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Climate-controlled root zone parameters show potential to improve water flux simulations by land surface models

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1. Catchment information

Table S1. Study catchment characteristics (Australian Bureau of Meteorology; http://www.bom.gov.au/water/hrs/). Soil type is based on the FAO soil map of the world (FAO, 2003) and vegetation characteristics from GLCC1.2 (ECMWF, 2016) with T_L and T_H the dominant low and high vegetation types and C_L and C_H the fractional coverage of low and high vegetation.

Catchment name	Station ID	Coordinates	Climate region	Area (km^2)	Soil type	T_L	T_H	C_L (-)	C_H (-)
East Alligator River (EA)	G8210010	133.332°E, 12.717°S	Tropical	2398	coarse	Tall grass	Interrupted forest	0.68	0.32
East Baines River (EB)	G8110004	130.034°E, 15.766°S	Tropical	2443	coarse	Semidesert		1.00	0.00
Gregory River (G)	912101A	139.252°E, 18.643°S	Tropical	12652	medium fine	Short grass		1.00	0.00
Herbert River (He)	116006B	145.922°E, 18.491°S	Tropical	7487	medium fine	Tall grass	Evergreen broadleaf	0.01	0.99
Mitchell River (Mi)	919003A	144.290°E, 16.472°S	Tropical	7734	coarse	Tall grass	Interrupted forest	0.43	0.57
Normanby River (No)	105101A	144.839°E, 15.281°S	Tropical	2306	coarse	Tall grass	Interrupted forest	0.01	0.99
Wenlock River (W)	925001A	142.638°E, 12.454°S	Tropical	3290	medium fine		Interrupted forest	0.00	1.00
Abercrombie River (A)	412028	149.325°E, 33.955°S	Temperate	2631	medium	Crops, mixed farming	Interrupted forest	0.23	0.76
Dogwood Creek (D)	422202B	150.179°E, 26.709°S	Temperate	2882	medium fine	Tall grass	Evergreen broadleaf	0.14	0.86
Murrumbidgee River (Mu)	410761	149.101°E, 35.540°S	Temperate	5158	medium fine	Tall grass	Interrupted forest	0.16	0.84
Namoi River (Na)	419005	150.778°E, 30.678°S	Temperate	2532	medium	Crops, mixed farming	Interrupted forest	0.33	0.67
Paroo River (P)	424201A	144.786°E, 28.689°S	Temperate	22885	medium	Semidesert		1.00	0.00
Avoca River (Av)	408200	143.299°E, 36.438°S	Mediterranean	2677	medium	Crops, mixed farming	Interrupted forest	0.79	0.21
Kent River (K)	604053	117.087°E, 34.888°S	Mediterranean	1786	coarse	Crops, mixed farming	Interrupted forest	0.65	0.35
Reedy Creek (R)	403209A	146.345°E, 36.332°S	Mediterranean	5506	medium fine	Crops, mixed farming	Evergreen broadleaf	0.02	0.98

Table S2. Hydrological characteristics of the study catchments with long-term (1973–2010) annual mean values for precipitation ($\overline{P}$), discharge ($\overline{Q}$) and potential evaporation ($\overline{E_p}$), aridity index (I_A), seasonality index (I_S), time-lag between maximum monthly mean precipitation and potential evaporation (φ) and root zone storage capacity estimates from the memory method ($S_{r,MM}$) and in the HTESSEL CTR model ($S_{r,CTR}$).

Catchment	$\overline{P}$ **(mm year^{-1})**	$\overline{Q}$ **(mm year^{-1})**	$\overline{E_p}$ **(mm year^{-1})**	I_A **(-)**	I_S **(-)**	φ **(months)**	$S_{r,MM}$ **(mm)**	$S_{r,CTR}$ **(mm)**
EA	1539	586	953	1.31	0.97	3	389	535
EB	879	134	745	2.53	0.99	3	300	535
G	509	55	453	3.96	0.95	1	194	513
He	1140	326	814	1.46	0.70	2	409	725
Mi	854	251	603	2.05	0.89	2	410	535
No	1207	288	920	1.40	0.85	2	722	535
W	1577	472	1105	1.10	0.95	3	633	725
A	787	94	693	1.55	0.07	0	208	566
D	661	24	637	2.69	0.38	0	266	725
Mu	588	59	530	2.04	0.08	2	205	725
Na	802	84	718	1.76	0.26	0	165	566
P	417	26	392	4.38	0.37	1	125	566
Av	505	8	497	2.69	0.25	5	160	566
K	889	41	848	1.36	0.50	6	315	535
R	1243	109	1133	1.02	0.26	6	487	725

2. Reference and modeled long-term annual mean fluxes

Table S3. Long-term (1975–2010) annual mean reference and modeled (HTESSEL CTR and MD models) precipitation ($\bar{P}$), discharge ($\bar{Q}$) and evaporation ($\bar{E}$) fluxes in the study catchments.

