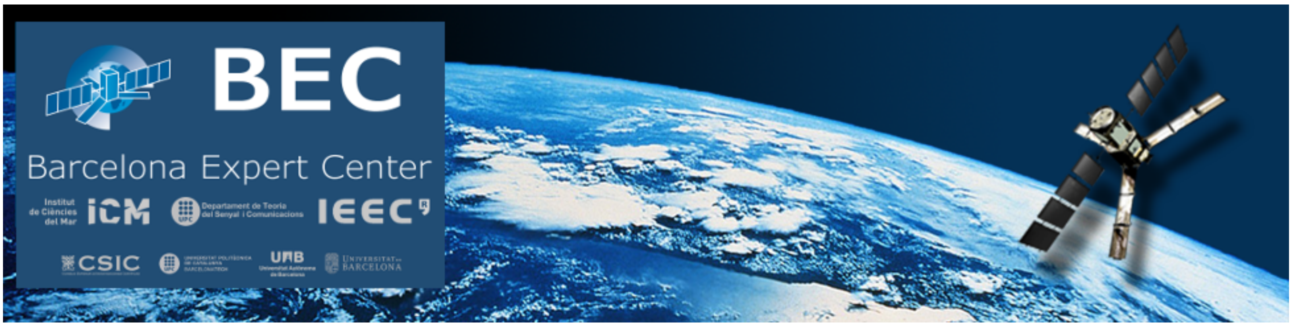


File: `BEC-SMOS-PD-SM-L3v4-L4v6.pdf` , version `1.0`

Title: BEC SMOS Soil Moisture Products Description

Authors: Miriam Pablos, Cristina González-Haro, Maria Piles, Gerard Portal and BEC Team

Contact: smos-bec@icm.csic.es

Date: 25/10/2022

BEC SMOS SOIL MOISTURE PRODUCTS DESCRIPTION

Abstract: This technical note describes the Soil Moisture and Ocean Salinity (SMOS) soil moisture products freely distributed in netCDF format by the Barcelona Expert Center (BEC) on Remote Sensing. The products can be visualized by means of a web map service. The data files can be accessed and downloaded through a secure ftp (sftp) server, after registration as a user on our website: https://bec.icm.csic.es.

Contents

1 INTRODUCTION

The Soil Moisture and Ocean Salinity (SMOS) is an Earth Explorer Opportunity mission of the European Space Agency (ESA). SMOS was specifically designed to remotely sense soil moisture over the land surfaces [Kerr *et al.*, 2010] and sea surface salinity over the oceans [Font *et al.*, 2010]. It was launched on November 2, 2009, carrying on board an L-band two-dimensional synthetic aperture radiometer with multi-angular and full polarimetric capabilities [McMullan *et al.*, 2008]. The innovative SMOS instrument was a technological challenge that required the development of dedicated calibration methods [González-Gambau, 2012] and image reconstruction algorithms [Corbella *et al.*, 2009]. SMOS is in orbit since its launch more than eleven years ago and its radiometer continues providing high-quality data for a wide range of applications [Mecklenburg *et al.*, 2016].

The Barcelona Expert Center (BEC) on Remote Sensing is an ESA Expert Support Laboratory (ESL) dedicated to developing and testing new algorithms to improve the baseline of SMOS Level 1 (L1) and ocean Level (L2) products. It also contributes to the improvement of land L2 products. The BEC aims at generating higher added-value products of interest for a broad range of users both in ocean and land applications.

This technical note presents the product specification document for the current SMOS soil moisture produced at BEC:

- **Global Level 3 (L3) soil moisture – version 4.0**
  This product is based on the SMOS L2 Soil Moisture User Data Product (SMUDP), which is distributed by the Data Processing Ground Segment (DPGS).

