Soil moisture monitoring at kilometer scale: assimilation of Sentinel-1 products in ISBA

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SUPPLEMENT

Table S1. Correlation coefficient (R), unbiased root mean square difference (ubRMSD) and number of observations between S1 SSM products and the Meteopole-Flux, SMOSMANIA and REMEDHUS stations within the three regions considered in this study from 2017 to 2019, at 18:00 UTC. Correlation coefficient (ubRMSD) values larger (smaller) than 0.5 (0.05 m^3 m^{-3}) are in bold.

Station	Region	*R*	ubRMSD (m^3 m^{-3})	Number
Meteopole-Flux	Toulouse	**0.60**	0.080	121
Lahas	Toulouse	0.44	0.082	117
Savenes	Toulouse	**0.64**	0.076	121
Saint-Felix-Lauragais	Toulouse	**0.59**	**0.048**	117
Pezenas	Montpellier	**0.66**	**0.035**	169
La Grand Combe	Montpellier	**0.85**	**0.025**	163
Villevieille	Montpellier	0.40	0.091	176
Canizal	Salamanca	**0.52**	0.061	350
Carretoro	Salamanca	0.50	**0.040**	360
Casa periles	Salamanca	0.36	0.054	359
Concejo del Monte	Salamanca	0.50	0.059	342
El Coto	Salamanca	0.32	**0.037**	179
El Tomillar	Salamanca	**0.54**	**0.032**	171
Granja G	Salamanca	0.36	0.066	352
Guarrati	Salamanca	0.42	0.120	172
La Cruz de Elias	Salamanca	0.50	**0.049**	353
Las Arenas	Salamanca	**0.57**	0.066	171
Las Bodegas	Salamanca	**0.60**	**0.041**	165
Las Brozas	Salamanca	0.09 (*)	0.054	344
Las Eritas	Salamanca	**0.65**	0.054	181
Las Tres Rayas	Salamanca	0.48	0.066	181
Las Vacas	Salamanca	**0.51**	**0.043**	360
Las Victorias	Salamanca	0.49	**0.036**	355
Llanos de la Boveda	Salamanca	0.42	0.056	360
Paredinas	Salamanca	**0.55**	**0.031**	360
Zamarron	Salamanca	**0.70**	**0.034**	177

* Non-significant correlation (P-value = 0.1)

Table S2. Correlation coefficient (R), unbiased root mean square difference (ubRMSD), and mean bias (MB) between OL simulations, S1 SSM products, and in situ observations at Meteopole-Flux, SMOSMANIA, and REMEDHUS stations within the three regions considered in this study from 2017 to 2019 at 18:00 UTC. The best scores from the comparison with in situ observations are shown in bold.

Meteopole-Flux

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.80**	**0.060**	**0.062**	**0.016**	125
S1 SSM vs. *in situ*	0.60	0.080	0.082	0.017	121
S1 SSM vs. OL	0.57	0.052	0.104	-0.090	125

Lahas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.82**	**0.055**	**0.055**	**0.008**	124
S1 SSM vs. *in situ*	0.44	0.082	0.135	0.107	117
S1 SSM vs. OL	0.55	0.054	0.114	-0.100	124

Savenes

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.80**	**0.060**	**0.062**	**0.016**	125
S1 SSM vs. *in situ*	0.64	0.076	0.096	0.058	121
S1 SSM vs. OL	0.78	0.038	0.057	-0.043	125

Saint-Felix-Lauragais

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.82**	**0.042**	0.111	-0.103	123
S1 SSM vs. *in situ*	0.59	0.048	**0.049**	**0.006**	117
S1 SSM vs. OL	0.67	0.055	0.121	-0.108	122

Pezenas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.87**	**0.035**	0.154	-0.150	173
S1 SSM vs. *in situ*	0.66	**0.035**	**0.071**	**-0.062**	169
S1 SSM vs. OL	0.53	0.058	0.103	-0.085	173

Villevieille

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.83**	**0.056**	**0.095**	-0.076	180
S1 SSM vs. *in situ*	0.40	0.091	0.097	**-0.034**	176
S1 SSM vs. OL	0.55	0.063	0.076	-0.043	177