	$\bar{P}$ (mm year^{-1})		$\bar{Q}$ (mm year^{-1})				$\bar{E}$ (mm year^{-1})			
Catchment	**GSWP-3**		**Station observations**	**CTR**	**MD**		**Water balance**	**FLUXCOM**	**CTR**	**MD**
EA	1429		590	423	436		839	753	1002	989
EB	788		132	176	167		656	587	612	621
G	514		50	19	42		464	434	498	471
He	1051		309	198	236		742	694	847	808
Mi	1155		231	256	264		923	622	891	883
No	1405		270	570	597		1135	765	827	801
W	1538		455	675	675		1082	900	856	857
A	769		87	69	85		682	634	702	682
D	674		25	34	36		648	586	638	635
Mu	686		60	77	96		626	464	615	590
Na	889		84	96	110		805	658	790	778
P	394		24	18	22		370	333	372	371
Av	531		7	6	20		524	449	529	511
K	1066		41	200	200		1024	730	867	866
R	1056		98	305	312		958	709	755	749

Table S4. Percent biases of modeled (HTESSEL CTR and MD models) long-term (1975–2010) annual mean discharge ($\bar{Q}$) and evaporation ($\bar{E}$) with for $\bar{Q}$ station observations as reference data and for $\bar{E}$ water balance and FLUXCOM as reference data.

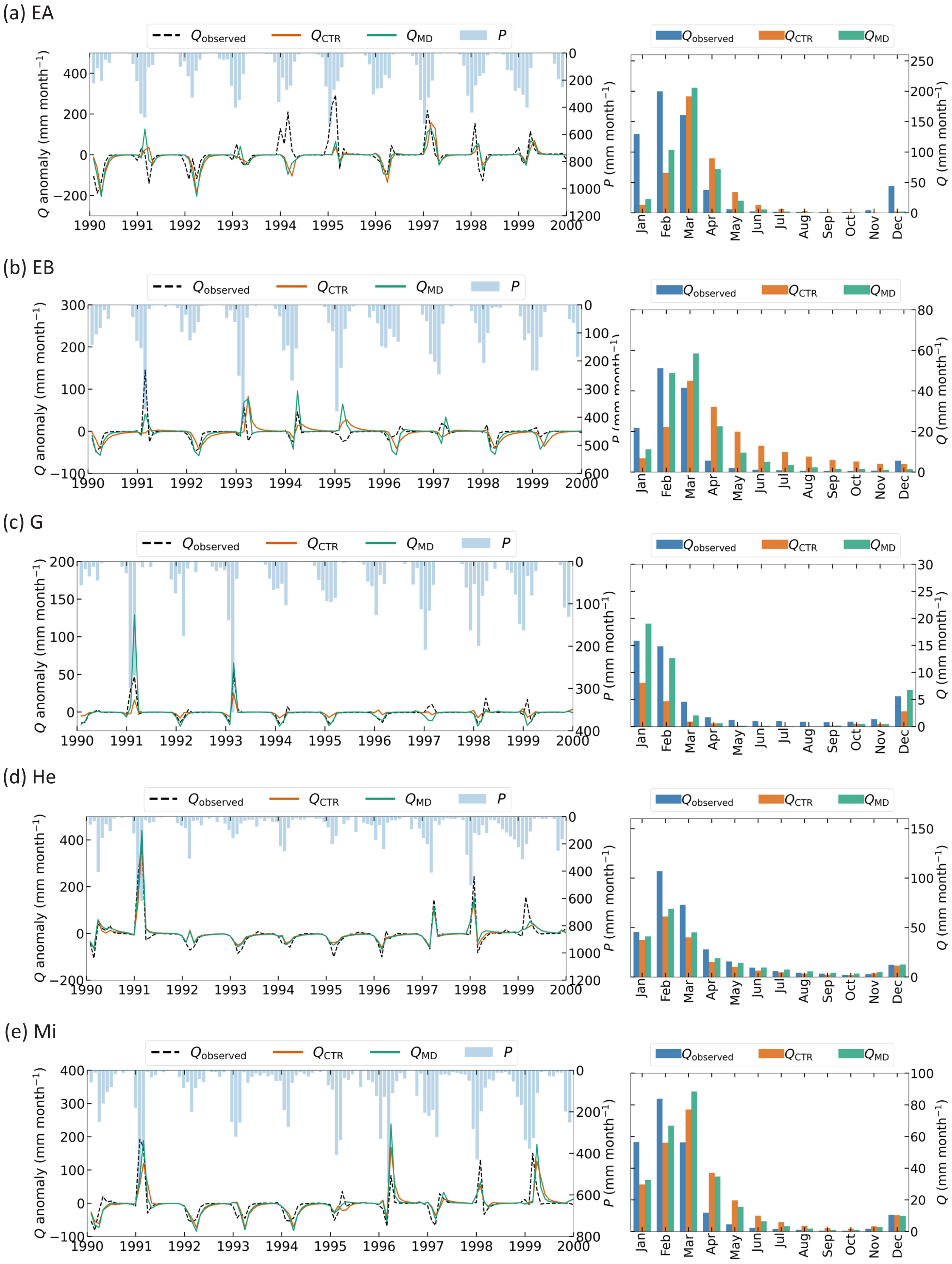
	$\bar{Q}$ (mm year^{-1})			$\bar{E}$ (mm year^{-1})			
	Station observations			**Water balance**		**FLUXCOM**	
Catchment	**CTR**	**MD**		**CTR**	**MD**	**CTR**	**MD**
EA	-28%	-26%		19.4%	17.9%	32.9%	31.3%
EB	33%	26%		-6.7%	-5.3%	4.3%	5.7%
G	-63%	-14%		7.3%	1.5%	14.8%	8.6%
He	-36%	-24%		14.2%	8.9%	22.0%	16.3%
Mi	11%	14%		-3.5%	-4.4%	43.2%	41.9%
No	111%	121%		-27.1%	-29.4%	8.0%	4.6%
W	48%	48%		-20.9%	-20.8%	-4.9%	-4.8%
A	-20%	-2%		3.0%	0.0%	10.7%	7.6%
D	34%	41%		-1.6%	-2.0%	8.8%	8.4%
Mu	28%	60%		-1.7%	-5.7%	32.7%	27.3%
Na	14%	31%		-1.8%	-3.4%	20.1%	18.2%
P	-25%	-6%		0.6%	0.2%	11.8%	11.4%
Av	-9%	196%		0.9%	-2.4%	17.6%	13.8%
K	386%	385%		-15.4%	-15.4%	18.7%	18.6%
R	211%	217%		-21.2%	-21.8%	6.5%	5.6%