  Version 4.0 of the global L3 soil moisture includes the following improvements with respect to the previous version:

  – It relies on the latest operational ESA baseline: the SMOS L2 soil moisture v700.
  – The L3 soil moisture files at 25 km Equal-Area Scalable Earth (EASE)-2 grid now also include Vegetation Optical Depth (VOD) data retrieved alongside surface soil moisture.
  – Since the Dissemination Service provides the ESA SMOS L2 soil moisture files not only in binary format but also in netCDF, the L3 files at 15 km Icosahedral Snyder Equal Area (ISEA) 4H9 grid including surface soil moisture, VOD and dielectric constant data are no longer produced by the BEC.

- **Regional Level 4 (L4) soil moisture – version 6.0**
  This product is a SMOS-based disaggregated soil moisture with an enhanced spatial resolution. It is obtained from the synergy of:

  1. SMOS horizontal and vertically polarized surface brightness temperature at three incidence angles ($\theta_i = 32.5°$, $42.5°$ and $52.5°$),
  2. Land Surface Temperature (LST) and
  3. Normalized Difference Vegetation Index (NDVI).

  The SMOS L3 soil moisture is used as a benchmark. In the current approach, LST data are provided by the European Center for Medium Weather Forecast (ECMWF) model and NDVI data are provided by Terra Moderate Resolution Imaging Spectroradiometer (MODIS).

Version 6.0 of the regional L4 soil moisture includes the following improvements with respect to the previous version:

- It relies on the latest operational ESA baselines: the SMOS L1C brightness temperature v724 and L2 soil moisture v700.
- A land-sea mask at 25 km EASE-2 is used to discriminate pixels over land from those over the sea, and to determine which pixels are close to the coastline.
- LST and NDVI are aggregated from their original grids to 25-km EASE-2 by means of an average before computing the coefficients of the linear linking model, instead of using linear interpolation.
- The quality_flag of the L4 soil moisture files incorporates information about possible Radio-Frequency Interferences (RFI), i.e., data flagged by the ESA in L1C brightness temperature files because exceeding a certain threshold. It also contains an updated description and new flag_meanings and flag_masks attributes. The quality_flag of the 3-day L4 files was simplified to be consistent with that of the daily L4 files.
- The production of L4 soil moisture using MODIS NDVI is discontinued in October 2022, since the Terra satellite carrying MODIS sensor has drifted to a lower orbit to minimize possible crossings with other missions. For this reason, only L4 files in reprocessed mode are currently provided. Further updates will be provided and we will notify all users once L4 soil moisture data production has resumed.

In addition to the specified changes, the following changes have been performed in both L3 and L4 soil moisture products:

- All files are produced and distributed in netCDF-4 format and satisfy the conventions Climate and Forecast (CF)-1.8.
- For better space efficiency, the main variables are scaled and compressed. Check scale_factor attribute before using data (see section 3).
- No data truncation is applied to neither L3 nor L4 soil moisture. However, note ESA SMOS L2 soil moisture is truncated within the interval [0, 1] m^3/m^3, and that translates to L3. In L4, the quality_flag informs on values laying outside the aforementioned interval.
- Since unsaturated soil moisture varies between zero and the soil porosity, a minimum of 0 m^3/m^3 and a maximum of 0.6 m^3/m^3 are included as attributes to approximately indicate the valid soil moisture dynamic range before saturation.
- All information related to the grid is summarized in the attributes of an empty variable called "crs" (Coordinate Reference System). They include the European Petroleum Survey Group (EPSG) code that unequivocally defines any projection (epsg:6933 for EASE-2) as well as the x- and y-axis projected coordinates corresponding to the outer edges of the upper-left pixel (ulx and uly) and the lower-right pixel (lrx and lry), among others.

A summary of the main changes and improvements of the last baseline of the ESA SMOS data compared to the previous release is found in SMOS Calibration team & ESL Level 1 [2021] for the L1C brightness temperature v724 and in ESL Level 2 Soil Moisture & ARGANS [2021] for the L2 soil moisture v700.

