

Answer to reviewer 2

The authors partly addressed the reviewers' comments. In my opinion, the main purpose of the paper, i.e., showing the improved performance of the all-weather SMOS L4_3.0 soil moisture product is not achieved. As mentioned in the HESSD review, I do not think that by performing a temporal analysis the added-value of a downscaled product can be evaluated. A spatial analysis should be performed. Looking at some of the figures, it seems that the proposed SMOS product fails in reproducing high variability of soil moisture at 1 km scale. Actually, it is not shown explicitly in the paper. Also the analysis for the initialization of SURFEX is weak, and not clear to me.

However, I do not want to force the authors to follow my suggestions. Several paper showing a downscaled soil moisture product have been accepted (in my opinion not correctly), therefore I may be wrong. Without a detailed spatial analysis, we must not say that the downscaled product are representative of high resolution. It is valid for all products, and also for modelling.

We agree with the reviewer that both a spatial and a temporal analysis are necessary to accurately describe the quality and added value of a downscaled product. We also agree that a detailed spatial analysis is needed to show that a downscaled product accurately represents high resolution. As we described previously in our answers to the reviewer, the temporal and spatial accuracy of the downscaled 1 km product has been previously extensively investigated and proved in many studies some of them referenced in this manuscript (e.g. Piles et al. 2011, 2013, 2014, 2015; Djamai et al 2016; Malbêteau et al 2018). Different observational networks around the world with different number of stations, positions, regional characteristic etc.. were used for this purpose.

In this study, we make use of an additional network with different characteristics to complement previous studies and illustrate our analysis. In agreement with all previous publications we used the information from the several in situ stations that form the VAS soil moisture network to assess the temporal as well as the spatial representativity of the downscaled product. In our analysis we pointed out the advantages and disadvantages of this product considering different temporal and spatial scale. Unfortunately, we are all constrained by the limitations in the number of stations, their locations, distance, soil characteristics etc... which come given mostly by a previous experimental campaign. We do not believe that any soil moisture product should be validated against model simulations, not even at very high resolution, since it is known that model simulations present significant biases in this regard which have to be considered and corrected.

We agree this is a relevant point raised by the reviewer, therefore, we propose to include in the conclusion the following paragraph:

“ This study also points out that in order to more accurately examine the reproducibility of the high spatial variability of this variable by the newly available satellite derived downscaled high-resolution soil moisture observations, large and dense networks of in situ soil moisture measurements covering different soil types and land uses as well as considering different soil depths are needed. In an effort to come a step forward in this direction, dedicated long-term

networks with the previously described characteristics should be established permanently in different regions around the world.”

Regarding the analysis for the initialization of SURFEX it has been indicated in the text (section 4.3.2) in agreement with the suggestions of the reviewers that this has to be just considered as an exercise to illustrate the relevance of the issue

“To exemplify the importance and implications of soil moisture initialization several experiments are performed.”

An improved perspective in the spatial representation of soil moisture: potential added value of SMOS disaggregated 1 km resolution “all weather” product

Samiro Khodayar¹, Amparo Coll², Ernesto Lopez-Baeza²

¹Institute of Meteorology and Climate Research (IMK-TRO), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

²University of Valencia, Spain. Earth Physics and Thermodynamics Department. Climatology from Satellites Group

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* Corresponding author. E-mail address: samiro.khodayar@kit.edu (S. Khodayar)

Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT),

Postfach 3640, 76021 Karlsruhe, Germany

1 **Abstract**

2 This study uses the synergy of multiresolution soil moisture (SM) satellite estimates from the
3 Soil Moisture Ocean Salinity (SMOS) mission, a dense network of ground-based SM
4 measurements, and a Soil Vegetation Atmosphere Transfer (SVAT) model, SURFEX
5 (Externalized Surface) – module ISBA (Interactions between Soil-Biosphere-Atmosphere), to
6 examine the benefits of the SMOS L4 version 3.0 or “all weather” high resolution soil
7 moisture disaggregated product (~ 1 km, SMOS_L4^{3.0}). The added value compared to
8 SMOS-L3 (~ 25 km) and L2 (~15 km) is investigated. In situ SM observations over the
9 Valencia Anchor Station (VAS; SMOS Calibration/Validation (Cal/Val) site in Europe) are
10 used for comparison. The SURFEX(ISBA) model is used to simulate point-scale surface SM
11 (SSM) and, in combination with high-quality atmospheric information data, namely ECMWF
12 and the SAFRAN meteorological analysis system, to obtain a representative SSM mapping
13 over the VAS. The sensitivity to realistic initialization with SMOS_L4^{3.0} to simulate the
14 spatial and temporal distribution of SSM is assessed. Results demonstrate: (a) all SMOS
15 products correctly capture the temporal patterns, but, the spatial patterns are not accurately
16 reproduced by the coarser resolutions probably in relation to the contrast with point-scale in
17 situ measurements. (b) The potential of SMOS-L4^{3.0} product is pointed out to adequately
18 characterize SM spatio-temporal variability reflecting patterns consistent with intensive point
19 scale SSM samples on a daily time scale. The restricted temporal availability of this product
20 dictated by the revisit period of the SMOS satellite compromises the averaged SSM
21 representation for longer periods than a day. (c) A seasonal analysis points out improved
22 consistency during December-January-February and September-October-November in
23 contrast to significantly worse correlations in March-April-May (in relation to the growing
24 vegetation) and June-July-August (in relation to low SSM values $< 0.1 \text{ m}^3/\text{m}^3$ and low spatial
25 variability). (d) The combined use of the SURFEX(ISBA) SVAT model with the SAFRAN

26 system, initialized with SMOS-L4^{3.0} 1 km disaggregated data is proven to be a suitable tool to
27 produce regional SM maps with high accuracy which could be used as initial conditions for
28 model simulations, flood forecasting, crop monitoring and crop development strategies,
29 among others.

30 *Key Words: soil moisture, SMOS 1-km disaggregated product, SURFEX, Valencia Anchor*
31 *Station, realistic initialization, SAFRAN*

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46 **1. Introduction**

47 Reliability of climate and hydrological models is constrained by associated uncertainties, such
48 as input parameters. Among them, soil moisture is a variable of pivotal importance
49 controlling the exchanges of water and energy at the surface/atmosphere interface (Entekhabi
50 et al., 1996). Thus, it is a highly relevant variable for climate, hydrology, meteorology and
51 related disciplines (e.g. Seneviratne et al. 2010).

52 Soil moisture is greatly variable spatially, temporally and across scales. The spatial
53 heterogeneity of soil, vegetation, topography, land cover, rainfall and evapotranspiration are
54 accounted responsible (Western et al., 2002; Bosh et al., 2007; Rosenbun et al. 2012).

55 The response of soil moisture to precipitation changes largely depends on soils water capacity
56 and climatic zones. Particularly, in dry climates such as the Iberian Peninsula (IP), soil
57 moisture quickly reacts to changes in precipitation (Li and Rodell 2013). Precipitation
58 variability and mean are positively correlated, thus, an increase in precipitation yields wetter
59 soils, which in turn results in higher spatial variability of soil moisture. An adequate
60 representation of the high spatio-temporal variability of soil moisture is needed to improve
61 climate and hydrological modelling (Koster et al., 2004; Seneviratne et al., 2006; Brocca et
62 al., 2010). Its impact has been seen on time scales from hours to years (e.g., ~ 20 km scale:
63 Taylor and Lebel, 1998; droughts: Schubert et al., 2004; decadal drying of the Sahel: Walker
64 and Rowntree, 1977; hot extremes: Seneviratne et al., 2006b; Hirschi et al., 2011; decadal
65 simulations: Khodayar et al., 2014). To obtain an appropriate representation of this variable,
66 especially at high-resolution, is not an easy task mainly because of its high variability.
67 Methods for the estimation of soil moisture can be divided in three main categories, (i)
68 measurement of soil moisture in the field, (ii) estimation via simulation models, and (iii)
69 measurement using remote sensing. In general, in situ measurements are far from global (e.g.,
70 Robock et al. 2000), and model simulations present important biases. Therefore, we have to

71 rely on space-borne sensors to provide such measurements, but until recent times no
72 dedicated, long-term, moisture space mission was attempted (Kerr, 2007).

73 Nowadays, by means of remote sensing technology surface soil moisture is available at global
74 scale (Wigneron et al., 2003). The best estimations result from microwave remote sensing at
75 low frequencies (e.g. Kerr, 2007; Jones et al., 2011) and several global soil moisture products
76 have been produced, such as the European Space Agency's Climate Change Initiative (ESA
77 CCI, Liu et al. 2011; Wagner et al. 2012) soil moisture products, the soil Moisture Active
78 Passive (SMAP; Entekhabi et al. 2010), the Advanced Microwave Scanning Radiometer-EOS
79 (AMSR-E; Owe et al. 2008), the advanced scatterometer (ASCAT; Naeimi et al. 2009) and
80 the Soil Moisture and Ocean Salinity (SMOS; Kerr et al., 2001) .

81 The SMOS mission is the first space-borne passive L-band microwave (1.4 GHz) radiometer
82 measuring at low frequency soil moisture over continental surfaces as well as ocean salinity
83 (Kerr et al., 2001, 2010). SMOS delivers global surface soil moisture measurements (~ 0-5
84 cm depth) at 0600 a.m. and 0600 p.m. LT (local time) in less than 3-days revisit at a spatial
85 resolution of ~ 44 km. The benchmark of the mission is to reach accuracy better than 0.04
86 m^3/m^3 for the provided global maps of soil moisture (Kerr et al., 2001).

87 SMOS data is not exempt of biases. Validating remote sensing-derived soil moisture products
88 is difficult, e.g. due to scale differences between the satellite footprints and the point
89 measurements on the ground (Cosh et al., 2004). However, in the last years a huge effort has
90 been made to validate the SMOS algorithm and its associated products. With this purpose, in
91 situ measurements across a range of climate regions were used assessing the reliability and
92 accuracy of these products using independent measurements (Delwart et al., 2008; Juglea et
93 al., 2010; Bircher et al., 2012; Dente et al., 2012; Gherboudj et al., 2012; Sánchez et al., 2012;
94 Wigneron et al., 2012). The strategy adapted by the European Space Agency (ESA) was to
95 develop specific land product validation activities over well-equipped monitoring sites. An

96 example for this is the Valencia Anchor Station (VAS; Lopez-Baeza et al., 2005a) in eastern
97 Spain, which was chosen as one of the two main test sites in Europe for the SMOS
98 Calibration/Validation (Cal/Val) activities. The validation sites were chosen to be slightly
99 larger than the actual pixel (3dB footprint), thus, VAS covers a 50x50 km² area. Within this
100 area, a limited number of ground stations were installed relying on spatialized soil moisture
101 information using the SVAT (Soil Vegetation Atmospheric Transfer) SURFEX (Externalized
102 Surface) model. Worldwide validation results reveal a coefficient of determination (R^2) of
103 about 0.49 when comparing the ~5 cm in situ soil moisture averages and the SMOS soil
104 moisture level 2 (SMOS-L2 ~ 15 km). For example, validation results by Bircher et al. (2012)
105 in Western Denmark show R^2 of 0.49-0.67 (SMOS retrieved initial soil moisture) and 0.97
106 (SMOS retrieved initial temperature). Besides, a significant under-/over-representation of the
107 network data (biases of -0.092 - 0.057 m³/m³) is also found. Over the Maqu (China) and the
108 Twente (The Netherlands) regions, the validation analysis resulted in R^2 of 0.55 and 0.51,
109 respectively, for the ascending pass observations, and of 0.24 and 0.41, for the descending
110 pass observations. Furthermore, Dente et al. (2012) pointed out a systematic SMOS soil
111 moisture (ascending pass observations) dry bias of about 0.13 m³/m³ for the Maqu region and
112 0.17 m³/m³ for the Twente region. Validation of the SMOS level 3 product (SMOS-L3 ~ 35
113 km) shows that the general dry bias in SMOS-L2 is also present in SMOS-L3 SM. This bias
114 is markedly present in the ascending products and shorter time series as described in Sanchez
115 et al. (2012) and Gonzalez-Zamora et al. (2015). In this case, the presence of dense vegetation
116 is seen to increase RMSE scores, whereas in low vegetated areas a lower dry bias is found
117 (Louvet et al. 2015).

