



*Supplement of*

## **Increasing resolution and accuracy in sub-seasonal forecasting through 3D U-Net: the western US**

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**Table S1.** Summary of the datasets used in this study.

Dataset	Type	Period	Resolution	Variable	Frequency
ECMWF	forecast	2015-2023	1.5°	t2m, tcw u, v, z, mslp, pr	daily 6-hourly
PRISM	reanalysis	2015-2023	0.042°	t2m, tcw, mslp, pr, topo, u, v, z	daily

### Definition of Pattern Correlation and Root Mean Square Error (RMSE)

$$\text{Pattern Correlation} := \frac{\sum_{i=1}^n w_i (f_i - \bar{f})(o_i - \bar{o})}{\sqrt{\sum_{i=1}^n w_i (f_i - \bar{f})^2} \sqrt{\sum_{i=1}^n w_i (o_i - \bar{o})^2}} \quad (\text{S1})$$

$$\text{RMSE} := \sqrt{\frac{\sum_{i=1}^n w_i (f_i - o_i)^2}{\sum_{i=1}^n w_i}} \quad (\text{S2})$$

5 where

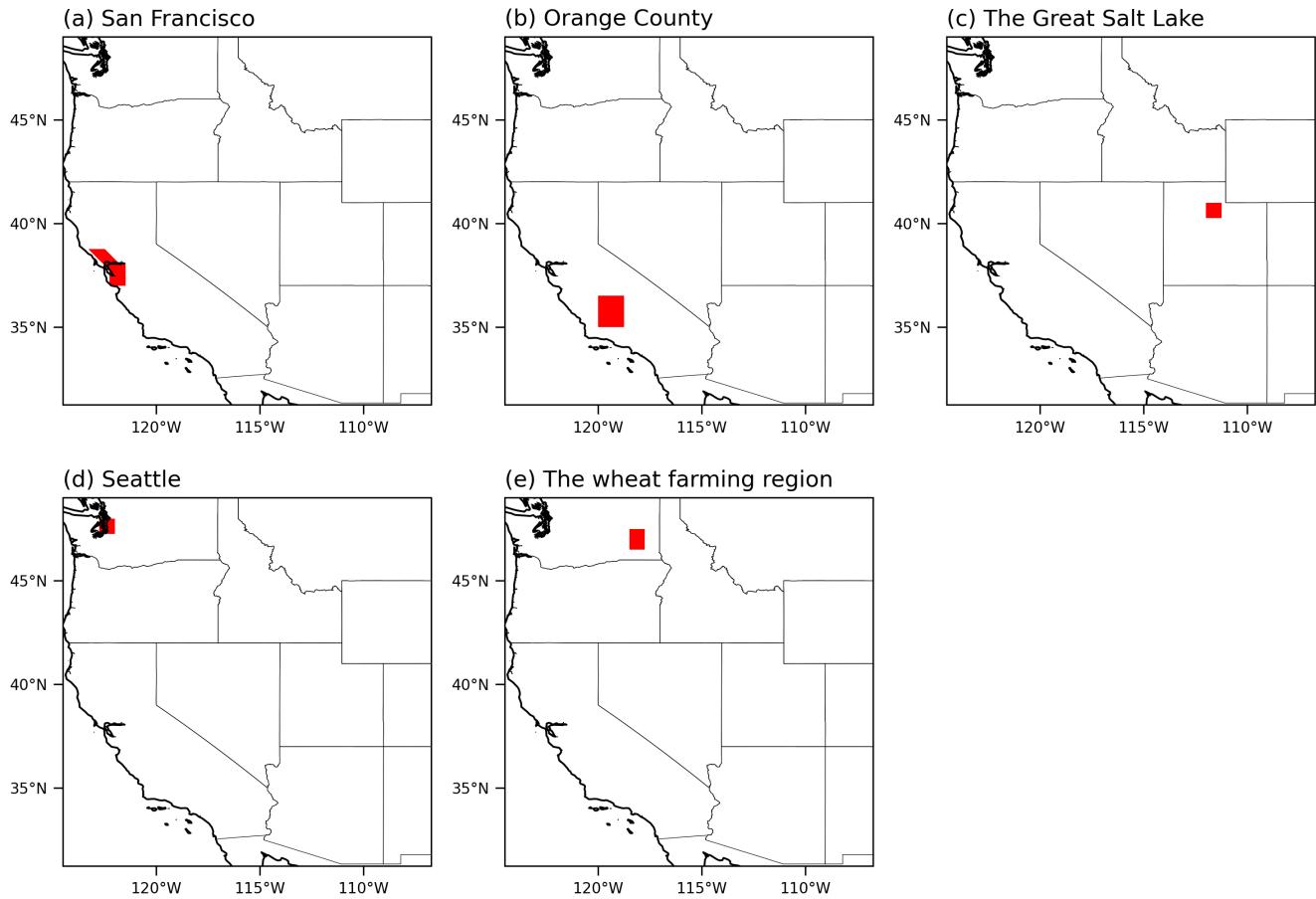
$f_i$  : the model forecast at grid cell  $i$

$o_i$  : the reference value (reanalysis) at grid cell  $i$

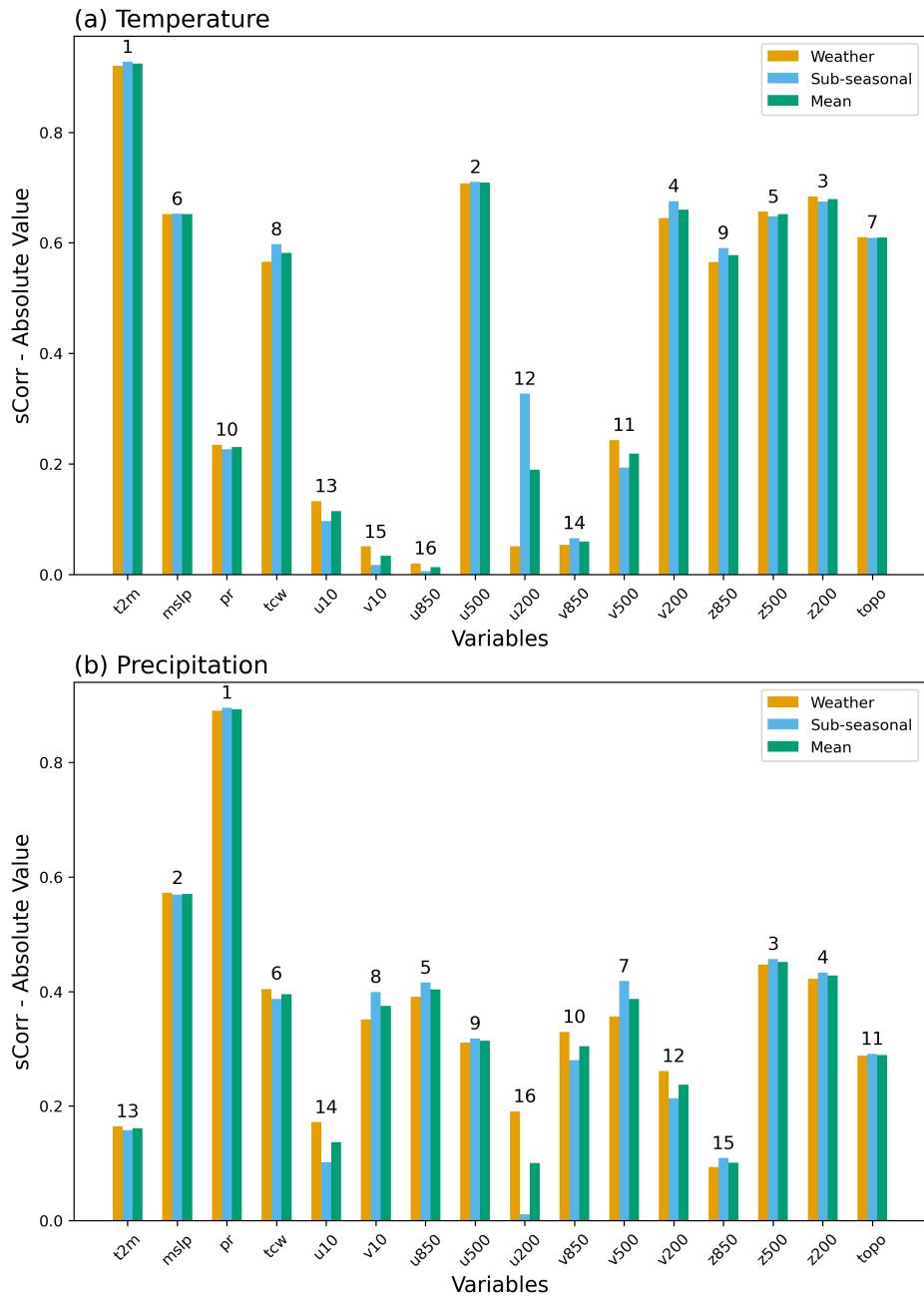
$w_i = \cos(\phi_i)$  : latitude-based weight for the grid cell at latitude  $\phi_i$