2 SCIENCE ALGORITHMS DESCRIPTION

2.1 Level 3 soil moisture algorithm

In order to generate the global L3 soil moisture product, ESA SMOS L2 soil moisture v700 data are first filtered and then binned into averaged maps at EASE-2 of 25 km. Since the VOD is obtained alongside surface soil moisture from the same retrieval algorithm [Arias & Kerr, 2019], VOD is also included in the L3 product. In this case, VOD data are directly binned to 25 km EASE-2 without applying any filtering.

The global L3 product is produced with different averaging periods and production rates: 1-day (daily), 3-day (daily), 9-day (every 3 days), 1-month (monthly) and 1-year (annually).

2.1.1 Soil moisture filtering

The following quality flags and descriptors of SMOS L2 SMUDP files [Bengoa *et al.*, 2020] are used to discard unreliable soil moisture values in SMOS L3 products:

- Grid points with the "no product" flag raised are discarded. This flag indicates that the retrieval has failed either due to the retrieved geophysical data not being of an acceptable quality or other factors.
- Grid points with the "probability of Radio-Frequency Interference (RFI)" flag for either horizontal or vertical polarization set to high are discarded.
- Grid points with the "out of range" flag raised are discarded. This flag indicates that the retrieved geophysical data are outside the extended range.
- Grid points with Data Quality Index (DQX) values greater than 0.07 m^3/m^3 are discarded.

2.1.2 Soil moisture and VOD binning

The global L3 soil moisture and VOD maps at the 25 km EASE-2 grid are obtained by means of a DQX-weighted averaging of the ESA L2 measurements from all SMOS orbits within a certain time period. The spatio-temporal averaged data value of each EASE-2 pixel k is computed as follows:

$$\langle X\rangle_k = \sum_{i=1}^{N} w_i X_i; \quad \text{where the DQX-based weight is:} \quad w_i = \frac{\frac{1}{DQX_i^2}}{\sum_{j=1}^{N} \frac{1}{DQX_j^2}}. \tag{1}$$

The X denotes the concerned variable (soil moisture or VOD) and the subscripts i and j correspond to all ISEA gridpoints that fall within the particular EASE-2 pixel.

The associated averaged DQX value is computed as:

$$\langle DQX \rangle_k = \sqrt{\frac{1}{\sum_{i=1}^{N} \frac{1}{DQX_i^2}}}. \tag{2}$$

The averaged variance is computed as:

$$Variance\ \langle X \rangle_k = \frac{\sum_{i=1}^{N} \frac{1}{DQX_i^2}}{\left(\sum_{i=1}^{N} \frac{1}{DQX_i^2}\right)^2 - \sum_{i=1}^{N} \frac{1}{DQX_i^4}} \left(\sum_{i=1}^{N} \frac{X_i^2}{DQX_i^2} - \langle X \rangle_k^2 \sum_{i=1}^{N} \frac{1}{DQX_i^2} \right) \tag{3}$$

The L3 processor has been implemented at the BEC facilities and it is executed twice daily: once for all ascending and once for all descending orbits.

2.2 Level 4 soil moisture algorithm

SMOS was built to measure soil moisture and ocean salinity at the global scale and help improve our understanding of water and energy fluxes interactions between the atmosphere, the soil surface, and the subsurface. However, its spatial resolution (around 40-50 km) is too coarse for its application in local or regional scale applications. One central research line at BEC is the development and improvement of data fusion algorithms to provide downscaled SMOS-based soil moisture products at finer scales (100 m to 1 km resolutions). Accurate knowledge of the soil moisture status at these scales is essential for water management, drought monitoring and/or flood prediction.

The SMOS L4 soil moisture is obtained by a downscaling algorithm, which was originally developed to exploit the synergy of microwave and optical satellite data. In particular, it relates the indirect relationship of LST and NDVI variations to soil moisture changes across space (the so-called "Universal Triangle" [Carlson *et al.*, 1994, Petropoulos *et al.*, 2009]) at fine scales with the direct sensitivity of microwaves to soil moisture at coarse scales. Firstly, the algorithm was proposed using a linear regression model to link soil moisture with top of atmosphere (TOA) brightness temperature at horizontal polarization ($T_{B_{H,TOA}}$) and at a single incidence angle (θ_i=42.5°, the same angle of the SMOS L1C Browse product), MODIS land surface temperature (LST) and Normalized Difference Vegetation Index (NDVI) across coarse and fine scales [Piles *et al.*, 2011].

