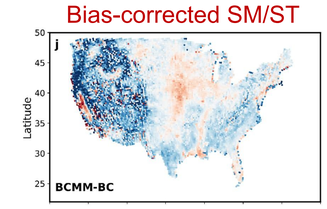
Improved daily-max T2 using bias-corrected SM and ST

Case 3: Bias-corrected ATM + Raw SM/ST



Some improvement, but biases remain in daily-max T2

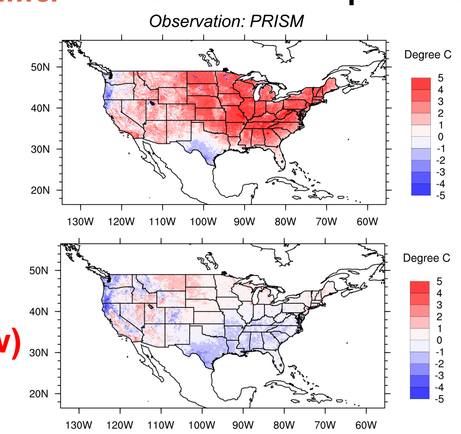
Case 4: Bias-corrected ATM + Bias-corrected SM/ST



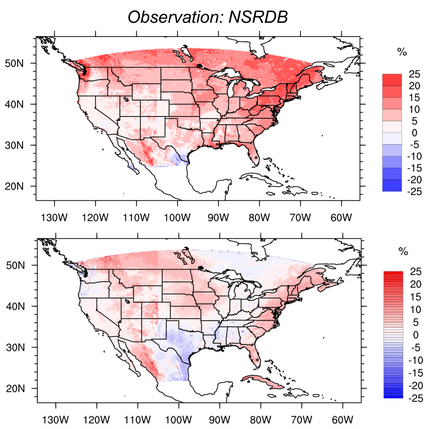
Most improvements achieved

5. Evaluation of 4-km Data Product (Version 1 vs. Version 2; 2000-2014)

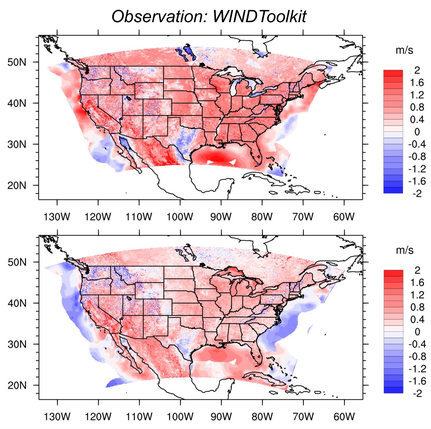
Summer **Bias of 2-m air temperature**



Bias of GHI

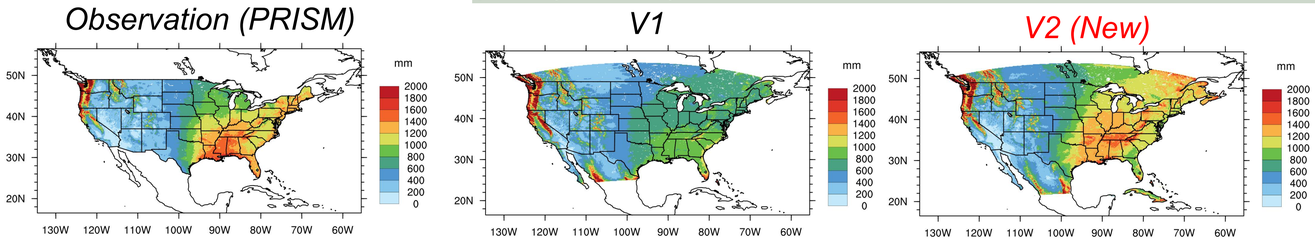


Bias of 10-m wind speed

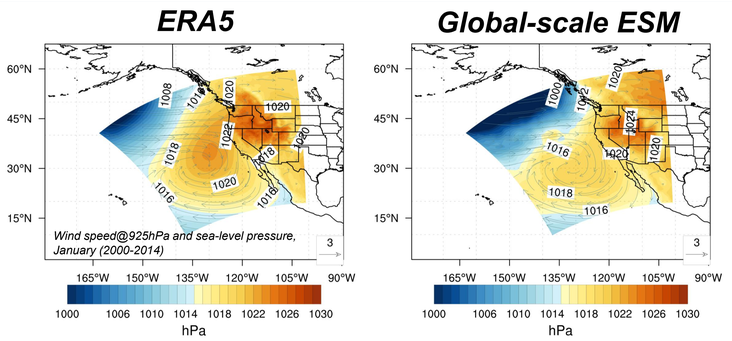


Achieved significant bias reductions (> 50%) in 2-m air temperature, global horizontal irradiance, 10-m wind speed, and precipitation over the historical period (2000–2014).

Averaged annual total precipitation



6. New Findings



- We have found that CMIP6 ESMs fail to capture the North Pacific High, which likely leads to a misrepresentation of relative humidity trends in the western US.

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