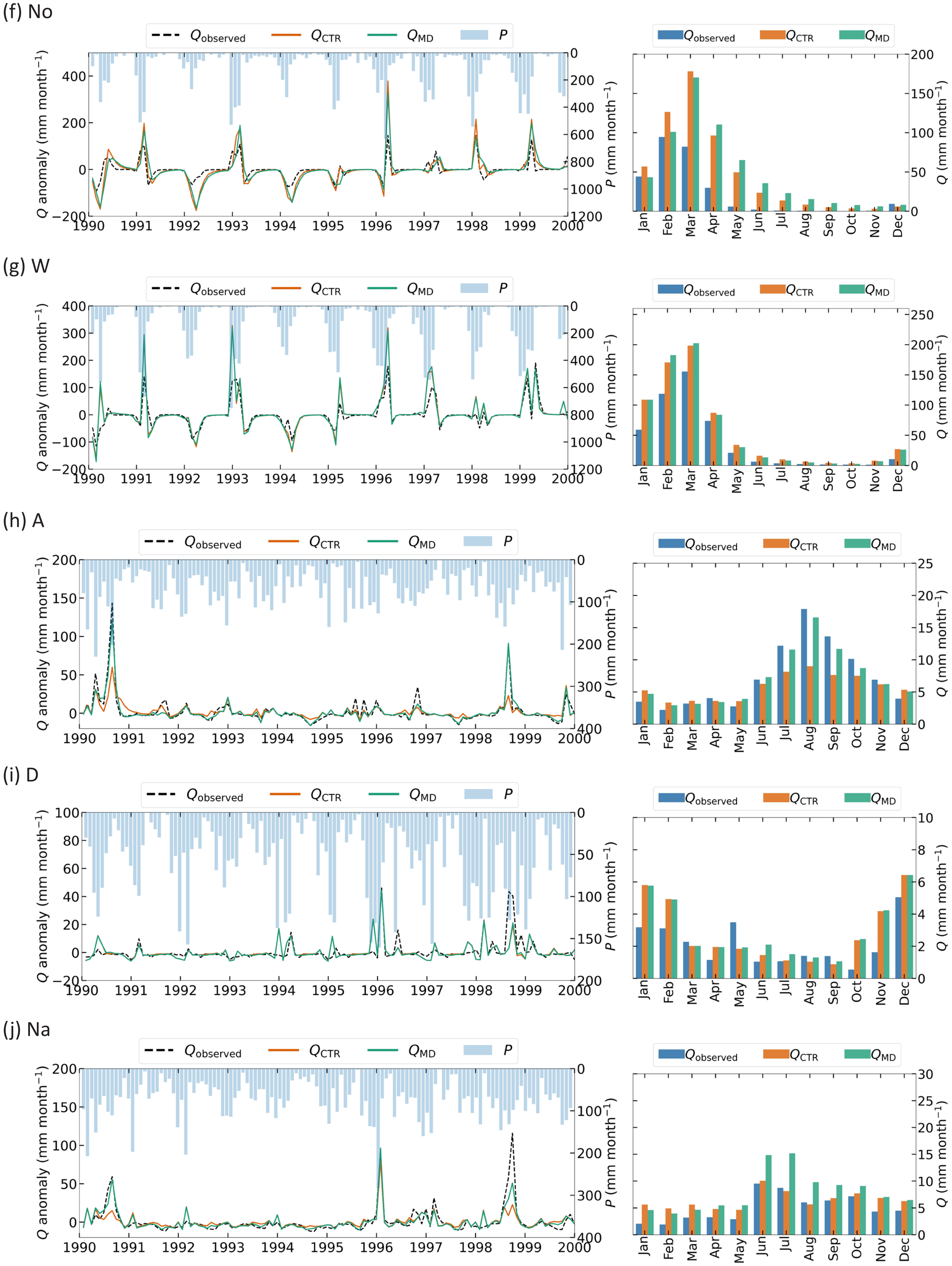
3. Model results monthly discharge

*Table S5. Model performance based on monthly modeled (HTESSEL CTR and MD models) discharge fluxes compared to station observations with Pearson correlation (r) and variability ($\alpha = \sigma_{mod}/\sigma_{obs}$) for inter-annual anomalies of monthly discharge fluxes and of monthly seasonal climatology of discharge fluxes for the time series 1975–2010 in the study catchments. For both r and α a value of 1 corresponds to a perfect model fit. The significance test of the MD improvements compared to CTR is represented by ** (passing 5% level) and * (passing 10% level) and additionally P-values are provided for the cases that MD improves compared to CTR.*

