

Supplement of Adv. Sci. Res., 18, 7–20, 2021
<https://doi.org/10.5194/asr-18-7-2021-supplement>
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Advances in
Science & Research
Open Access Proceedings

Supplement of

Multi-sensor analysis of monthly gridded snow precipitation on alpine glaciers

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SUPPLEMENTARY MATERIAL

1 Extracting daily changes in SWE from a cumulative time series

Figure S1a shows the cumulative time series of SWE observed by the cosmic ray sensor on Plaine Morte. To obtain daily changes in SWE (ΔSWE_d), we first take an average centered around 06:00 UTC. The daily change is then considered the difference between these two days d and $d+1$ and is reported on day d . Figure S1b shows the hourly snowfall amounts. The daily snowfall totals include all hourly sums from 06:00 UTC of day d to 06:00 $d+1$ and is reported for day d . Figure S1 shows the daily changes of SWE, which can also be negative (e.g., 6 December 2018).

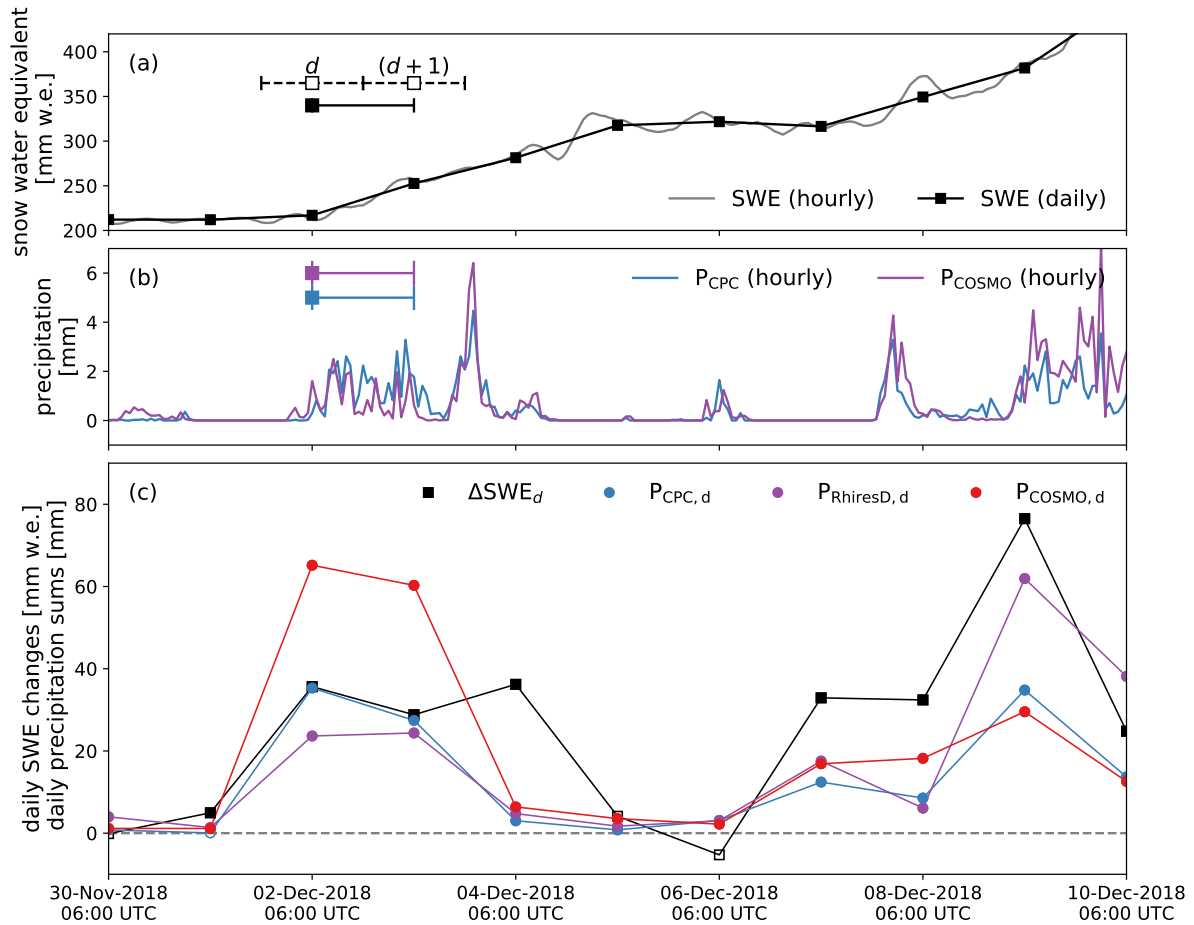


Figure S1. (a) Cumulative time series of SWE by the cosmic ray sensor on Plaine Morte, (b) hourly precipitation and (c) daily changes in SWE and daily precipitation sums. The dashed black bars in (a) show the period with the centered average (white box). The solid black bars in (a) and the colored bars in (b) show the time period that is considered for precipitation sums and daily SWE (see text for further information).

Table S1. Meteorological conditions including the onset of the snowpack, the number of days per season, the end-of-season SWE and precipitation totals, daily mean precipitation amounts, daily air temperature (mean, minimum, maximum), wind speed (mean) and wind gusts (mean, maximum), daily relative air humidity (mean, maximum, minimum) and daily mean incoming shortwave radiation. All the meteorological parameters are averaged over the accumulation season, i.e., from the onset of the snowpack to 30 April provided that data was available.

	Plaine Morte				Findelen	
	2016/17	2017/18	2018/19	2019/20	2018/19	2019/20
Winter season						
Onset of snowpack	22 Oct 2016	5 Dec 2017	27 Oct 2018	01 Nov 2019	09 Oct 2018	12 Oct 2019
Days [d]	190	141	185	181	203	201
SWE _w [mm w.e.]	1228	1754	1721	1570	1344	1073
P _{RhiresD,w} [mm]	786	1063	998	1037	968	937
P _{CPC,w} [mm]	580	769	650	782	469	454
P _{CPC_AF,w} [mm]	1440	1958	1622	1948	1723	1586
P _{COSMO,w} [mm]	762	863	847	951	951	873
Daily mean P _{RhiresD,d} [mm]	4.1	7.5	5.4	5.7	4.8	4.6
Daily mean P _{CPC,d} [mm]	3.0	5.4	3.5	4.3	2.3	2.3
Daily mean P _{CPC_AF,d} [mm]	7.5	13.6	8.7	10.8	8.5	7.9
Daily mean P _{COSMO,d} [mm]	4.0	6.0	4.5	5.3	4.7	4.3
Daily mean air temperature [°C]	-5.3	-7.9	-6.3	-5.2	-7.6	-6.3
Daily maximum air temperature [°C]	-1.4	-3.2	-2.4	-1.4	-3.9	-2.4
Daily minimum air temperature [°C]	-9.3	-13.0	-10.8	-9.4	-11.1	-9.9
Daily mean wind speed [m s ⁻¹]	3.4	4.2	3.5	3.5	3.9	3.9
Daily maximum wind gust [m s ⁻¹]	11.2	14.2	11.9	11.5	12.5	12.1
Daily mean wind gust [m s ⁻¹]	6.9	9.2	7.5	7.2	7.6	7.4
Daily mean relative humidity [%]	73.4	88.4	79.3	80.6	65.4	68.1
Daily maximum relative humidity [%]	89.0	97.9	92.5	92.6	83.3	85.9
Daily minimum relative humidity [%]	53.8	72.8	60.6	64.2	43.9	47.2
Daily mean direct shortwave radiation [W m ⁻²]	-	143	162	165	144	153

