

S1. Taylor diagrams

Figures S1 to S5 show Taylor diagrams comparing modeled net radiation, friction velocity, sensible heat flux, and latent heat flux against observations at the US-UMB, DE-HAI, US-Me2, US-MMS, and AU-Tum FLUXNET sites for all experiments. In these diagrams, the red star denotes the observations; model results plotted closer to this reference point indicate better performance, reflecting higher correlation, more realistic variability, and lower centered RMSE. The Taylor scores for all the experiments and FLUXNET stations are quantified in Table 3 in the main text.

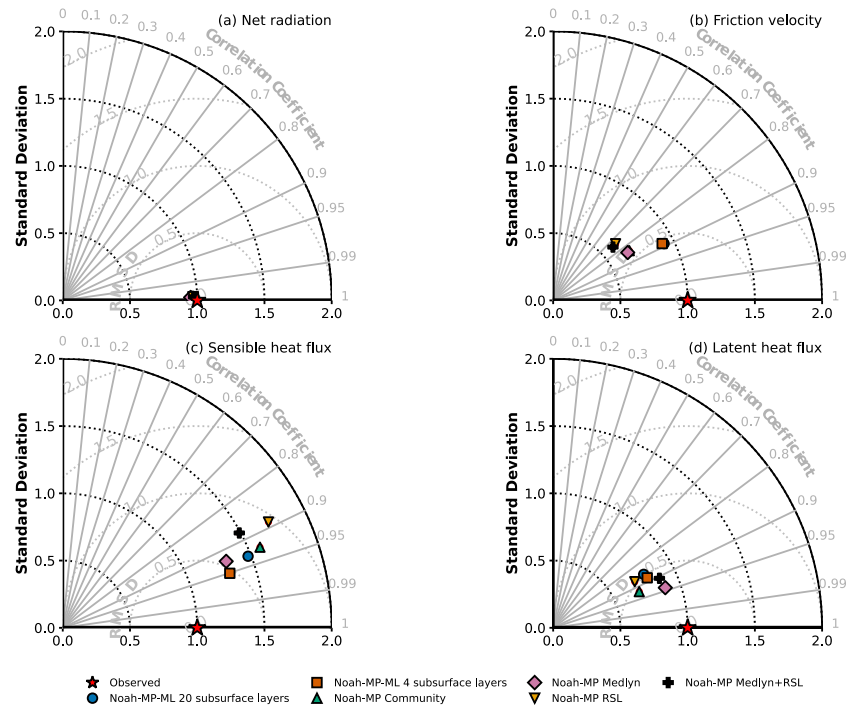


Figure S1. Taylor diagram comparing modeled net radiation, frictional velocity, sensible heat flux, and latent heat flux for different experiments with observations at the US-UMB FLUXNET station.

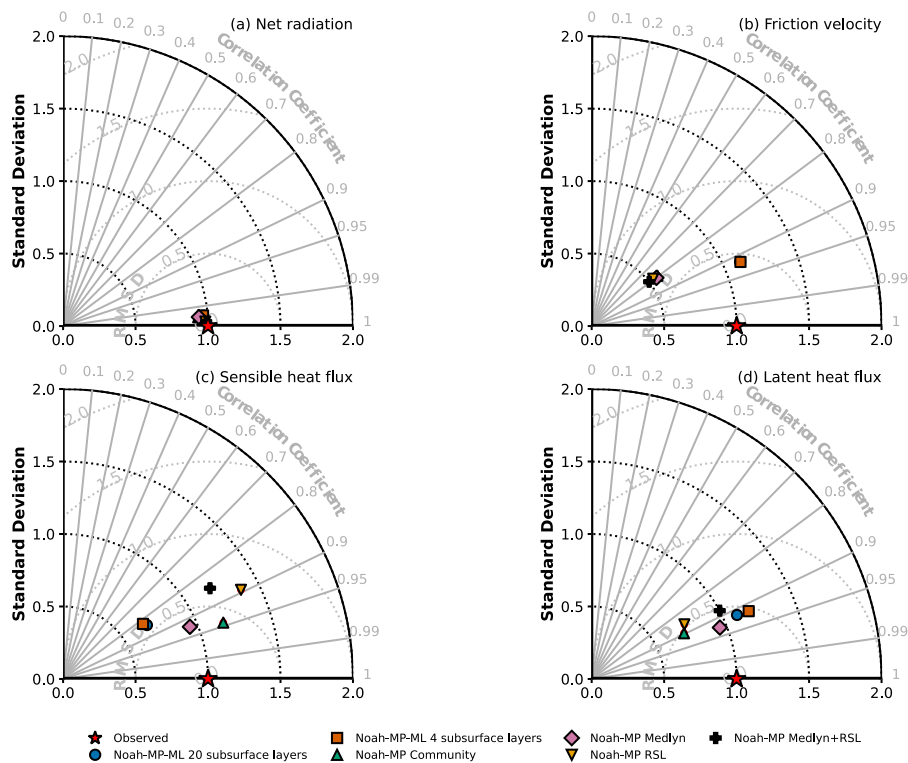


Figure S2. Same as Figure S1 but at DE-HAI FLUXNET station.

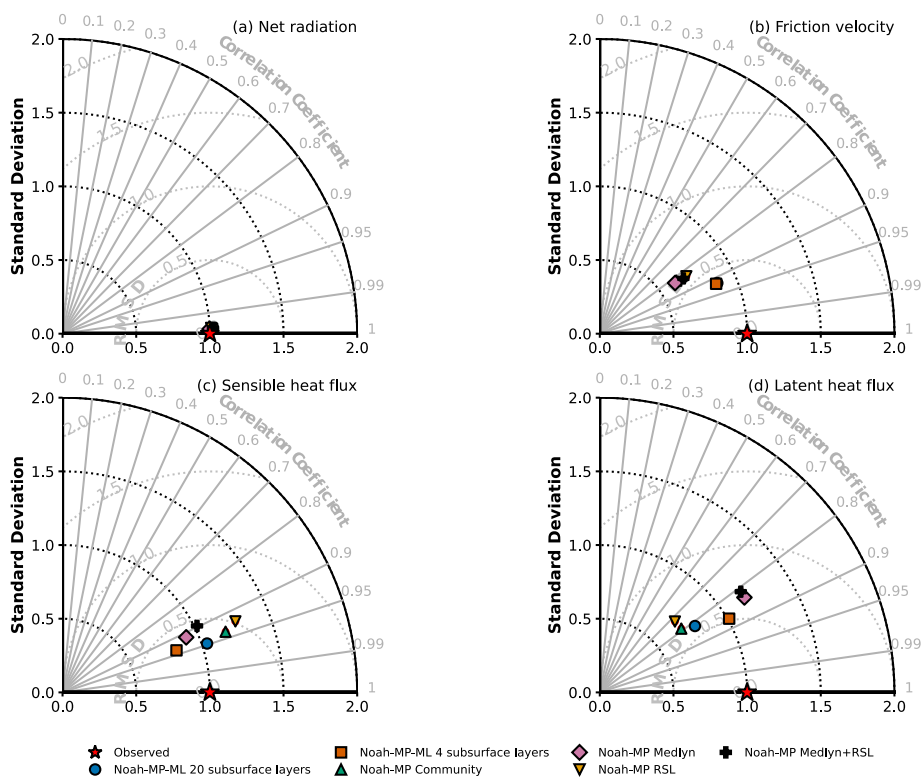


Figure S3. Same as Figure S1 but at the US-Me2 FLUXNET station.