118 Since the launch of the SMOS satellite, the processing prototypes of the SMOS L2 soil
119 moisture have evolved, and their quality has improved. Furthermore, efforts have been made
120 to cover the need of a reliable product with finer resolution for hydrological and climatic

121 studies where the spatial variability of soil moisture plays a crucial role, e.g. in the estimation
122 of land surface fluxes (evapotranspiration (ET) and runoff). Piles et al. (2011) presented a
123 downscaling approach to optimally combine SMOS' soil moisture estimates with MODIS
124 (Moderate Resolution Imaging Spectroradiometer) visible/infrared (VIS/IR) satellite data into
125 1 km soil moisture maps over the IP without significant degradation of the root mean square
126 error (RMSE). This product has been evaluated using the REMEDHUS (REd de MEDicion
127 de la HUmedad del Suelo) soil moisture network in the semi-arid area of the Duero basin,
128 Zamora, Spain (Piles et al. 2014). Results show that downscaling maintains temporal
129 correlation and root mean squared differences with ground-based measurements, hence,
130 capturing the soil moisture dynamics. Complementary studies after Piles et al. (2011) have
131 produced similar downscaled high-resolution SMOS-L4 soil moisture products (e.g.
132 Malbêteau et al (2018); Djamaï et al (2016)). Being similar, however, the algorithms
133 originating them are totally different from those of SMOS-L4 used in this study. Whereas
134 SMOS-L4 products in this study proceed from the original SMOS-L2 (15 km resolution soil
135 moisture) disaggregated by 1-km MODIS LST and NDVI, Malbêteau et al (2018) and
136 Djamaï et al (2016) products proceed from the original SMOS-L1 (15 km resolution
137 brightness temperature).

138 A big limitation for the downscaling approach used in Piles et al. (2011) is the lack of
139 information in cloudy conditions of the hereafter named SMOS_L4^{2.0}, which significantly
140 limits the availability and usefulness of this product. In this study, we examine a new version
141 of the SMOS_L4 product, the SMOS Level 4 3.0 "all weather" disaggregated ~ 1 km SM
142 (SMOS_L4^{3.0}), which was developed and has been recently made available by SMOS-BEC
143 (Barcelona Expertise Centre). In this advanced high-resolution soil moisture product the
144 limitation on clouds is modulated by the use of ERA-Interim LST data, thus providing soil
145 moisture measurements independently of the cloud conditions.

146 Contrary to SMOS-L3 and -L2 products, which have been extensively validated as described
147 above and used for assimilation purposes in models (e.g. De Lannoy et al. 2016; Leroux et al.
148 2016), few studies deal with the disaggregated 1 km SMOS-L4^{0.2} and SMOS-L4^{0.3} products
149 (mostly in relation to wildfire activity) and validation efforts have concentrated only on the
150 REMEDHUS soil moisture network in Zamora (north-western Spain; e.g. Piles et al. 2014).
151 The objective of this paper is to provide information about the advantages and drawbacks and
152 the added value of the disaggregated 1 km SMOS-L4^{3.0} “all weather” soil moisture product
153 with respect to coarser resolution products. The proposed investigation covers a one year
154 period (a complete hydrological cycle) and focuses on the semi-arid VAS area (eastern Spain)
155 and the IP where water availability and fire risk are big environmental issues, thus, knowledge
156 of soil moisture conditions is of pivotal importance. Furthermore, as spring time soil moisture
157 anomalies over the IP are believed to be a pre-cursor to droughts and heat waves in Europa
158 (Vautard et al. 2007; Zampieri et al. 2009), accurate monitoring and prediction of surface
159 states in this region may be key for improvements in seasonal forecasting systems.

160 The following objectives are then pursued: (a) Examination of soil moisture temporal and
161 spatial distribution with SMOS-derived soil moisture products over the investigation domain
162 using a multi-resolution approach: L3 (~ 25 km), L2 (~15 km), and L4^{3.0} (~ 1 km), (b)
163 Validation with the in situ soil moisture measurements’ network (VAS) to estimate the
164 reliability of the SMOS SM products, and (c) Evaluation of the impact of realistic SM
165 initialization using SMOS-L4^{3.0} on point-scale and regional SURFEX(ISBA) model
166 simulations over the VAS area.

167 This investigation is structured as follows, in Section 2, the study area and the data sets are
168 presented including the in situ network measurements, the SMOS data products, and the
169 SURFEX(ISBA) model and related atmospheric forcings used. Section 3 summarizes the

170 methodology applied. The results are discussed in Section 4. Finally, conclusions are drawn in
171 Section 5.

172

173 **2. Study area and data set**

174 2.1 Investigation domain and in situ measurements over the VAS

175 The main investigation areas in this study are the Iberian Peninsula and the Valencia Anchor
176 Station (VAS) site located in eastern Spain (39.69°-39.22° N,-1.7°-(-1.11°) W). The VAS site
177 covering approximately a 50x50 km² area was established in December 2001 by the
178 University of Valencia as a Calibration/Validation (Cal/Val) site for different low-resolution
179 Earth Observation data products (Bolle et al., 2006). The extension and homogeneity of the
180 area as well as the mostly flat conditions (slopes lower than 2%) make it an ideal reference
181 site. Nevertheless, the small variations in the area, 750 to 950 m, influence the climate of the
182 region, which oscillates between semiarid to dry-sub-humid. Most of the area is dedicated to
183 vineyards (65%), followed by trees, shrubs, forest and industrial and urban cover types.
184 Mostly bare soil conditions are observed beside the vineyard growing season (March/April to
185 September/October). Mean temperatures in the region are between 12°C and 14°C with
186 annual mean precipitation about 450 mm, with maximums in spring and autumn. Within the
187 VAS, a network consisting of eight ThetaProbe ML2x soil moisture stations was deployed by
188 the Climatology from Satellites Group from the Earth Physics and Thermodynamics
189 Department at the University of Valencia. The eight in situ stations are distributed over a
190 10x10 km² area (Figure 1), according to land use, soil type, and other environmental
191 conditions. Details about the characteristics of each station are summarized in Table 1. Soil
192 moisture measurements every 10 min, mostly from 2006, were carried out for the top first 5
193 cm. More details about the VAS characteristics and soil moisture measurements could be

194 found in Juglea et al. (2010). Precipitation measurements over the IP and the VAS are from
195 the AEMET (Agencia Estatal de Meteorología; Spanish Weather Service) network.
196 Measurements every 10 min are available.

197 2.2 The SMOS surface soil moisture products

198 ESA's derived SMOS Soil Moisture Level 2 (SMOS-L2) data product, ~ 15 km, contains the
199 retrieved soil moisture and optical thickness and complementary parameters such as
200 atmospheric water vapour content, radio frequency interferences and other flags. The SMOS-
201 L2 algorithms have been refined since the launch of SMOS, resulting in more precise SM
202 retrievals (ARRAY, 2014). The Level 3 SM product, SMOS-L3, was obtained from the
203 operational CATDS archive. This is a daily product that contains filtered data. The best
204 estimation of SM is selected for each node when several multi-orbit retrievals are available
205 for a given day. A detection of particular events is also performed in order to flag the data.
206 The processing of the data separates morning and afternoon orbits. The aggregated products
207 are generated from this fundamental product. The Level 4 SM, SMOS-L4 2.0 data (SMOS-
208 L4^{2.0}), with 1 km spatial resolution is provided by BEC and covers the IP, Balearic Islands,
209 Portugal, South of France, and North of Morocco (latitudes 34°– 45° N and longitudes 10° W
210 – 5° E). A downscaling method that combines highly accurate, but low-resolution SMOS
211 radiometric information (SMOS-L2 data) with high-resolution (brightness temperature
212 measurements), but low sensitivity, visible-to-infrared imagery (NDVI (Normalized
213 Difference vegetation Index) and LST (Land Surface Temperature) from Aqua MODIS) to
214 SSM across spatial scales is used to derive the SMOS-L4^{2.0} data (Piles et al 2010). The impact
215 of using different vegetation indices from MODIS with higher spatial and temporal resolution
216 in the downscaling method was explored in Sanchez-Ruiz et al. (2014), showing that the use
217 of more frequent and higher spatial-resolution vegetation information lead to improved SM
218 estimates. The latest SMOS-L4 product is the version 3.0 or “all weather” (SMOS-L4^{3.0}),

219 which is the product used and examined in this study. The downscaling approach is based on
220 Piles et al. (2014) and Sanchez-Ruiz et al. (2014), with the novelty of introducing ERA-
221 Interim LST data in the MODIS LST/NDVI scape, thus providing soil moisture
222 measurements independently of the cloud conditions. ERA-Interim provides a resolution of
223 about 0.125° , whereas MODIS is a ~ 1 km product. The evaluation of the SMOS-L4 2.0 and
224 3.0 products support the use of the “all weather” version, since it does not depend on cloud
225 cover and the accuracy of the estimates with respect to in-situ data is improved or preserved
226 (Piles et al. (2015), SMOS-BEC Team (2016)).

227 In this study, the SMOS-L2 V5.51 data coming from a L1C input product (obtained from
228 MIRAS measurements), the SMOS-L3 V2.72 and the SMOS-L4 V3.0 are employed.

229 2.3 The SURFEX(ISBA) SVAT model

230 The SVAT model SURFEX (Externalized Surface, Le Moigne et al. 2009) – module ISBA
231 (Interactions between Soil-Biosphere-Atmosphere, Noilhan and Planton 1989) is used to
232 generate point-scale and spatially distributed SM spatial at 1 km grid spacing and temporal
233 fields from initial conditions and atmospheric forcing. SURFEX(ISBA) was developed at the
234 National Center for Meteorological Research (CNRM), at Météo France, and it has been
235 widely validated over vegetated and bare surfaces (e.g. Calvet et al. 1998). The ISBA scheme
236 uses the Clapp and Hornberger (1978) soil water model and Darcy’s law for the estimation of
237 the diffusion of water in the soil, and allows 12 land use and related vegetation
238 parameterization types. Crops are considered for the VAS area since mainly vineyards,
239 almond and olive trees and shrubs compose the region.

240 The surface characteristics are considered in the SVAT input, roughness and the fraction of
241 vegetation are adopted from ECOCLIMAP (Masson et al. 2003), topography is obtained from
242 GTOPO (GTOPO30 Documentation) and soil types are defined using FAO (FAO, 2014).

243 To obtain an accurate simulation of soil moisture in the study area, the model was originally
244 calibrated by Juglea et al. (2010) to be applied over the entire site for any season/year.
245 Particularly relevant for this study is the specific definition of the soil hydraulic parameters
246 which they made for the VAS area, since most of the hydrological parameters are site
247 dependent and not available from SMOS observations. A new set of empirical equations as a
248 function of the percentages of sand and clay was defined using Cosby et al. (1984) and Boone
249 et al. (1999). New definitions and recommendations by Juglea et al. (2010) for the VAS area
250 were adopted in this investigation.

251 *Atmospheric forcing information: ECMWF and SAFRAN*

252 High quality atmospheric forcing is needed to carry out accurate simulations. To run the
253 SURFEX(ISBA) model, the following atmospheric forcing data are needed: air temperature
254 and humidity at screen level, atmospheric pressure, precipitation, wind speed and direction
255 and solar and atmospheric radiation. Three different sets of atmospheric forcing information
256 are used in this study as input forcing for the SURFEX(ISBA) simulations; (a) SURFEX-
257 OBS: meteorological data from 3 fully equipped stations in the OBS area, MELBEX-I,
258 MELBEX-II and VAS, (b) SURFEX-ECMWF: ECMWF (European Centre for Medium-
259 Range Weather Forecast) data, and (c) SURFEX-SAFRAN: information from the SAFRAN
260 (Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige)
261 meteorological analysis system (Durand et al. 1999; Quintana-Seguí et al. 2008; Vidal et al.
262 2010).

263 Precipitation, air temperature, surface pressure, air specific humidity, wind speed and
264 direction, downward longwave radiation, diffuse shortwave radiation, downward direct
265 shortwave radiation, snowfall rate and CO₂ concentration are used as input data from the
266 meteorological stations aforementioned in the OBS area. A temporal resolution of 10 min is
267 available. From ECMWF, dew point and temperature at 2 m, pressure, precipitation and wind

268 components, are used as forcing data, with a 6 h temporal resolution and $0.125^{\circ} \times 0.125^{\circ}$
269 spatial resolution. Precipitation, air temperature, surface pressure, air specific humidity, wind
270 speed and downward shortwave and longwave radiation from SAFRAN are used as input
271 information with a spatial resolution of $8 \times 8 \text{ km}^2$ and an hourly temporal resolution. In this last
272 case, we have an optimal spatial and temporal distribution of the atmospheric forcing over the
273 VAS area ($\sim 50 \times 50 \text{ km}^2$) and a rare to find complete database to force the land surface model.
274 More details about the SAFRAN system and its validation in north-eastern Spain could be
275 found in Quintana-Seguí et al. (2016).