La Grand-Combe

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.87**	0.043	0.165	0.159	165
S1 SSM vs. *in situ*	0.85	**0.024**	**0.028**	**-0.013**	163
S1 SSM vs. OL	0.71	0.058	0.156	-0.145	164

Canizal

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.70**	**0.050**	**0.051**	**0.007**	353
S1 SSM vs. *in situ*	0.52	0.061	0.086	0.060	350
S1 SSM vs. OL	0.54	0.057	0.076	-0.051	353

Carretoro

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.68**	0.045	0.157	-0.150	361
S1 SSM vs. *in situ*	0.50	**0.040**	**0.104**	**-0.095**	360
S1 SSM vs. OL	0.55	0.055	0.071	-0.046	361

Casa periles

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.79**	**0.034**	0.175	-0.171	360
S1 SSM vs. *in situ*	0.36	0.054	**0.057**	**-0.020**	359
S1 SSM vs. OL	0.64	0.044	0.157	-0.150	360

Concejo del Monte

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.62**	**0.055**	**0.057**	**-0.012**	348
S1 SSM vs. *in situ*	0.50	0.059	0.108	0.091	342
S1 SSM vs. OL	0.63	0.048	0.115	-0.104	348

El Coto

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.44**	0.054	0.229	-0.222	181
S1 SSM vs. *in situ*	0.32	**0.037**	**0.081**	**-0.072**	179
S1 SSM vs. OL	0.62	0.047	0.146	-0.139	181

El Tomillar

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.62**	0.044	0.273	-0.270	173
S1 SSM vs. *in situ*	0.54	**0.032**	**0.089**	**-0.083**	171
S1 SSM vs. OL	0.54	0.046	0.192	-0.187	173

Granja G

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.82**	**0.038**	0.128	-0.122	355
S1 SSM vs. *in situ*	0.36	0.066	**0.082**	**-0.048**	352
S1 SSM vs. OL	0.35	0.059	0.094	-0.073	355

Guarrati

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.69**	**0.101**	**0.105**	**-0.029**	175
S1 SSM vs. *in situ*	0.42	0.120	0.152	0.098	172
S1 SSM vs. OL	0.61	0.0423	0.135	-0.128	174

La Cruz de Elias

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.76**	**0.039**	0.085	-0.076	360
S1 SSM vs. *in situ*	0.50	0.049	**0.050**	**-0.010**	353
S1 SSM vs. OL	0.62	0.047	0.081	-0.066	360

Las Arenas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.75**	**0.053**	0.133	-0.122	174
S1 SSM vs. *in situ*	0.57	0.066	**0.082**	**0.048**	171
S1 SSM vs. OL	0.68	0.037	0.174	-0.170	174

Las Bodegas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.83**	**0.036**	0.085	-0.078	169
S1 SSM vs. *in situ*	0.60	0.041	**0.041**	**0.001**	165
S1 SSM vs. OL	0.65	0.049	0.094	-0.080	169

Las Brozas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.54**	**0.053**	0.163	-0.154	347
S1 SSM vs. *in situ*	0.09	0.054	**0.110**	**-0.096**	344
S1 SSM vs. OL	0.08	0.063	0.086	-0.058	347

Las Eritas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.75**	**0.046**	**0.049**	**-0.015**	185
S1 SSM vs. *in situ*	0.65	0.054	0.158	0.149	181
S1 SSM vs. OL	0.78	0.036	0.168	-0.164	185

Las Tres Rayas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.59**	**0.063**	0.154	-0.140	185
S1 SSM vs. *in situ*	0.48	0.066	**0.088**	**-0.059**	181
S1 SSM vs. OL	0.65	0.047	0.093	-0.081	185

Las Vacas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.82**	**0.036**	0.153	-0.148	361
S1 SSM vs. *in situ*	0.51	0.043	**0.073**	**-0.059**	360
S1 SSM vs. OL	0.45	0.057	0.106	-0.090	361

Las Victorias

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.58**	0.046	0.278	-0.274	357
S1 SSM vs. *in situ*	0.49	**0.036**	**0.146**	**-0.141**	355
S1 SSM vs. OL	0.61	0.045	0.141	-0.133	357

