Are atmospheric models too-cold in mountains? The state of science and insights from the SAIL field campaign

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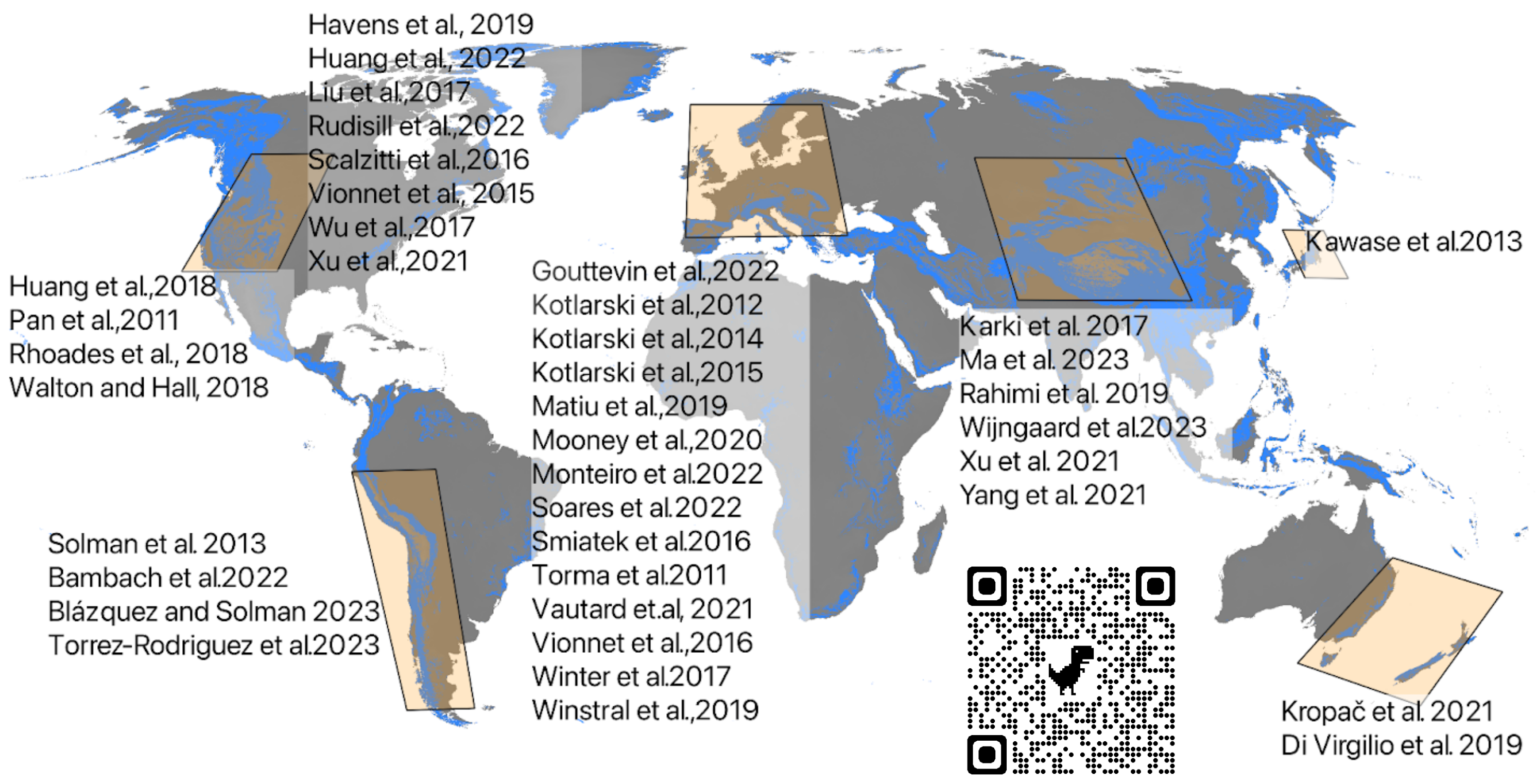
RCM and VrGCM are Cold Biased During Winter