276

277 **3. Analysis methodology**

278 In order to investigate the characteristics and potential added values of fine-scale SMOS-
279 derived soil moisture, the spatial variability, the temporal evolution as well as the probability
280 distribution is investigated. With this purpose, SMOS-derived soil moisture products at
281 different spatial resolutions, in situ measurements and model simulations are jointly
282 evaluated.

283 The spatial distribution and temporal evolution of precipitation and SMOS-derived soil
284 moisture over the IP and the VAS area are assessed for the time period from December 2011
285 to December 2012 considering also hydrological seasons (DJF: December-January-February,
286 MAM: March-April-May, JJA: June-July-August, SON: September-October-November).
287 Special attention is paid to the autumn season since in this period the western Mediterranean
288 is characterized by a large thermal gradient between the atmosphere and the sea (Duffourg
289 and Ducrocq, 2011, 2013) resulting in intense precipitation extremes (Raveh-Rubin and
290 Wernli 2015). Furthermore, during 2012, the Hydrological Cycle in the Mediterranean
291 Experiment (HyMeX; Dobrinski et al. 2014) took place in the Western Mediterranean with

292 the IP and particularly the Valencia region as target areas. During the SON period of 2012,
293 the Special Observation Period (SOP1; Ducrocq et al. 2014) with intensive experimental
294 deployment over the area took place. This provides us with valuable information about the
295 environmental conditions as well as the occurrence of precipitation events in the investigation
296 area. Particularly, precipitation in the IP during the autumn (SON) period of 2012 was above
297 average (Khodayar et al. 2015). It was also the hydrological season in which higher variability
298 in the soil moisture was observed as a result of the precipitation distribution. Two unique
299 events, at the end of September (27-29) affecting south and eastern Spain and at the end of
300 November (19-20) affecting the Ebro valley (Jansà et al. 2014), largely determined the
301 positive anomaly in precipitation and soil moisture in this period.

302 SMOS-L3 (~ 25 km), SMOS-L2 (~ 15 km), and SMOS-L4^{3.0} (~ 1km) are used for the
303 evaluation of soil moisture distribution at different grid spacing. Piles et al. (2014) pointed out
304 that differences may exist between SMOS-L3–L2 and the 1 km disaggregated soil moisture
305 SMOS-L4 because of the distinct methodology used to obtain these products. Only SMOS
306 descending passes or a mean between ascendant and descent passes are used to calculate
307 mean daily values of SMOS-derived soil moisture. Soil moisture derived from the afternoon
308 orbits was found to be more accurate than the morning passes (Piles et al. 2014). The fine
309 temporal resolution of the model simulations (1 h) and the observations (10 min) allow
310 comparisons at the time of the SMOS overpasses. Because of the 3-day revisit period of the
311 SMOS swath, the IP will not be fully covered by the satellite on daily basis. However, despite
312 identified difficulties (radio frequency interferences, missing data ...), the IP is well observed
313 being 1.5 days the average observations frequency over the IP. Only those images with
314 coverage higher than 50% are considered in our calculations. A conservative remapping to
315 coarser resolutions is applied, when required, to make comparisons among each other or with
316 respect to ground-based observations on equal terms. Remapping allows point to point

317 comparisons between these data sets. In addition to the yearly and seasonal approach, an
318 exemplary short time period, 19 to 20 October of 2012, is considered. This corresponds to one
319 of the periods in which an extreme precipitation event occurred in the Ebro valley (at the end
320 of November; Jansà et al. 2014). Therefore, high variability in the soil moisture distribution is
321 expected.

322 The coefficient of variation (CV), defined as the ratio of the standard deviation to the mean,
323 of the precipitation and soil moisture fields over the IP, the VAS (50x50 km²) and the OBS
324 (10x10 km²) area are examined for the analysis of the spatial variability and its evolution in
325 time. The soil moisture daily index ($SM_{index,i}$) is calculated to assess the evolution pattern
326 allowing the study of daily variations

327 $SM_{index,i} = (SM_{i+1} - SM_i) / SM_i$, where SM_{i+1} is the soil moisture of the day $i+1$ and SM_i is the
328 soil moisture of the day before i .

329 For these calculations, SMOS afternoon (descendant; Piles et al. 2014) orbits are selected as
330 well as observations at the time of the SMOS overpasses. For the IP and VAS, SMOS-L2 and
331 SMOS-L4^{3.0} have been remapped to the coarser grid spacing for an adequate comparison.
332 Ground-based observations are aggregated using a mean over all stations for comparison with
333 the corresponding SMOS-L4^{3.0} data (the closest grid point is selected).

334 The reliability of SMOS-L3, SMOS-L2 and SMOS-L4^{3.0} soil moisture products is evaluated
335 by comparison with in situ soil moisture measurements in the OBS area. The spatial and
336 temporal variability are considered as well as the probability distribution. Different
337 approaches are applied: (a) the nearest grid point is selected for point-like comparisons
338 between SMOS-L2 and SMOS-L4^{3.0} against in situ soil moisture stations, to reduce sampling
339 biases in this region of diverse soil characteristics (Table 1), (b) SMOS-L4^{3.0} soil moisture
340 grid cells are averaged over the 10x10 km² area and compared to the mean from the soil

341 moisture network stations to address the issue related to spatial averaging due to the high
342 spatial and temporal variability of the upper-most SSM. For the comparison between the
343 SMOS-L2 and the in situ observations: when single ground-based stations are considered the
344 closest SMOS pixel is selected, in case of considering the OBS (10x10 km²) or VAS (50x50
345 km²) areas the mean over all pixels which centre falls within the area is used. For the
346 comparison with SMOS descending passes the corresponding values from in situ
347 measurements are considered. Additionally, a separation between wet days (precipitation over
348 1 mm/d) and dry days is applied to consider possible implications of wet/dry soils for SMOS
349 measurements.

350 Linear regression, the coefficient of determination (R^2), the mean bias (MB), and the root
351 mean square deviation (RMSD) are used to predefine the accuracy. A debiased or centred
352 RMSD (CRMSD) is applied to discriminate the systematic and random error components
353 removing the overall bias before calculating the RMSD.

354 Soil moisture modeling is performed by the use of the SVAT, SURFEX (Externalized
355 Surface) – module ISBA (Interactions between Soil-Biosphere-Atmosphere) from Météo-
356 France. Configuration and specifications described in Juglea et al. (2010), which proved
357 successful in adequately simulate the associated soil moisture heterogeneity over the wide
358 VAS surface (50x50 km²), are adapted in this study. Simulations start on 1 December 2011 at
359 00UTC and cover the whole investigation period until 31 December 2012 with an hourly-
360 output time resolution. Point-scale SURFEX(ISBA) simulations over the soil moisture
361 network stations in the VAS domain are validated with the in situ measurements to assess the
362 usefulness of the model for further investigation, picturing the potential of the model in
363 simulating upper level soil moisture variability on different soil characteristics (Table 1).

364 To try to simulate the spatial and temporal heterogeneity of the soil moisture fields over the
365 VAS surface, the SURFEX(ISBA) scheme is used in combination with high quality forcing

366 data from ECMWF (hereafter SURFEX-ECMWF) and the SAFRAN system (hereafter
367 SURFEX-SAFRAN) for spatialization purposes. Soil moisture initialization in spatialized
368 SURFEX(ISBA) simulations requires a single representative value for the whole simulation
369 area. The benefit of initializing the simulations with SMOS-L4^{3.0} data in comparison to
370 climatological means is discussed. In-situ soil moisture observations over the VAS area are
371 considered for verification. A comparison between SURFEX-SAFRAN point-scale and 10x10
372 km² mean simulations initialized with SMOS-L4^{3.0} data is done against ground measurements
373 to assess the accuracy of the simulated SSM maps.

374

375 **4. Results**

376 4.1 SMOS-derived soil moisture at different resolutions

377 4.1.1 Spatial variability on seasonal and sub-seasonal time scales

378 Figure 2a shows the north-south precipitation gradient for the SON period mean. The SSM
379 satisfactorily reflects this gradient (Figure 2b), but, more markedly for the SMOS-L3 and
380 SMOS-L2 than the higher resolution SMOS-L4^{3.0} showing lower standard deviation, SMOS-
381 L3($\sim 0.15 \pm 0.01$), SMOS-L2($\sim 0.17 \pm 0.01$), SMOS-L4($\sim 0.22 \pm 0.007$). The same performance is
382 seen over the VAS domain (not shown). The SSM variability associated to the extreme
383 precipitation events in this period is not well represented in the SMOS-L4^{3.0} seasonal mean.
384 Table 2 shows the number of days (percentage) in which there is more than 50 % of data over
385 the IP for each SMOS product. These periods have been used as basis for the calculation of
386 the spatial distributions in Figure 2b. SMOS-L3 (88 %) and SMOS-L2 (84 %) show a good
387 coverage and similar number of days. However, a large difference is observed with respect to
388 the SMOS-L4^{2.0} product with only 28 days (32 %) of adequate coverage for the period of
389 SON 2012. This is due to the problematic associated to the downscaling approach used to

390 obtain the 1 km soil moisture maps, in which the lack of Land Surface Temperature (LST)
391 information from MODIS visible/infrared (VIS/IR) satellite data in cloudy conditions (section
392 2.2) constrains derived-SSM information. The availability and usefulness of this product is
393 therefore significantly reduced. The new product L4^{3.0}, used in this study, in which the
394 previous limitation is resolved using ERA-Interim-derived LST information, shows a
395 coverage percentage in the order of 92 %, even higher than the SMOS-L3 and -L2 products.
396 However, Figure 2b demonstrates that the spatial representation of the seasonal mean does not
397 improve with this product, as a consequence of the limited temporal availability of the
398 SMOS-derived SSM product dictated by the revisit period of the satellite.

399 In Figure 3, only common available days from all different operational levels are selected for
400 an inter-SMOS product comparison. When remapped to the same resolution (coarser grid
401 spacing) comparable values are identified between SMOS-L3, -L2 and -L4^{3.0} for the JJA and
402 SON period, whereas relevant differences are pointed out from December to May. In this last
403 period, we identify higher means for the SMOS-L4^{3.0} product and SMOS-L3 with respect to
404 SMOS-L2, which is in agreement with a systematic dry bias identified for SMOS-L2 also in
405 previous studies (section 1).

406 At sub-seasonal scales, e.g. event scale on the 19-20 November 2012 (Figure 4), the SMOS-
407 L4^{3.0} product shows SSM mean and variability in the same range of the SMOS-L2 and -L3
408 products, but with a finer-improved resolution representation of the spatial distribution.
409 Comparisons with the mean ground-based SSM at the VAS (OBS area: 0.25 ± 0.0002) show
410 better agreement with the mean SSM from the SMOS-L4^{3.0}-1 km disaggregated product
411 (0.23 ± 0.002) and poorer correlation with SMOS-L2 (0.20 ± 0.002). The problematic of SMOS-
412 L4^{3.0} on seasonal time scales vanishes at sub-seasonal (event) scales where the potential
413 added value of the 1 km product is manifest.

414 4.1.2 Temporal evolution of surface soil moisture data sets

415 The SMOS and in situ measured SSM time series are investigated and compared in this
416 section in Figures 5 and 6 over the IP, the VAS (50x50 km²) and the OBS (10x10 km²) areas.
417 Overall, the averaged SMOS-L2 and -L4^{3.0} data over the IP are much more variable than the
418 SMOS-L3, showing a more extreme daily index (SMOS-L2: -1 to 2; SMOS-L4^{3.0}: -0.7 to
419 1.45). Over the VAS, SMOS-L2 is clearly more variable than the higher resolution SMOS-
420 L4^{3.0}. But, the last one shows a wider range of values as well as more extreme daily index
421 values when compared to the averaged in situ soil moisture measurements. The CVs of the
422 spatially averaged SMOS-L4^{3.0} is lower than those of SMOS-L3, -L2 and in situ observations
423 indicating that this data are less scattered. Despite detected differences within in situ
424 observations, SMOS responds well to soil moisture variations over time.

425 Although absolute values are not totally captured, all three SMOS products adequately
426 reproduce the temporal dynamics at a regional scale. The systematic dry bias present on
427 SMOS-L2 data (Piles et al. 2014) is evident particularly on the first half of the year. A mean
428 bias in the order of -0.09 to -0.07 m³/m³ is identified for the DJF-MAM period; this difference
429 is reduced to -0.02 m³/m³ for the JJA-SON period (Table 3). During the DJF-MAM period the
430 vineyards are bare, only the vine stocks are present. The water content of the vine stocks
431 negatively impacts the SMOS measurements (Schwank et al. 2012).