The linear model was later improved, including surface brightness temperature at both polarizations ($T_{B_{H,\theta_i}}$ and $T_{B_{V,\theta_i}}$) and three different incidence angles (θ_i=32.5°, 42.5° and 52.5°) to take benefit of the dual-polarization and multi-angle capability of the SMOS radiometer [Piles *et al.*, 2012]. This was the first SMOS downscaling approach (v1.0) implemented at BEC to provide the SMOS L4 soil moisture maps at 1 km over the Iberian Peninsula. These maps were produced in two different modes: Near Real-Time (NRT) and reprocessed (REP). MODIS LST and NDVI over the Iberian Peninsula were kindly provided in NRT by the Laboratorio de Teledetección de la Universidad de Valladolid (LATUV) [Piles *et al.*, 2013]. Reprocessed products used MODIS data provided by the U.S. Land Processes Distributed Active Archive Center (LPDAAC), particularly the 16-day Terra NDVI (MOD13A2 v5) and the daily Terra/Aqua LST at daytime or nighttime (MOD11A1/MYD11A1 v5) corresponding to the closest acquisition to SMOS passes over the Iberian Peninsula [Piles *et al.*, 2014].

In the following version of the downscaling algorithm (v2.0), the REP mode was refined using Aqua MODIS LST at daytime for both ascending and descending SMOS overpasses [Pablos *et al.*, 2016a,b]. Apart from the Iberian Peninsula, other regions such as Ghana and South Africa were also processed and distributed for specific periods. In parallel, another version (v3.0) in REP mode was also developed, in which the MODIS LST was replaced by the modeled ECMWF ERA-Interim skin temperature at 12 h to derive cloud-free L4 soil moisture. While the coverage of the L4 products improved drastically in v3.0 with modeled LST, the maps showed smoother spatial features compared to those from v2.0 due to the coarse resolution of ERA-Interim (around 79 km). Still, similar statistics in terms of correlation and errors were obtained during validation with *in-situ* soil moisture [Piles *et al.*, 2015].

Since version 4.0, the downscaling algorithm employs a shape adaptive moving window to calculate the coefficients of the regression model. It allows the method to be applied over any non-frozen region of the world, independently of the region size to be processed, and even if the region includes different climates [Portal *et al.*, 2018b]. The use of ECMWF ERA-5 skin temperature at 12 h, with a spatial resolution of around 31 km, was shown to produce cloud-free soil moisture data with more spatial details than that observed with ERA-Interim in v3.0 and with minor differences in accuracy with respect to that obtained with MODIS LST [Portal *et al.*, 2018a]. A study showed that the SMOS L4 maps produced with ERA-5 are comparable to the ones provided by the Soil Moisture Active Passive (SMAP) L4 maps obtained from the synergy of the SMAP radiometer and Sentinel 1 Synthetic Aperture Radar (SAR) data [Portal *et al.*, 2020]. Since ERA-Interim and ERA-5 are ECMWF reanalyses and therefore recent data availability can be compromised, the operational version of the model (ECMWF skin temperature at 12 h with a spatial resolution of around 9 km) is used in v4.0, v5.0, and v6.0.

Recently, some improvements were introduced to the downscaling process regarding the aggregation method applied to LST and NDVI data just before the regression coefficients computation. The resulting L4 soil moisture v6.0 maps allow us to better capture the land heterogeneity than those obtained in the previous version (v5.0). Additionally, their performances in terms of correlation and unbiased Root Mean Square Error (ubRMSE) are similar when validating against *in-situ* soil moisture observations, showing non-significant differences between v5.0 and v6.0 in most networks across Europe, except in Finland (see section A).