ACROSS THE WORLD'S MAJOR MOUNTAIN RANGES



- *RCM and VrGCM studies from the last ~decade where two-meter air temperature (T2m) cold biases are reported in major mountain ranges.*
- *Biases are primarily found in winter.*
- *No common explanation has been reported explaining causes of bias across models.*

Fig 1: Generalized geographic locations of studies (yellow boxes) reporting mountain cold-biases with global mountain classifications from Snethlage et al., 2022 shown in blue. The 41 studies are all reported in the peer-reviewed literature with publication dates spanning 2011-2023 and include both single model experiments and multi-model ensemble evaluations.

The Physical Mechanisms Influencing Mountain T2m

AND THE CHALLENGES FOR MODELS

- *A range of physical processes make T2m challenging to predict in mountain environments.*
- *Local wind circulations (katabatibc flows) and cold air pools decouple surface layers from the free atmosphere.*
- *Snow cover (high albedo, high emissivity, strong thermal insulator) promotes stable near surface layers — which are challenging for models (decoupling).*
- *T2m lapse rates are seldom -6.5 C km^{-1}.*
- *T2m is a **diagnostic quantity in models**, and depends on the skin temperature, lowest model level temperature, and sfc. layer formulation.*

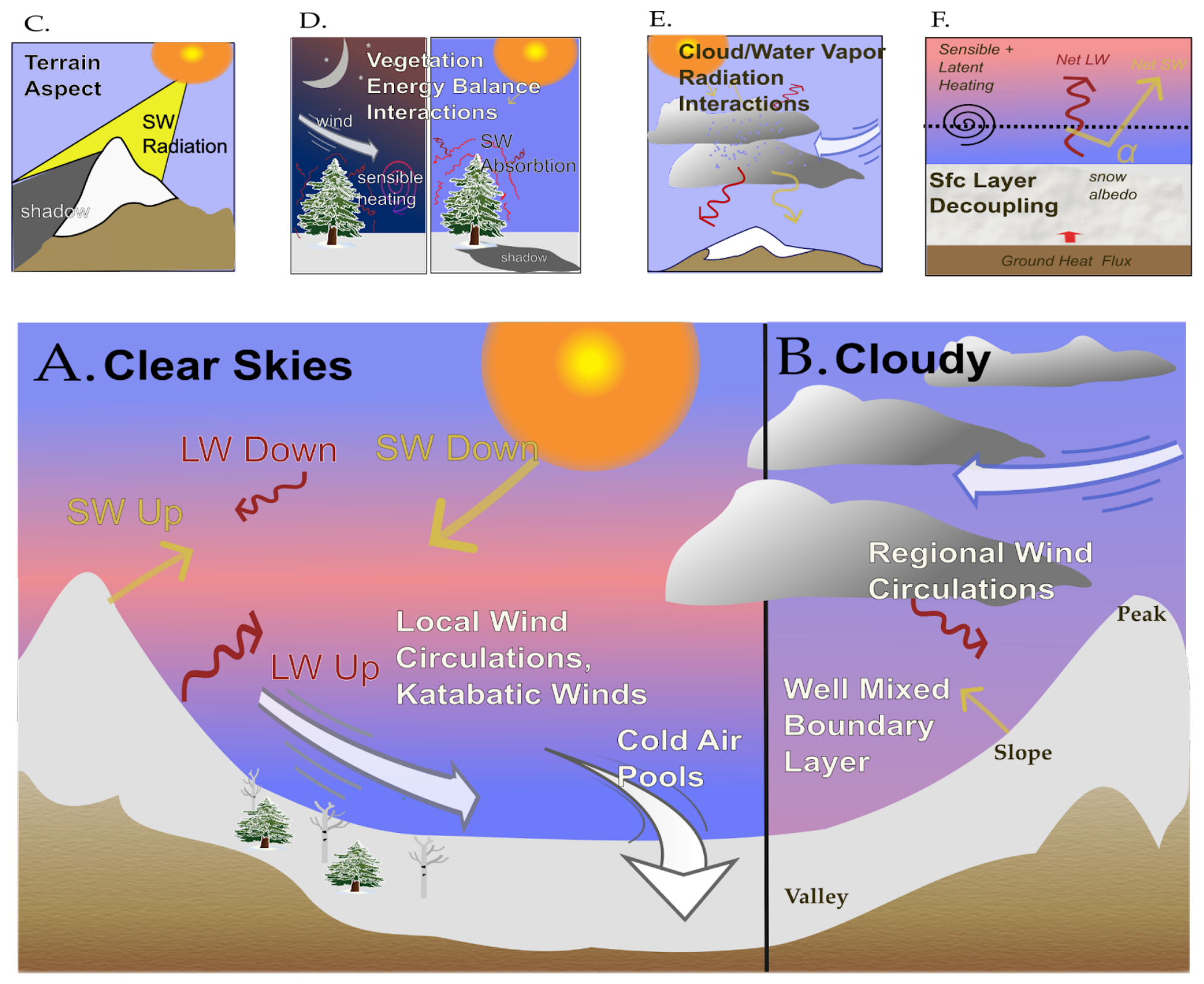


Figure 3: Processes influencing mountain T2m A) temperature inversions form during clear-sky, cloud free conditions. Warmer air aloft is entrained from above maintaining the circulation. B) Synoptic forcing leads to upper air and boundary layer temperature mixing. Top row from left: 1) Solar radiation loading differences between aspects 2) Vegetation surface roughness and lower albedos cause warming 3) clouds interact with radiation and 4) snowpacks are cold, suppress turbulence, and decouple from the atmosphere

Case Study: NCAR CONUS 4km WRF Model

BIASES IN THE MAJOR WUS MOUNTAIN RANGES

- *T2m biases are normally distributed across CONUS with a mean near zero. Every major mountain range of the WUS is cold biased.*
- *Continental interior ranges have a more extreme cold bias than the coastal ranges.*
- *Cold biases persist even when only the grid cells containing weather station observations are compared between WRF and PRISM, suggesting that biases are not merely a product of out-of-sample predictions made by PRISM.*
- *Valleys are WARM biased, whereas ridge locations are COLD biased.*