2 Sensitivity of the end-of-season bias with varying thresholds

2.1 Plaine Morte

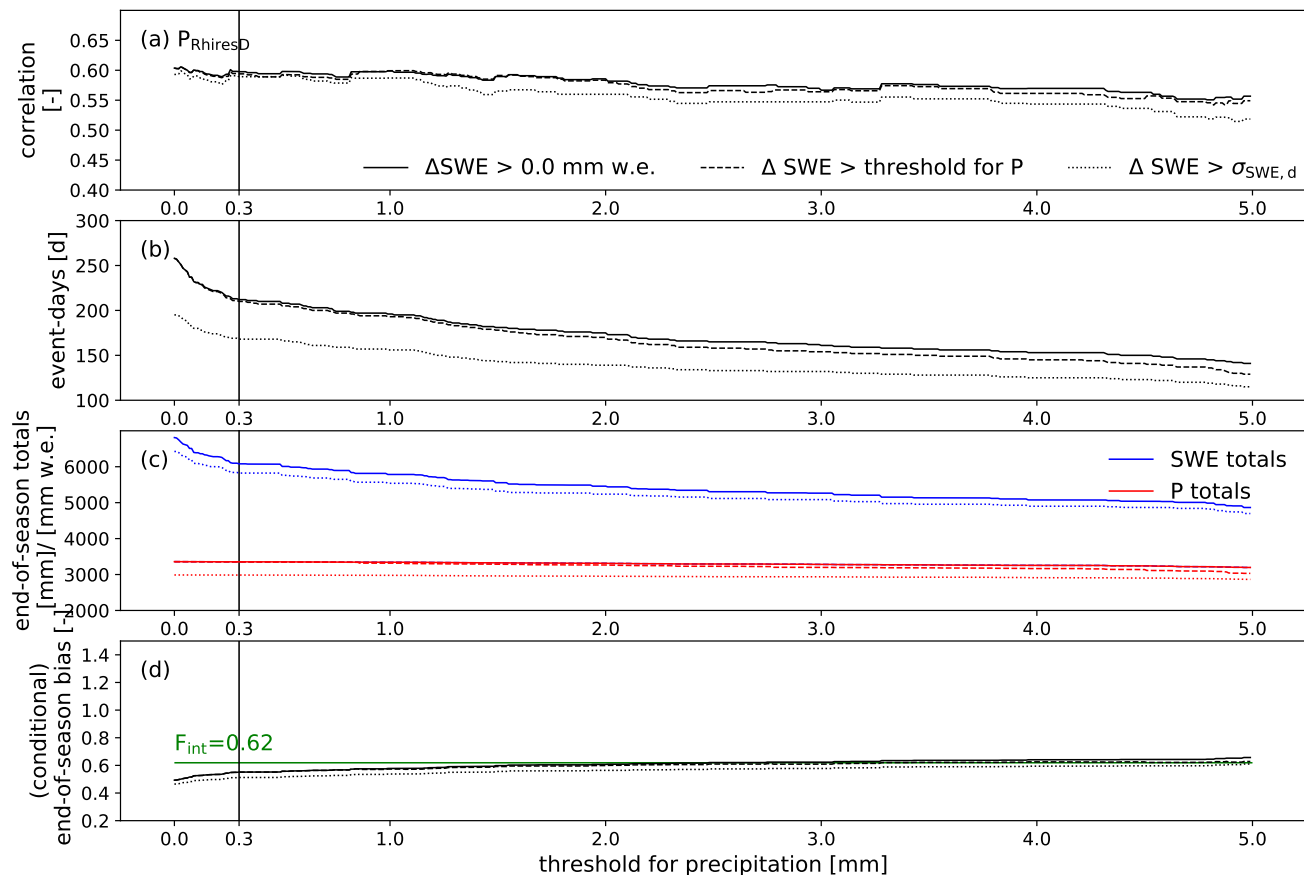


Figure S2. Shown is the sensitivity of the (a) correlation between daily SWE amounts and daily precipitation totals by RhiresD with a varying threshold on Plaine Morte. The threshold applied to the precipitation estimates is shown on the x-axis. For daily SWE amounts, three main thresholds were applied; 0.0 mm d^{-1} (solid line), $\sigma_{\text{SWE},d}$ (dotted line) and the same as on the precipitation estimates (dashed line). Moreover, the number of (b) event-days, (c) end-of-season totals and (d) (double) conditional bias are shown as a function of the applied threshold.

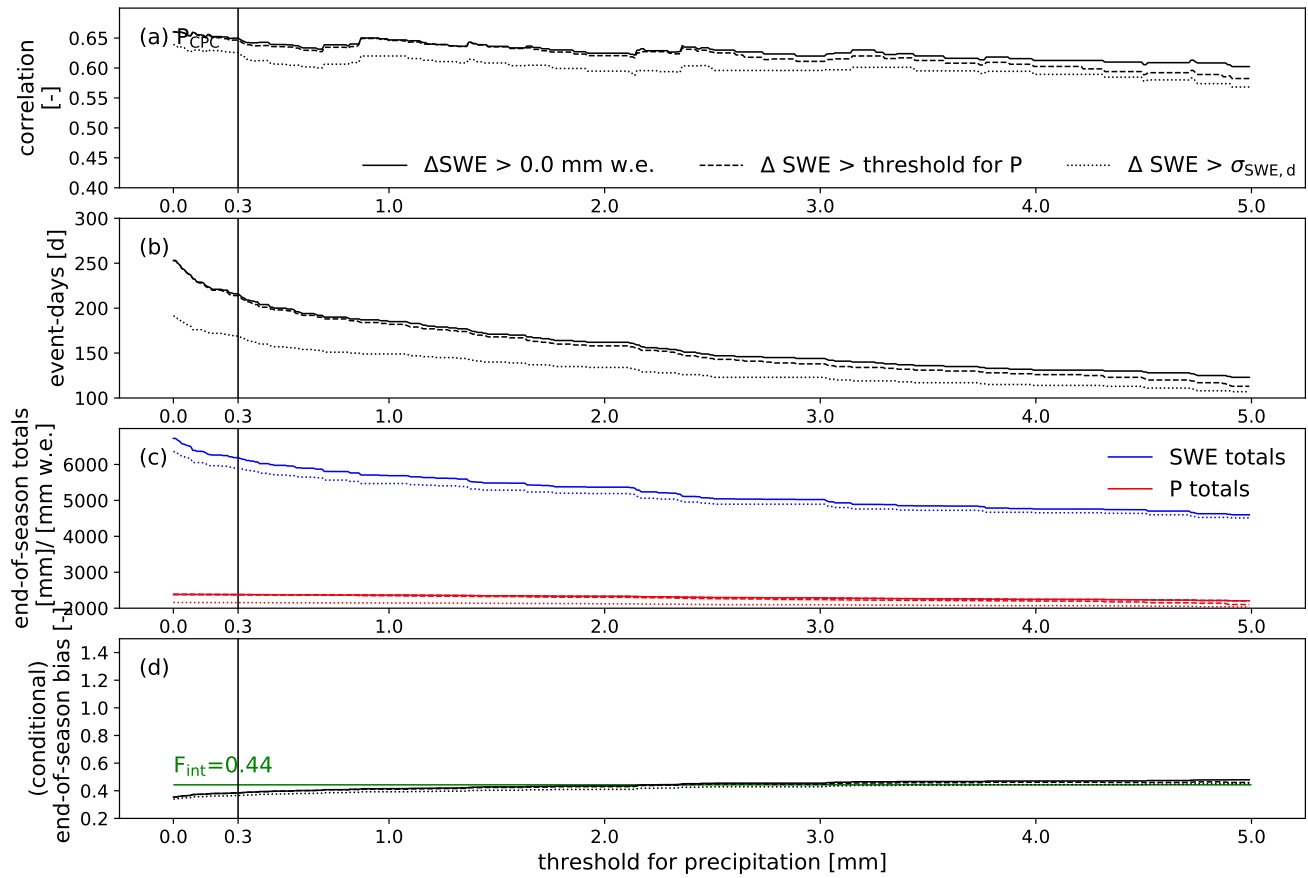


Figure S3. Same as Fig. S2 with precipitation estimates from CombiPrecip.

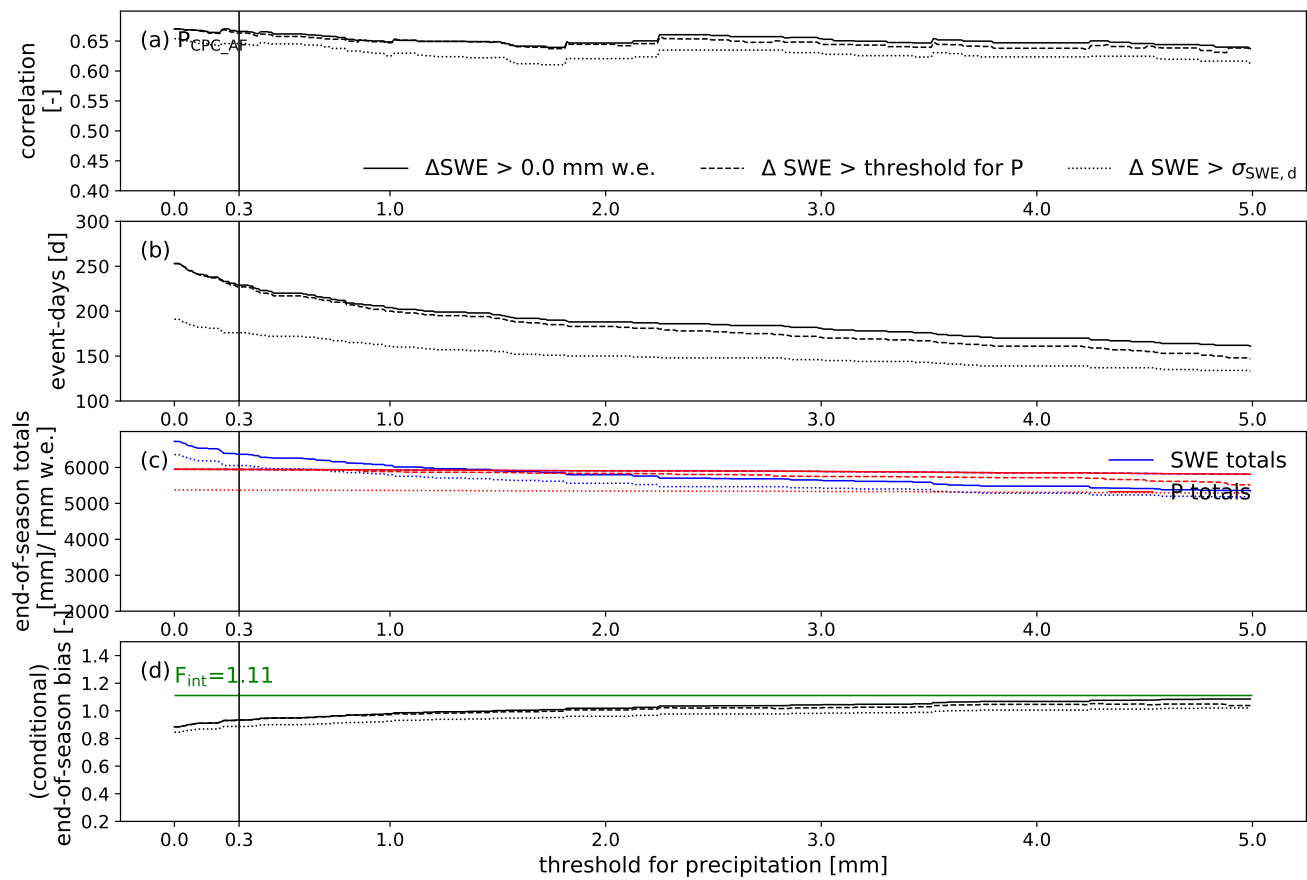


Figure S4. Same as Fig. S2 with precipitation estimates from CombiPrecip-adj.