Llanos de la Boveda

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.78**	**0.039**	0.107	-0.100	361
S1 SSM vs. *in situ*	0.42	0.056	**0.063**	**0.028**	360
S1 SSM vs. OL	0.55	0.047	0.136	-0.128	361

Paredinas

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.70**	0.044	0.212	-0.208	360
S1 SSM vs. *in situ*	0.55	**0.031**	**0.103**	**-0.099**	360
S1 SSM vs. OL	0.53	0.048	0.120	-0.109	360

Zamarron

Comparison	*R*	ubRMSD ($m^3\ m^{-3}$)	RMSD ($m^3\ m^{-3}$)	MB ($m^3\ m^{-3}$)	Number
OL vs. *in situ*	**0.83**	**0.032**	0.211	-0.209	180
S1 SSM vs. *in situ*	0.70	0.034	**0.086**	**-0.079**	177
S1 SSM vs. OL	0.73	0.040	0.136	-0.130	180

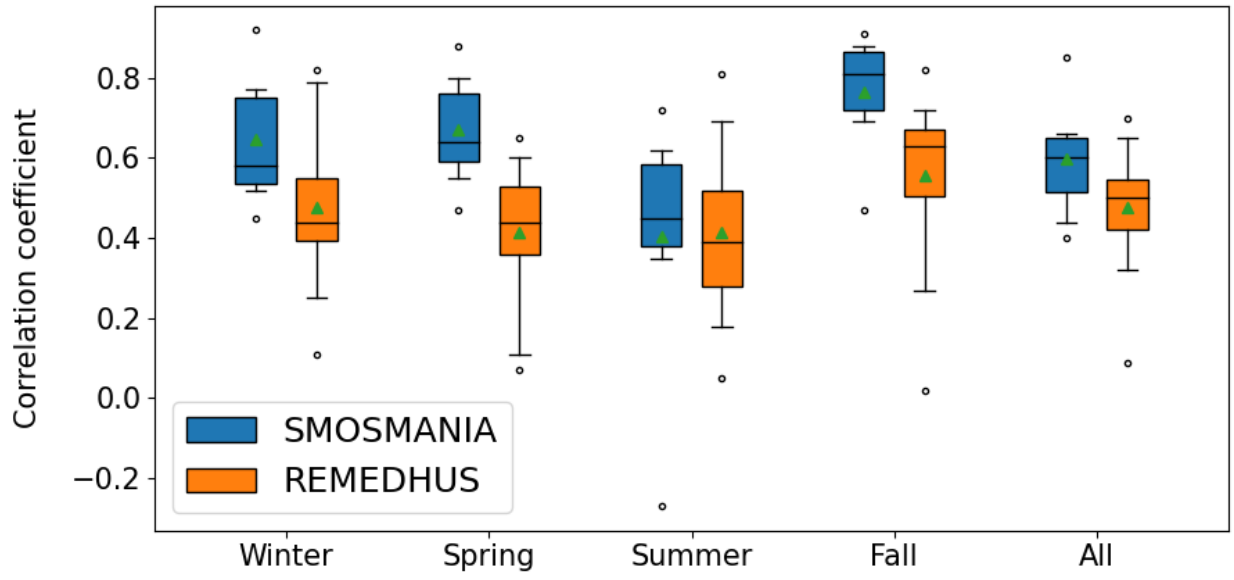

Figure S1. Correlation coefficient distributions of S1 SSM for the 7 SMOSMANIA stations in southern France (blue) and the 19 REMEDHUS stations of Salamanca (orange), for the four seasons of the year and for all the period of study. Freezing cases are sorted out by excluding data for which soil temperature at -5 cm is less than 4 °C. Statistical distributions are represented by box-and-whisker plots, where the boxes indicate the 25th and 75th data percentiles, the whiskers indicate the 5th and 95th percentiles, the middle line represents the median, the green triangle the mean, and the outliers shown as dots.