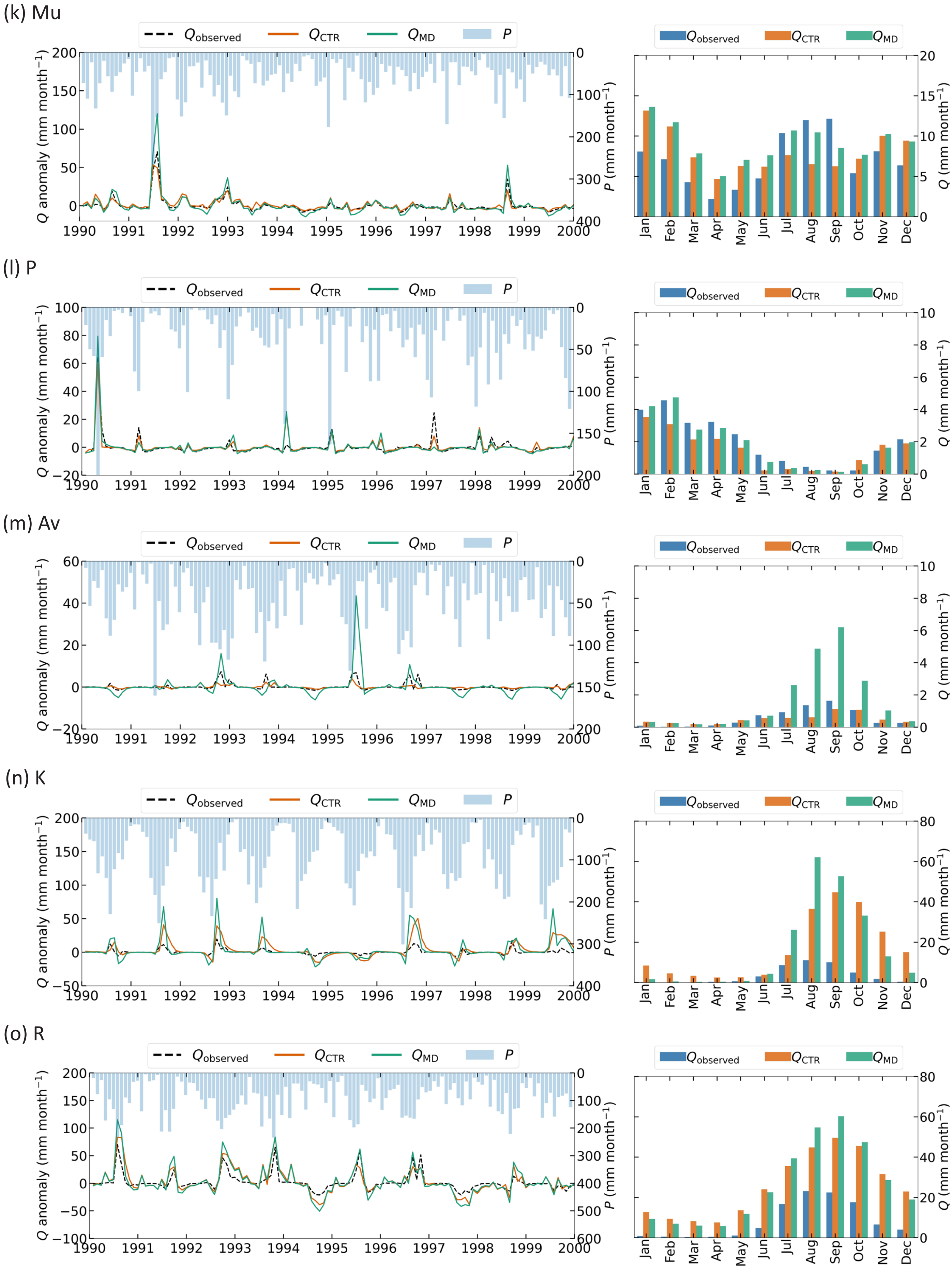
	Monthly seasonal climatology							**Inter-annual anomalies**					
	***r* (-)**			***α* (-)**				***r* (-)**			***α* (-)**		
Catchment	**CTR**	**MD**	**P-value**	**CTR**	**MD**	**P-value**		**CTR**	**MD**	**P-value**	**CTR**	**MD**	**P-value**
EA	0.63	0.77**	0.001	0.79	0.87**	0.045		0.61	0.65**	0.002	1.02	1.07	-
EB	0.60	0.92**	<0.001	0.73	1.11*	0.069		0.52	0.71**	<0.001	0.79	1.06**	<0.001
G	0.96	0.98	0.337	0.46	1.14**	0.05		0.85	0.86	0.39	0.47	1.65	-
He	0.98	0.99	0.281	0.58	0.63*	0.10		0.86	0.87	0.342	0.68	0.74**	<0.001
Mi	0.83	0.87	0.178	0.84	1.00**	0.003		0.64	0.71**	<0.001	0.93	1.09	
No	0.91	0.82	-	1.71	1.55**	0.022		0.86	0.80	-	1.52	1.39**	<0.001
W	0.99	0.99	-	1.31	1.37	-		0.85	0.85	-	1.35	1.39	-
A	0.94	0.99	0.206	0.39	0.84**	<0.001		0.83	0.90**	0.03	0.50	0.85**	<0.001
D	0.74	0.73	-	1.47	1.39**	0.001		0.77	0.78**	<0.001	0.91	0.93**	0.006
Mu	0.90	0.97	0.074	0.63	1.49	-		0.88	0.94**	0.007	0.84	1.45	-
Na	0.21	0.62**	0.022	0.76	0.72	-		0.72	0.84**	<0.001	0.65	0.84**	<0.001
P	0.92	0.98**	0.002	0.77	1.03**	0.023		0.78	0.79	0.421	0.81	1.23	-
Av	0.88	0.95	0.319	0.55	3.64	-		0.67	0.71	0.255	0.81	3.39	-
K	0.75	0.95**	<0.001	3.77	5.22	-		0.62	0.76**	0.002	2.55	3.47	-
R	0.96	0.98**	0.018	1.72	2.20	-		0.83	0.89**	<0.001	1.72	1.99	-

Figure S1: Monthly anomalies (left) and monthly seasonal climatology (right) of modeled discharge with the HTESSEL CTR and MD models compared to discharge from station observations in the study catchments (Table S1). Monthly anomaly discharge is presented for the time series 1990-2010 and monthly seasonal climatology is based on the time series of 1975-2010.