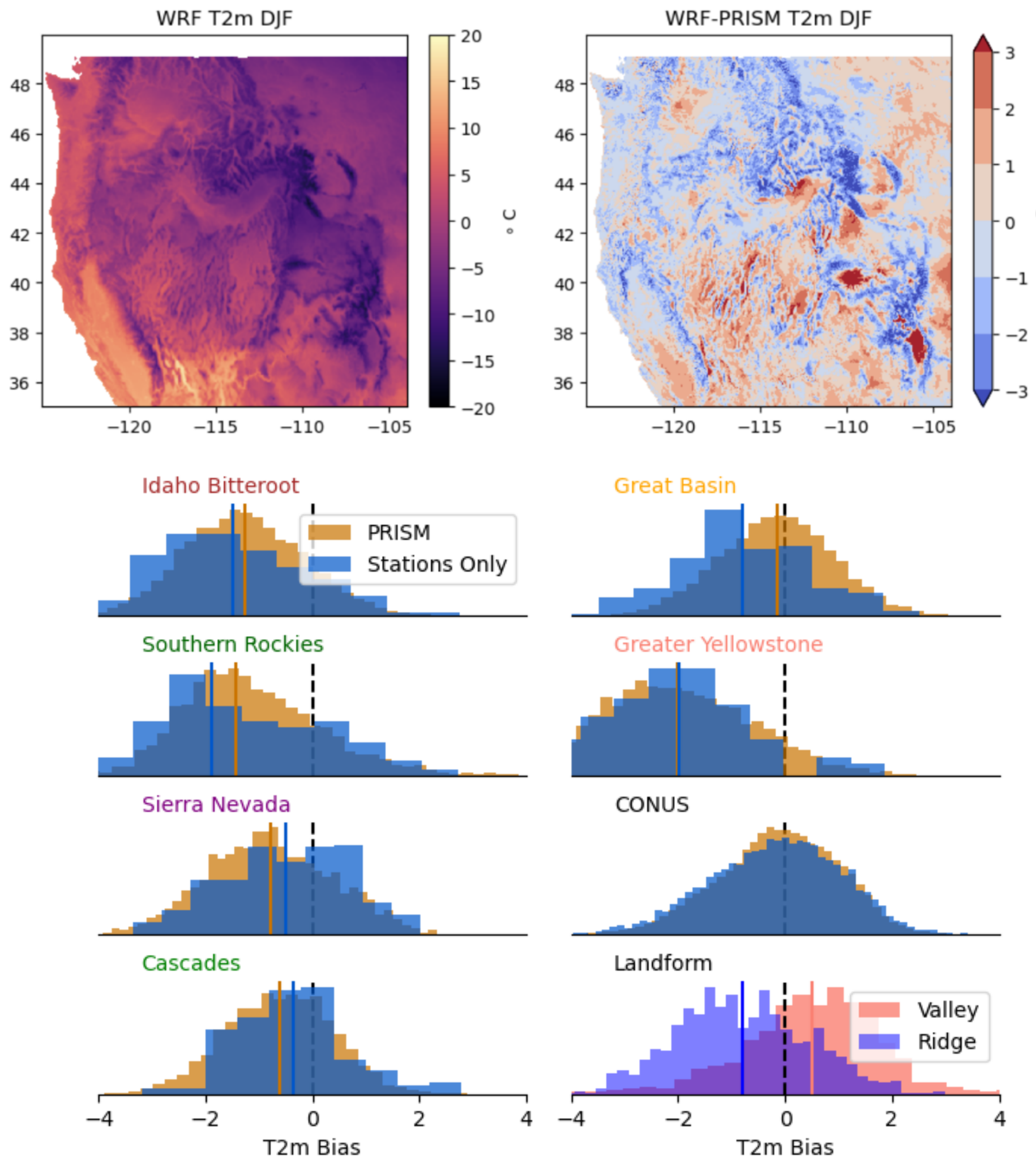


Figure 2: T2m from the NCAR 4km CONUS dataset from Liu et al. (2017) compared against PRISM for DJF 2008. T2m bias (WRF-PRISM) shown top right. Distributions of biases partitioned by mountain range shown below. "Stations Only" compares only grid-cells containing an observation.

SAIL Field Campaign Isolates Potential Causes of T2m Bias

THE VALUE OF INTENSIVE FIELD OBSERVATIONS

- *Intensive measurements collected by the SAIL field Campaign allows us to test hypotheses related to cold-biases (below) in unprecedented detail.*
- *WRF (from Xu et. al, 2022) and HRRR model are cold biased during windy conditions and particularly at night — and warm biased during daytime low/no cloud conditions.*
- *Both models are too dry (Q) and low biased w.r.t DLW.*

Table 3: Potential causes of model T2m cold biases articulated in the literature

Cause	Study
Too little cloud cover	Vionnet et al. (2016), Monteiro et al. (2022)
High snow bias	Vionnet et al. (2016), Ma et al. (2023), Liu et al. (2017), Kotlarski et al. (2014), Careto et al. (2022), McCrary et al. (2017)
Surface albedo	Torrez-Rodriguez et al. (2023), Yang et al. (2021), Xu et al. (2019), Careto et al. (2022)
Snow covered area parameterization	Liu et al. (2017)
Wind speeds too-slow	Xu et al. (2021), Gouttevin et al. (2022)
Downwelling shortwave radiation too low	Xu et al. (2021), Vionnet et al. (2016)
Downwelling longwave radiation too low	Gouttevin et al. (2022), Vionnet et al. (2016)
Surface layer parameterization	Rontu et al. (2016), Monteiro et al. (2022)
Observation sparsity	Huang et al. (2018), Fernández et al. (2021), Torrez-Rodriguez et al. (2023), Torma et al. (2011), Huang et al. (2018)
Observation quality	Rasmussen et al. (2023)
Model-to-observation elevation differences	Kotlarski et al. (2014)