2.2.1 Input data

Currently, a cloud-free approach of the latest version (v6.0) of the downscaling algorithm has been implemented at the BEC facilities in REP mode. The required input data are:

- Daily SMOS L3 soil moisture v4.0 at 25 km EASE-2, which is produced by the BEC from the ESA L2 soil moisture v700.
- Daily SMOS L3 surface brightness temperature at both horizontal and vertical polarization at 25 km EASE-2 and at three incidence angles (θ_i=32.5°, 42.5° and 52.5°), which is internally produced by the BEC from the ESA SMOS L1C brightness temperature v724.
- Daily LST or skin temperature at 12 h UTC at around 9 km, which is a forecast provided by the operational ECMWF model (https://www.ecmwf.int).
- 16-Day Terra MODIS NDVI at 1 km (MOD13A2 v6), which is distributed by the National Aeronautics and Space Administration (NASA, https://earthdata.nasa.gov).

2.2.2 Soil moisture downscaling

The ESA SMOS L1C brightness temperature is firstly processed. Since it is measured at the antenna plane, it is corrected by the geometry of the antenna, the Faraday rotation and the atmospheric effects to set it at the Earth's surface. Then, the brightness temperatures are estimated at the three desired incidence angles through the linear fit of all values included in the interval $\theta_i \pm 5°$ by minimizing chi-square [Press *et al.*, 1992]. After that, the brightness temperatures are filtered by the presence of strong RFI (discarding values higher than 350 K) and binned to a 25 km EASE-2 grid by a simple average of all ISEA 4H9 pixels that fall within each final pixel.

The SMOS surface brightness temperatures close to the coast are affected by sea-land contamination. To correct this effect, all pixels of 25 km EASE-2 over land at a distance of 1 pixel from the coast (in horizontal, vertical, and/or diagonal directions) are erased. A land-sea mask at 25 km EASE-2 [Brodzik & Knowles, 2011] is used for this purpose. Later, coastal pixels are refilled using an inverse-distance weighting interpolation [Howat, 2007] of the brightness temperature values with a distance lower than 2 pixels (approx. 50 km).

In order to fill soil moisture data gaps in areas where the L3 product (which directly depends on the ESA L2 soil moisture) is not providing information over land, the following linear model is utilized at low resolution (25 km):

$$SM = a_0 + \frac{a_1}{3}\sum_{i=1}^{3} T_{B_{H,\theta_i}} + \frac{a_2}{3}\sum_{i=1}^{3} T_{B_{V,\theta_i}}, \tag{4}$$

where SM corresponds to the L3 soil moisture that is used to obtain the a_i coefficients. Once they have been obtained, they are applied in equation 4 with the brightness temperature ($T_{B_{H,\theta_i}}$, $T_{B_{V,\theta_i}}$) for estimating the enhanced L3 soil moisture.

In the following step, the LST is aggregated from its native irregular grid at around 9 km to 25 km EASE-2, using the mean value. Similarly, NDVI is also aggregated from the 1 km regular grid to 25 km EASE-2. To avoid data over frozen soil, LST values lower than 2 Celsius are removed. In NDVI, values lower than 0 are removed to discard pixels over water.

A linear linking model that relates soil moisture with brightness temperature, LST and NDVI data is applied at low resolution (25 km):

$$SM = b_0 + b_1 LST_N + b_2 NDVI_N + \frac{b_3}{3}\sum_{i=1}^{3} T_{B_{H,\theta_i,N}} + \frac{b_4}{3}\sum_{i=1}^{3} T_{B_{V,\theta_i,N}}, \tag{5}$$

where the subscript N indicates that all variables are normalized by their maximum and minimum values, which are calculated as:

$$X_N = \frac{X - X_{min}}{X_{max} - X_{min}}, \tag{6}$$

being X the variable to normalize, i.e. LST, $NDVI$, $T_{B_{H,\theta_i}}$ and $T_{B_{V,\theta_i}}$. Note that the maximum and minimum can change depending on the region (entire study area) to be downscaled and the orbits (ascending or descending).