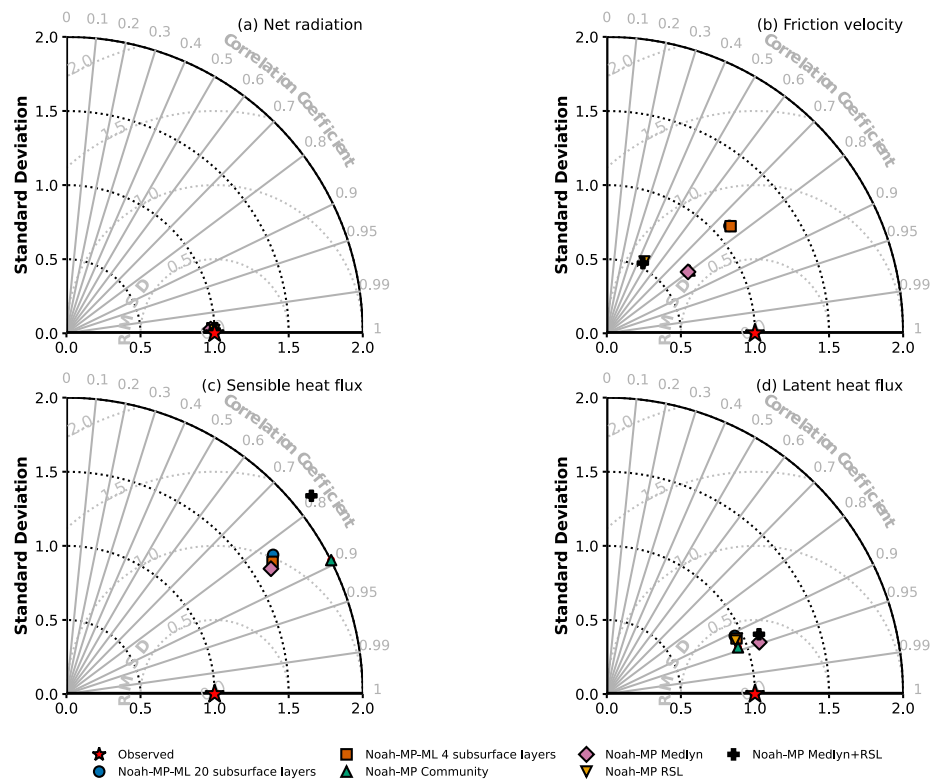


Figure S4. Same as Figure S1 but at the US-MMS FLUXNET station.

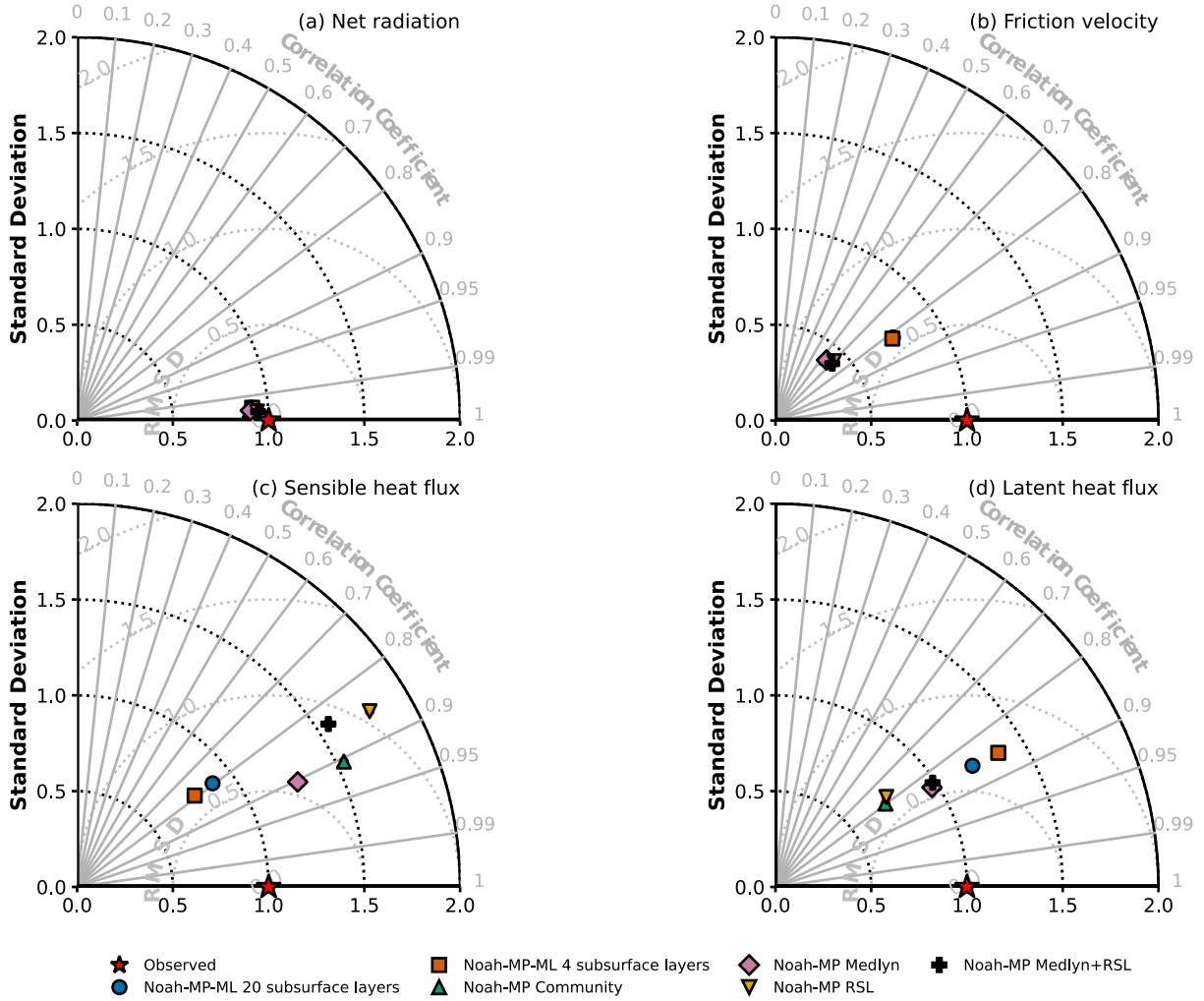


Figure S5. Same as Figure S1, but at the AU-Tum FLUXNET station.

S2. Diurnal profiles

Figure 8 in the main text shows the diurnal profiles of net radiation, frictional velocity, sensible heat flux and latent heat flux for the US-UMB FLUXNET station averaged over the simulation time period. Figure S6 to S9 show similar plots but for DE-HAI, US-Me2, US-MMS and AU-Tum FLUXNET sites.