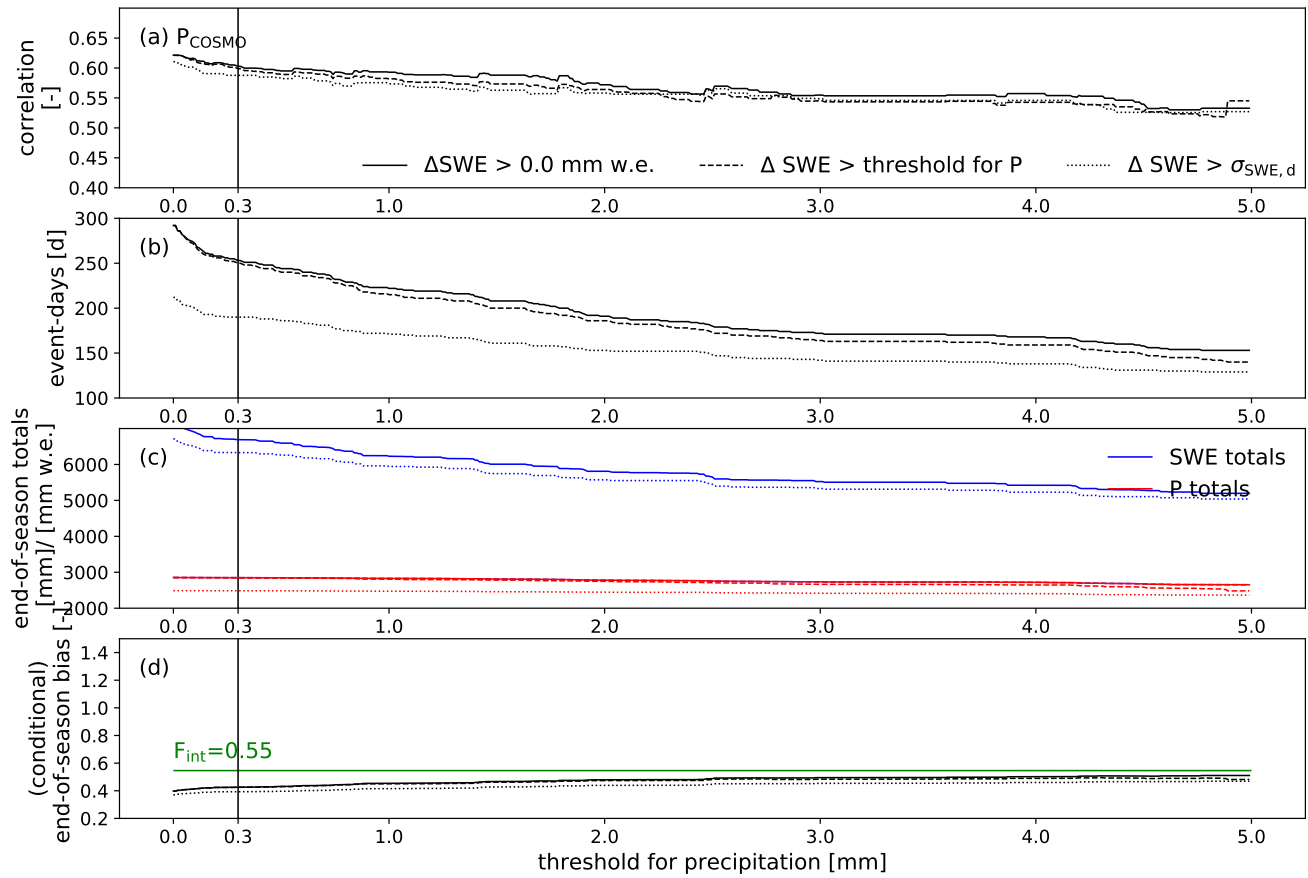


Figure S5. Same as Fig. S2 with precipitation estimates from COSMO-1.

2.2 Findelen

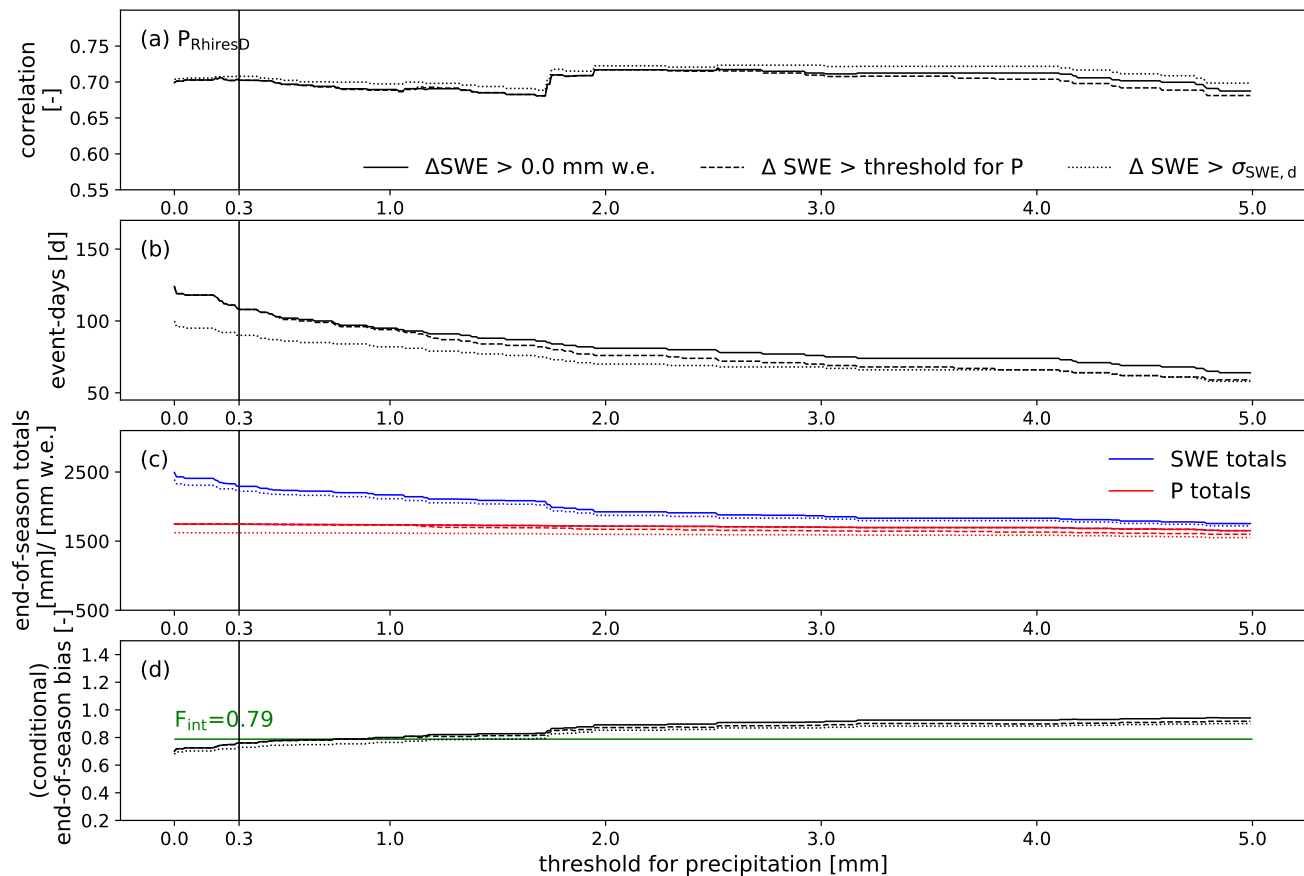


Figure S6. Shown is the sensitivity of the (a) correlation between daily SWE amounts and daily precipitation totals by RhiresD with a varying threshold on Findelen. The threshold applied to the precipitation estimates is shown on the x-axis. For daily SWE amounts, three main thresholds were applied; 0.0 mm d^{-1} (solid line), $\sigma_{SWE,d}$ (dotted line) and the same as on the precipitation estimates (dashed line). Moreover, the number of (b) event-days, (c) end-of-season totals and (d) (double) conditional bias are shown as a function of the applied threshold.