$\bar{f} = \frac{\sum_{i=1}^n w_i f_i}{\sum_{i=1}^n w_i}$  : latitude-weighted means of the forecast

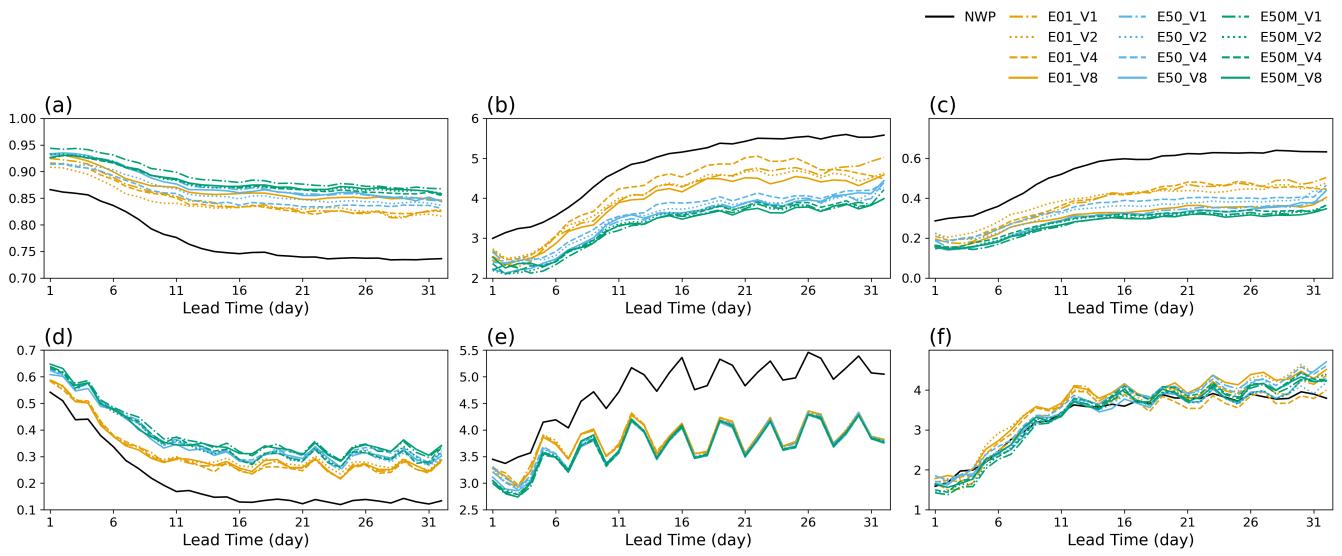
10  $\bar{o} = \frac{\sum_{i=1}^n w_i o_i}{\sum_{i=1}^n w_i}$  : latitude-weighted means of reference fields



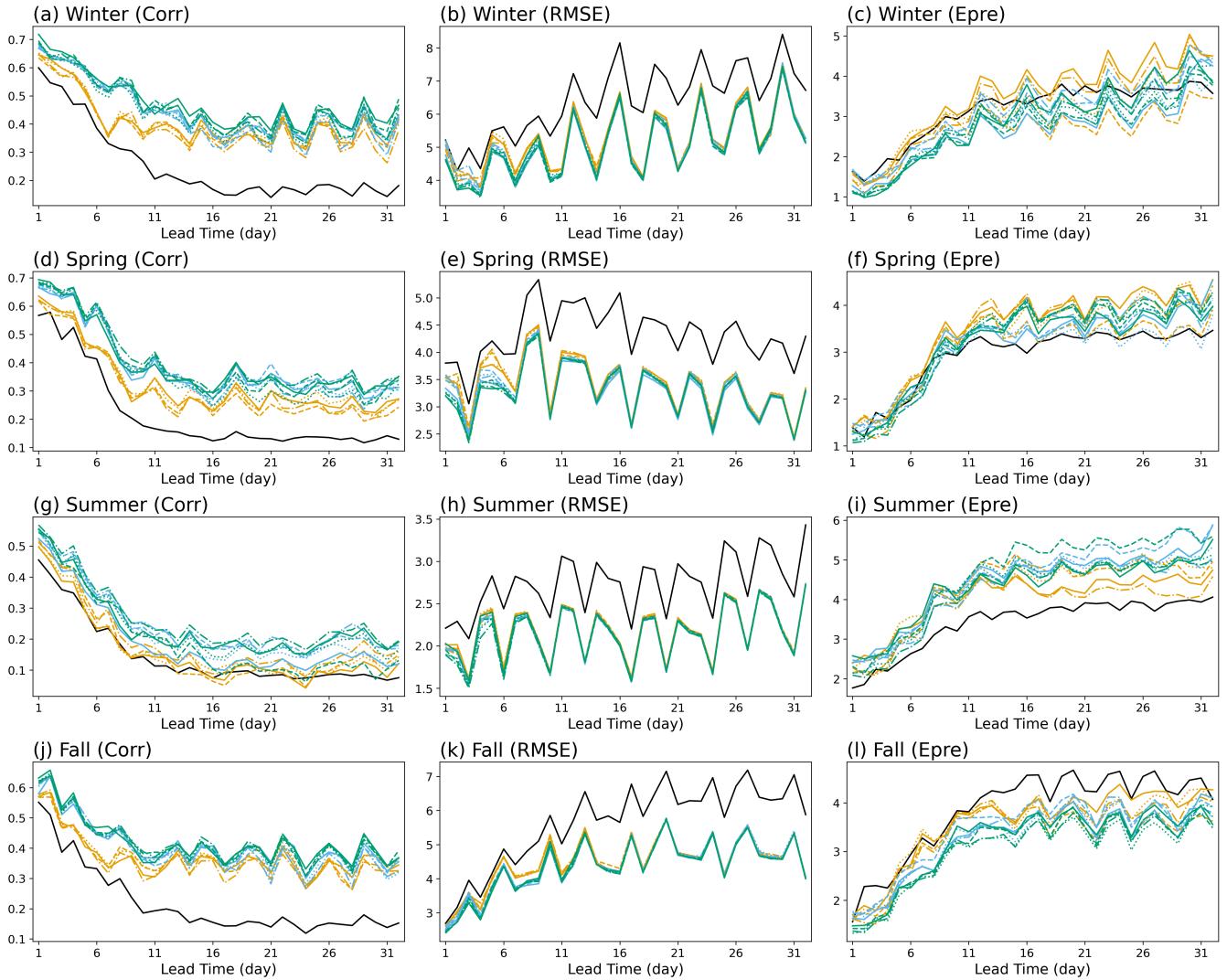
**Figure S1.** Location map of the five selected regions (a) San Francisco, California, (b) Orange County, California, (c) The Great Salt Lake, Utah, (d) Seattle, Washington and (e) The wheat farming region, Washington, which are used to evaluate the model's performance in finer-scale analysis.