432 Good agreement is found between the SMOS-L4^{3.0} product and the mean of the in situ
433 observations (the network's variability (shaded grey) contains the SMOS-L4^{3.0} data). Scores
434 confirm this result particularly for the periods DJF and SON (slope~1, R²~0.7). Poorer
435 correlation is found for the MAM (slope~0.6, R²~0.4). In this period, soil moisture maxima
436 immediately after the precipitation events are not always well captured by the SMOS-L4^{3.0}
437 data, showing additionally a too rapid drying after this. This observation agrees with the
438 SMOS' inability of correctly measuring in situations when liquid water is present at the soil.
439 The measured signal is perturbed during the vegetation growing season, which could explain

440 the worse statistics. On the other hand, during JJA, low slope \sim 0.1 and $R^2\sim$ 0.01 could be in
441 relation to SSM values close to or lower than $0.1\text{ m}^3/\text{m}^3$ and very low spatial variability,
442 which was found to be necessary for an adequate performance of the algorithm used for the
443 derivation of the SMOS-L4 1 km product in Molero et al. (2016).

444 4.2 Spatial comparison at high-resolution: SMOS-L4^{3.0} versus ground measurements

445 High-resolution spatio-temporal correlations are assessed by spatial comparison with in situ
446 observations. Characteristics of each of the in-situ stations are presented in Table 1. A
447 seasonal analysis is performed focusing on the selected year of measurements covering a
448 complete hydrological cycle (from 1 December 2011 to 31 December 2012). Comparisons
449 between SMOS-L2 and ground measurements are additionally included. Statistics for
450 individual comparisons at all stations are summarized in Table 3. Comparisons between
451 SMOS-L3 and ground measurements were similarly performed evidencing the expected bad
452 correlations ($R^2 \sim 0,002$, not shown)In Figure 7, the scatter plots display (a) possible
453 differences between dry and wet days ($> 1\text{ mm/d}$), and (b, c) the agreement between remotely
454 sensed and in situ soil moisture measurements from the OBS network using the seasonal
455 classification. To consider any uncertainties arising from spatial averaging, ground
456 measurements are compared to point like and $10\times 10\text{ km}^2$ SSM means. The $10\times 10\text{ km}^2$ area
457 used covers the OBS area, i.e., the network of in situ measurements within the VAS. For
458 comparison, all grid points from SMOS-L4^{3.0} and SMOS-L2 included within the area are
459 considered.

460 In Figure 7a, the separation between days with and without precipitation ($< 1\text{ mm/d}$) points
461 out similar correlations during dry than wet days (RMSD \sim 0.015, $R^2\sim$ 0.7) for SMOS-L4^{3.0},
462 whereas a slightly better agreement is found for the dry days (not shown) for SMOS-L2. A
463 systematic mean dry bias of about 0.05 (dry days) to 0.08 (wet days) m^3/m^3 is assessed for
464 SMOS-L2, while a lower bias with changing sign is identified for the L4^{3.0} product (~ 0.005

465 (wet days); ~ -0.02 (dry days)). Comparisons using the corresponding mean over the 10x10
466 km² OBS area, in Figure 7b and Table 3, show good agreement with respect to the SMOS-
467 L4^{3.0} and poorer scores for SMOS-L2 (only one grid point of SMOS-L2 is located within the
468 OBS area). Worse consistency is found in both cases for the MAM and JJA periods. CRMSD
469 is in all cases in the required range of ≤ 0.04 m³/m³. Point-like comparisons with the
470 individual in situ stations, in Figure 7c and Table 3, show that spatial patterns are captured at
471 1km with RMSD ~ 0.007 to 0.1 m³/m³ but, in most cases, accuracy for SMOS-L4^{3.0}-1 km
472 disaggregated product is within the required range of less than 0.04 m³/m³ (not shown).
473 Higher RMSD is found for SMOS-L2, ~ 0.008 to 0.13 m³/m³, accounting for the previously
474 identified dry bias ($\sim (-0.14) - (-0.02)$) reduced in SMOS-L4^{3.0} ($\sim (-0.08) - (-0.01)$). The
475 CRMSD is in all cases ≤ 0.04 m³/m³. For all stations, better correlations are found in DJF and
476 SON and poorer scores in JJA and MAM, in agreement with the areal-mean comparisons
477 (section 4.1.3). Best scores are obtained for Nicolas, VAS and La Cubera stations, probably in
478 relation to their common soil type distribution, over vineyards, and homogeneous conditions,
479 over a plain (Figure 8a, Table 3). The SON time period reveals the best agreement, at this
480 time the vineyards are completely grown (however, senescent thus containing less water) and
481 SSM exhibits substantial spatial variability driven by precipitation and irrigation thus
482 improving spatio-temporal correlations. Worse statistics are found for Melbex-I, Melbex-II
483 and Ezpeleta, probably in relation to the location of the soil moisture probes in rockier and
484 orographically more complex areas, also in proximity to forestall and man-made construction
485 areas.

486 The soil moisture probability distribution function (PDF; Figure 8b) of all in situ
487 measurements versus SMOS-L4^{3.0} data reveals that the later overestimates SSM below 0.1
488 m³/m³, values mainly observed during the JJA period. But, an underestimation occurs in the
489 range between 0.1 and 0.3 m³/m³, which is consistent with the identified underestimation of

490 maximum soil moisture reached after a precipitation event and the rapid drying of the soil in
491 comparison to the much slower response seen in the observations during the MAM period
492 (Figure 6c).

493 4.3 SURFEX model simulations and realistic initialization with 1-km soil moisture data

494 4.3.1 SURFEX model simulations of selected stations and realistic initialization

495 As a first step, the performance of the SURFEX(ISBA) SVAT model is evaluated.
496 SURFEX(ISBA) point-like simulations are performed for all in situ soil moisture stations at
497 the VAS area to assess the usefulness of the model for further investigation (Table 4).

498 SURFEX(ISBA) simulations show good agreement with soil moisture ground-based
499 observations at all stations, adequately capturing the associated spatio-temporal variability
500 (slope~1, R^2 ~ 0.7 to 0.9; MB~0.1 m³/m³; CRMSD~0.02 m³/m³). It can be concluded that the
501 model performs well and is therefore suitable for further investigation. The seasonal analysis
502 points out the best simulations in the SON period (R^2 ~0.9 for all stations), but CRMSD is ≤
503 0.04 m³/m³ for all stations at all periods.

504 Using the mean of the ground-based measurement on the day of the model simulation
505 initialization (realistic initialization; REAL-I) the temporal mean comparison for each station
506 presented in Figure 9 and Table 4 reveals mean R^2 ~0.8 when the all hydrological year is
507 considered.

508 4.3.2 Spatialization

509 As a first step, point-scale SURFEX-ECMWF and SURFEX-SAFRAN simulations covering
510 the whole investigation period are performed for all in situ soil moisture stations to examine
511 its ability to reproduce soil moisture dynamics. Ground measurements at each station are used
512 for initialization. Scores clearly indicate better agreement with all in situ observations for the

513 SURFEX-SAFRAN simulations (slopes~ 1, R^2 ~ 0.9, $RMSD < 0.1 \text{ m}^3/\text{m}^3$), rather than the
514 SURFEX-ECMWF simulations (slopes> 1, R^2 ~ 0.6, and $RMSD > 0.1 \text{ m}^3/\text{m}^3$).

515 In a second step, SURFEX-ECMWF and SURFEX-SAFRAN simulations are spatialized to
516 obtain maps of soil moisture over the investigation area. In our CTRL simulations, the daily
517 soil moisture from the mean of the in-situ measurements on the initialization day is used for
518 model initialization. Mean SSM from in situ measurements for the whole investigation period
519 is in the order of 0.14 ± 0.005 , whereas SURFEX-ECMWF derived SSM field is about
520 0.18 ± 0.007 and SURFEX-SAFRAN derived SSM field is 0.15 ± 0.002 , thus, closer to ground-
521 based observations. Performing a seasonal analysis, we demonstrate that this consistency is
522 maintained for all seasons (not shown). The higher resolution of the SAFRAN-atmospheric
523 forcing better reproduces the high spatial heterogeneity over the VAS area resulting in
524 improved mapping of simulated SSM.

525 To exemplify the importance and implications of soil moisture initialization several
526 experiments are performed. Initialization of the SURFEX-SAFRAN simulation using SMOS-
527 L4^{3.0} (EXP-SMOS) is examined against a sensitivity simulation using for the initial soil
528 moisture scenario the climatological soil moisture from observations (daily mean over 10
529 years, which has been selected to be far from observations; EXP-CLIM). These experiments
530 are initialized in dry periods, following Khodayar et al. (2014) recommendations, to
531 maximize the impact, and run for about 3-4 months. In the first case, initialization is
532 performed in a winter month (December) and the whole simulation period remains almost
533 dry. In the second case, a summer month (July) is chosen for the initialization and it is
534 followed by a wet autumn period with frequent heavy precipitation events in the area.

535 The temporal evolution of the RMSD (Figure 10a) demonstrates that the initial soil moisture
536 scenario influences its evolution until the end of the simulation, in agreement with previous
537 results in section 4.3.1. Larger deviations occur during dry periods, in both scenarios. Longer

538 spin-up times, defined as the time that soil needs to re-establish quasi-equilibrium,
539 characterize the dry scenario. It is after heavy precipitation events that deviations decrease.
540 Soil quickly reacts to changes in the precipitation field in the semi-arid IP. When the upper
541 level soil gets close to saturation soil memory is almost lost. Before the high precipitation
542 events, SSM evolves following the direction of the initial perturbation, i.e., higher initial SSM
543 yields higher SSM, however, a stochastic behaviour is identified afterwards.

544 As an example, differences in the spatial distribution of soil moisture for the winter/dry period
545 simulation are discussed (Figure 10b). A relevant difference in the mean is identified when
546 compared to the CTRL simulation (0.17 ± 0.004): EXP-CLIM (0.014 ± 0.003), EXP_SMOS
547 (0.17 ± 0.003). Clearly, better agreement is found in this last case.

548 Considering the EXP-SMOS initialization scenario simulation, a comparison between
549 simulated point-like and the $10 \times 10 \text{ km}^2$ mean against corresponding ground measurements
550 was done for verification (Figure 10c). Correlations in the order of $R^2 \sim 0.9$ confirm that the
551 combined use of SURFEX-SAFRAN and SMOS-L4^{3.0} for initialization successfully
552 reproduces soil moisture spatial and temporal variability becoming an optimal tool for
553 mapping soil moisture heterogeneity over a study region for diverse purposes.

554

555 **5. Discussion and conclusions**

556 High-resolution soil moisture products are essential for our understanding of hydrological and
557 climatic processes as well as improvement of model skills. Due to its high spatial and
558 temporal variability, it is a complicated variable to assess. Mapping high-resolution soil
559 moisture fields using intensively collected in-situ measurements is infeasible. Thus, state of
560 the art high-resolution modelling and satellite-derived products have to fill this gap, although
561 verification is needed. In this study, we examine the potential of the state of the art SMOS-

562 L4^{3.0}-1 km “all weather” disaggregated product for assessment of soil moisture variability,
563 and improvement of the SVAT SURFEX(ISBA) simulations, in combination with the
564 SAFRAN meteorological analysis system (SURFEX-SAFRAN), through realistic
565 initialization. A dense network of ground-based soil moisture measurements over the
566 Valencia Anchor Station (VAS; one of the SMOS test sites in Europe) is used for verification.
567 The proposed analysis focuses on the semi-arid IP and covers the one year period of 2012
568 (from December 2011 to December 2012). The comparison of the SMOS-L4^{3.0}-1km product
569 to different grid spacing soil moisture data products from SMOS, namely SMOS-L3 (~ 25
570 km) and SMOS-L2 (~15 km) shows that on seasonal time scales SMOS-L4^{3.0} does not
571 accurately capture the spatial variability of the soil moisture field, contrary to SMOS-L3 and
572 SMOS-L2, despite the novelty of introducing ERA-Interim LST data in the MODIS
573 LST/NDVI space (Piles et al. 2014; Sanchez-Ruiz et al. 2014). This is probably in relation to
574 the so different spatial resolution of ERA-Interim and MODIS. This new downscaling
575 approach greatly enhances the potential applicability of the data for those days/periods in
576 which measurements are available, but cannot accurately fill in those periods without
577 measurements dictated by the revisit period of the SMOS satellite, hence, compromising the
578 soil moisture representation as a mean for longer periods than a day. On sub-seasonal time
579 scales, when SMOS images are available, the SMOS-L4^{3.0} high-resolution product shows its
580 potential. It adequately captures the surface soil moisture variability in association with the
581 precipitation field, also when extreme precipitation takes place.