The paper focuses on the Montpellier region. The three assimilation experiments were also performed for the other two regions where Sentinel-1 surface soil moisture products (S1 SSM) at 1 km spatial resolution are available. The three experiments are:
(1) assimilation of S1 SSM alone,
(2) assimilation of PROBA-V Leaf Area Index (LAI) alone, and
(3) the joint assimilation of these two satellite products.

I. Toulouse region

The land cover map from Copernicus Global Land Service is shown in Fig. S1, with the irrigation map from Meier et al. (2018). This region is predominantly covered with croplands in the southwestern part where the SMOSMANIA and stations are located. The rest of the region consists of both open and closed forests. The irrigation map from Meier et al. (2018) indicates that only a few cropland areas are irrigated

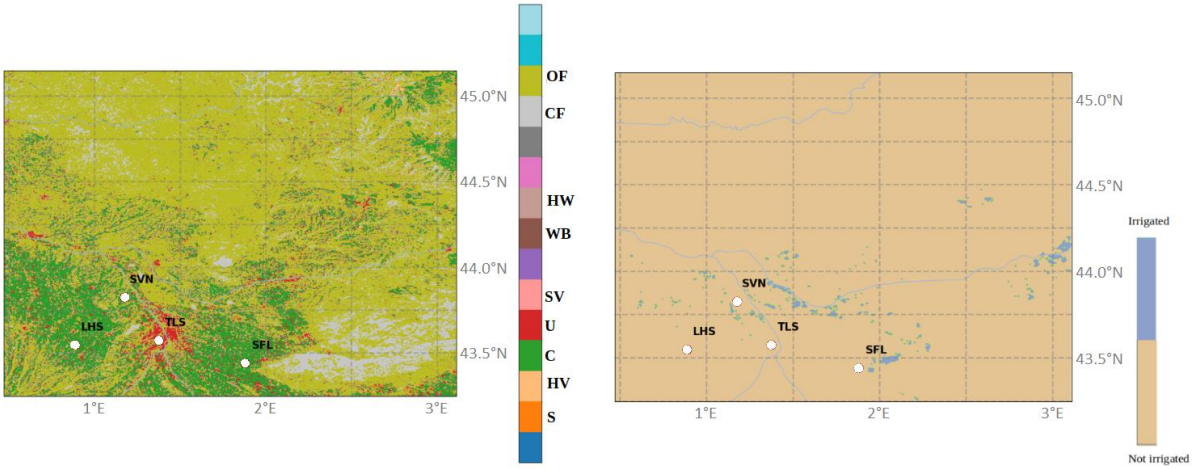

Figure S2. Land cover classification from CGLS (left) and irrigation map from Meier et al. (2018) (right) for the Toulouse region. Lands cover classes: Open forest ("OF"), closed forest ("CF"), herbaceous wetland ("HW"), permanent water bodies ("WB"), sparse vegetation ("SV"), urban ("U"), cropland ("C"), herbaceous vegetation ("HV") and shrubs ("S"). The location of the SMOSMANIA stations is shown (white dots).

Figure S2 illustrates the open-loop and analysis differences between July 2019 and July 2018 for the Toulouse region at 30 cm soil depth (WG5). Negative differences (red) are spotted at the southwestern and northeastern parts, and for mostly the rest of the domain July 2019 was drier than July 2018. Figure S3 shows the results of the three modeling experiments carried out and their impact on WG5. The impact of the assimilation of S1 SSM alone is small, except for an area in the northeast. The assimilation of LAI has a larger impact on WG5.