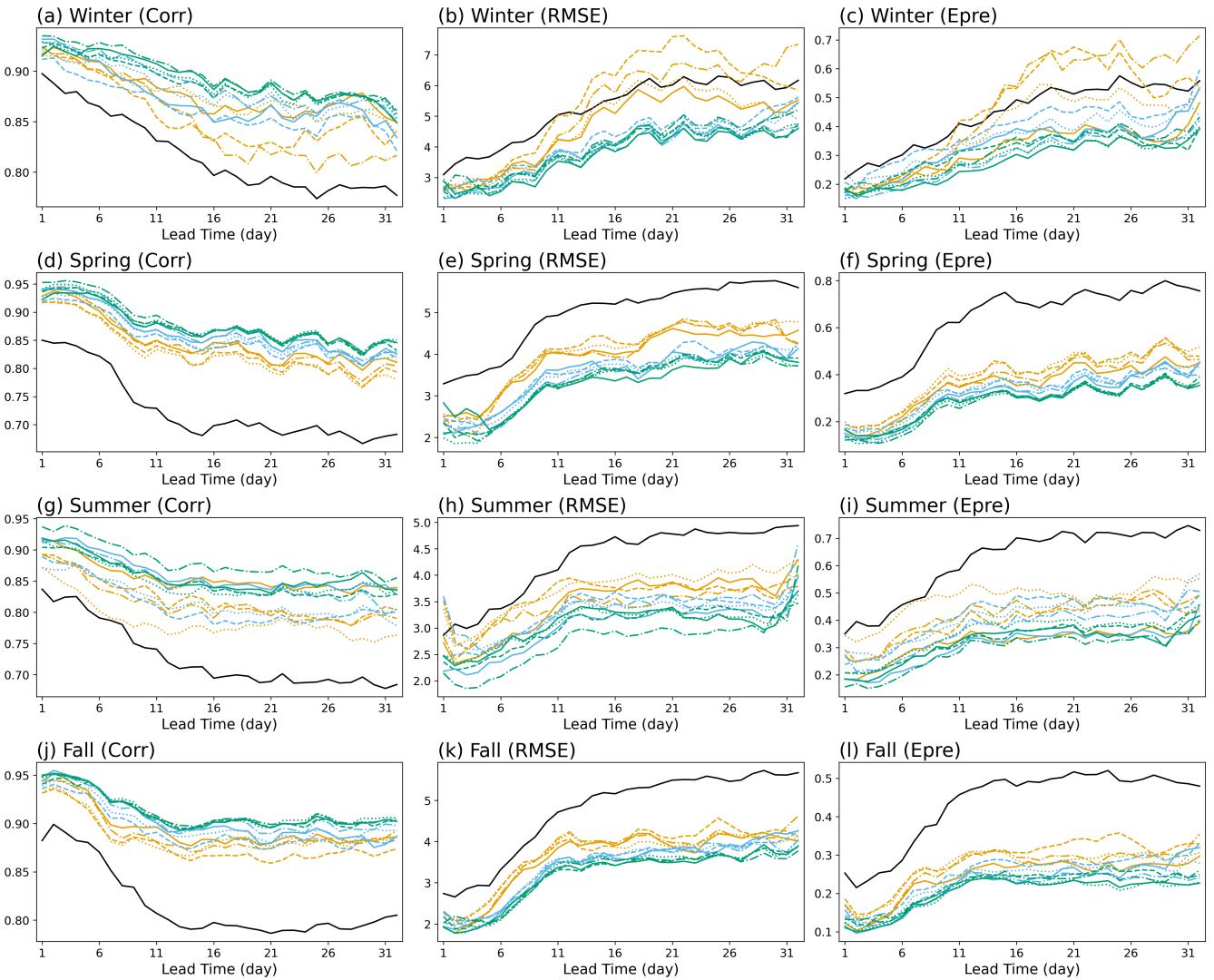
**Figure S2.** Absolute spatial correlation values between various meteorological variables and (a) temperature and (b) precipitation for weather and sub-seasonal timescales in the Western U.S. Variables are ranked by their mean correlation across both timescales, with rankings shown above each bar. The top 8 variables for each target variable were selected for use in the 3D U-Net model.