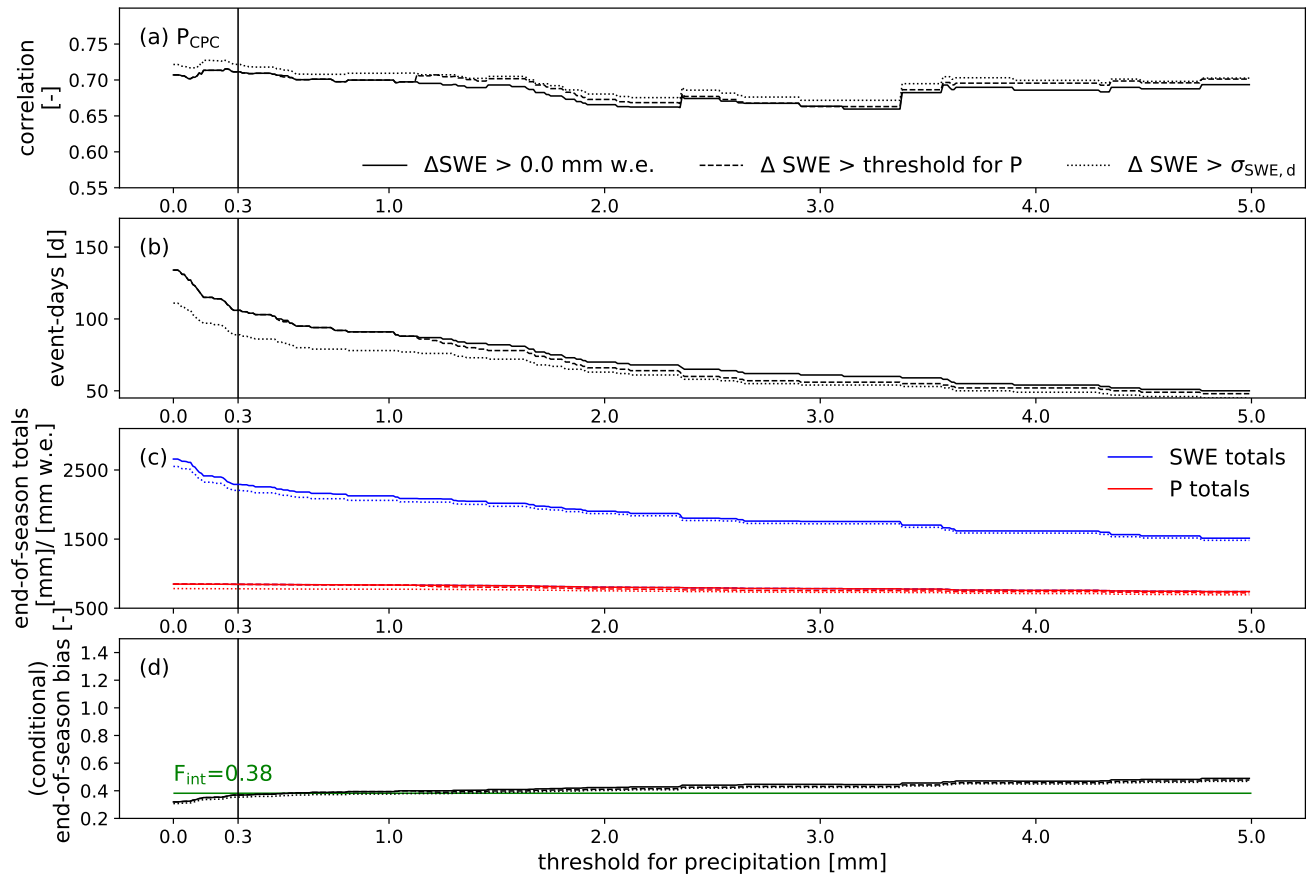


Figure S7. Same as Fig. S6 for precipitation estimates from CombiPrecip.

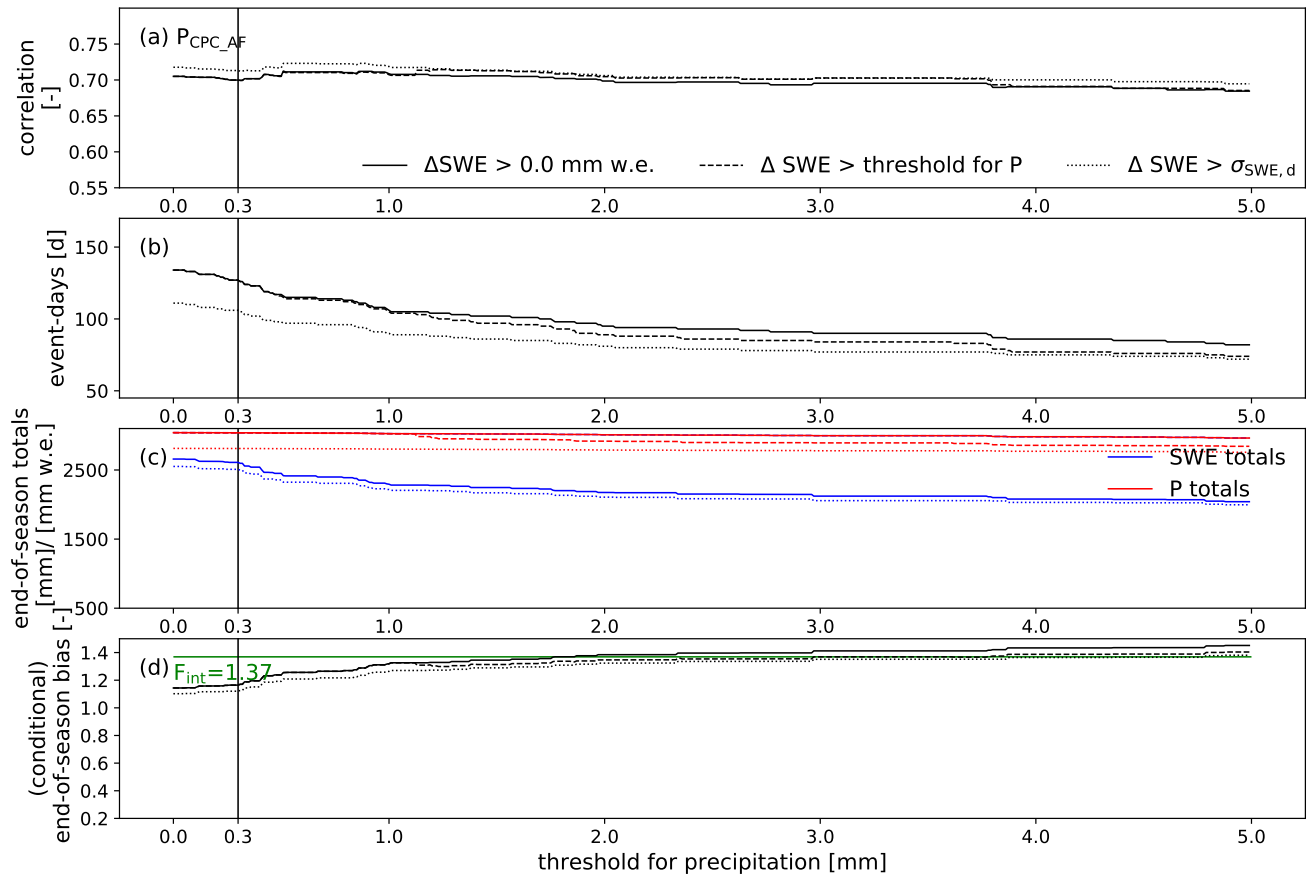


Figure S8. Same as Fig. S6 for precipitation estimates from CombiPrecip-adj.