582 Mean and single station comparisons with in-situ measurements reveal that characteristics of
583 SMOS-L4^{3.0} soil moisture fields are closer to in-situ observations than SMOS-L3 and -L2
584 products. Point-like and 10x10 km² comparisons show good agreement with respect to the
585 SMOS-L4^{3.0} and poorer scores for SMOS-L2 (e.g. DJF period: SMOS-L3/-L2: Slope:1.1/1.0,
586 R²:0.5/0.7, Bias:-0.09/(-0.03)). Generally, all three SMOS products adequately reproduce the

587 soil moisture temporal dynamics meeting the desired accuracy of the mission (0.04 m³/m³);
588 however, the spatial patterns did not always reach the expected precision in agreement with
589 former studies in other regions (Gonzalez-Zamora et al. 2015). Comparisons with ground soil
590 moisture measurements from the eight stations in the OBS network (10x10 km²) over the
591 VAS area shows that the spatial patterns are captured at 1 km with RMSD~ 0.007 to 0.1
592 m³/m³. The best correlations are in DJF and SON, and poorer scores in MAM and JJA, in
593 agreement with the areal-mean comparisons. SMOS-L4^{3.0} data shows better agreement at
594 those stations over plain areas and with uniform conditions (vineyards), against those over
595 more complex and less homogeneous terrains (rocky soils and areas close to forestall and
596 man-made constructions). The SMOS-L4^{3.0} soil moisture probability distribution function
597 (PDF) in comparison to that of the in-situ measurements reveals a SMOS overestimation
598 below 0.1 m³/m³ and an underestimation in the range between 0.1 to 0.3 m³/m³. A seasonal
599 analysis points out better scores for the DJF and SON periods, whereas poorer correlation is
600 found for the MAM and JJA periods. In the MAM period, an under-representation of the
601 rainy events is found, as well as faster and stronger drying changes coinciding with the
602 vegetation growth season. In JJA, the very low soil moisture values (< 0.1 m³/m³) with
603 associated low spatial variability results in low R². No significant differences are found during
604 dry and wet days (> 0.1 mm/d).

605 SURFEX(ISBA) SVAT simulations covering the whole investigation period over all in-situ
606 measurement stations at the VAS area show good agreement with ground-based observations.
607 Mean values are well reproduced for all stations and the temporal variability is well captured
608 (R²~0.7 to 0.95; RMSD~0.02). The synergetic use of SURFEX(ISBA) simulations with
609 SAFRAN atmospheric forcing information initialized with realistic SSM values from the
610 SMOS-L4^{3.0} data set was successful combination to obtain soil moisture maps over the VAS
611 domain. Good agreement was reached when comparisons between point-like and 10x10 km²

612 simulations with SURFEX-SAFRAN initialized with SMOS-L4^{3.0} data and in-situ soil
613 moisture measurements were made ($R^2 \sim 0.9$ and $\text{RMSD} < 0.04 \text{ m}^3/\text{m}^3$).

614 In this study, the comparison and suitability of different operational satellite products from the
615 SMOS platform is investigated to provide realistic information on the water content of the
616 soil. The comparison carried out helps drawing guidelines on best practices for the sensible
617 use of these products. Currently, there is not a consensus about what is the “best” SMOS
618 product. Different users utilize different products depending on their application rather than
619 based on performance arguments. This study and the conclusions obtained on the comparison
620 are important to provide information on the advantages and drawbacks of these datasets. The
621 high temporal and spatial resolution soil moisture maps obtained in this study could be of use
622 for hydrological and agronomical applications, to build climatologies of SSM, as initial
623 condition for convective system modelling, for flood forecasting and for downstream local
624 applications such as crop monitoring and crop development strategies as well as for irrigation
625 data sets, among others. Additionally, an accurate representation of SSM will permit the
626 calculation of SM profiles by application of e.g. exponential filters, which has been
627 demonstrated to be a successful technique. Furthermore, the added value of the SMOS-L4^{3.0}-1
628 km disaggregated product for initialization purposes is demonstrated, which suggests its
629 potential for assimilation purposes. These two last aspects are out of the scope of this paper,
630 but they are investigated in detail in a follow-up study. Important aspects of the SMOS-L4^{3.0}
631 SSM product have still to be improved, namely its temporal availability (e.g. successful
632 investigations on the increase of SMOS-L3 temporal resolution to 3h are available (Louvet et
633 al. 2015)), its spatio-temporal correlation with in situ measurements over complex
634 topographic areas, in areas/periods with low spatial variability and in rainy periods when an
635 under-representation and rapid decay of SSM has been identified. -This study also points out
636 that in order to more accurately examine the reproducibility of the high spatial variability of

637 this variable by the newly available satellite derived downscaled high-resolution soil moisture
638 observations, large and dense networks of in situ soil moisture measurements covering
639 different soil types and land uses as well as considering different soil depths are needed. In an
640 effort to come a step forward in this direction, dedicated long-term networks with the
641 previously described characteristics should be established permanently in different regions
642 around the world.

643

644

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967 **Tables**

968

969 **Table 1:** Characteristics of soil moisture stations within the VAS domain.

NAME	STATION	DOMINANT VEGETATION USED FOR SIMULATIONS	TYPE OF VEGETATION	SAND	SILT	CLAY	ALTITUDE (m)	ANNUAL MEAN TEMPERATURE (°C)	ANNUAL MEAN PRECIPITATION (mm)
Melbex_I		Schrub	Schrub	0,47	0,38	0,15	849	(12-14)	451
Nicolas		Vineyard	Schrub/ Vineyard	0,47	0,35	0,18	859		
La Cubera		Vineyard	Vineyard	0,45	0,35	0,20	762		
Ezpeleta		Olive tree	Olive tree	0,44	0,39	0,17	781		
VAS		Vineyard	Vineyard	0,46	0,37	0,17	804		
Melbex_II		Vineyard	Vine stump/ Vine row	0,45	0,29	0,26	797		

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Table 2: Number of days (percentage) in which the SMOS (ascendant and descendent swaths) coverage is higher than 50 %.

LEVEL SMOS	SEPTEMBER		OCTOBER		NOVEMBER		SON	
	days	%	days	%	days	%	days	%
L4 ^{2.0} (~1km)	10	34	9	31	9	31	28	32
L4 ^{3.0} (~1km)	23	74	29	90	30	100	82	92
L2 (~15km)	20	67	28	90	28	93	76	83
L3 (~25km)	22	73	29	93	29	96	80	88

1009

1010 **Table 3:** Statistics of the comparisons between SMOS-L2 and SMOS-L4^{3.0} soil moisture
 1011 versus ground-based measurements in the VAS network (the area covering the ground-
 1012 based network has been called OBS, Figure 1). SMOS descendent orbits are selected for
 1013 the comparison. Characteristics of the individual stations are given in Table 1. The acronyms
 1014 for the names of the stations are as follows: (M-I: Melbex_I, M_II: Melbex_II, VAS: VAS, NIC:
 1015 Nicolas, EZ: Ezpeleta, LC: La Cubera). The period December 2011 to December 2012 is
 1016 evaluated. The seasonal analysis follows the hydrological cycle. OBS stands for the average
 1017 of (i) SMOS-L2 and/or SMOS-L4^{3.0} soil moisture values within the 10x10 km² where the
 1018 ground-based network is placed, and (ii) in the case of the in situ observations it refers to the
 1019 mean of all stations. In Table (a) a seasonal comparison between the mean of all in situ
 1020 stations and the corresponding mean of SMOS-L2 and/or SMOS-L4^{3.0} soil moisture values
 1021 within the 10x10 km² area. In (b) SMOS-L2 and SMOS-L4^{3.0} soil moisture observations are
 1022 compared to point-like ground measurements using the closest grid point. The column on the
 1023 right shows the mean of all stations

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1025 (a)

OBS vs SMOS-L2	Slope	R2	Bias	CRMS	OBS vs SMOS-L4 ^{3.0}	Slope	R2	Bias	CRMS
DJF	1.1	0.5	-0.09	0.03	DJF	1.0	0.7	-0.03	0.04
MAM	0.6	0.2	-0.07	0.03	MAM	0.6	0.4	-0.03	0.03
JJA	0.3	0.01	-0.02	0.03	JJA	0.1	0.01	-0.003	0.03
SON	1.1	0.8	-0.02	0.04	SON	0.8	0.7	-0.003	0.04

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1027 (b)

SMOSL2 vs SMOSL4 ^{3.0}	M-I	M-II	VAS	NIC	EZ	LC	OBS (mean all stations)
DJF							
Slope	0.17/-0.04	1.0/1.7	1.6/2.3	1.1/1.7	0.8/0.9	0.9/1.7	1.1/0.6
R2	0.02/0.01	0.6/0.5	0.8/0.5	0.9/0.7	0.5/0.2	0.7/0.7	0.5/0.7
MB	-0.03/-0.08	-0.08/-0.14	0.01/-0.04	0.006/-0.05	0.03/-0.02	0.004/-0.05	-0.09/-0.03
CRMSD	0.04/0.03	0.03/0.02	0.04/0.03	0.03/0.03	0.04/0.03	0.04/0.03	0.03/0.04
MAM							
Slope	0.4/0.36	0.6/0.4	0.8/0.6	0.6/0.8	0.5/0.3	0.9/0.7	0.6/0.6
R2	0.2/0.08	0.3/0.04	0.5/0.15	0.9/0.5	0.3/0.14	0.4/0.2	0.2/0.4
MB	-0.04/-0.08	-0.08/-0.11	0.005/-0.03	0.003/-0.03	0.02/-0.02	-0.02/-0.05	-0.07/-0.03
CRMSD	0.03/0.03	0.03/0.03	0.03/0.03	0.03/0.03	0.04/0.03	0.03/0.03	0.03/0.03
JJA							
Slope	0.26/0.38	0.3/0.4	0.02/0.15	0.1/0.3	0.08/-0.04	0.05/0.06	0.3/0.1
R2	0.02/0.01	0.04/0.005	0.001/0.002	0.8/0.17	0.003/0.012	0.01/0.003	0.01/0.01
MB	-0.01/-0.03	-0.04/-0.05	0.03/0.012	0.01/0.002	0.05/0.04	0.03/0.02	-0.02/-0.003
CRMSD	0.03/0.03	0.03/0.03	0.03/0.03	0.03/0.03	0.03/0.03	0.03/0.03	0.03/0.03
SON							
Slope	0.69/1.06	0.9/1.3	1.2/1.7	0.8/1.2	0.7/1.1	0.8/1.3	1.1/0.8
R2	0.5/0.6	0.6/0.6	0.7/0.8	0.9/0.7	0.8/0.7	0.8/0.7	0.8/0.07
MB	-0.02/-0.04	-0.03/-0.05	0.04/-0.03	0.03/0.006	0.03/0.01	0.04/0.02	-0.02/-0.003
CRMSD	0.04/0.04	0.04/0.04	0.04/0.04	0.04/0.04	0.04/0.04	0.04/0.04	0.04/0.04

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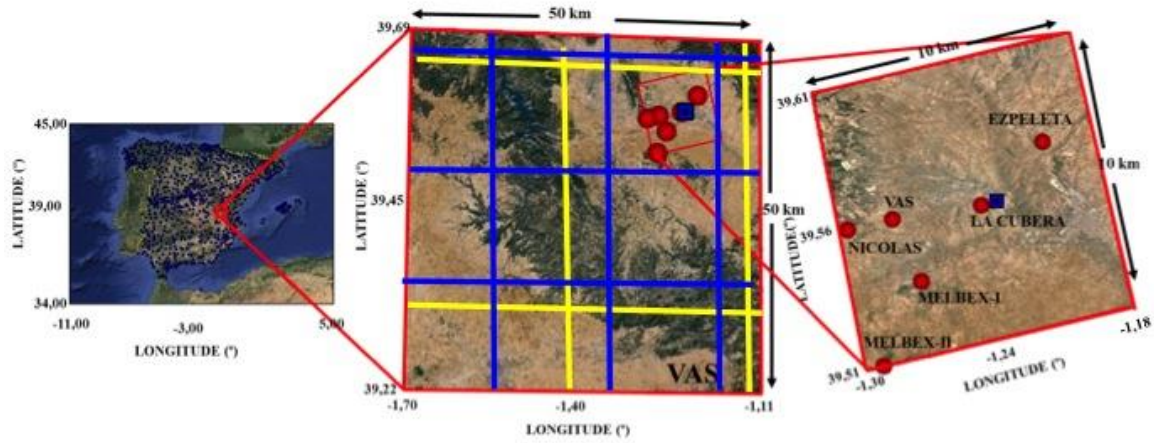
Table 4: Statistics of daily areal averages of ground-based SSM measurements in the OBS area versus point-like SURFEX(ISBA) simulations at the same sites. The acronyms for the names of the stations are as described in Table 3.