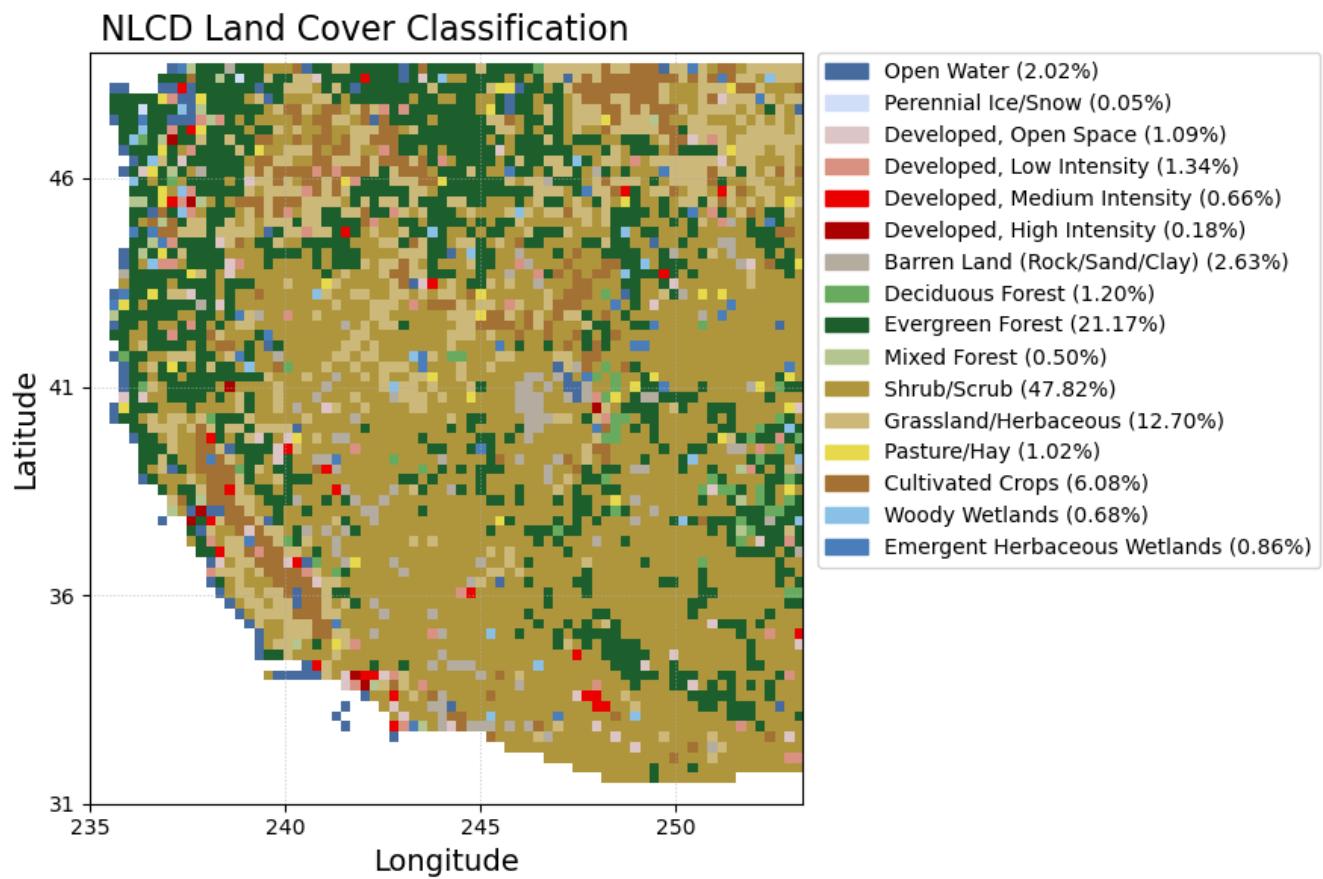
**Figure S3.** Ensemble sensitivity benchmark scores for the Western U.S., comparing NWP and 3D U-Net models with varying input variables (V1, V2, V4, V8) and ensemble configurations (E01, E50, E50M) for temperature (a-c) and precipitation (d-f) forecasts over 32 days. Metrics shown are (a, d) pattern correlation, (b, e) RMSE, and (c, f)  $E_{pre}$ .



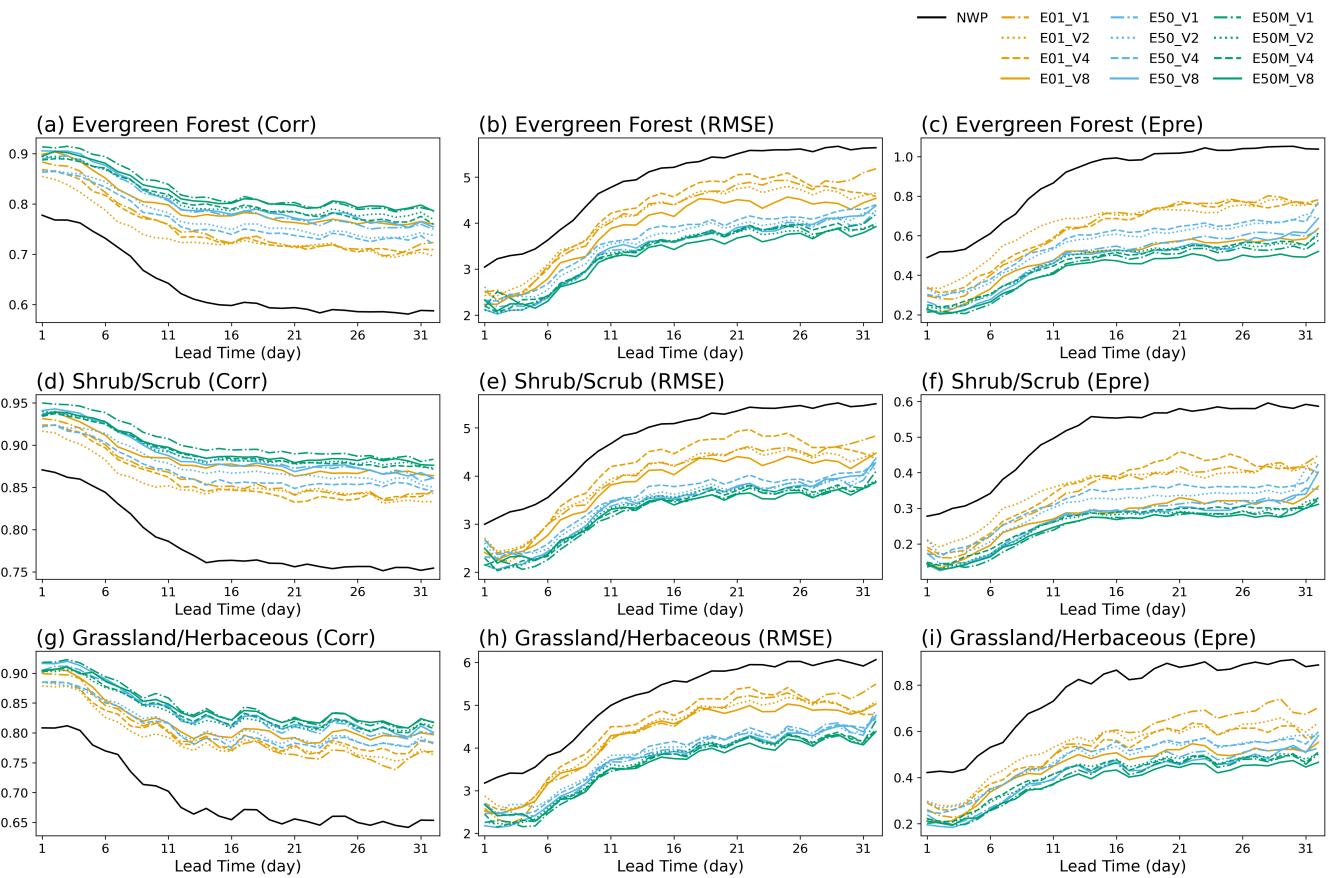
**Figure S4.** Seasonal benchmark scores for the Western U.S., comparing NWP and 3D U-Net models for precipitation forecasts. The scores are categorized by initialization dates for DJF (first row), MAM (second row), JJA (third row), and SON (fourth row).