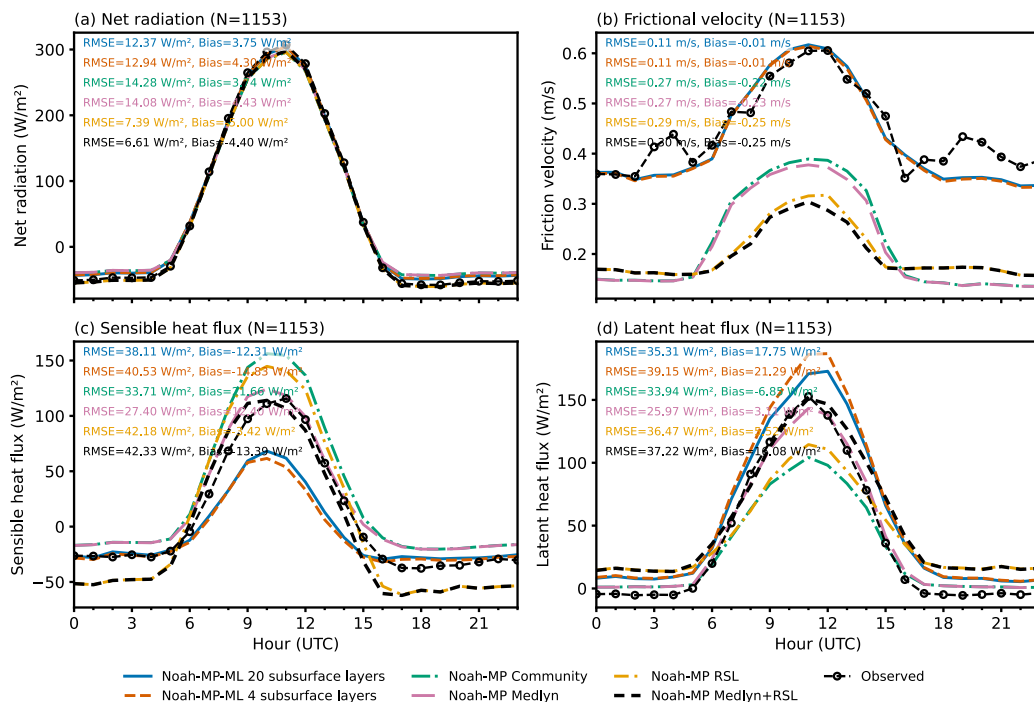


Figure S6. Averaged diurnal profiles of net radiation, frictional velocity, sensible heat flux, and latent heat flux for all the experiments at the DE-HAI Station.

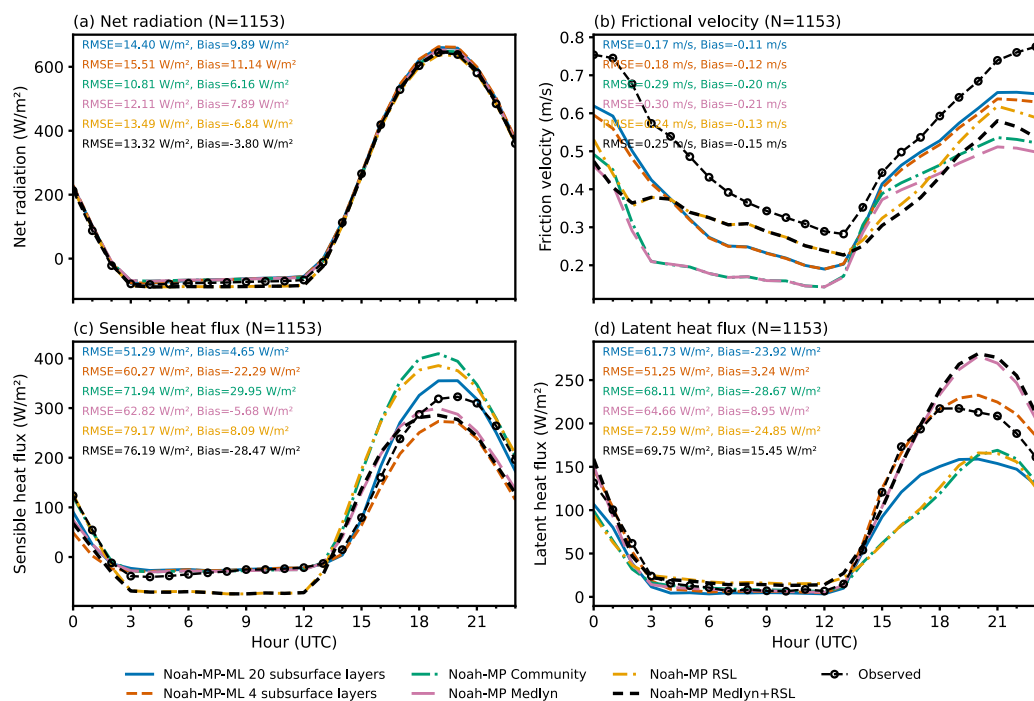


Figure S7. Same as Figure S6 but for US-Me2 FLUXNET station.

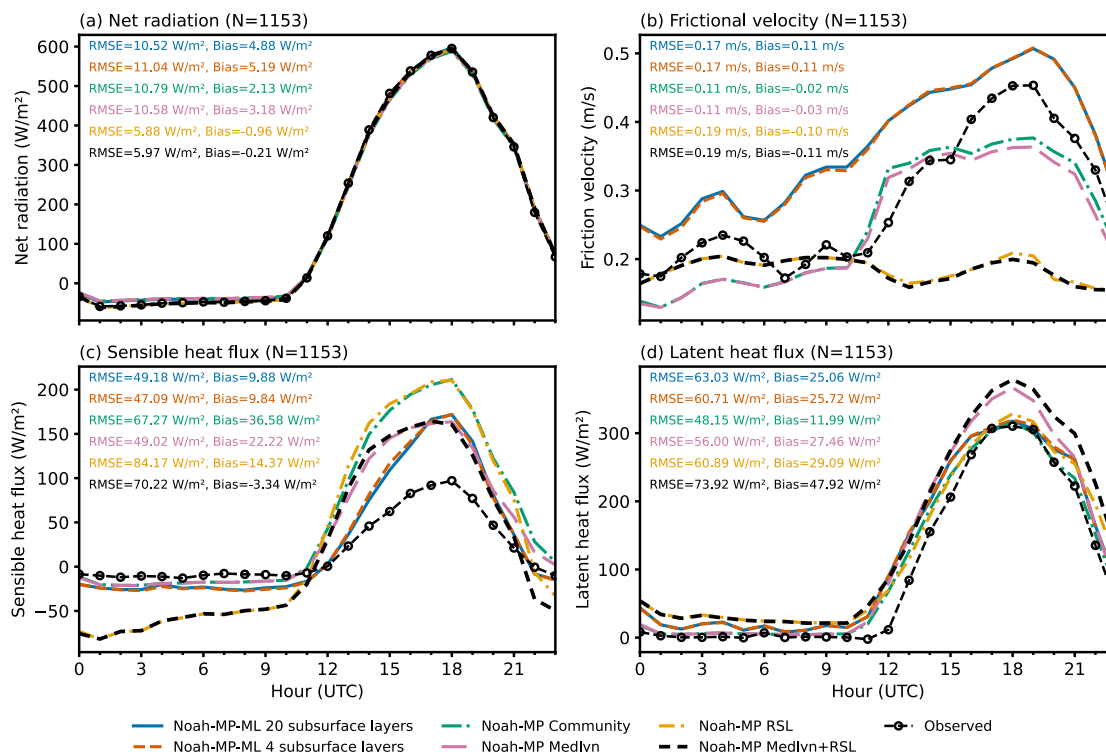


Figure S8. Same as Figure S6 but for the US-MMS FLUXNET station.