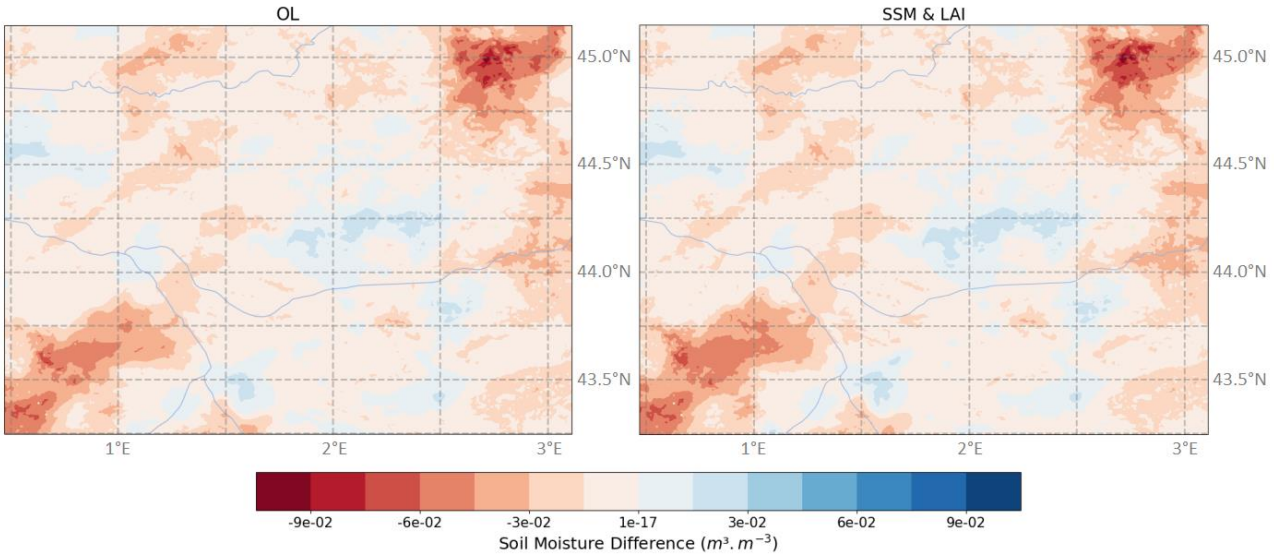

Figure S3. Map over the Toulouse domain of the WG5 difference between the averaged values of July 2019 and July 2018 from (left) the open-loop and (right) the joint assimilation of SSM and LAI.