**Figure S5.** Same as Fig. S4, but for temperature forecasts.

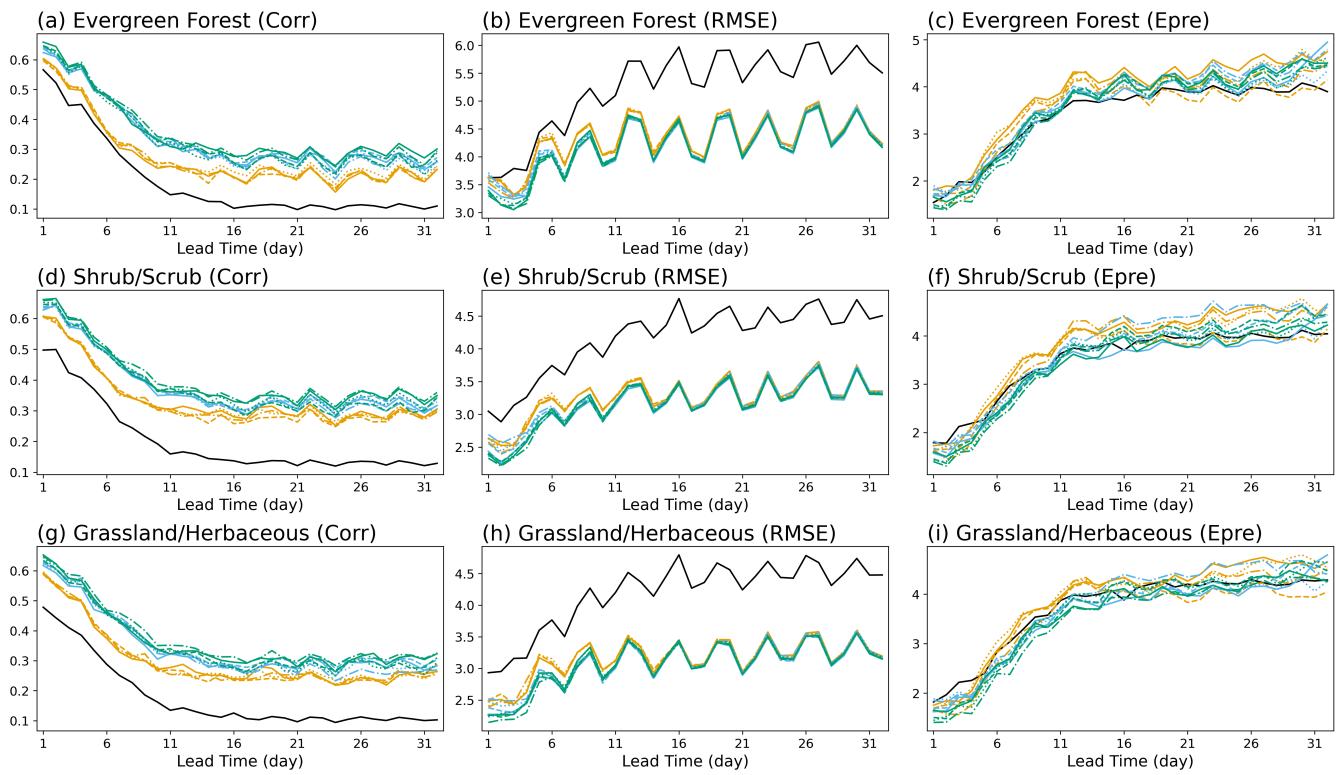


**Figure S6.** Land cover classification of the study area using the National Land Cover Database (NLCD).

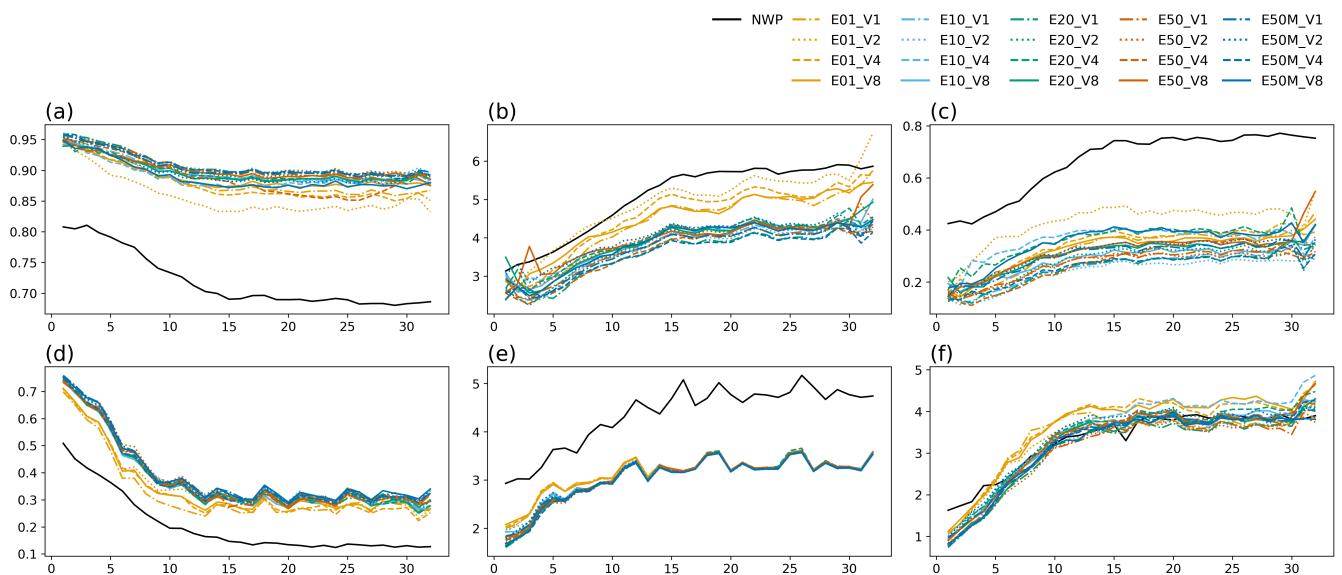


**Figure S7.** Benchmark scores for precipitation forecasts, similar to Fig. S4 but focusing on three major land cover classes: Shrub/Scrub, Evergreen Forest, and Grassland/Herbaceous.