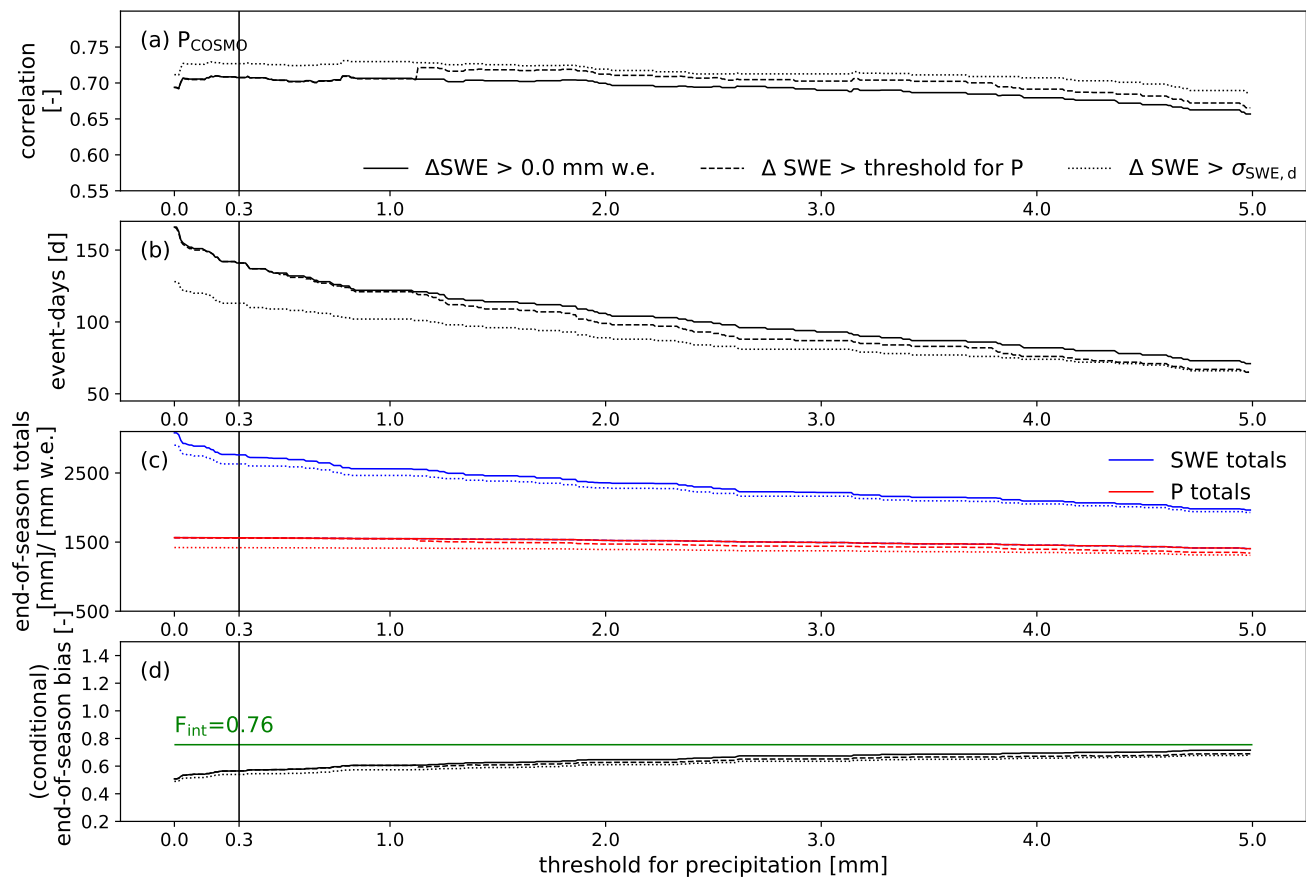


Figure S9. Same as Fig. S6 for precipitation estimates from COSMO-1.

10 2.3 Influence of the threshold on the end-of-season bias and total amounts

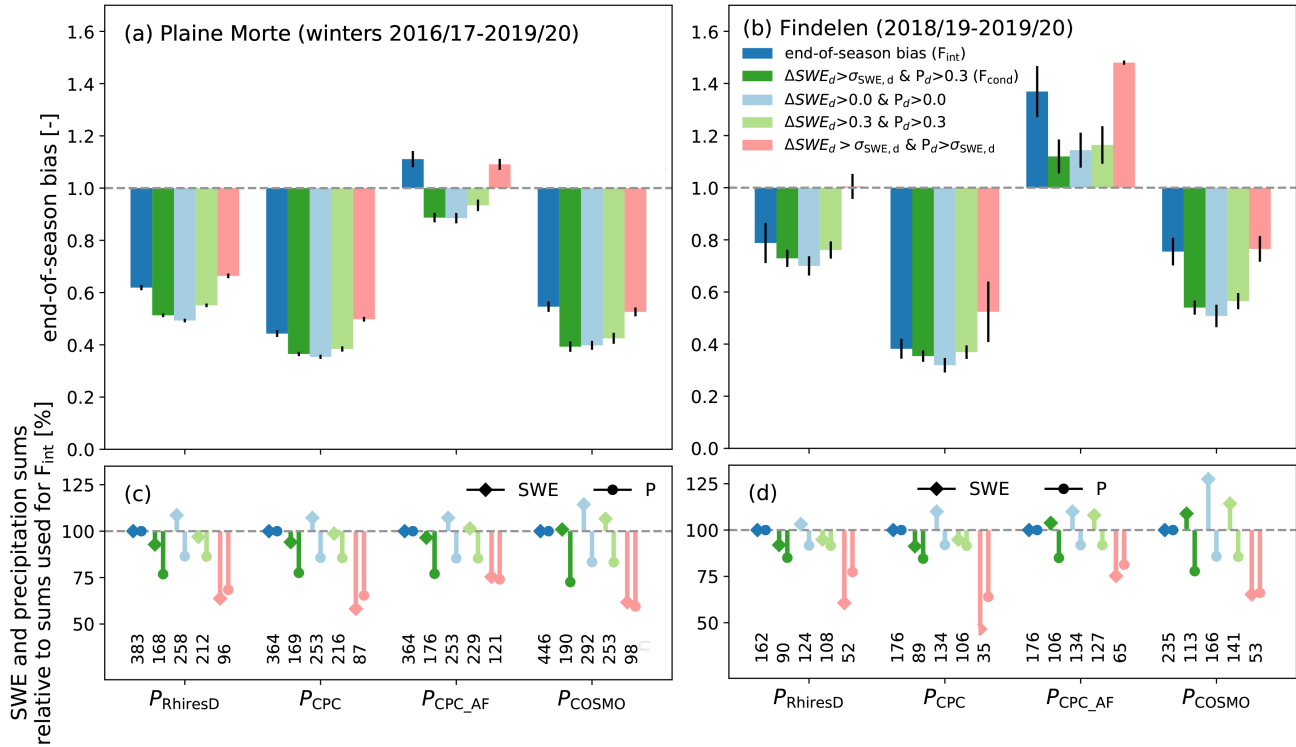


Figure S10. End-of-season conditional bias resulting from different thresholds for (a) Plaine Morte and (b) Findelen. Panels (c) and (d) show the total amounts of SWE (diamonds) and precipitation (circles) over all available winter seasons relative to the total SWE observed on 30 April (dark blue diamond) and the non-conditional cumulative precipitation sums over all accumulation seasons (dark blue circle). The in situ SWE observed on 30 April and the cumulative precipitation are used to derive the integrated bias (F_{int}). Number of event-days throughout all available winter seasons are given in the bottom of Panels (c) and (d). Event-days of the integrated bias (dark blue) are identified by the precipitation products where daily precipitation is greater than 0.0 mm d^{-1} (single conditional).

3 Sensitivity of the monthly bias with varying thresholds

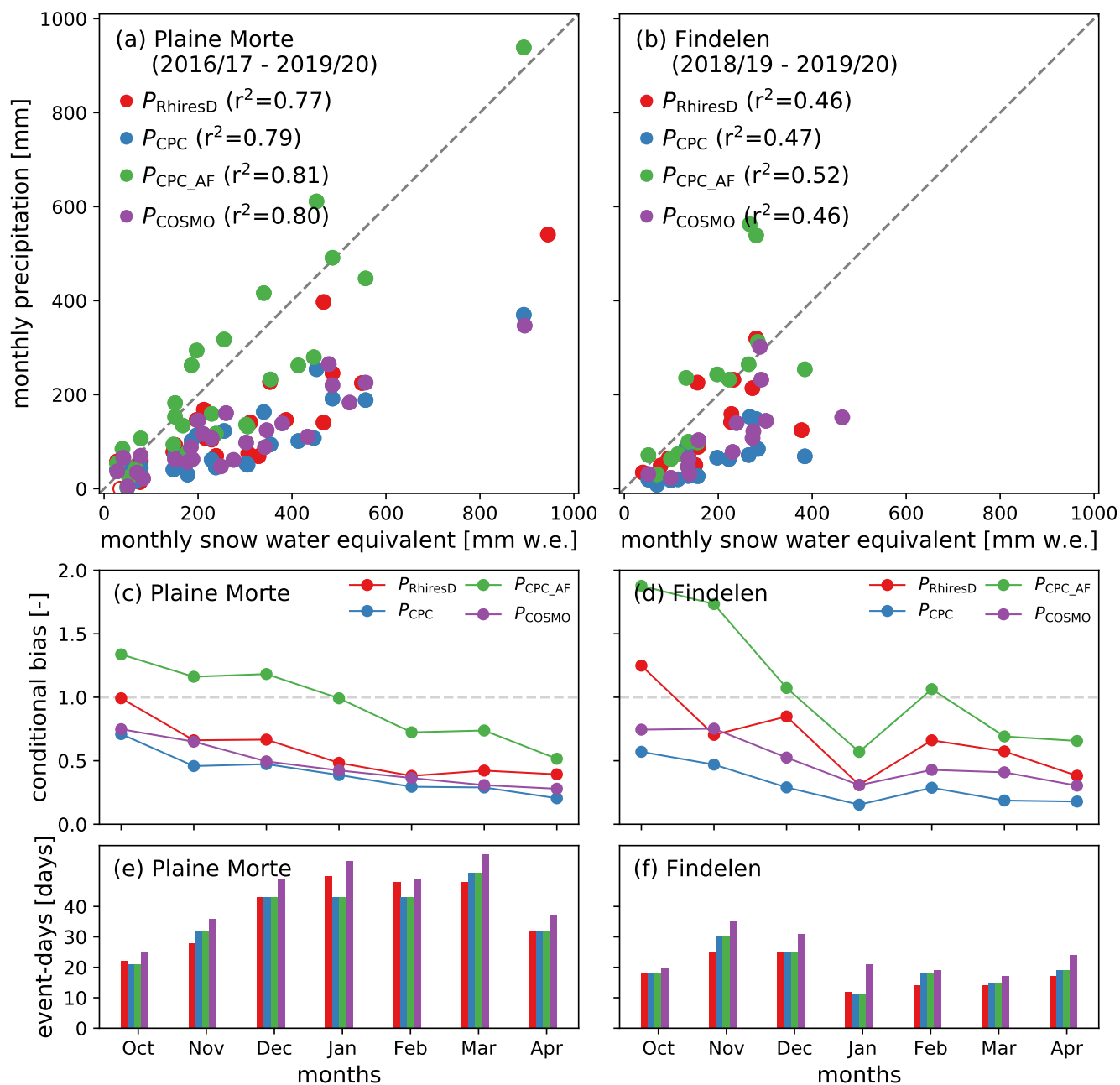


Figure S11. Same figure as Fig.3 in the main manuscript, but the results are calculated with a threshold of 0.0 mm d^{-1} for daily precipitation totals and daily SWE. Please note the different y-axis scale in (e) and (f) compared to Fig.3.