	M-I	M-II	VAS	NIC	EZ	LC	OBS
All period							
Slope	0.9	1.3	0.9	0.7	1.0	0.9	1.0
R2	0.8	0.8	0.8	0.8	0.8	0.7	0.9
MB	0.004	-0.012	0.011	0.006	0.02	0.006	0.005
CRMSD	0.02	0.02	0.02	0.02	0.01	0.02	0.02
DJF							
Slope	0.2	1.3	0.8	1.2	1.2	1.1	1.1
R2	0.03	0.4	0.4	0.7	0.7	0.5	0.6
MB	0.01	-0.03	0.02	0.03	0.02	0.03	0.01
CRMSD	0.04	0.05	0.03	0.04	0.03	0.03	0.04
MAM							
Slope	0.8	1.0	1.0	0.7	0.8	0.7	0.9
R2	0.5	0.4	0.6	0.4	0.6	0.5	0.6
MB	0.002	-0.02	0	0.01	0.01	-0.02	-0.004
CRMSD	0.04	0.02	0.03	0.04	0.03	0.04	0.04
JJA							
Slope	0.4	0.8	1.6	3	1.6	2	1.5
R2	0.7	0.8	0.7	0.5	0.7	0.6	0.8
MB	0.004	0.01	0.01	-0.02	0.02	0.005	0.005
CRMSD	0.04	0.02	0.03	0.04	0.03	0.04	0.04
SON							
Slope	0.9	1.1	0.9	0.8	1.0	1.1	1.0
R2	0.8	0.8	0.8	0.9	0.9	0.8	0.9
MB	0.002	0	0.01	0	0.02	0.01	0.006
CRMSD	0.04	0.006	0.03	0.04	0.04	0.03	0.04

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1052 **Figures**

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1056 **Figure 1:** Area of investigation and orography. Location of rain gauges from AEMET
1057 (Meteorological Service of Spain) is shown over the Iberian Peninsula (blue square dots).
1058 The positions of the soil moisture network stations within the 10x10 km² (OBS area) in the
1059 Valencia Anchor Station (VAS; 50x50 km²) area are indicated by red circles.

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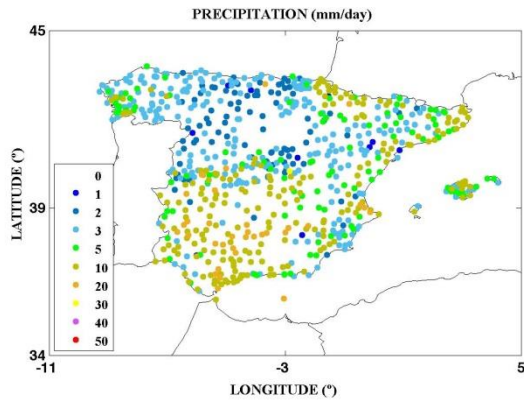
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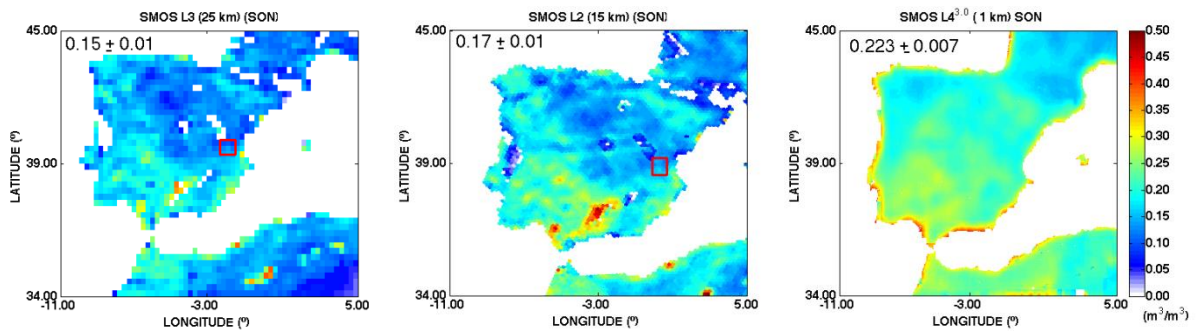
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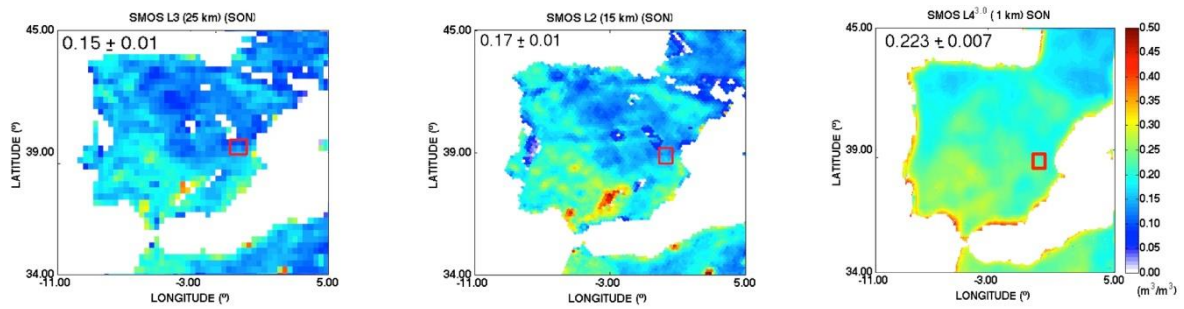
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1076 **Figure 2:** (a) Spatial distribution of precipitation over the Iberian Peninsula from the network
 1077 of rain gauges of AEMET. The period of September to November (SON) 2012 is shown. (b)
 1078 Spatial distribution of SMOS-derived soil moisture over the Iberian Peninsula (merged
 1079 product: ascending and descending orbits, days with areal coverage higher than 50 % are
 1080 considered).

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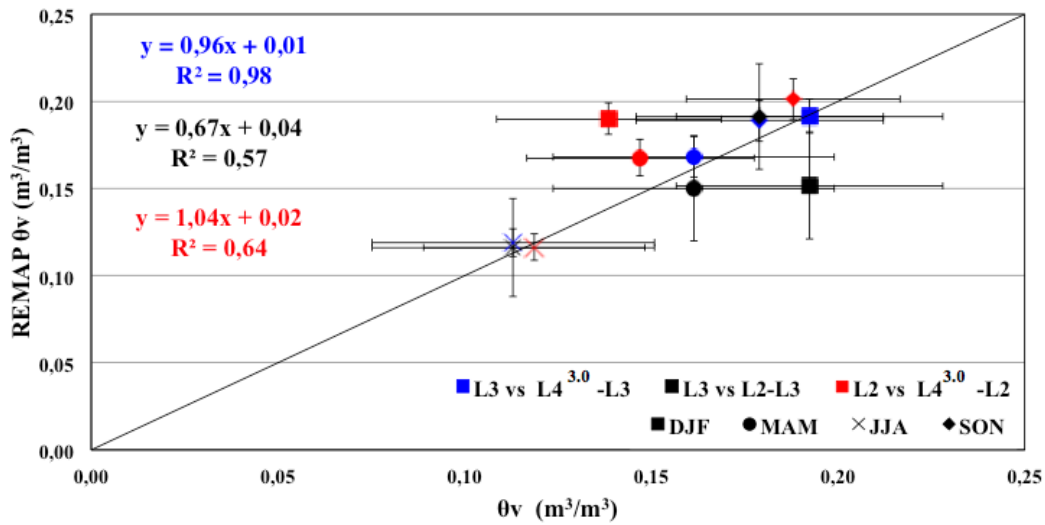
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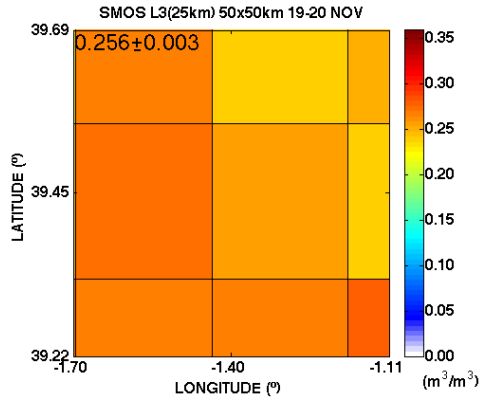
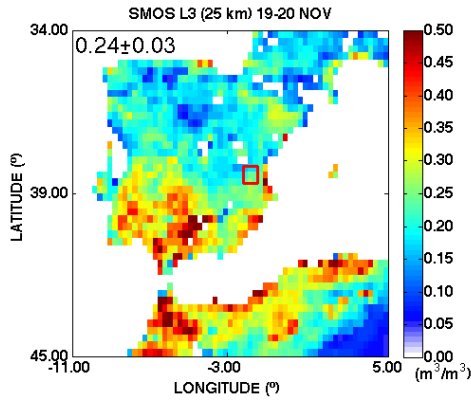


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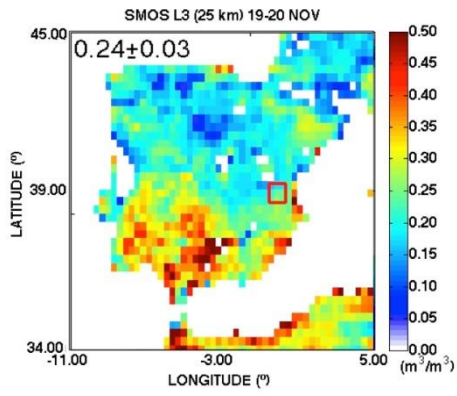
Figure 3: SMOS-derived SSM products comparison from different operational levels over the Iberian Peninsula.

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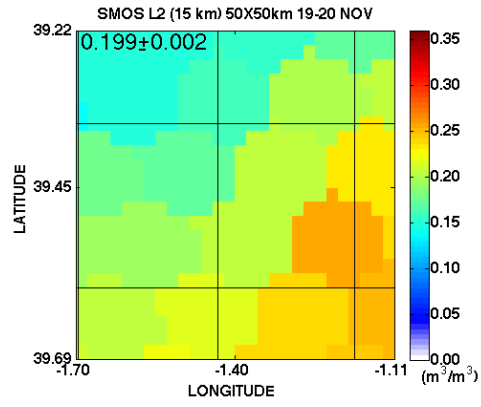
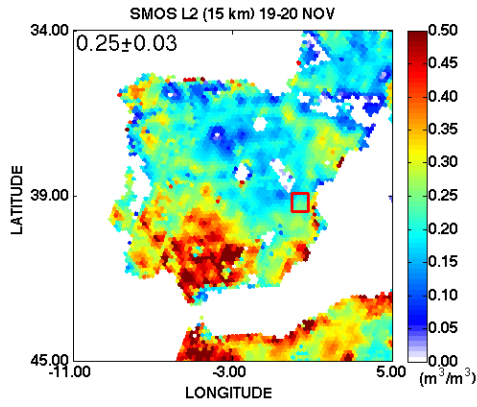
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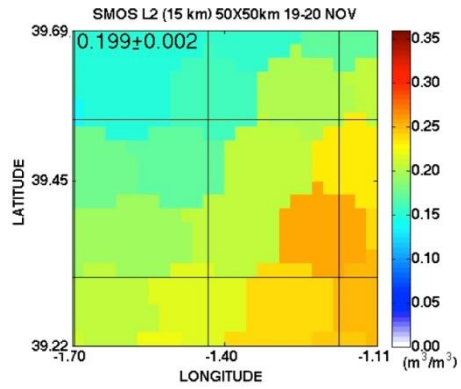
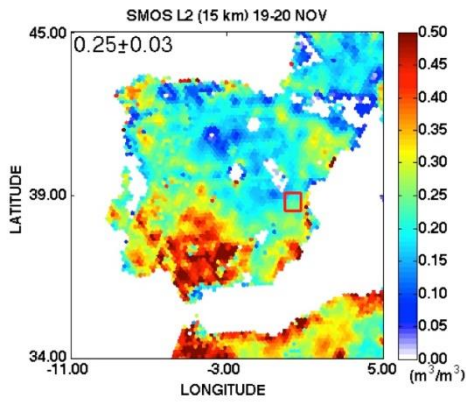
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1128 (b)