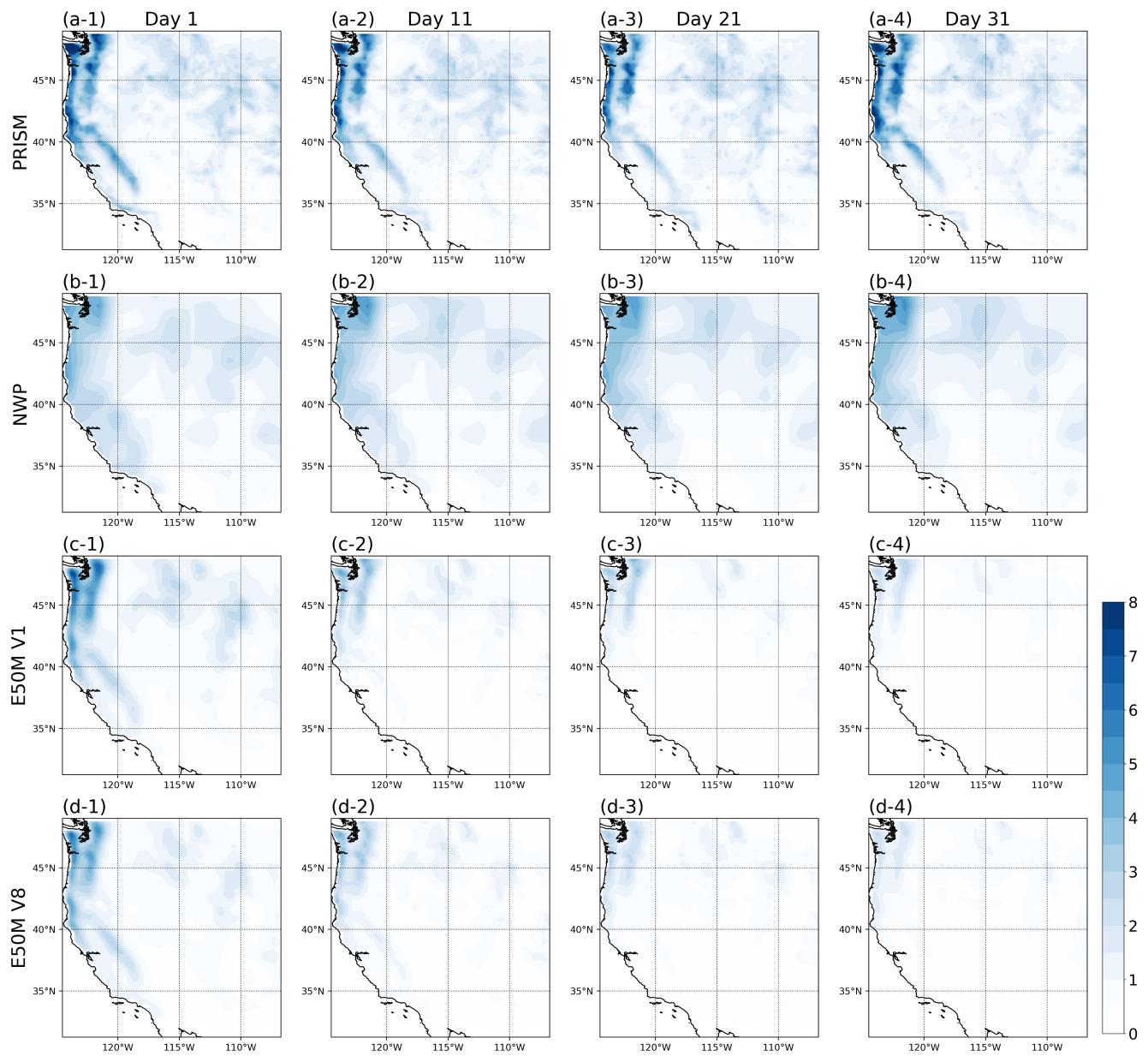
— NWP    — E01\_V1    — E50\_V1    — E50M\_V1  
 — E01\_V2    — E50\_V2    — E50M\_V2  
 — E01\_V4    — E50\_V4    — E50M\_V4  
 — E01\_V8    — E50\_V8    — E50M\_V8



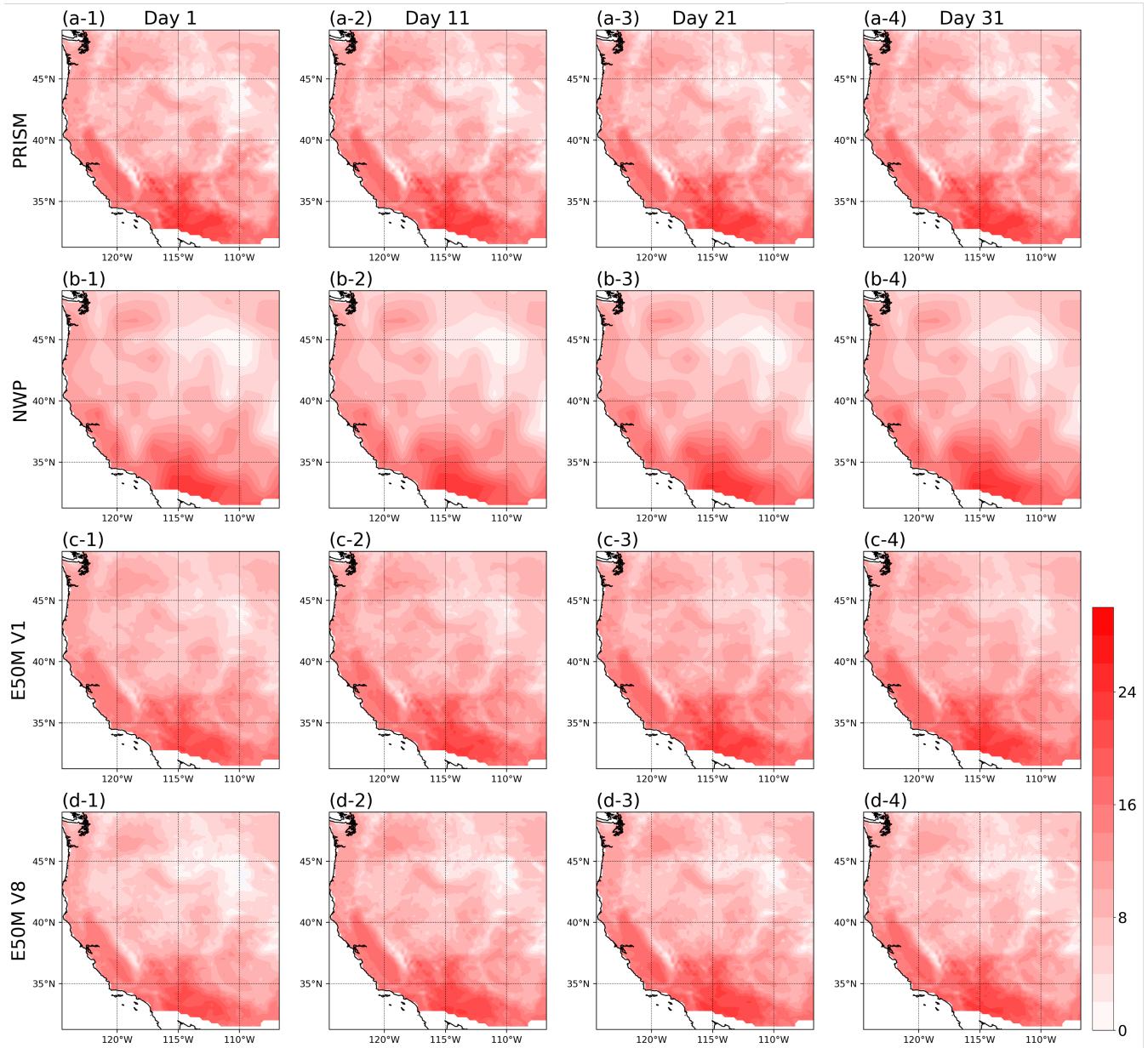
**Figure S8.** Same as Fig. S7, but for temperature forecasts.