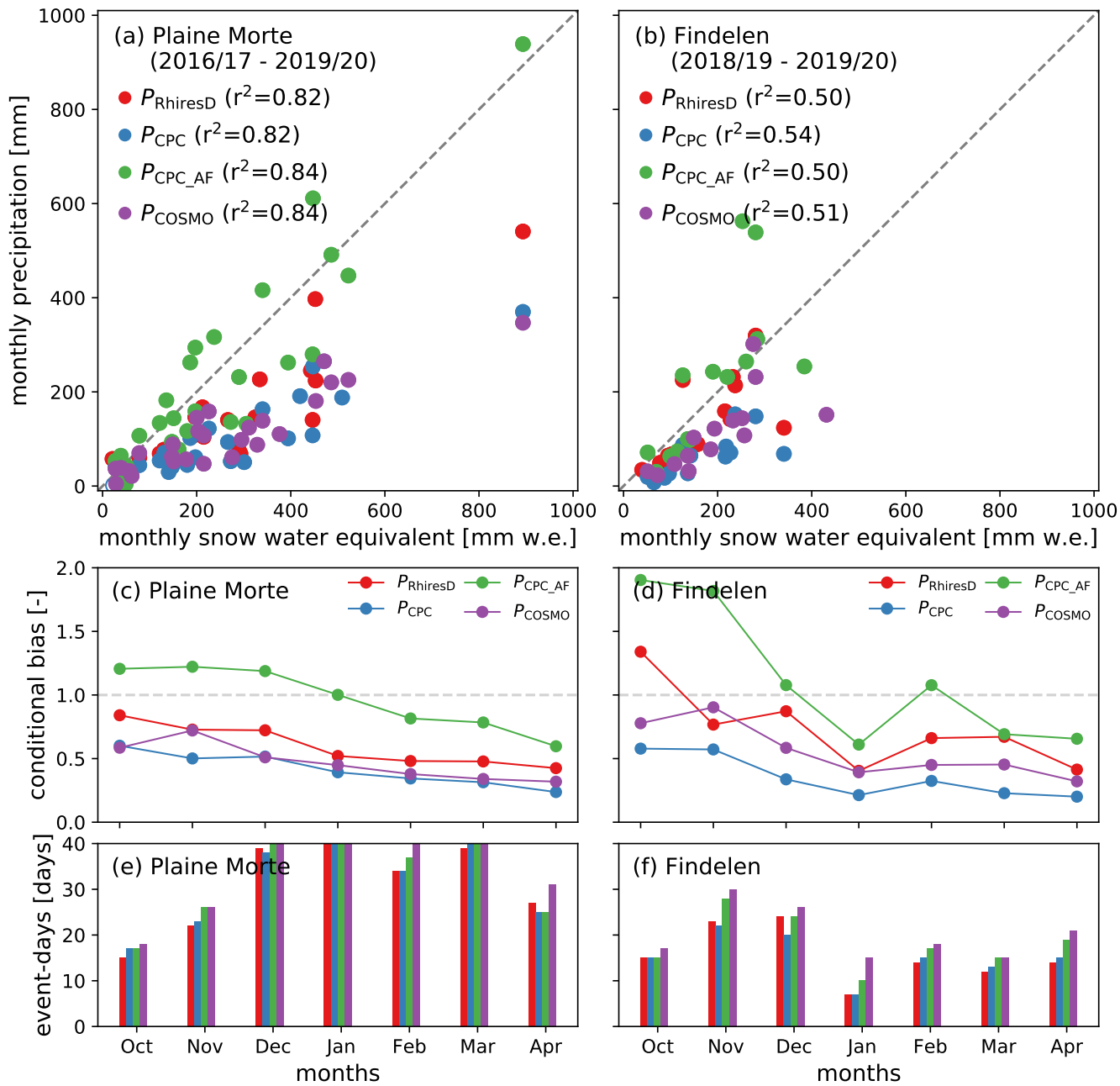


Figure S12. Same figure as Fig.3 in the main manuscript, but the results are calculated with a threshold of 0.3 mm d^{-1} for daily precipitation totals and daily SWE.

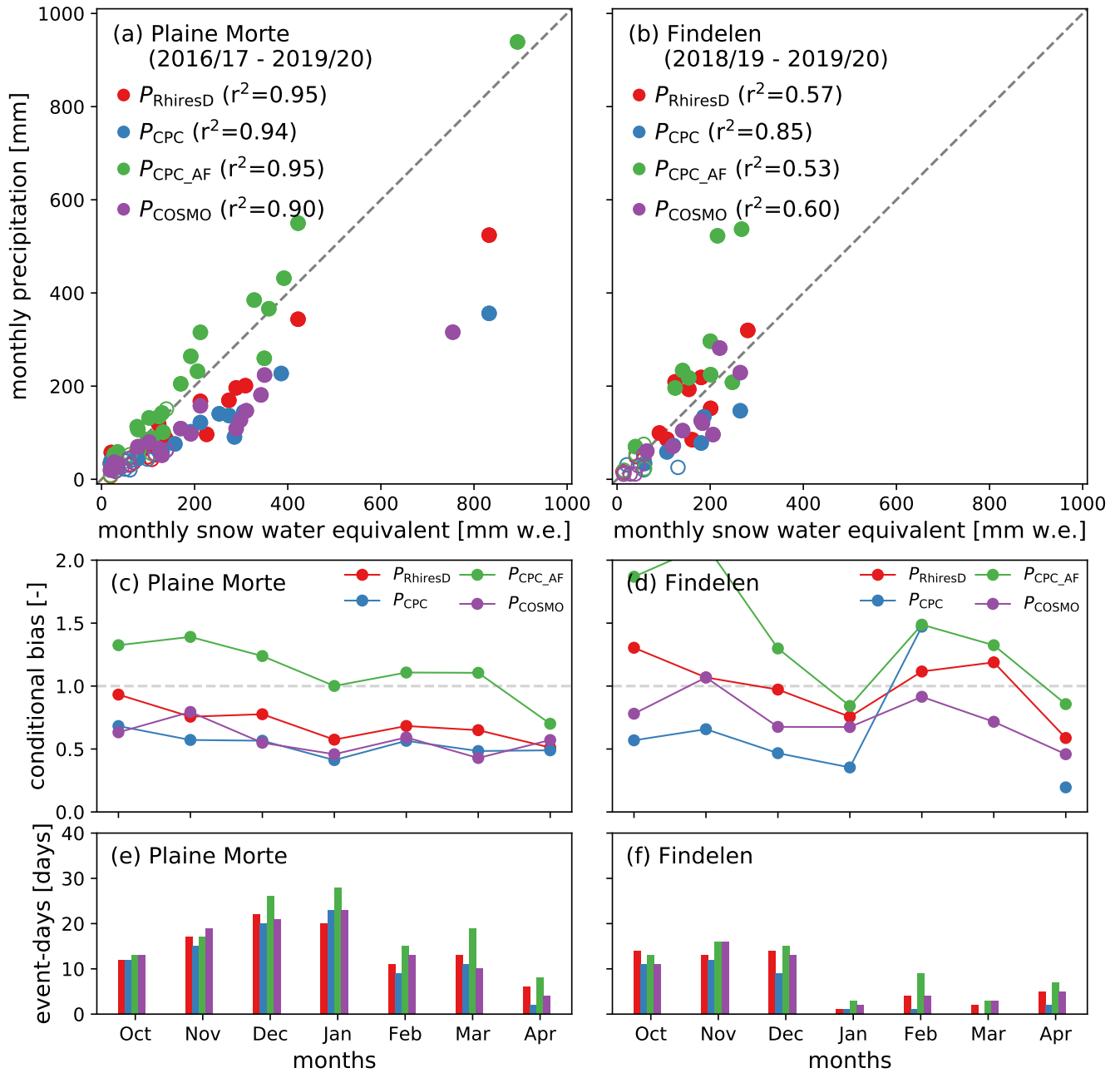


Figure S13. Same figure as Fig.3 in the main manuscript, but the results are calculated with a threshold of $\sigma_{SWE,d}$ for daily precipitation totals and daily SWE. Note the different y-axis scale in (e) and (f) compared to the previous figures.