(f) No
(g) W
(h) A
(i) D
(j) Na
$Q_{observed}$
Q_{CTR}
Q_{MD}
P
Q anomaly (mm month^{-1})
P (mm month^{-1})
Q (mm month^{-1})
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



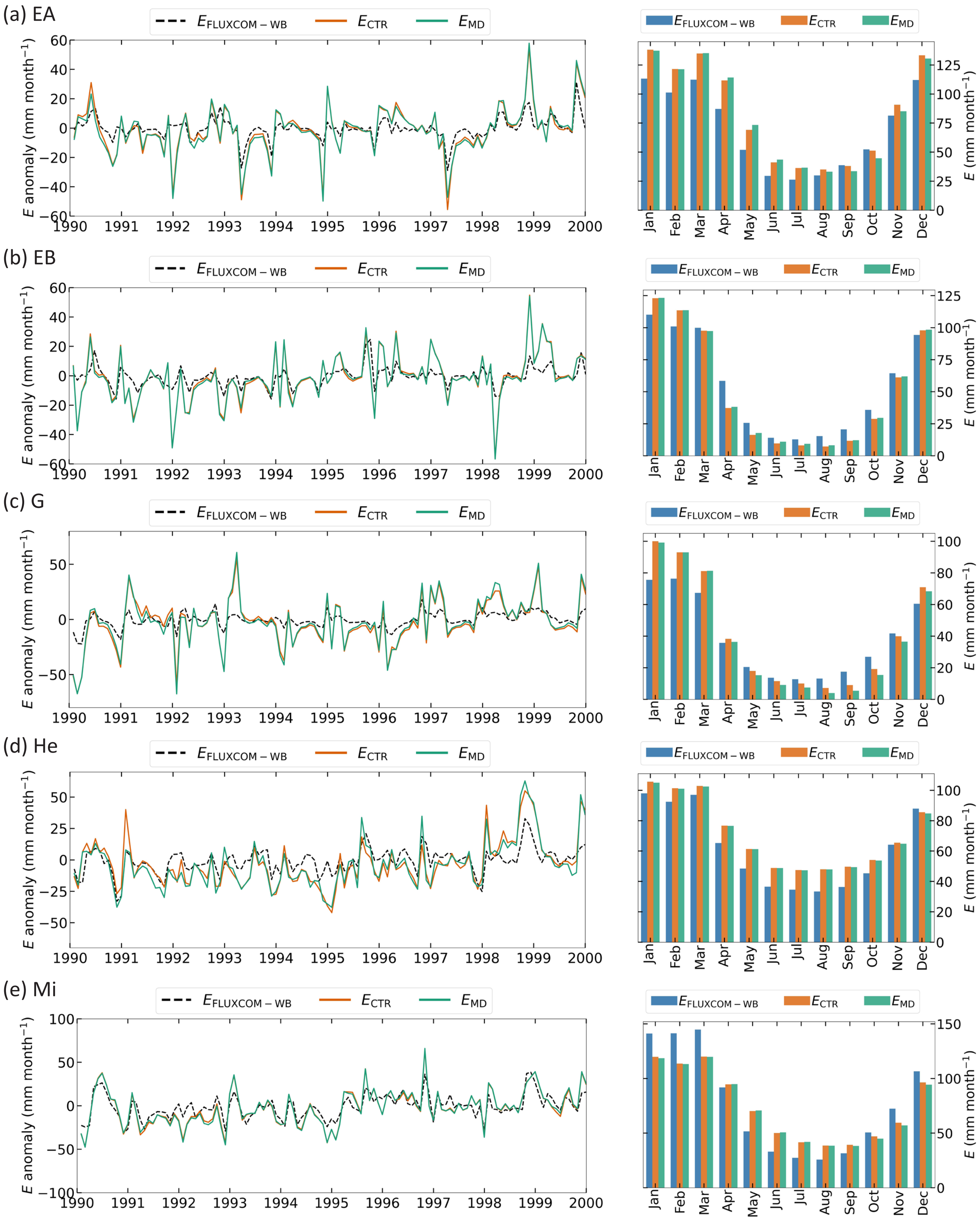
(k) Mu
(l) P
(m) Av
(n) K
(o) R
Q observed
Q CTR
Q MD
P
Q anomaly (mm month⁻¹)
P (mm month⁻¹)
Q (mm month⁻¹)
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