Finally, the b_i coefficients previously computed and all the variables are linearly interpolated to 1 km EASE-2. To avoid the loss of data over the outer half part of the pixels at 25 km beside the ocean, the nearest neighbor interpolation is additionally applied to the brightness temperatures and the b_i coefficients to fill this part of the pixels. After that, the LST and NDVI at 1 km are filtered to avoid frozen soil and water, respectively. All variables and coefficients at high resolution are then normalized using the same minimum and maximum values as at low resolution. Then, the equation 5 is applied again, but this time at high resolution (1 km).

To generate the daily L4 soil moisture at 1 km EASE-2, the L4 processor is executed twice per day, once for all ascending orbits of the same day within a particular region and once for all descending orbits. The 3-day L4 soil moisture is obtained by averaging the corresponding three daily L4 soil moisture files.

3 SOIL MOISTURE PRODUCTS DESCRIPTION

A detailed description of current SMOS soil moisture products is included in this section. In the future, the inclusion of complementary remotely sensed products is envisaged.

3.1 Naming convention

The name of the resulting soil moisture products follows the layout:

```
BEC_VVVVV_SSSSS_REG_LLL_X_YYYYMMDDTHHMMSS_GGGGG_TT_PPP_vV.V.nc
```

where each field of the filename is as follows:

- BEC: indicates Barcelona Expert Center, the institution that produced the data file;
- VVVVV: indicates the main variable,
  - SM___: soil moisture (note that VOD is included in the same L3 file);
- SSSSS: indicates the sensor,
  - SMOS_: Soil Moisture and Ocean Salinity;
- REG: indicates the region,
  - GLO: global,
  - EUM: European and Mediterranean countries;
- LLL: indicates the data level,
  - L3_: Level 3,
  - L4_: Level 4;
- X: indicates the half-orbit type,
  - A: ascending,
  - D: descending;
- YYYYMMDDTHHMMSS: central date (year, month, day, hour, minute and second) in Coordinated Universal Time (UTC) of the period covered by the file;
- GGGGG: indicates the spatial resolution of the grid,
  - 025km: EASE-2 global grid of 25 km (EASE2_M25km),
  - 001km: EASE-2 global grid of 1 km (EASE2_M01km);
- TT: indicates the temporal coverage of the data file,
  - 1d: 1 day,
  - 3d: 3 days,
  - 9d: 9 days,

- 1m: 1 month,
- 1y: 1 year;

- DDD: indicates the production mode (only used in L4):
  - REP: reprocessed,
  - NRT: Near Real-Time (used in older versions of L4),
- vV.V: product version number
  - v4.0: for current L3,
  - v6.0: for current L4;

3.2 L3 soil moisture products

The L3 soil moisture products, including both soil moisture and VOD information, at 25 km EASE-2 are produced in a variety of periods (and generation rates): 1 day (daily), 3 days (daily), 9 days (every 3 days), 1 month (monthly) and 1 year (annually) (see Table 2). In all periods, ascending and descending orbits are processed separately. The daily L3 products have a latency of 2 days.

A comprehensive evaluation of the BEC SMOS L3 soil moisture at 25 km EASE-2 over the Iberian Peninsula, using two complementary small-scale and large-scale *in situ* networks and a surface water balance model, was performed [González-Zamora *et al.*, 2015]. Results showed that soil moisture is consistent with ground-based measurements in the time series comparisons, with correlation coefficients (R) and an Agreement Index (AI) higher than 0.8 for the total average and the land-use averages, and higher than 0.85 for the soil-texture averages. The BEC L3 soil moisture was also compared with a modeled soil moisture with a reasonable agreement between them [Polcher *et al.*, 2016]. The BEC L3 product has also been employed in a variety of application studies, including the analysis of dominant features of global soil moisture dynamics [Piles *et al.*, 2019, Bueso *et al.*, 2020] and monitoring drought [Sánchez *et al.*, 2018, Souza *et al.*, 2018], among others.