4 Correlation of conditional monthly bias with air temperature and wind speed

4.1 Plaine Morte

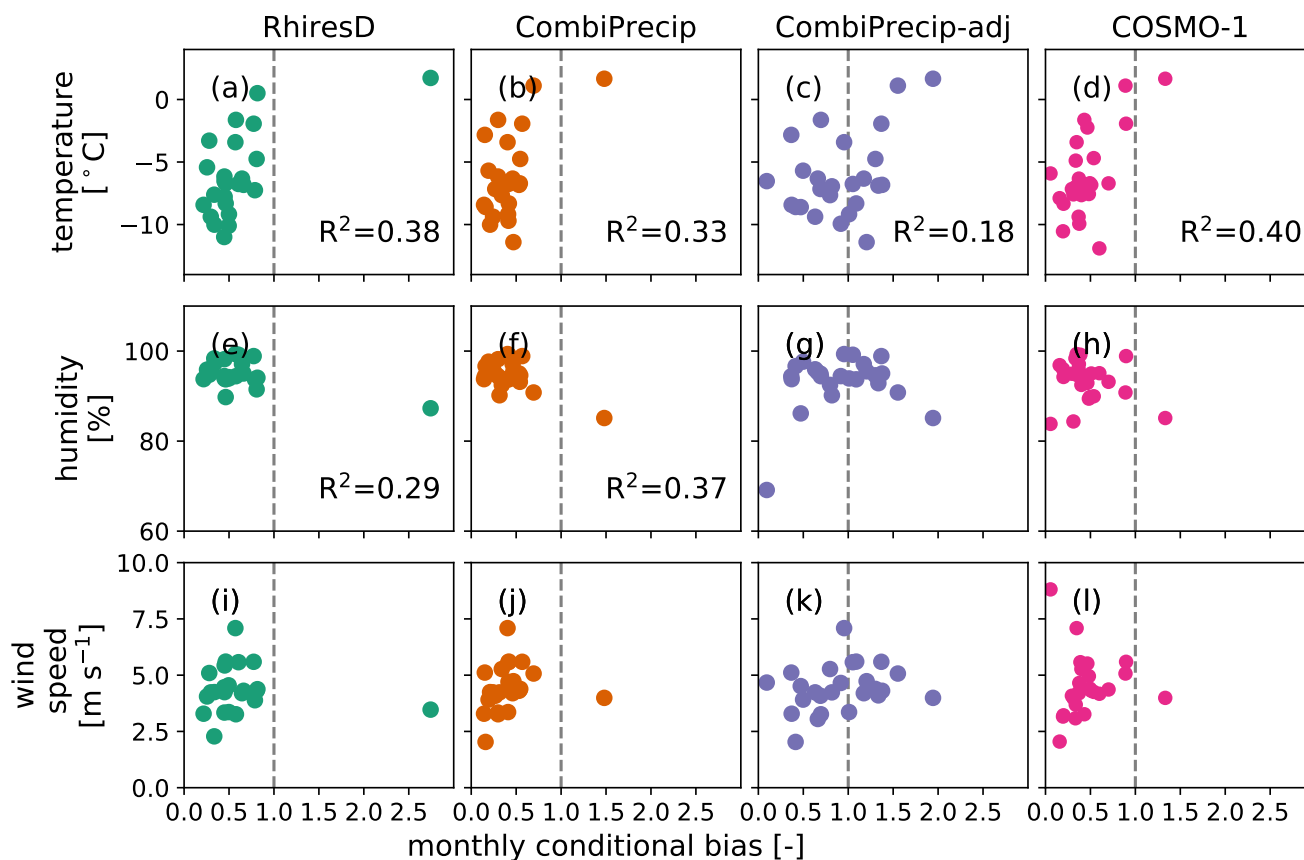


Figure S14. Monthly air temperature (a-d), air humidity (e-f) and wind speed (i-l) compared to the monthly conditional bias on Plaine Morte for RhiresD (a,e,i), CombiPrecip (b,f,j), CombiPrecip-adj (c,g,k) and COSMO-1 (d,h,l). If the correlation is significant, the coefficient of determination (r^2) is given.

4.2 Findelen

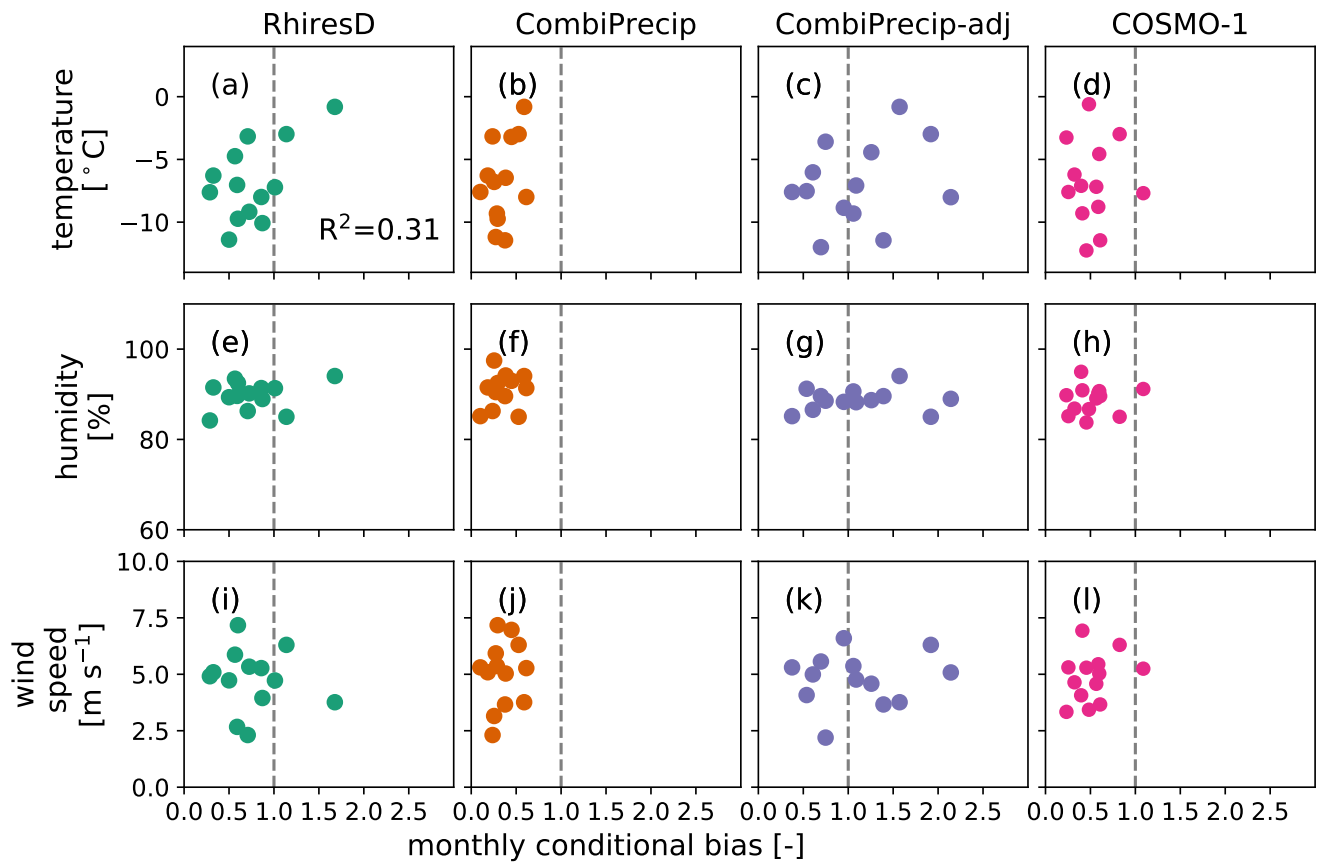


Figure S15. Monthly air temperature (a-d), air humidity (e-f) and wind speed (i-l) compared to the monthly conditional bias on Findelen for RhiresD (a,e,i), CombiPrecip (b,f,j), CombiPrecip-adj (c,g,k) and COSMO-1 (d,h,l). If the correlation is significant, the coefficient of determination (r^2) is given.