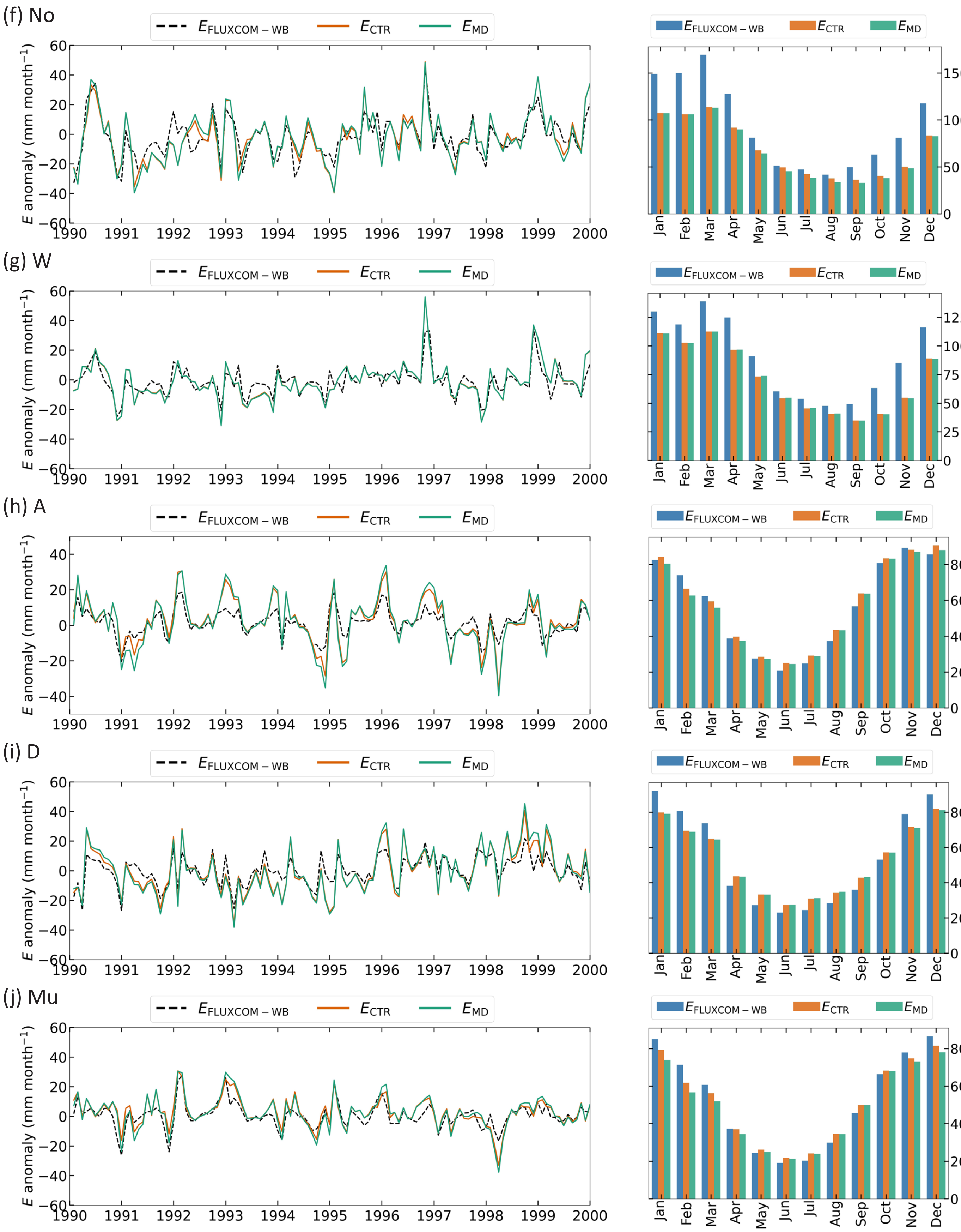
4. Model results monthly evaporation

*Table S6. Model performance based on monthly modeled (HTESSEL CTR and MD models) evaporation fluxes compared to FLUXCOM-WB with Pearson correlation (r) and variability ($\alpha = \sigma_{mod}/\sigma_{obs}$) for inter-annual anomalies of monthly evaporation fluxes and of monthly seasonal climatology evaporation for the time series 1975–2010 in the study catchments. For both r and α a value of 1 corresponds to a perfect model fit. The significance test of the MD improvements compared to CTR is represented by ** (passing 5% level) and * (passing 10% level) and additionally P-values are provided for the cases that MD improves compared to CTR.*

	Monthly seasonal climatology							**Inter-annual anomalies**					
	r (-)			**α (-)**				**r (-)**			**α (-)**		
Catchment	**CTR**	**MD**	**P-value**	**CTR**	**MD**	**P-value**		**CTR**	**MD**	**P-value**	**CTR**	**MD**	**P-value**
EA	0.99	0.98	-	1.22	1.23	-		0.81	0.81	-	2.12	2.16	-
EB	0.99	0.99	-	1.18	1.17**	0.004		0.70	0.70	-	2.57	2.57*	0.072
G	0.99	0.99	-	1.40	1.45	-		0.82	0.83**	0.001	3.30	3.40	-
He	0.99	0.98	-	0.88	0.97**	0.015		0.71	0.75**	<0.001	1.72	1.89	-
Mi	0.98	0.97	-	0.69	0.69	-		0.83	0.83	-	1.36	1.38	-
No	0.98	0.99	0.154	0.65	0.68**	0.002		0.85	0.83	-	1.19	1.23	-
W	0.98	0.97	-	0.86	0.86	-		0.84	0.84	-	1.20	1.21	-
A	0.99	0.98	-	0.96	0.94	-		0.86	0.86*	0.064	1.88	2.05	-
D	0.99	0.99	-	0.73	0.72	-		0.84	0.84	-	1.52	1.64	-
Mu	0.99	0.98	-	0.87	0.82	-		0.82	0.85**	<0.001	1.32	1.50	-
Na	1.00	1.00	-	0.79	0.75	-		0.79	0.80**	0.05	1.88	2.17	-
P	0.98	0.97	-	0.77	0.76	-		0.73	0.73	0.281	2.92	3.05	-
Av	0.94	0.89	-	1.07	1.14	-		0.82	0.82	0.222	2.28	2.40	-
K	0.51	0.53**	0.031	0.60	0.64**	<0.001		0.66	0.67	0.149	2.29	2.31	-
R	0.99	0.99	-	0.74	0.74	0.486		0.86	0.85	-	1.46	1.51	-