3.2.1 Data definition

The structure of the L3 soil moisture files at 25 km EASE-2 grid is detailed here:

```
netcdf BEC_SM____SMOS__GLO_L3__A_20220101T122425_025km_1d_____v4.0 {
dimensions:
    time = UNLIMITED ; // (1 currently)
    lat = 584 ;
    lon = 1388 ;
variables:
    int time(time) ;
        time:long_name = "Time" ;
        time:standard_name = "time" ;
        time:units = "seconds since 1970-1-1 00:00:00" ;
        time:coordinate_defines = "center" ;
        time:calendar = "gregorian" ;
    float lat(lat) ;
        lat:long_name = "latitude" ;
        lat:standard_name = "latitude" ;
```

```
        lat:units = "degrees_north" ;
        lat:coordinate_defines = "center" ;
    float lon(lon) ;
        lon:long_name = "longitude" ;
        lon:standard_name = "longitude" ;
        lon:units = "degrees_east" ;
        lon:coordinate_defines = "center" ;
    short SM(time, lat, lon) ;
        SM:long_name = "Surface Soil Moisture" ;
        SM:units = "m^ 3/m^ 3" ;
        SM:description = "Surface Soil Moisture" ;
        SM:coordinates = "time lat lon" ;
        SM:scale_factor = 0.0001f ;
        SM:add_offset = 0.f ;
        SM:valid_min = 0.f ;
        SM:valid_max = 0.6f ;
        SM:missing_value = -999s ;
        SM:_FillValue = -999s ;
    short VOD(time, lat, lon) ;
        VOD:long_name = "Vegetation Optical Depth" ;
        VOD:description = "Vegetation Optical Depth at nadir" ;
        VOD:coordinates = "time lat lon" ;
        VOD:scale_factor = 0.0001f ;
        VOD:add_offset = 0.f ;
        VOD:missing_value = -999s ;
        VOD:_FillValue = -999s ;
    short SM_DQX(time, lat, lon) ;
        SM_DQX:long_name = "DQX of Surface Soil Moisture" ;
        SM_DQX:units = "m^ 3/m^ 3" ;
        SM_DQX:description = "Data Quality Index of Surface Soil Moisture" ;
        SM_DQX:coordinates = "time lat lon" ;
        SM_DQX:scale_factor = 0.0001f ;
        SM_DQX:add_offset = 0.f ;
        SM_DQX:missing_value = -999s ;
        SM_DQX:_FillValue = -999s ;
    short VOD_DQX(time, lat, lon) ;
        VOD_DQX:long_name = "DQX of Vegetation Optical Depth" ;
        VOD_DQX:description = "Data Quality Index of Vegetation Optical Depth
        at nadir" ;
        VOD_DQX:coordinates = "time lat lon" ;
        VOD_DQX:scale_factor = 0.0001f ;
        VOD_DQX:add_offset = 0.f ;
        VOD_DQX:missing_value = -999s ;
        VOD_DQX:_FillValue = -999s ;
    short SM_VARIANCE(time, lat, lon) ;
        SM_VARIANCE:long_name = "Variance of Surface Soil Moisture" ;
        SM_VARIANCE:units = "(m^ 3/m^ 3)^ 2" ;
        SM_VARIANCE:description = "Variance of Surface Soil Moisture" ;
        SM_VARIANCE:coordinates = "time lat lon" ;
```

```
        SM_VARIANCE:scale_factor = 0.0001f ;
        SM_VARIANCE:add_offset = 0.f ;
        SM_VARIANCE:missing_value = -999s ;
        SM_VARIANCE:_FillValue = -999s ;
    short VOD_VARIANCE(time, lat, lon) ;
        VOD_VARIANCE:long_name = "Variance of Vegetation Optical Depth" ;
        VOD_VARIANCE:description = "Variance of Vegetation Optical Depth at nadir" ;
        VOD_VARIANCE:coordinates = "time lat lon" ;
        VOD_VARIANCE:scale_factor = 0.0001f ;
        VOD_VARIANCE:add_offset = 0.f ;
        VOD_VARIANCE:missing_value = -999s ;
        VOD_VARIANCE:_FillValue = -999s ;
    ubyte N_SM(time, lat, lon) ;
        N_SM:long_name = "Number of L2 SM Measures" ;
        N_SM:description = "Number of L2 SM Measures" ;
        N_SM:coordinates = "time lat lon" ;
        N_SM:missing_value = 0UB ;
        N_SM:_FillValue = 0UB ;
    ubyte N_VOD(time, lat, lon) ;
        N_VOD:long_name = "Number of L2 VOD Measures" ;
        N_VOD:description = "Number of L2 VOD Measures" ;
        N_VOD:coordinates = "time lat lon" ;
        N_VOD:missing_value = 0UB ;
        N_VOD:_FillValue = 0UB ;
    char crs ;
        crs:long_name = "Coordinate Reference System" ;
        crs:grid_mapping_name = "EASE2_M25km" ;
        crs:description = "Equal Area Scalable Earth version 2.0 (EASE v2.0)
        at 25 km" ;
        crs:cell_area = "25.02526_km_x_25.02526_km" ;
        crs:number_of_columns = 1388 ;
        crs:number_of_rows = 584 ;
        crs:datum = "WGS_84" ;
        crs:standard_parallel = 30.f ;
        crs:central_meridian = 0.f ;
        crs:false_easting = 0.f ;
        crs:false_northing = 0.f ;
        crs:proj4text = "+proj=cea +lon_0=0 +lat_ts=30 +x_0=0 +y_0=0
        +ellps=WGS84 +towgs84=0,0,0,0,0,0,0 +units=m +no_defs" ;
        crs:epsg = "6933" ;
        crs:ulx = -17367530.45 ;
        crs:uly = 7307375.92 ;
        crs:lrx = 17367530.45 ;
        crs:lry = -7307375.92 ;
// global attributes:
    :title = "SMOS L3 Surface Soil Moisture binned map at 25 km EASE-2" ;
    :institution = "Barcelona Expert Centre (BEC), ICM-CSIC and UPC, Barcelona,
    Spain" ;
    :url = "https://bec.icm.csic.es" ;
```