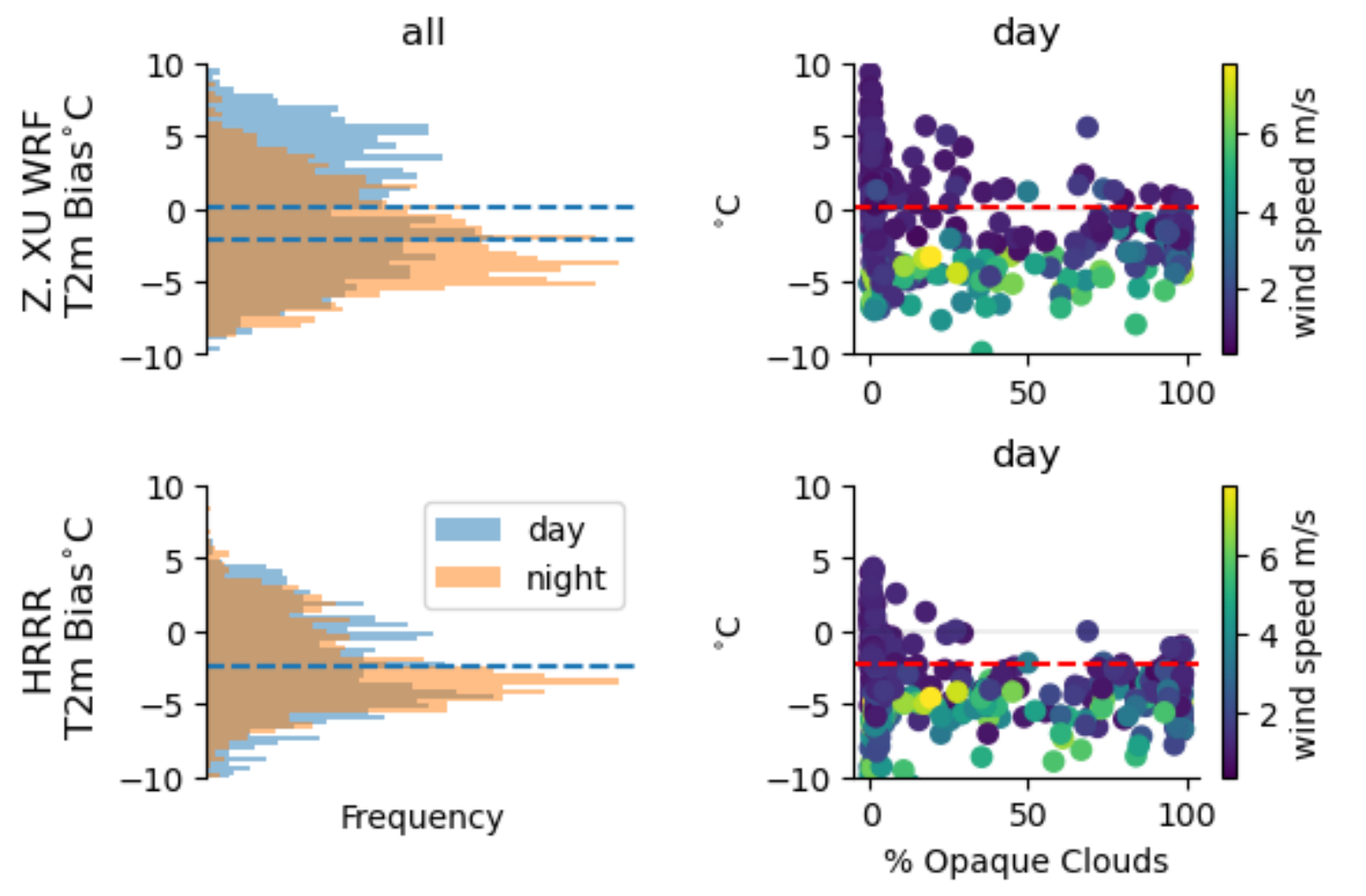


Figure 4: HRRR (3x3 km) and WRF (500x500m) biases computed against SAIL met. obs. January 1, 2022 - April 1, 2022.