Figure S2: Monthly anomalies (left) and monthly seasonal climatology (right) of modeled evaporation with the HTESSEL CTR and MD models compared to FLUXCOM-WB evaporation in the study catchments (Table S1). Monthly anomaly evaporation is presented for the time series 1990-2010 and monthly seasonal climatology is based on the time series of 1975-2010.




(f) No
(g) W
(h) A
(i) D
(j) Mu
$E_{FLUXCOM-WB}$
E_{CTR}
E_{MD}
E anomaly (mm month−1)
E (mm month−1)
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Jan
Feb
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Nov
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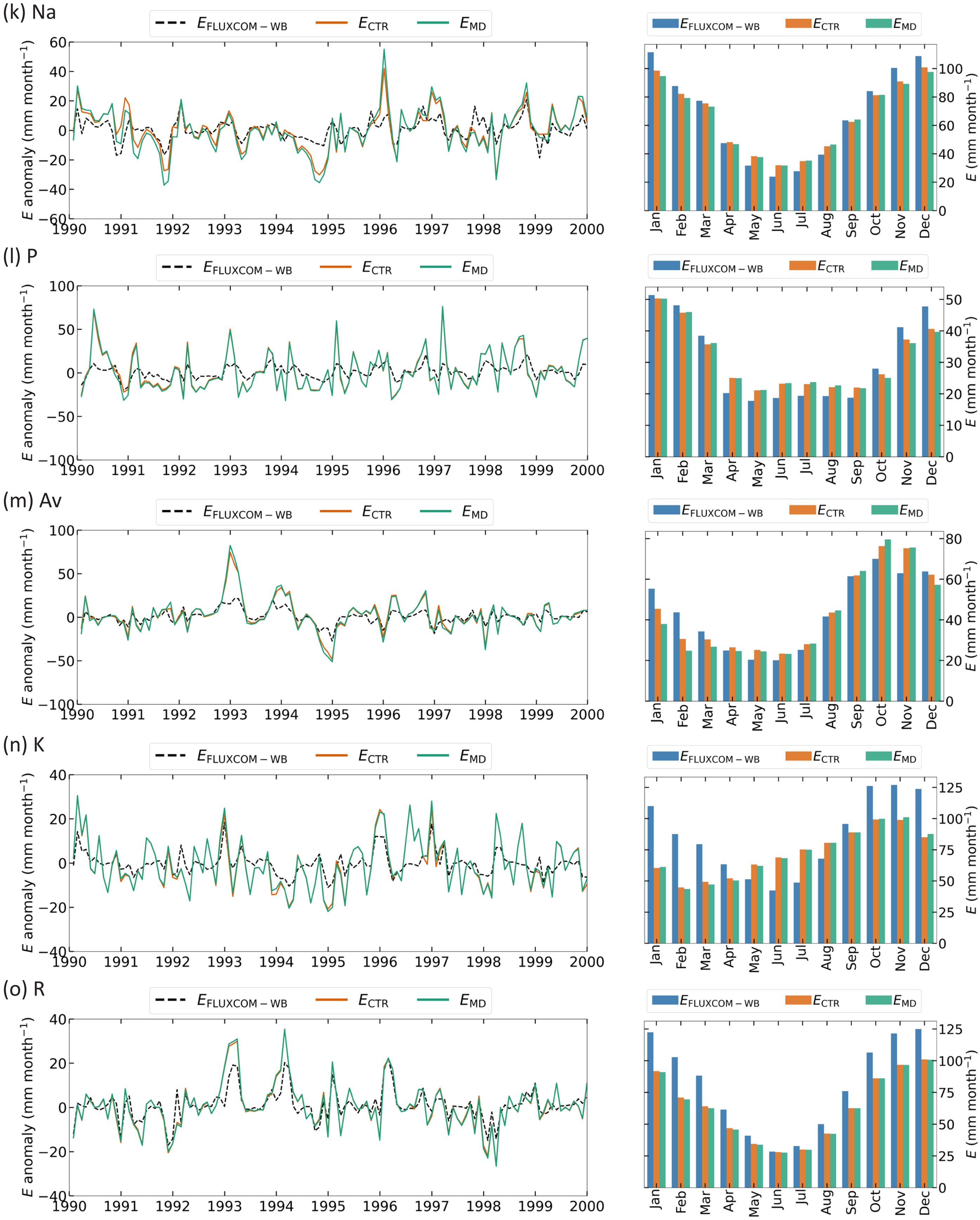
(k) Na
(l) P
(m) Av
(n) K
(o) R
E_FLUXCOM – WB
E_CTR
E_MD
E anomaly (mm month⁻¹)
E (mm month⁻¹)
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