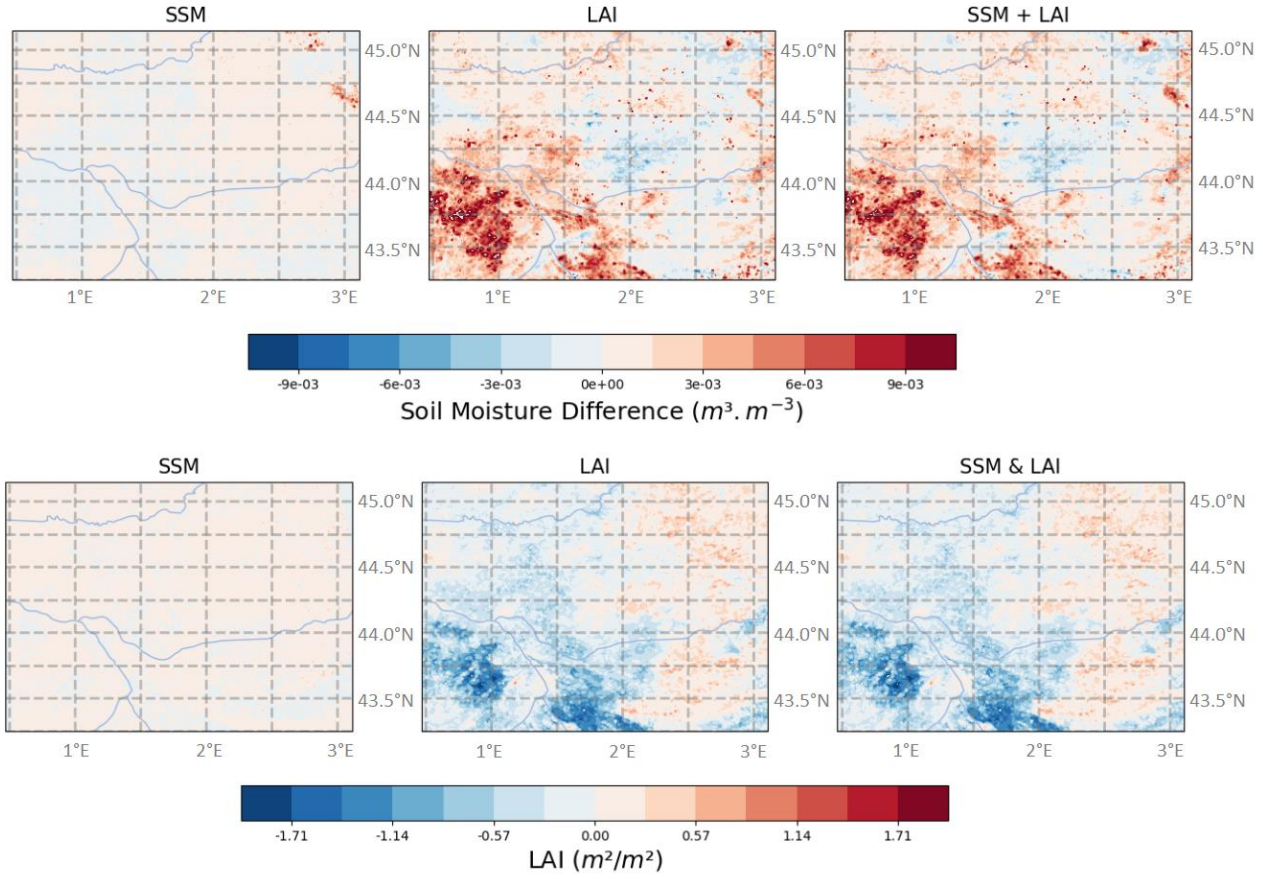

Figure S4. Year-to-year evolution from 2018 to 2019 over the Toulouse domain of the mean differences in July between (top) analyzed and open-loop WG5 and (bottom) LAI, when (left) S1 SSM is assimilated alone, (center) PROBA-V LAI is assimilated alone, (right) SSM and LAI are jointly assimilated. The red (blue) color indicates that the analysis adds (remove) water to the root-zone and increases (decreases) LAI more in 2019 than in 2018 in response to the assimilation.

II. Salamanca region

As for the Toulouse and Montpellier regions, the added value of the assimilation of S1 SSM is investigated. Figure S4 displays the land cover map of the Salamanca region, where croplands are primarily distributed between the cities of Salamanca and Valladolid, as well as in the north and northeastern parts. The rest of the region is characterized by open forest.

The irrigation map in Fig. S4 shows that most of the irrigated areas in the southwest are covered by open forest, with some croplands interspersed between them. It is noteworthy that Meier et al. (2018) [1] used different irrigation maps and gathered with their own, and that's why one can detect two other irrigation colors with respect to Figure S1.

Figure S5 presents the open-loop and analysis differences for WG5 between July 2019 and July 2018. The majority of the region is depicted in red, indicating more humid conditions in July 2018, with the northwestern part exhibiting a more accentuated difference.

The results of the three assimilation experiments are illustrated in Fig. S6. For this specific case, no impact is observed when S1 SSM products are assimilated, as the difference between the two years is close to zero. In contrast, LAI assimilation impacts WG5 primarily in the cropland areas, augmenting LAI compared to July 2018 and the open-loop.