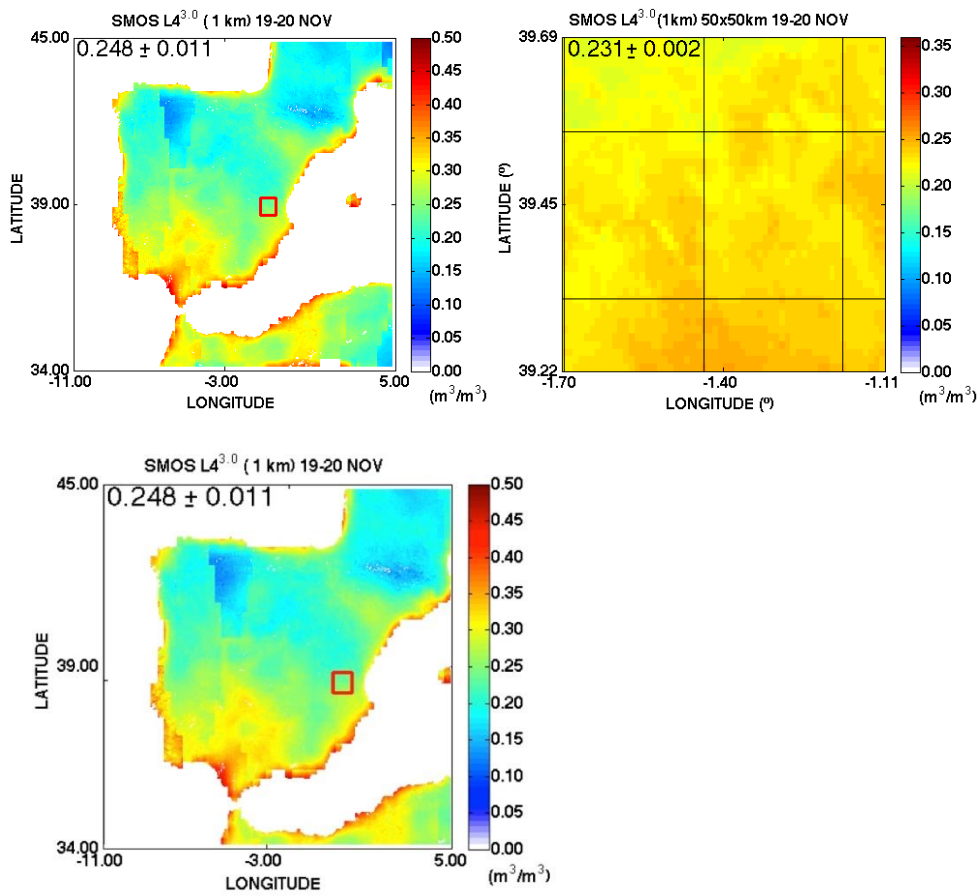


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1165 (c)



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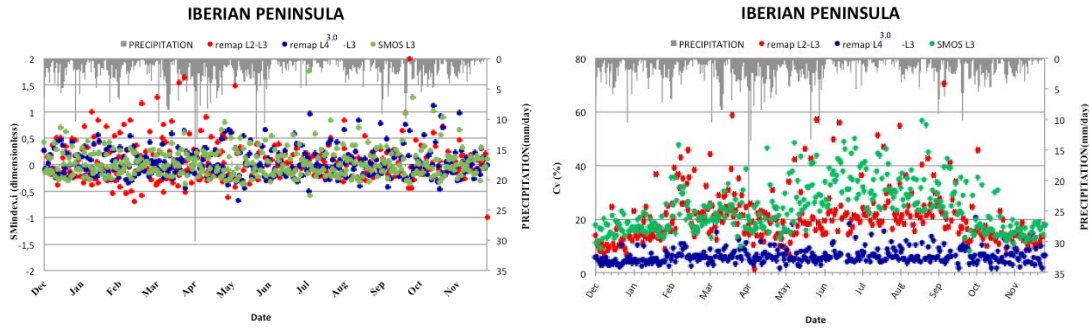
1169 **Figure 4:** Spatial distribution of SMOS-derived soil moisture (merged product: ascending and
1170 descending orbits are considered) over the Iberian Peninsula (left) and the VAS (right) as a
1171 mean for the 19-20 November of 2012 (a) SMOS-L3 (~25 km), (b) SMOS-L2 (~15 km), (c)
1172 SMOS-L4^{3.0} (~1 km). White empty pixels in (a) and (b) are indicative of a lack of data. Please
1173 be aware of the different colour scale used for the IP and VAS.

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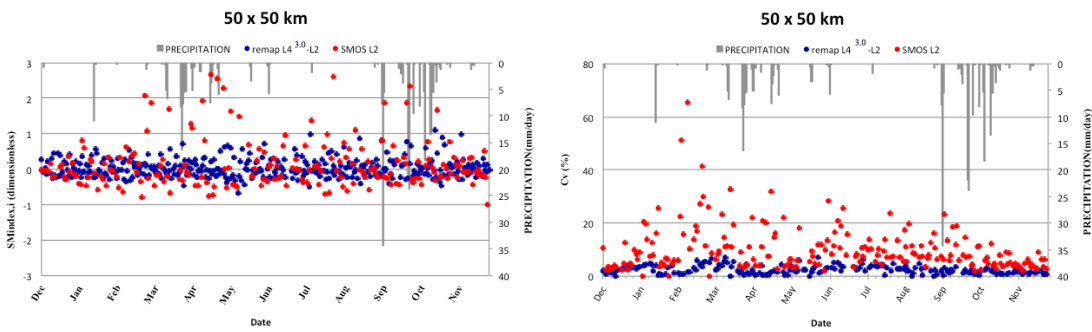
1184 (a)



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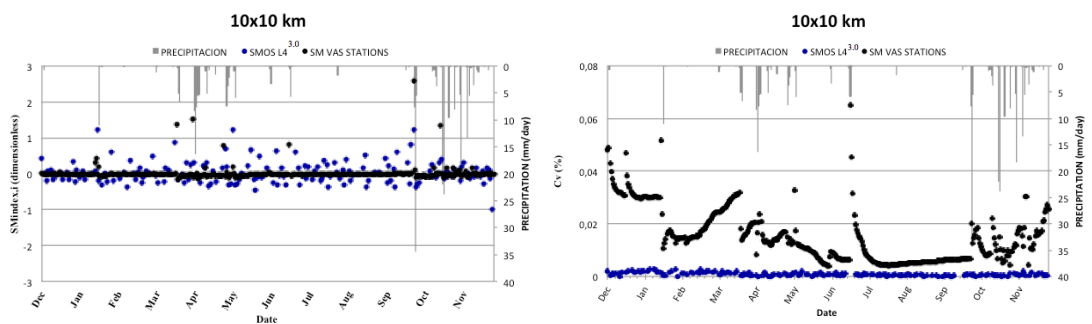
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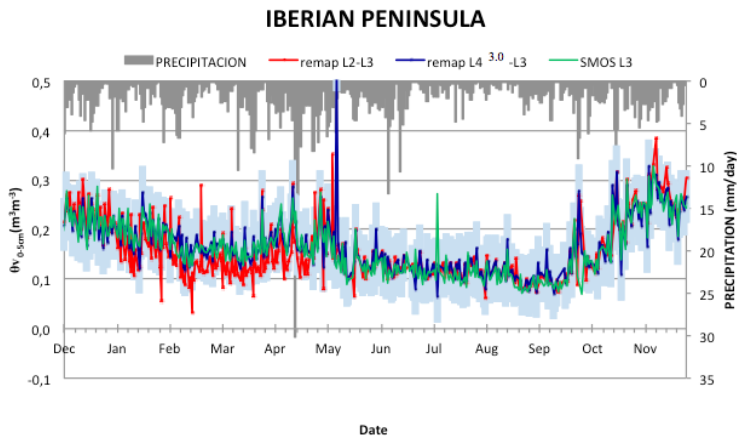
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1191 **Figure 5:** Averaged SMOS products and averaged ground-based observations of soil
 1192 moisture evolution over the Iberian Peninsula (IP; top), the VAS area (centre), and the OBS
 1193 area (bottom). Descending orbits are used. Precipitation from AEMET rain gauges on top.
 1194 Left) Soil moisture daily index ($\Theta_{v \text{ index},i}$; dimensionless) and right) Coefficient of variation (Cv,
 1195 %).

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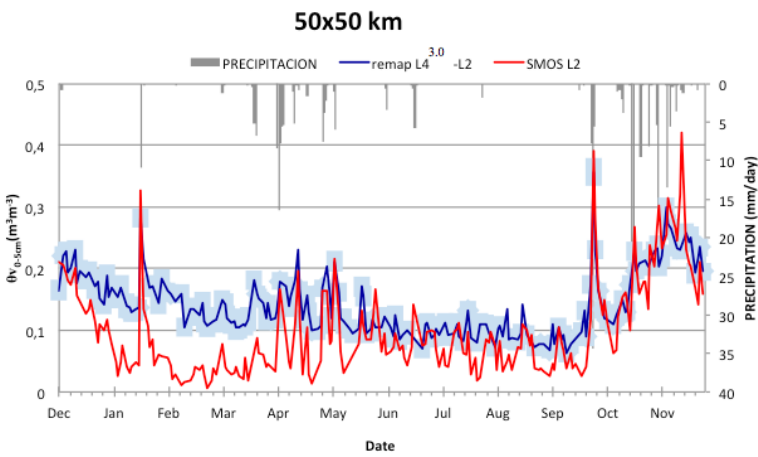
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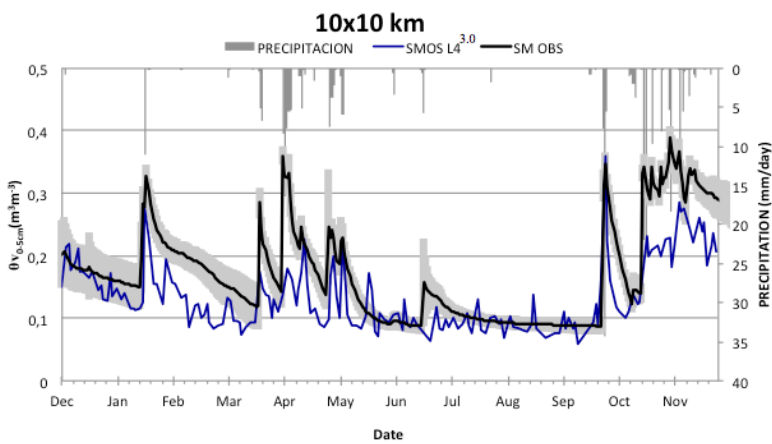
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1200 (b)



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1202 (c)



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1204 **Figure 6:** Temporal evolution of surface soil moisture time series averaged over the Iberian
 1205 Peninsula (top), the VAS area (50 x 50 km²; centre) and the OBS area (10 x 10 km²; bottom).
 1206 SMOS afternoon orbits are considered. Daily mean precipitation from the AEMET stations is

1207 shown on top of each plot. SMOS and remapped SMOS products are indicated in the plots.
1208 Shaded areas show standard deviations, respectively.