5. Effective root zone storage capacity

Figure S3 presents an analysis of the model S_r computed using the modelled soil moisture deficits and an extreme value analysis as done in the memory method ($S_{\mathrm{r,eff}}$). From this figure it is confirmed that the $S_{\mathrm{r,CTR}}$ estimates implied by the model soil depth are larger than the effectively used S_{r} in CTR ($S_{\mathrm{r,CTR,eff}}$) (Fig. S3c). This is likely related to the relatively small root percentage in layer 4 prescribed from look-up tables in this layer for most vegetation types compared to the other layers. In contrast with the finding that $S_{\mathrm{r,CTR}}$ is larger than $S_{\mathrm{r,MM}}$ in most catchments (Fig. S3a), the $S_{\mathrm{r,CTR,eff}}$ is smaller than $S_{\mathrm{r,MM}}$ in 5 tropical and 2 Mediterranean catchments (Fig. S3b). On the other hand, the $S_{\mathrm{r,MM}}$ we implemented in the MD model is in general close to $S_{\mathrm{r,MD,eff}}$ being based on modelled soil moisture deficits in the MD model, with slightly larger deviations in the aforementioned 5 tropical and 2 Mediterranean catchments (Fig S3d). In follow-up studies on the model S_{r} we need to further investigate the role of the root distribution parameter that is likely causing the apparent deviations between the soil depth based S_{r} and $S_{\mathrm{r,eff}}$.

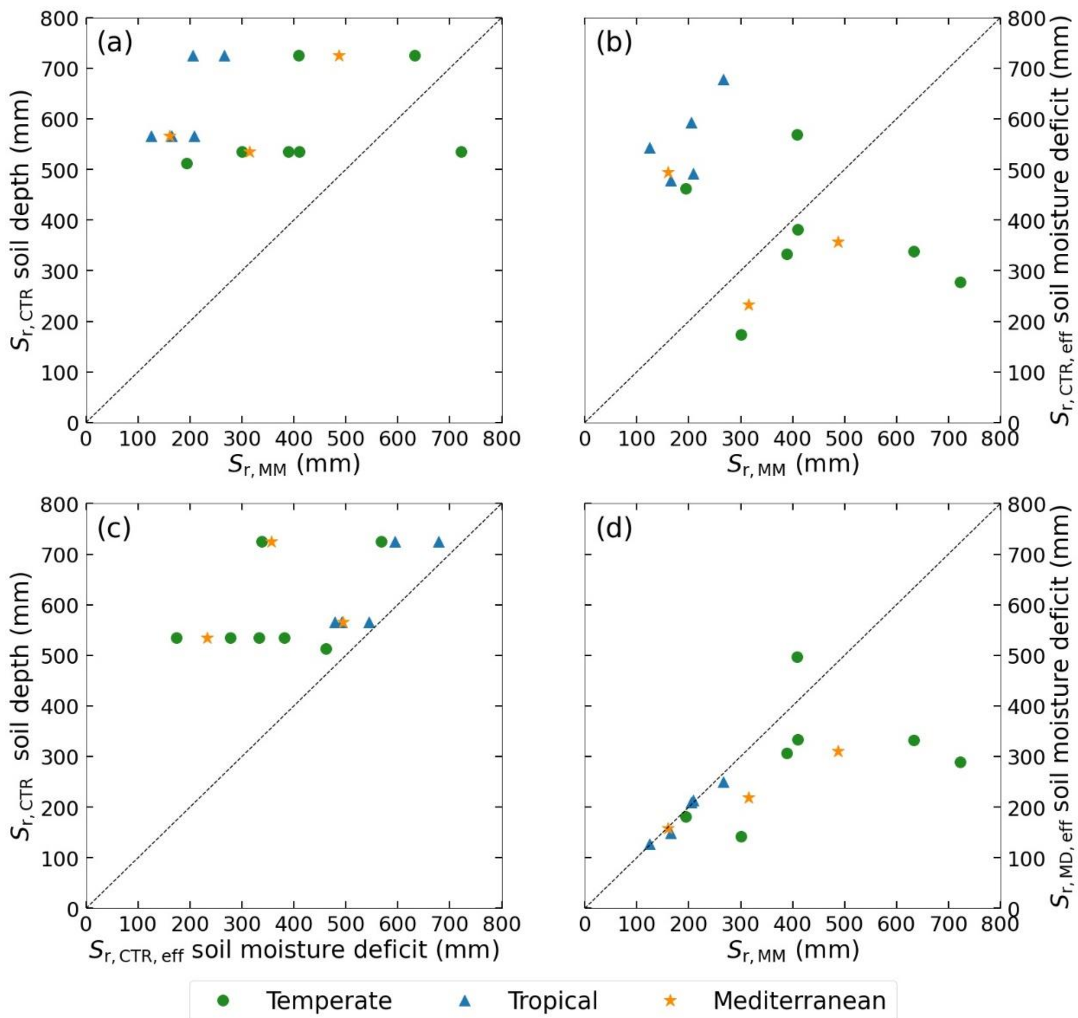

Figure S3. Model S_r analysis. (a) $S_{r,MM}$ from the memory method vs. $S_{r,CTR}$ based on HTESSEL soil depth. (b) $S_{r,MM}$ from the memory method vs. $S_{r,CTR,eff}$ based on modelled soil moisture deficits. (c) $S_{r,CTR}$ based on soil depth vs. $S_{r,CTR,eff}$ based on modelled soil moisture deficits. (d) $S_{r,MM}$ from the memory method vs. $S_{r,MD,eff}$ based on modelled soil moisture deficits