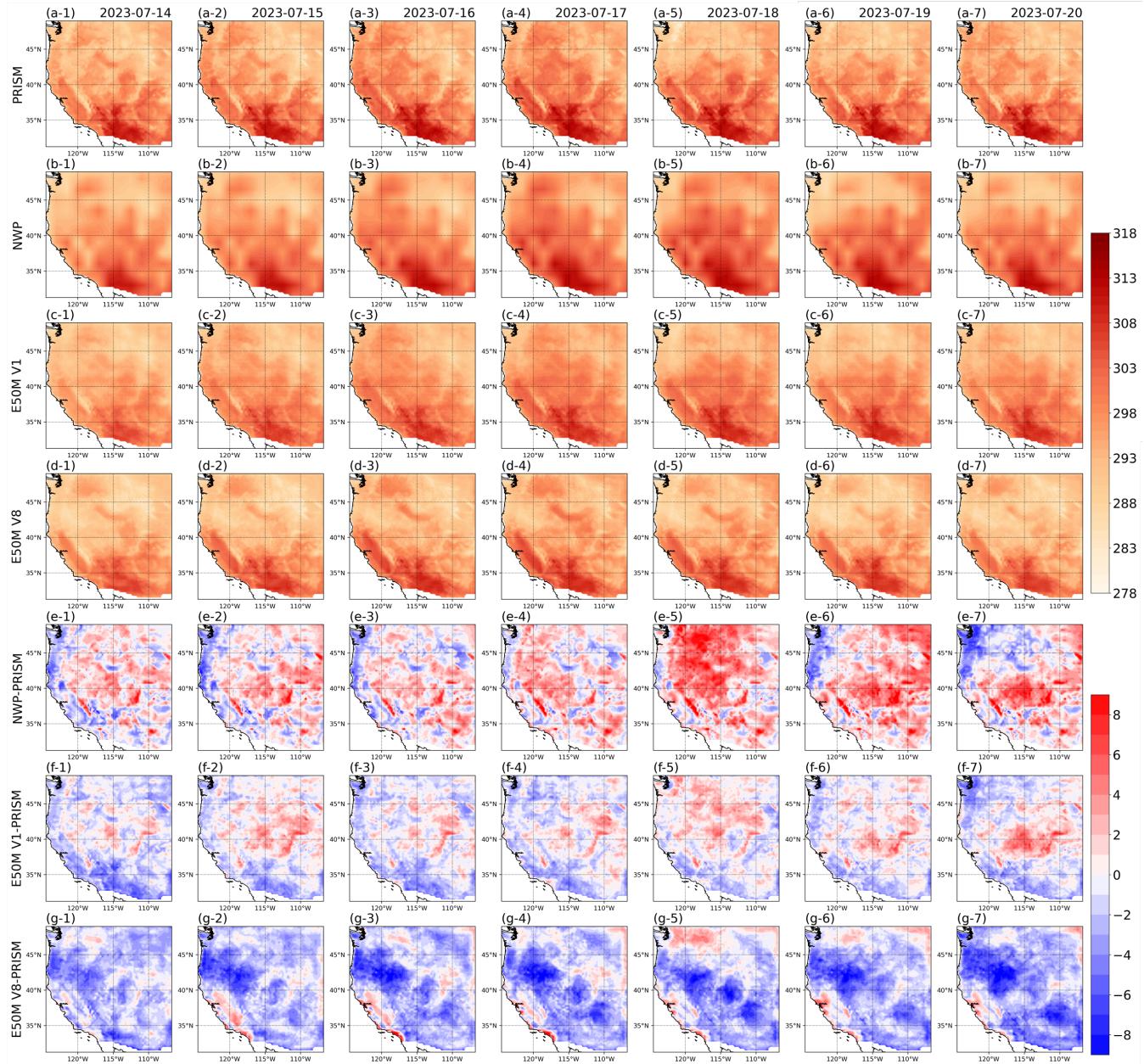
**Figure S9.** Same as Fig. S3, but for ERA5 training and test set, and using 10 and 20 ensemble members.



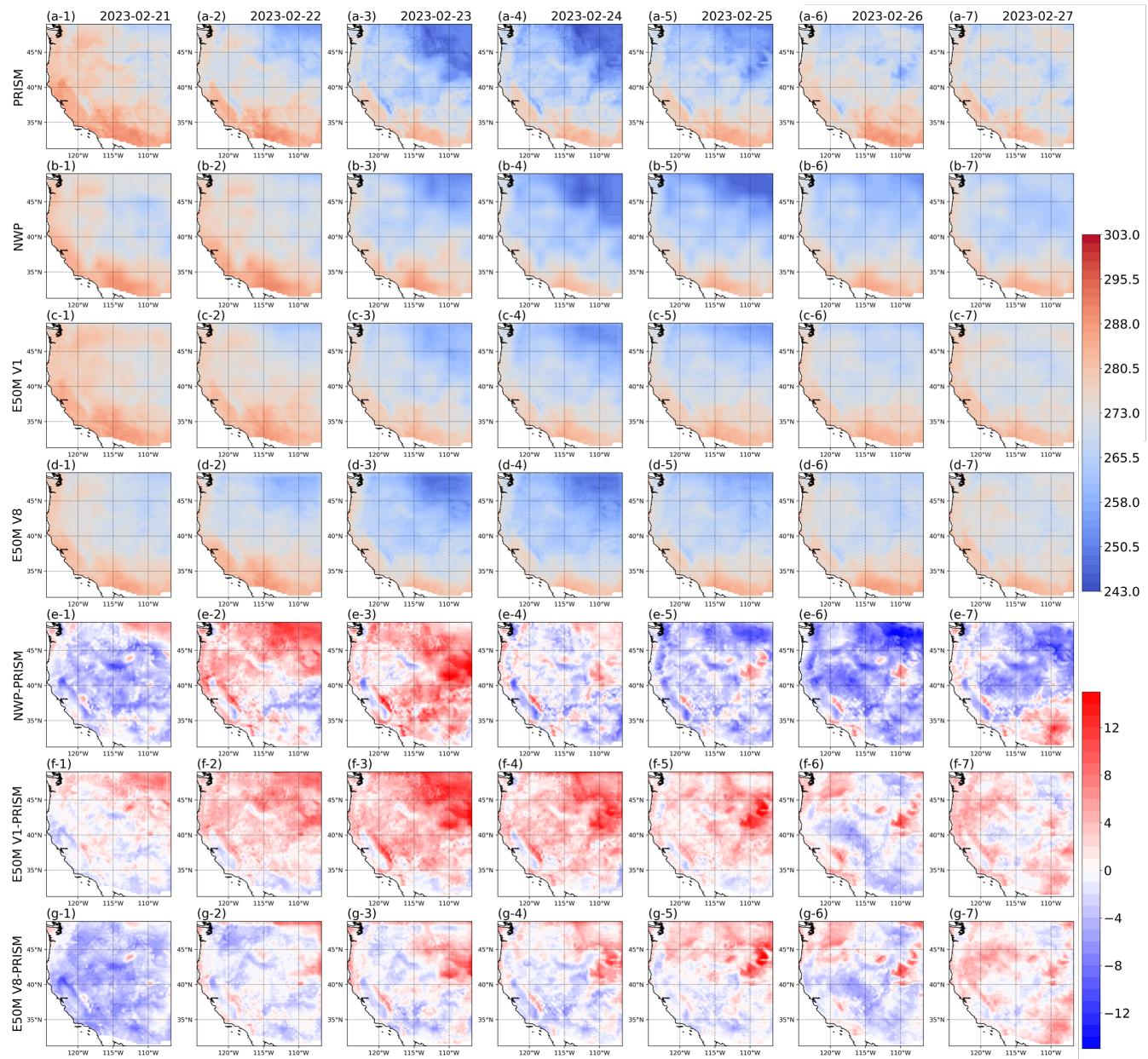
**Figure S10.** Comparison of precipitation forecasts (104 forecasts in 2023 are averaged) across lead times for the Western U.S. Rows represent (a) PRISM observations, (b) NWP forecasts, (c) 3D U-Net E50M V1 predictions, and (d) 3D U-Net E50M V8 predictions. Precipitation amounts (rows a-d) are shown using the scale in the upper color bar (0-8 mm/day). Columns show forecasts for Days 1, 11, 21, and 31.