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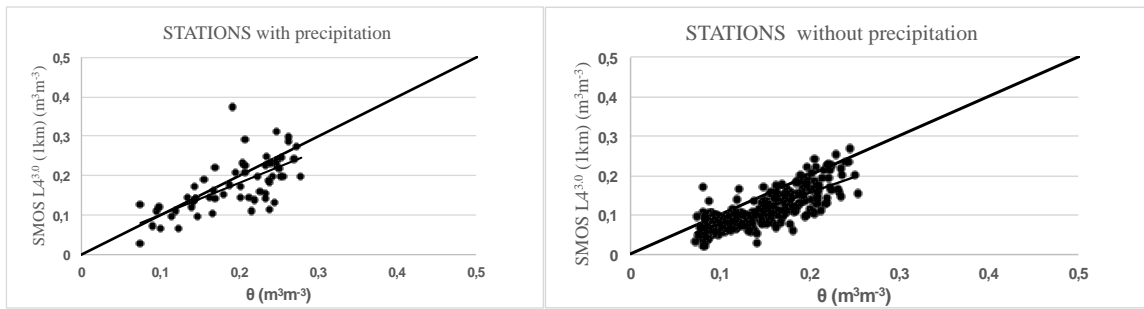
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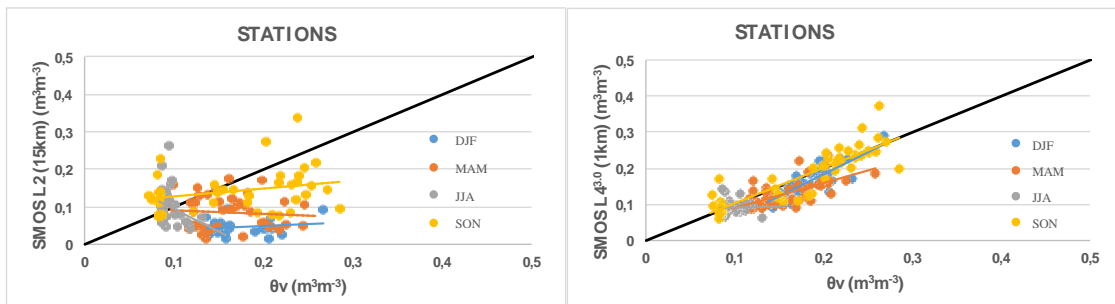
1235 (a)



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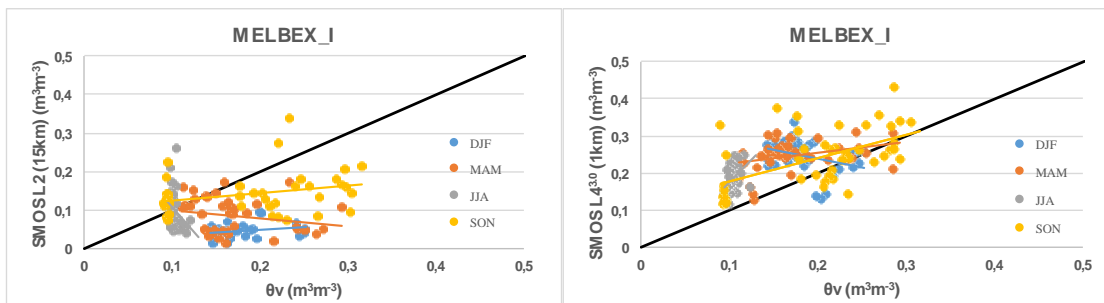


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1241 (c)

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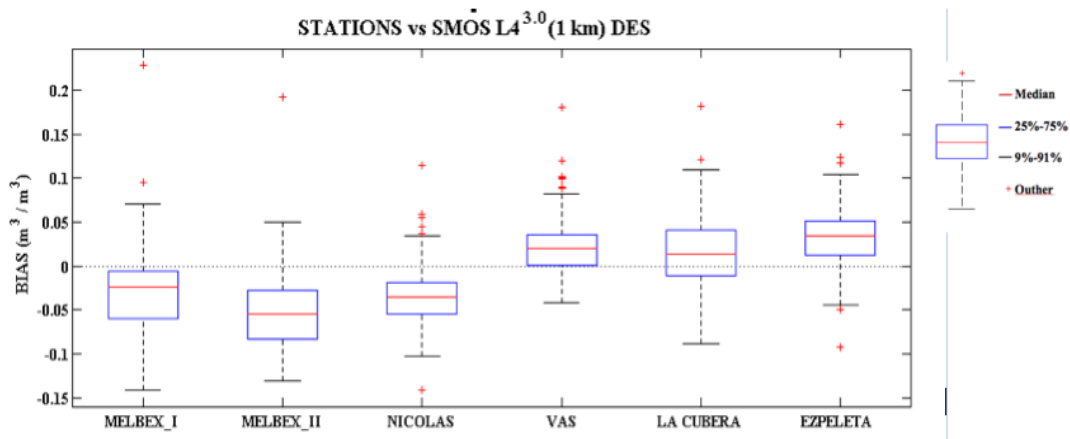
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1245 **Figure 7:** Results of the seasonal analysis for the hydrological year starting in December
 1246 2011. Scatter plots of (a) SMOS-L4^{3.0} SSM (ascending and descending orbits) versus
 1247 averaged 10x10 km² in situ soil moisture measurements (left) for days with precipitation, and
 1248 (right) and without precipitation (< 1 mm /d). (b) SMOS-L2 and SMOS-L4^{3.0} SSM (descending
 1249 orbits) versus averaged 10x10 km² in situ soil moisture measurements. (c) SMOS-L2 and
 1250 SMOS-L4^{3.0} SSM (descending orbits) versus point-like ground measurements from
 1251 MELBEX_I station, using the closest grid point. Segments are linear fit of seasonal data (3
 1252 months data). Statistics for individual comparisons at all stations are summarized in Table 3.

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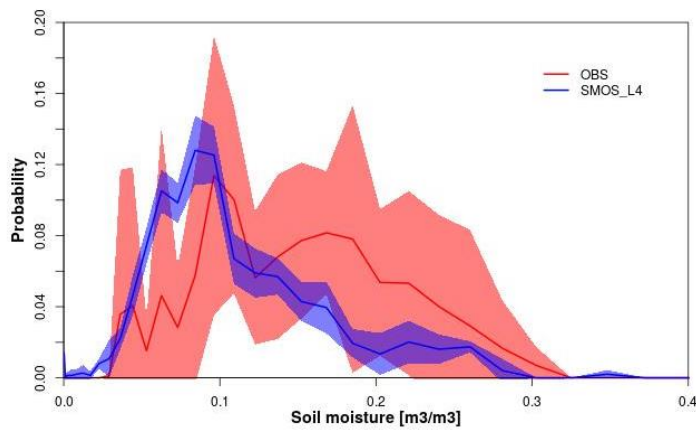
1254 (a)



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1257 (b)



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1259 **Figure 8:** (a) Box plot of the comparison between point-like ground measurements at all
1260 stations over the VAS area and closest SMOS-L4^{3.0} SSM data. (b) Probability
1261 function (PDF) of SSM from in situ observations and SMOS- L4^{3.0} SSM measurements. The
1262 standard deviations are indicated with shaded areas. Full lines represent the mean over all
1263 ground stations and over the 10 x 10 km² of the OBS area in VAS where the in SSM network
1264 is located.

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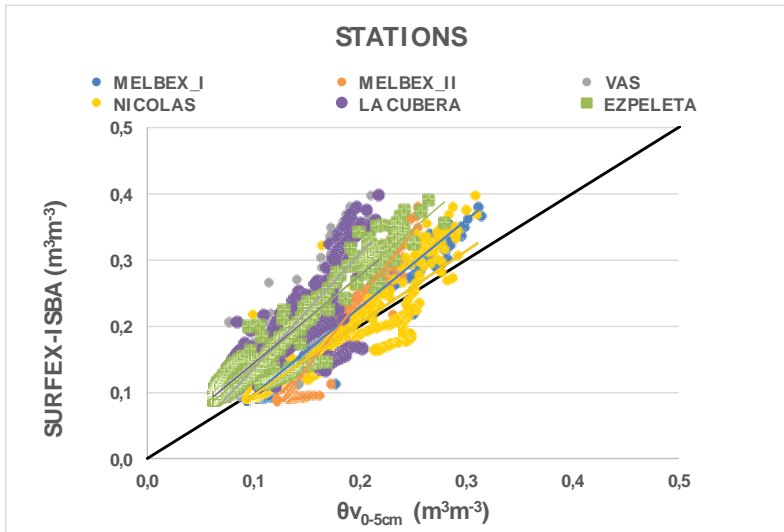
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1274 **Figure 9:** Scatter plot of temporal mean (over the whole simulation period) SSM ground
1275 measurements versus SURFEX(ISBA) simulations (realistic initial scenario; REAL-I) at all
1276 stations. Statistics for all stations using the REAL-I initial scenario are presented in Table 4.

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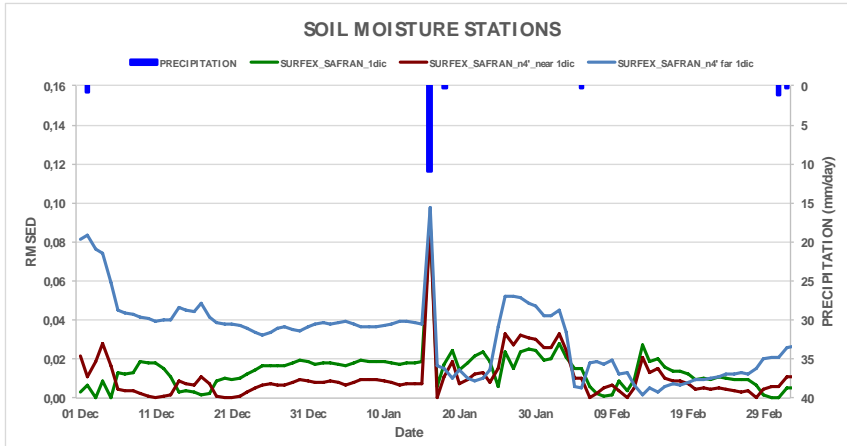
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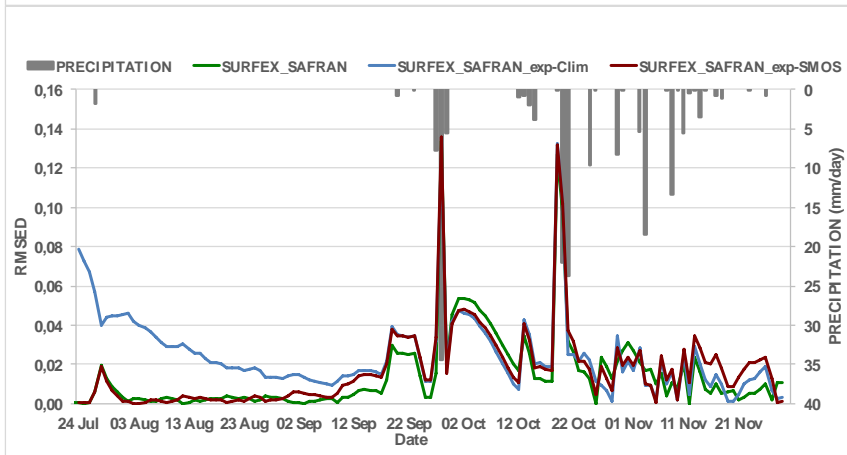
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1294 (a)



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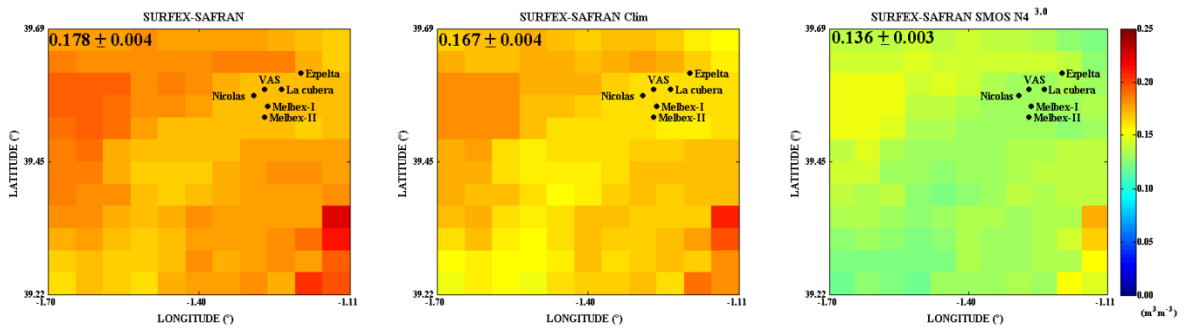


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1298 (b)

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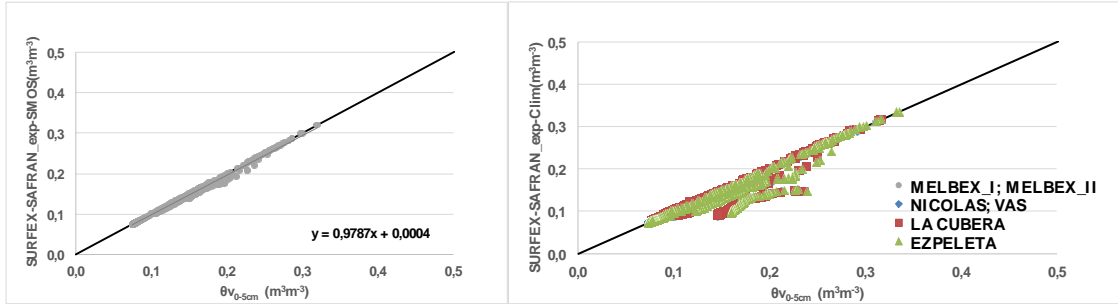
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1306 (c)

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1311 **Figure 10:** (a) RMSD for the daily mean SSM from the three SURFEX(ISBA) simulations
1312 with perturbed initial SSM scenarios (details in section 4.3.2). (b) Spatial distribution of
1313 mean SSM for the winter simulation (a, left) for the 3 simulations. (c) Scatter plot depicting
1314 the comparison between in situ SSM observations and SURFEX-SAFRAN-SMOSL4^{3.0}
1315 simulations, as a mean over all stations (left) and for each of the stations (right).

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