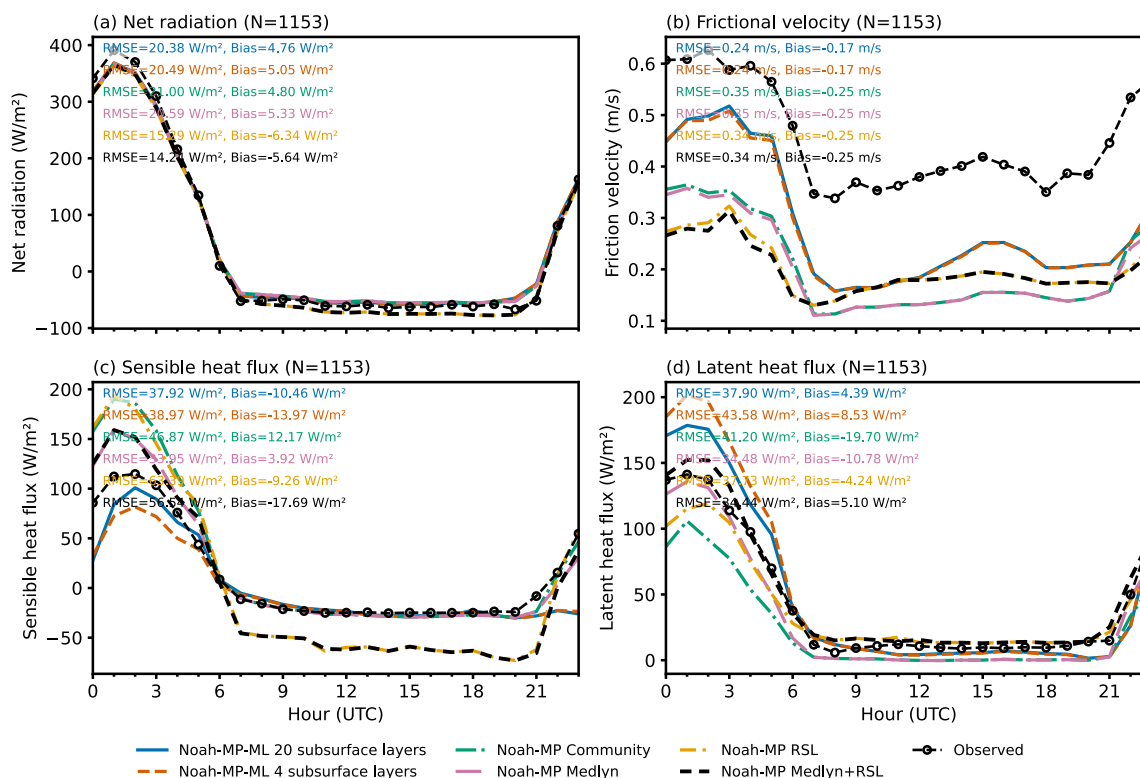


Figure S9. Same as Figure S6 but for AU-Tum FLUXNET station.

S3. Soil moisture time series

Figure 9 in the main text shows the comparison of modeled and measured soil liquid water content at the US-UMB FLUXNET station. Here, the soil liquid water content is the same as volumetric soil moisture as there is no soil ice. The modeled soil moisture at the grid midpoints were matched to the nearest observational depths in Figure 9. Figures S10 to S13 show similar plots for DE-HAI, US-Me2, US-MMS and, AU-Tum FLUXNET stations.

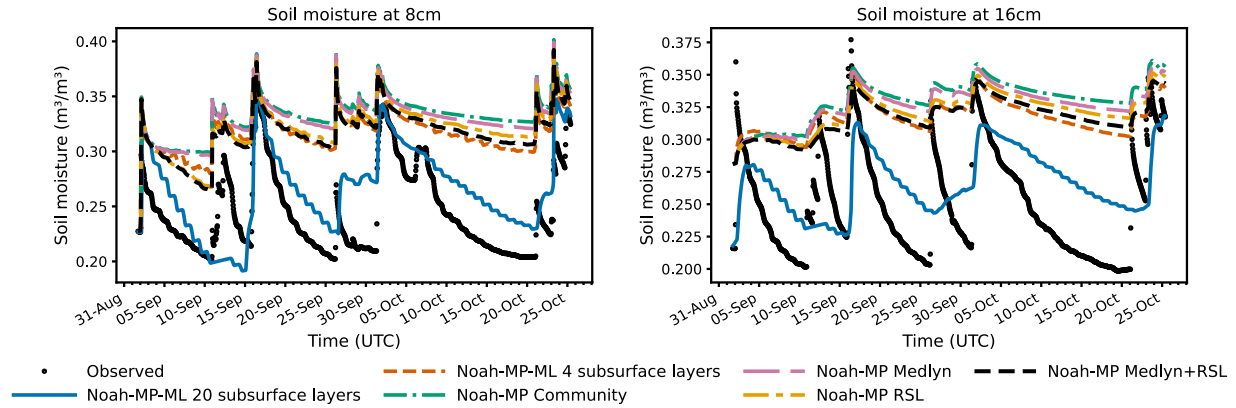


Figure S10. Soil liquid water (in this case, equals the volumetric soil moisture) simulation at different depths for various experiments conducted at the DE-HAI FLUXNET station. Note that the nearest model grid midpoint was chosen for comparison.