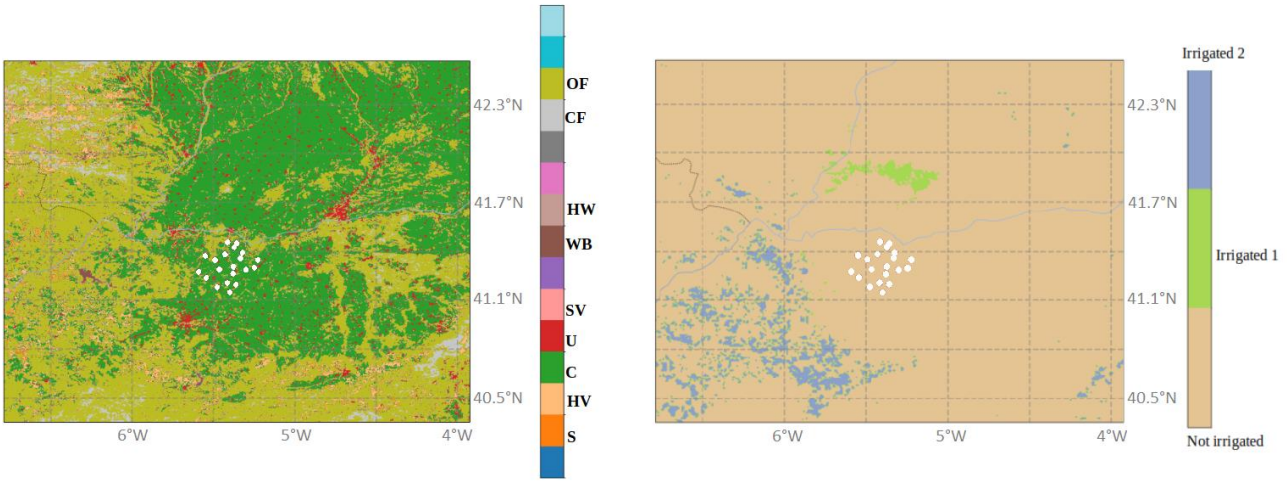

Figure S5. Land cover classification (left) and irrigation maps (right) for the Salamanca region (from Meier et al. (2018). Lands cover classes: Open forest ("OF"), closed forest ("CF"), herbaceous wetland ("HW"), permanent water bodies ("WB"), sparse vegetation ("SV"), urban ("U"), cropland ("C"), herbaceous vegetation ("HV") and shrubs ("S"). The location of the REMEDHUS stations is shown (white dots).

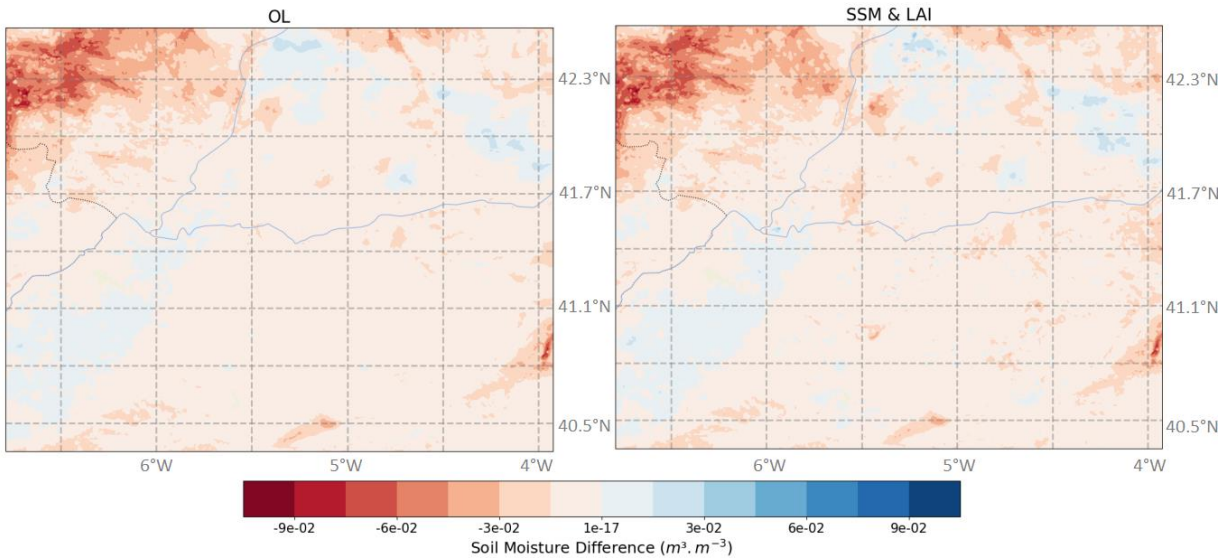

Figure S6. Map over the Salamanca domain of the WG5 difference between the averaged values of July 2019 and July 2018 from (left) the open-loop and (right) the joint assimilation of SSM and LAI.