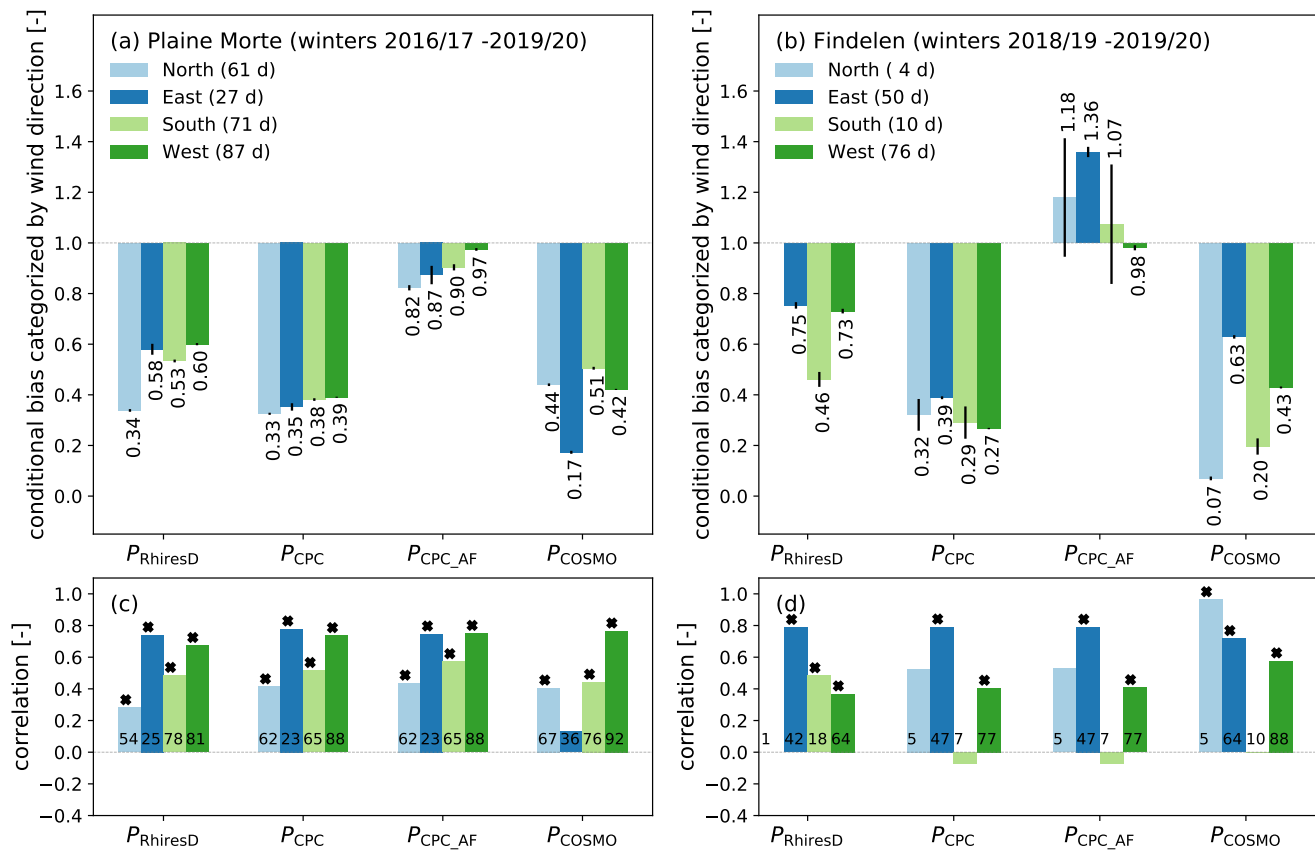


Figure S16. Same figure as Fig.4 in the main manuscript, but the results are calculated with a threshold of 0.0 mm d^{-1} for daily precipitation totals and daily SWE.

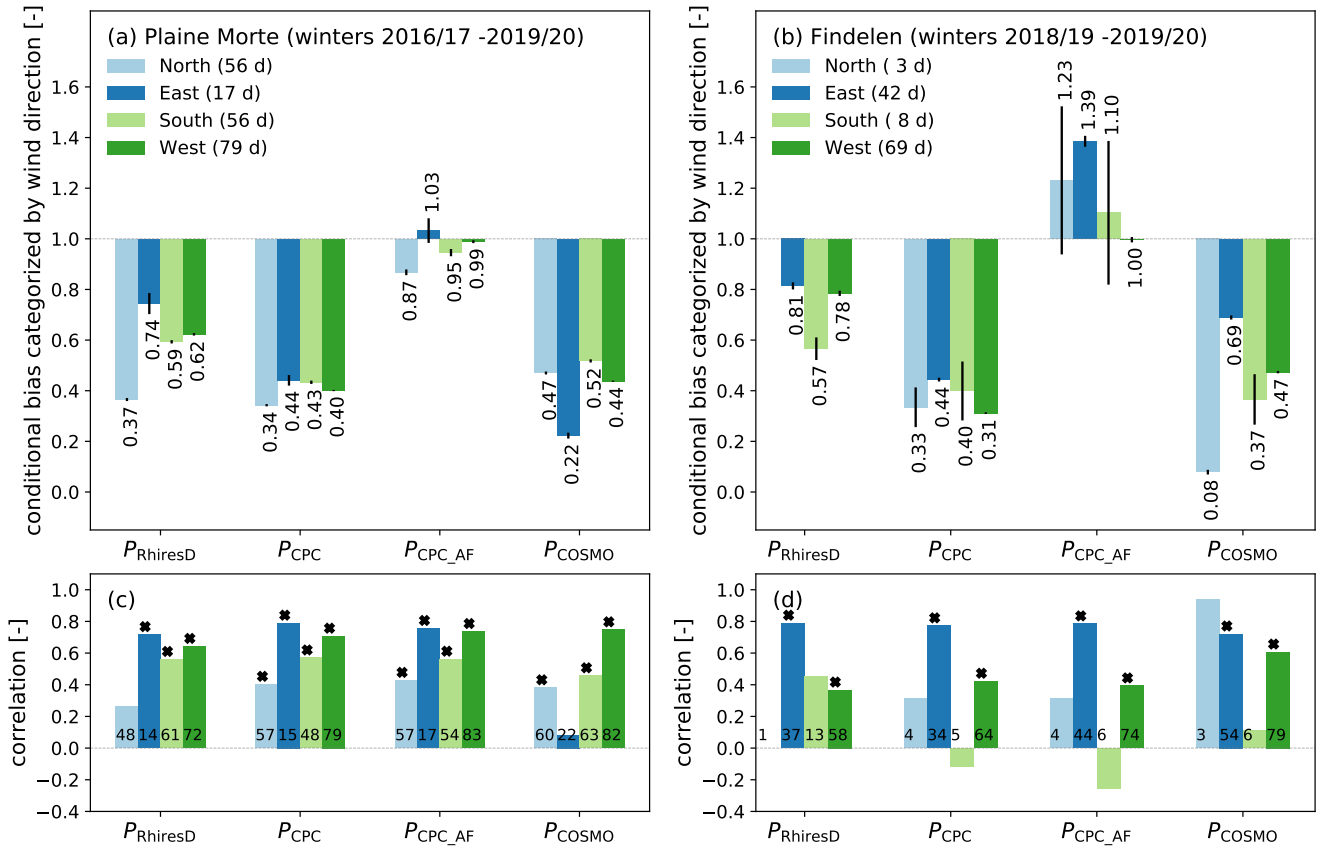


Figure S17. Same figure as Fig.4 in the main manuscript, but the results are calculated with a threshold of 0.3 mm d^{-1} for daily precipitation totals and daily SWE.

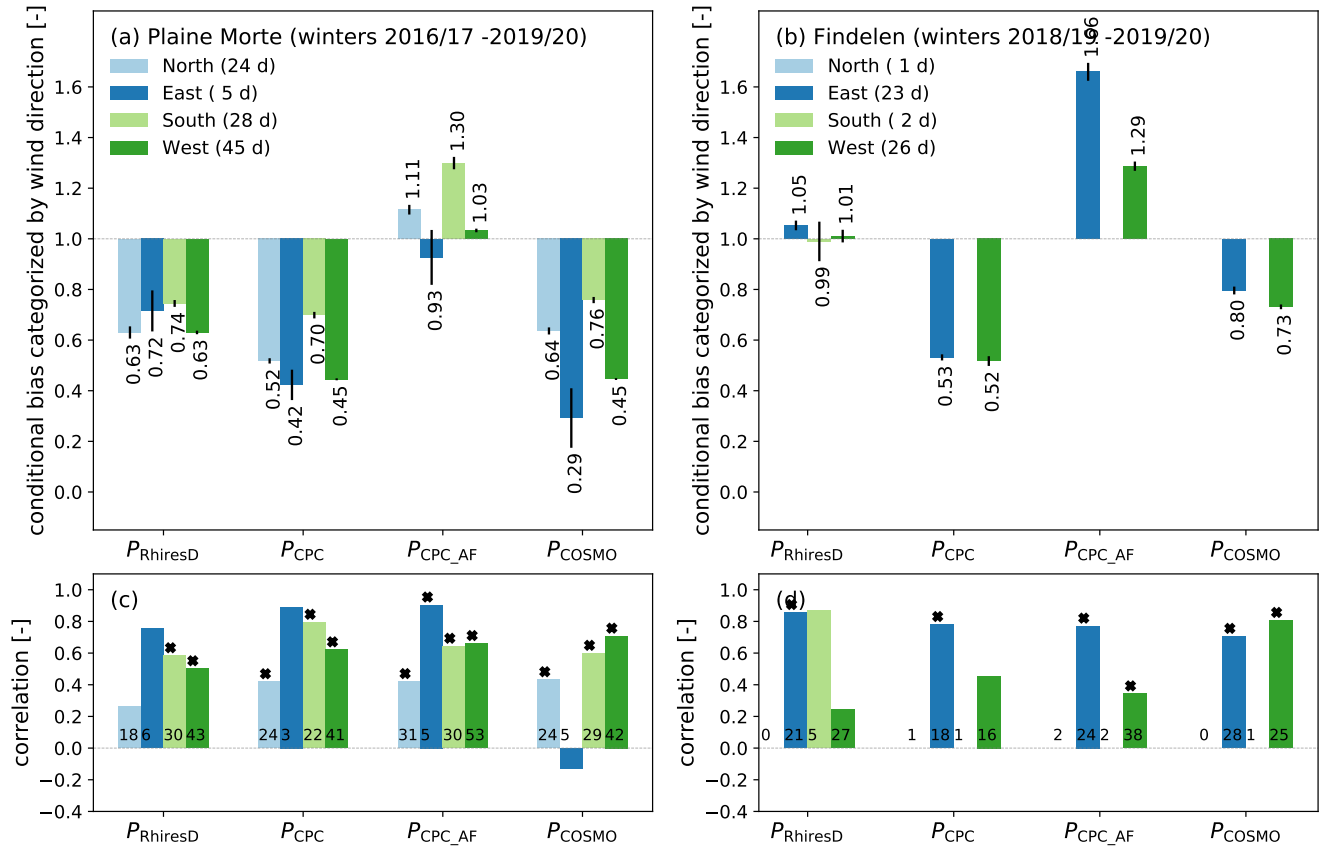


Figure S18. Same figure as Fig.4 in the main manuscript, but the results are calculated with a threshold of $\sigma_{SWE,d}$ for daily precipitation totals and daily SWE.