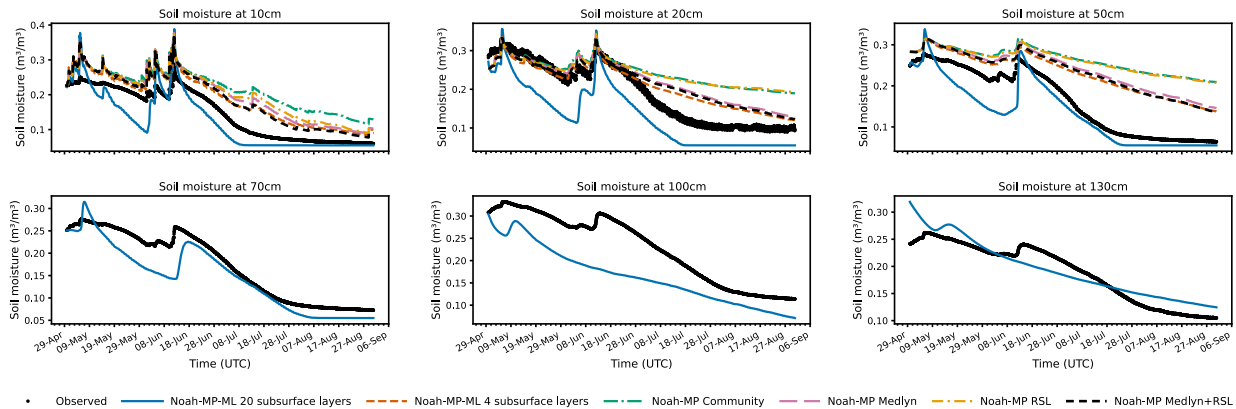


Figure S11. Same as Figure S10 but for US-Me2 FLUXNET station.

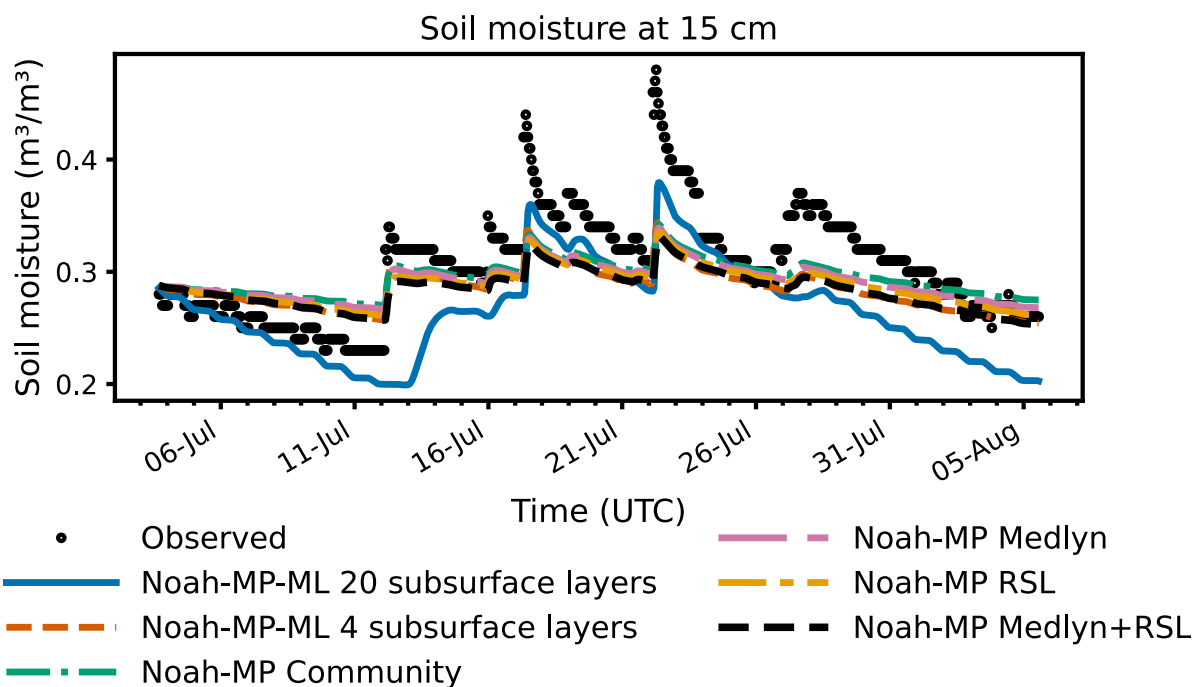


Figure S12. Same as Figure S10 but for the US-MMS FLUXNET station.

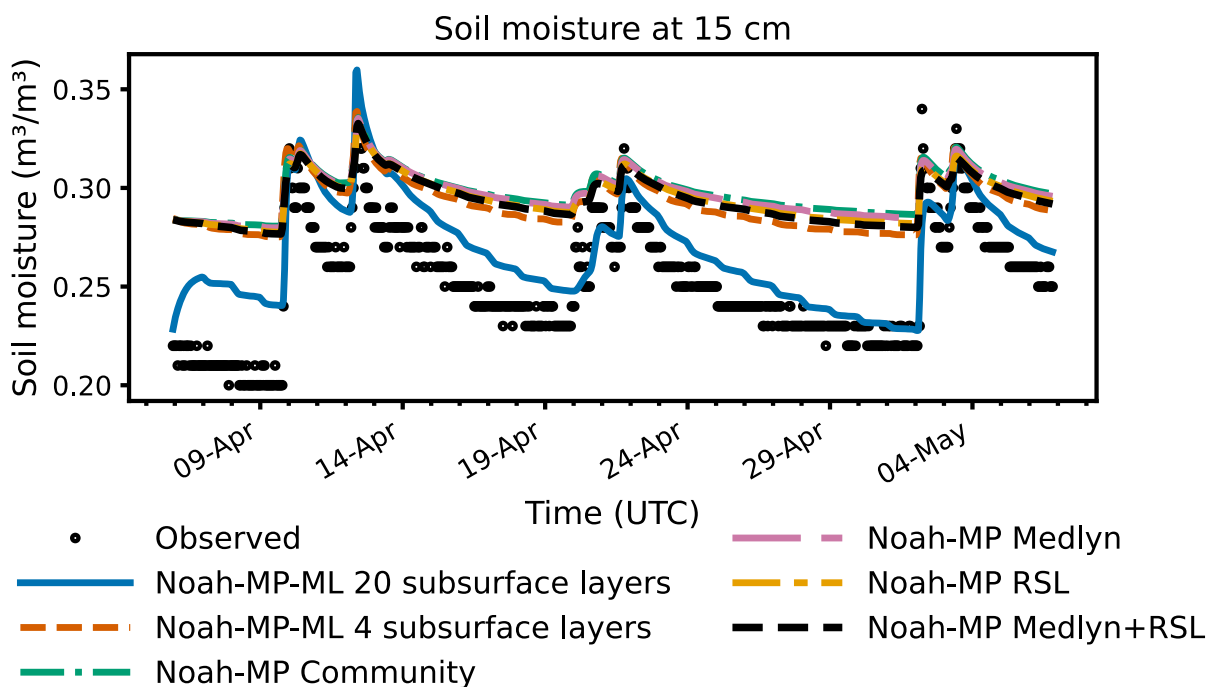


Figure S13. Same as Figure S10 but for AU-Tum FLUXNET station.

S4. Soil temperature time series

Figure 10 in the main text shows the comparison of modeled and measured soil temperature at the US-UMB FLUXNET station. The modeled soil temperature at the grid midpoints were matched to the nearest observational depths in Figure 10. Figures S14 to S17 show similar plots for DE-HAI, US-Me2, US-MMS, AU-Tum FLUXNET stations.