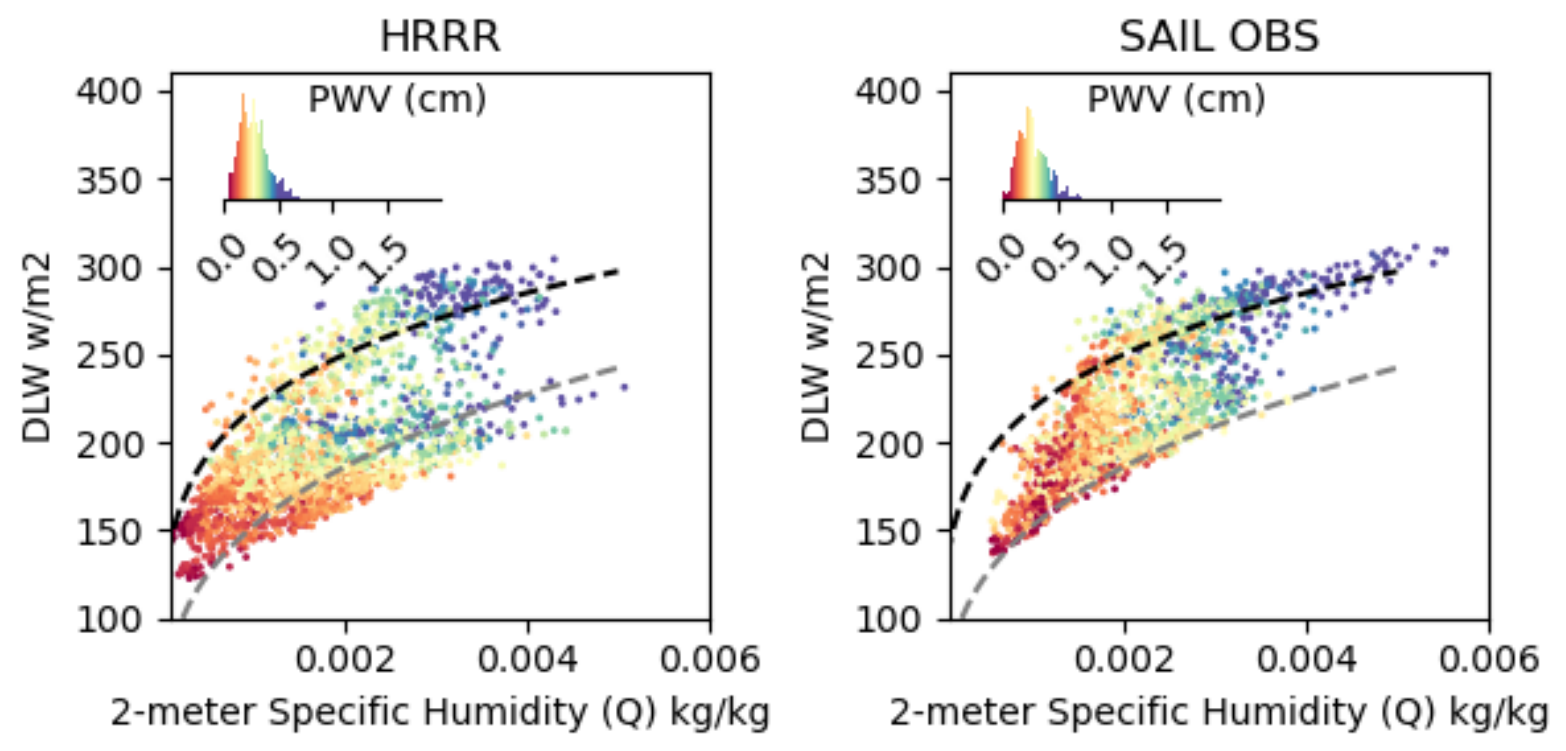


Figure 5: 2-meter specific humidity (Q) and downwelling longwave radiation (DLW). Grid cells are colored by the precipitable water vapor (PWV) content (cm).

Acknowledgments

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