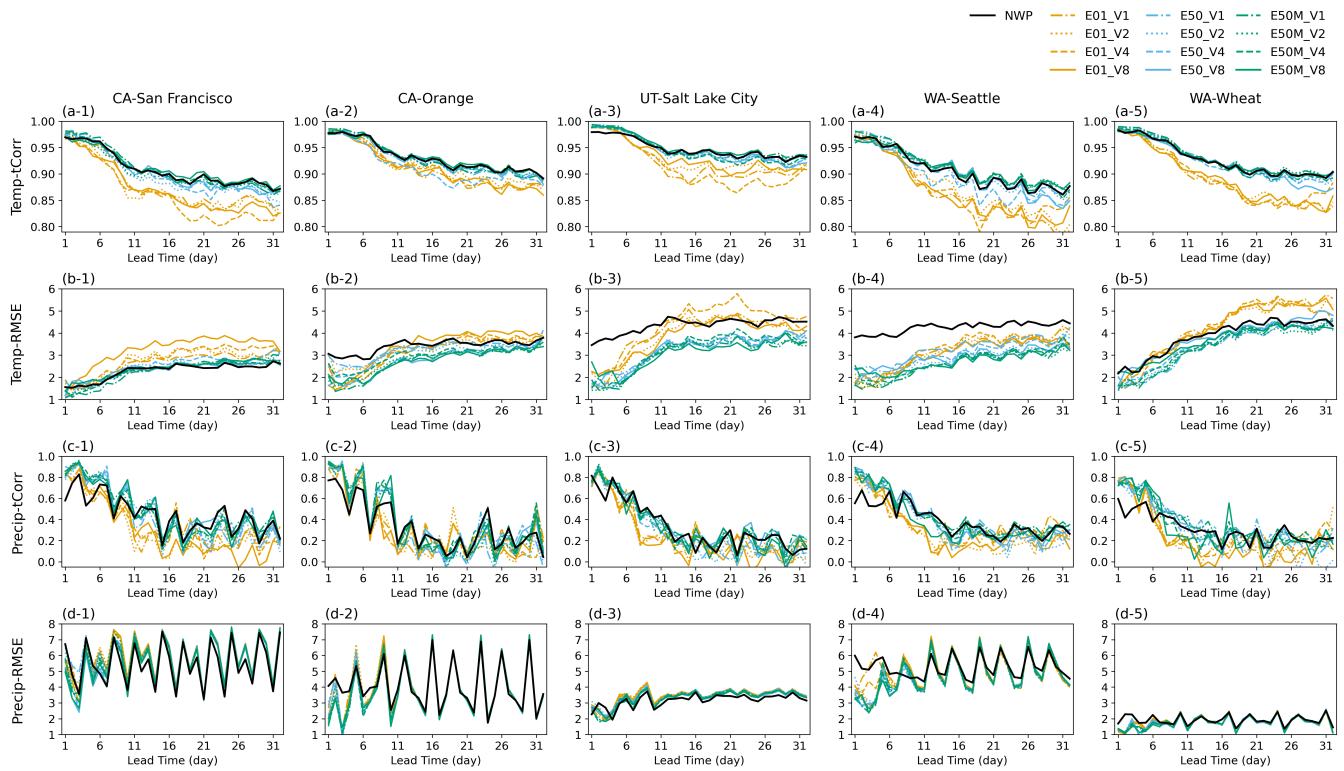
**Figure S11.** Same as Fig. S10, but for temperature forecasts.



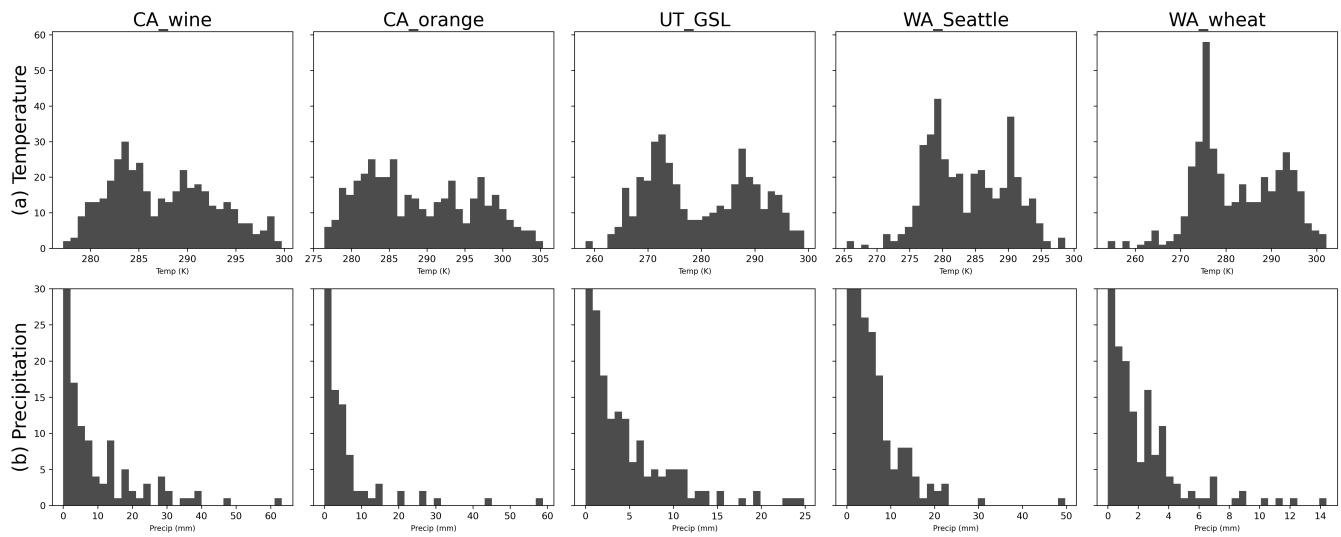
**Figure S12.** Daily temperature forecasts for the Western U.S. from July 14 to July 20, 2023, with initial condition on July 13. Rows represent (a) PRISM observations, (b) NWP forecasts, (c) 3D U-Net E50M V1 predictions, (d) 3D U-Net E50M V8 predictions, (e) differences between NWP and PRISM, (f) differences between E50M V1 and PRISM, and (g) differences between E50M V8 and PRISM. Columns show forecasts for date on the top.



**Figure S13.** Daily temperature forecasts for the Western U.S. from February 21 to February 27, 2023, with initial condition on February 20, 2023. Layout is the same as Figure S12.



**Figure S14.** Performance metrics for temperature (Temp) and precipitation (Precip) forecasts across five county-level regions in the Western U.S., comparing NWP and various 3D U-Net model configurations (E01, E50, E50M with V1-V8 input variables) over a 32-day lead time. Metrics include  $tCorr$  and RMSE. (a) Temperature correlation, (b) Temperature RMSE, (c) Precipitation correlation, (d) Precipitation RMSE. Columns represent different regions: (1) San Francisco, CA (2) Orange farm, CA, (3) Salt Lake City, UT, (4) Seattle, WA, and (5) Wheat farming area, WA.



**Figure S15.** Distribution of (a) temperature and (b) precipitation on five regions in Fig. S1.