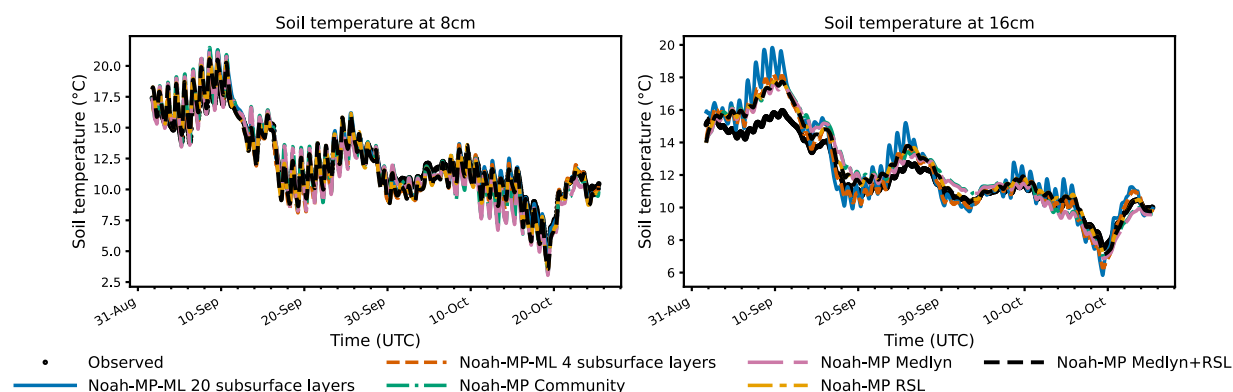


Figure S14. Soil temperature simulation at different depths for various experiments conducted at the DE-HAI FLUXNET station. Note that the nearest model grid midpoint was chosen for comparison.

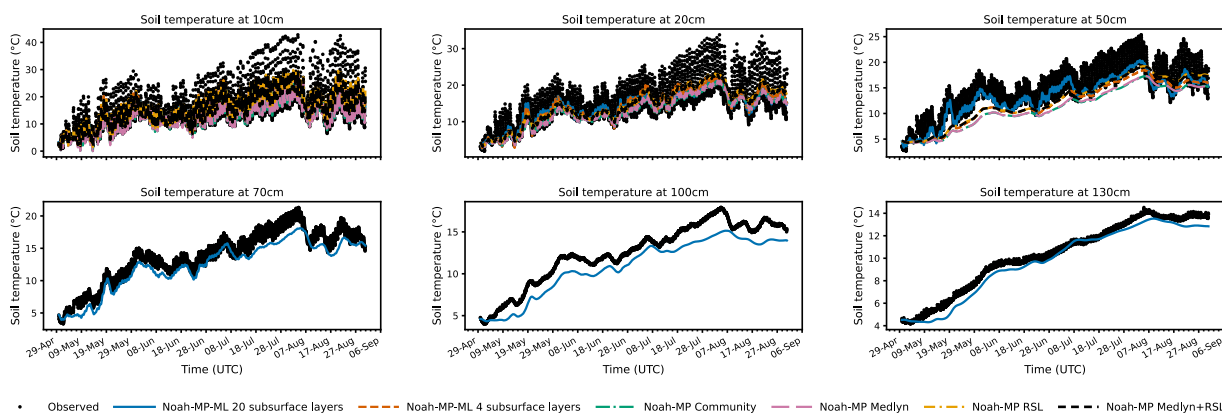


Figure S15. Same as Figure S14 but for the US-Me2 FLUXNET station.

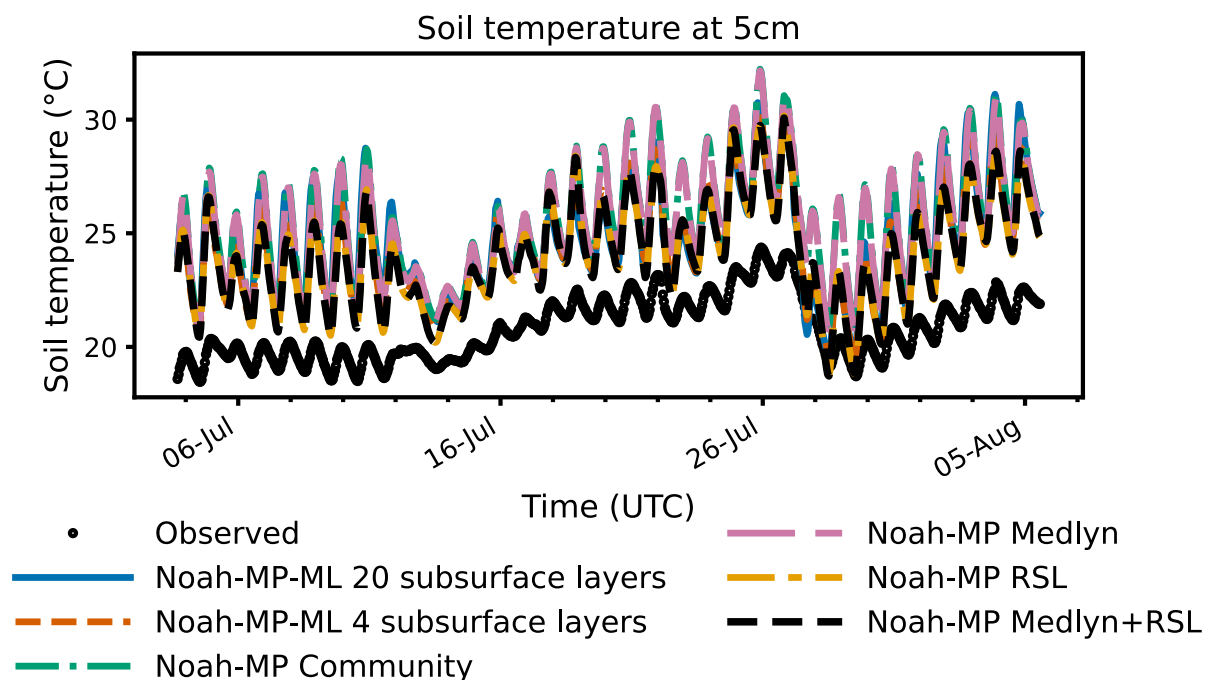


Figure S16. Same as Figure S14 but for the US-MMS FLUXNET station.