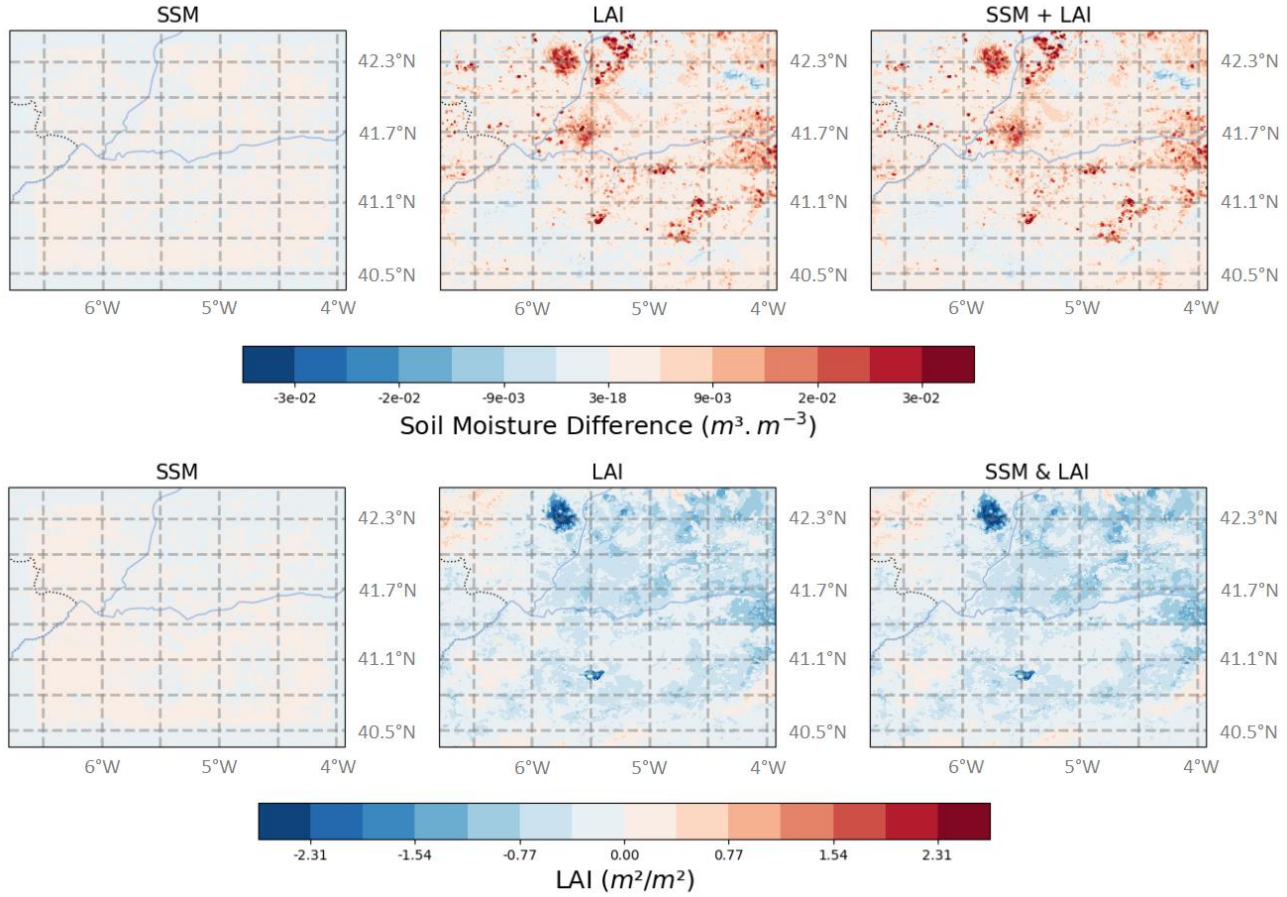

Figure S7. Year-to-year evolution from 2018 to 2019 over the Salamanca domain of the mean differences in July between (top) analyzed and open-loop WG5 and (bottom) LAI, when (left) S1 SSM is assimilated alone, (center) PROBA-V LAI is assimilated alone, (right) SSM and LAI are jointly assimilated. The red (blue) color indicates that the analysis adds (remove) water to the root-zone and increases (decreases) LAI more in 2019 than in 2018 in response to the assimilation.

References

Meier, J.; Zabel, F.; Mauser, W. A Global Approach to Estimate Irrigated Areas – a Comparison between Different Data and Statistics. *Hydrology and Earth System Sciences* **2018**, *22*, 1119–1133, https://doi.org/10.5194/hess-22-1119-2018.