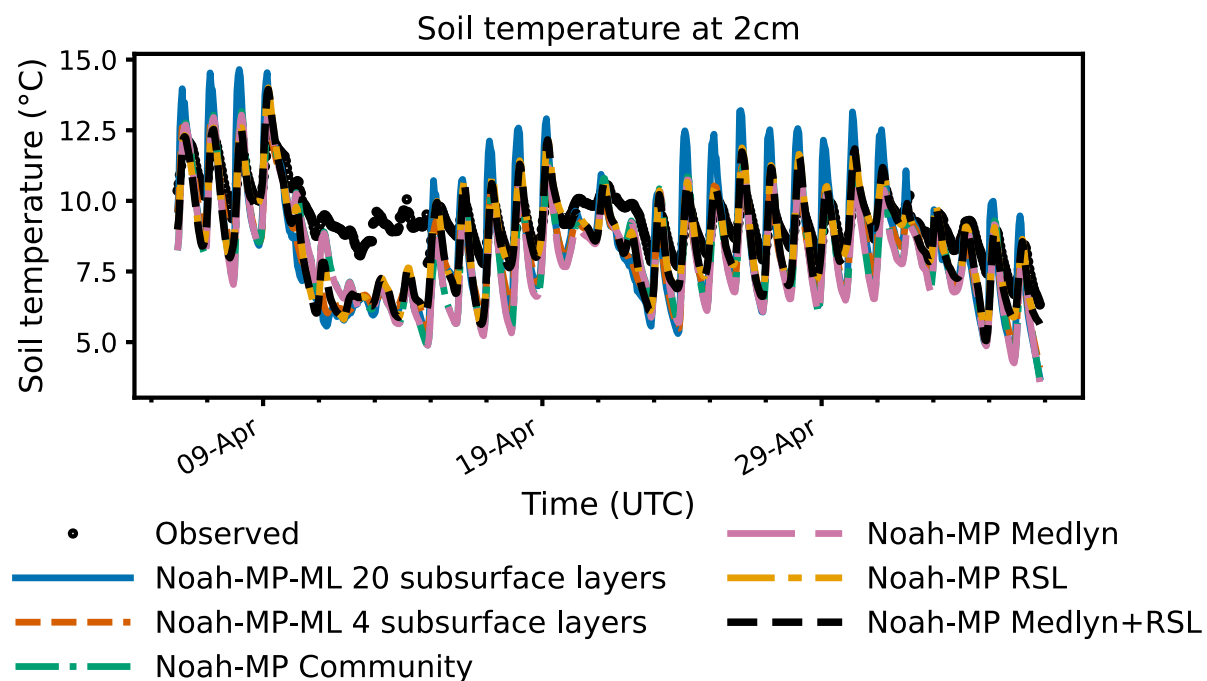


Figure S17. Same as Figure S14 but for the AU-Tum FLUXNET station.

S5. Sub-surface error metrics

Table 4 in the main text shows the error metrics for top-layer soil moisture and soil temperature. Here, we present a series of Tables that show the error metrics for soil moisture and temperature at all the FLUXNET sites and all the observational depths. Note that the nearest model grid midpoint was used for comparison, as mentioned before.

Table S1. Validation of soil moisture at different observational depths at the US-UMB FLUXNET station.

	Model experiment	RMSE (m ³ /m ³)	Bias (m ³ /m ³)	R	KGE
5cm	Noah-MP-ML ² 20 subsurface layers	0.02	0.01	0.72	0.04
	Noah-MP-ML ² 4 subsurface layers	0.05	0.04	0.63	0.14
	Noah-MP Community	0.05	0.05	0.62	0.06
	Noah-MP Medlyn	0.04	0.04	0.71	0.21
	Noah-MP RSL	0.05	0.04	0.65	0.12
	Noah-MP Medlyn+RSL	0.04	0.04	0.74	0.27
10cm	Noah-MP-ML ² 20 subsurface layers	0.01	0.00	0.91	0.50
15cm	Noah-MP-ML ² 20 subsurface layers	0.02	-0.02	0.93	0.54
30cm	Noah-MP-ML ² 20 subsurface layers	0.01	-0.01	0.94	0.56
	Noah-MP-ML ² 4 subsurface layers	0.03	0.03	0.54	0.35
	Noah-MP Community	0.03	0.03	0.72	0.28
	Noah-MP Medlyn	0.02	0.02	0.83	0.46
	Noah-MP RSL	0.03	0.03	0.77	0.32
	Noah-MP Medlyn+RSL	0.02	0.02	0.86	0.50
60cm	Noah-MP-ML ² 20 subsurface layers	0.02	0.01	0.54	0.46
	Noah-MP-ML ² 4 subsurface layers	0.02	0.02	0.55	0.39
	Noah-MP Community	0.02	0.02	0.35	0.21
	Noah-MP Medlyn	0.01	0.01	0.91	0.77
	Noah-MP RSL	0.02	0.02	0.47	0.31
	Noah-MP Medlyn+RSL	0.01	0.00	0.92	0.88
100cm	Noah-MP-ML ² 20 subsurface layers	0.00	0.00	0.98	0.61

Table S2. Same as Table S1 but for DE-HAI FLUXNET station.

	Model experiment	RMSE (m ³ /m ³)	Bias (m ³ /m ³)	R	KGE
8cm	Noah-MP-ML ² 20 subsurface layers	0.03	0.02	0.74	0.71
	Noah-MP-ML ² 4 subsurface layers	0.08	0.07	0.73	0.27
	Noah-MP Community	0.09	0.09	0.56	0.15
	Noah-MP Medlyn	0.09	0.08	0.60	0.17
	Noah-MP RSL	0.08	0.08	0.63	0.26
	Noah-MP Medlyn+RSL	0.08	0.07	0.67	0.28
16cm	Noah-MP-ML ² 20 subsurface layers	0.04	0.02	0.44	0.29
	Noah-MP-ML ² 4 subsurface layers	0.07	0.07	0.75	0.17
	Noah-MP Community	0.09	0.08	0.44	0.05
	Noah-MP Medlyn	0.08	0.08	0.49	0.07
	Noah-MP RSL	0.08	0.07	0.49	0.08
	Noah-MP Medlyn+RSL	0.08	0.07	0.54	0.10

Table S3. Same as Table S1 but for US-Me2 FLUXNET station.

	Model experiment	RMSE (m ³ /m ³)	Bias (m ³ /m ³)	R	KGE
10cm	Noah-MP-ML ² 20 subsurface layers	0.04	-0.02	0.91	0.64
	Noah-MP-ML ² 4 subsurface layers	0.05	0.04	0.97	0.62
	Noah-MP Community	0.08	0.07	0.94	0.32
	Noah-MP Medlyn	0.06	0.05	0.97	0.55
	Noah-MP RSL	0.06	0.06	0.95	0.49
	Noah-MP Medlyn+RSL	0.05	0.04	0.98	0.65
20cm	Noah-MP-ML ² 20 subsurface layers	0.07	-0.06	0.95	0.45
	Noah-MP-ML ² 4 subsurface layers	0.03	0.02	0.97	0.62
	Noah-MP Community	0.07	0.05	0.95	0.30
	Noah-MP Medlyn	0.04	0.03	0.96	0.56
	Noah-MP RSL	0.07	0.05	0.96	0.29
	Noah-MP Medlyn+RSL	0.04	0.03	0.96	0.59
50cm	Noah-MP-ML ² 20 subsurface layers	0.04	-0.03	0.94	0.77
	Noah-MP-ML ² 4 subsurface layers	0.07	0.07	0.97	0.32
	Noah-MP Community	0.11	0.10	0.96	0.03
	Noah-MP Medlyn	0.08	0.07	0.96	0.26
	Noah-MP RSL	0.11	0.10	0.96	0.04
	Noah-MP Medlyn+RSL	0.08	0.07	0.96	0.31
70cm	Noah-MP-ML ² 20 subsurface layers	0.04	-0.03	0.95	0.80
100cm	Noah-MP-ML ² 20 subsurface layers	0.07	-0.06	0.93	0.69
130cm	Noah-MP-ML ² 20 subsurface layers	0.02	0.01	0.91	0.88

Table S4. Same as Table S1 but for US-MMS FLUXNET station.

Model experiment		RMSE (m ³ /m ³)	Bias (m ³ /m ³)	R	KGE
15cm	Noah-MP-ML ² 20 subsurface layers	0.05	-0.04	0.77	0.73
	Noah-MP-ML ² 4 subsurface layers	0.04	-0.02	0.88	0.40
	Noah-MP Community	0.03	-0.01	0.93	0.34
	Noah-MP Medlyn	0.04	-0.01	0.91	0.35
	Noah-MP RSL	0.04	-0.02	0.90	0.36
	Noah-MP Medlyn+RSL	0.04	-0.02	0.86	0.37

Table S5. Same as Table S1 but for AU-Tum FLUXNET station.

Model experiment		RMSE (m ³ /m ³)	Bias (m ³ /m ³)	R	KGE
15cm	Noah-MP-ML ² 20 subsurface layers	0.02	0.02	0.88	0.79
	Noah-MP-ML ² 4 subsurface layers	0.04	0.04	0.94	0.35
	Noah-MP Community	0.05	0.05	0.96	0.29
	Noah-MP Medlyn	0.05	0.05	0.96	0.30
	Noah-MP RSL	0.05	0.04	0.95	0.30
	Noah-MP Medlyn+RSL	0.05	0.04	0.94	0.31

Table S6. Validation of soil temperature at different observational depths at the US-UMB FLUXNET station.

	Model experiment	RMSE (K)	Bias (K)	R
5cm	Noah-MP-ML ² 20 subsurface layers	2.48	2.01	0.93
	Noah-MP-ML ² 4 subsurface layers	2.91	2.53	0.92
	Noah-MP Community	2.74	2.40	0.90
	Noah-MP Medlyn	2.65	2.30	0.90
	Noah-MP RSL	2.93	2.59	0.89
	Noah-MP Medlyn+RSL	2.84	2.50	0.90
10cm	Noah-MP-ML ² 20 subsurface layers	1.87	1.55	0.93
15cm	Noah-MP-ML ² 20 subsurface layers	1.54	1.36	0.95
30cm	Noah-MP-ML ² 20 subsurface layers	1.64	1.58	0.95
	Noah-MP-ML ² 4 subsurface layers	2.76	2.42	0.78
	Noah-MP Community	2.33	2.21	0.88
	Noah-MP Medlyn	2.23	2.12	0.89
	Noah-MP RSL	2.52	2.36	0.84
	Noah-MP Medlyn+RSL	2.44	2.27	0.84
60cm	Noah-MP-ML ² 20 subsurface layers	1.73	1.69	0.93
	Noah-MP-ML ² 4 subsurface layers	2.37	2.25	0.75
	Noah-MP Community	2.21	2.12	0.73
	Noah-MP Medlyn	2.13	2.04	0.75
	Noah-MP RSL	2.32	2.21	0.69
	Noah-MP Medlyn+RSL	2.26	2.15	0.70
100cm	Noah-MP-ML ² 20 subsurface layers	1.31	1.21	0.59

Table S7. Same as Table S6 but for the DE-HAI FLUXNET station.

	Model experiment	RMSE (K)	Bias (K)	R
8cm	Noah-MP-ML ² 20 subsurface layers	0.69	0.06	0.99
	Noah-MP-ML ² 4 subsurface layers	0.87	-0.36	0.99
	Noah-MP Community	1.06	-0.19	0.98
	Noah-MP Medlyn	1.06	-0.28	0.98
	Noah-MP RSL	0.81	-0.12	0.99
	Noah-MP Medlyn+RSL	0.80	-0.14	0.99
16cm	Noah-MP-ML ² 20 subsurface layers	1.23	0.59	0.97
	Noah-MP-ML ² 4 subsurface layers	0.79	0.29	0.99
	Noah-MP Community	0.93	0.53	0.98
	Noah-MP Medlyn	0.89	0.45	0.98
	Noah-MP RSL	0.81	0.56	0.99
	Noah-MP Medlyn+RSL	0.80	0.54	0.99

Table S8. Same as Table S6 but for the US-Me2 FLUXNET station.

	Model experiment	RMSE (K)	Bias (K)	R
10cm	Noah-MP-ML ² 20 subsurface layers	5.36	-1.49	0.75
	Noah-MP-ML ² 4 subsurface layers	4.41	-1.31	0.84
	Noah-MP Community	4.77	-2.26	0.85
	Noah-MP Medlyn	4.74	-2.18	0.85
	Noah-MP RSL	4.41	-0.37	0.83
	Noah-MP Medlyn+RSL	4.51	-0.43	0.82
20cm	Noah-MP-ML ² 20 subsurface layers	4.10	-1.59	0.77
	Noah-MP-ML ² 4 subsurface layers	4.01	-1.50	0.78
	Noah-MP Community	4.62	-2.61	0.77
	Noah-MP Medlyn	4.60	-2.55	0.76
	Noah-MP RSL	3.94	-0.94	0.77
	Noah-MP Medlyn+RSL	3.96	-1.01	0.77
50cm	Noah-MP-ML ² 20 subsurface layers	2.60	-1.57	0.90
	Noah-MP-ML ² 4 subsurface layers	3.62	-2.78	0.87
	Noah-MP Community	4.40	-3.67	0.85
	Noah-MP Medlyn	4.35	-3.61	0.86
	Noah-MP RSL	3.35	-2.30	0.86
	Noah-MP Medlyn+RSL	3.37	-2.35	0.86
70cm	Noah-MP-ML ² 20 subsurface layers	1.80	-1.52	0.97
100cm	Noah-MP-ML ² 20 subsurface layers	1.74	-1.62	0.99
130cm	Noah-MP-ML ² 20 subsurface layers	0.60	-0.48	0.99

Table S9. Same as Table S6 but for US-MMS FLUXNET station.

	Model experiment	RMSE (K)	Bias (K)	R
5cm	Noah-MP-ML ² 20 subsurface layers	4.27	3.91	0.69
	Noah-MP-ML ² 4 subsurface layers	3.85	3.58	0.81
	Noah-MP Community	4.90	4.64	0.81
	Noah-MP Medlyn	4.81	4.55	0.81
	Noah-MP RSL	3.50	3.24	0.84
	Noah-MP Medlyn+RSL	3.50	3.24	0.84

Table S10. Same as Table S6 but for AU-Tum FLUXNET station.

Model experiment		RMSE (K)	Bias (K)	R
2cm	Noah-MP-ML ² 20 subsurface layers	1.80	-0.89	0.73
	Noah-MP-ML ² 4 subsurface layers	1.47	-1.10	0.86
	Noah-MP Community	1.56	-1.16	0.87
	Noah-MP Medlyn	1.59	-1.22	0.88
	Noah-MP RSL	1.32	-0.74	0.79
	Noah-MP Medlyn+RSL	1.32	-0.77	0.80