:email = "smos-bec@icm.csic.es" ;
:copyright = "BEC research products are freely distributed. If these data are used for publication, the following acknowledgment should be included: These data were produced by the Barcelona Expert Center (bec.icm.csic.es), a joint initiative of the Spanish Research Council (CSIC) and the Technical University of Catalonia (UPC), mainly founded by the Spanish National Program on Space" ;
:product_version = "4.0" ;
:Conventions = "CF-1.8" ;
:SM_source = "ESA SMOS Level 2 v700" ;
:VOD_source = "ESA SMOS Level 2 v700" ;
:sensor = "SMOS/MIRAS" ;
:platform = "PROTEUS" ;
:time_coverage_start = "20220101T001713 UTC" ;
:time_coverage_end = "20220102T003137 UTC" ;
:date_created = "20220713T004538 GMT" ;
:geospatial_lat_min = -84.4379f ;
:geospatial_lat_max = 84.4379f ;
:geospatial_lat_units = "degrees_north" ;
:geospatial_lon_min = -179.99f ;
:geospatial_lon_max = 179.99f ;
:geospatial_lon_units = "degrees_east" ;
:ascending_flag = "A" ;
:license = "This product is distributed under Creative Commons Attribution license (CC BY 4.0). You are free to share and adapt this product under the following terms: You must give appropriate credit (see copyright), provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use." ;
:license_url = "https://creativecommons.org/licenses/by/4.0/" ;
:DOI = "10.20350/digitalCSIC/14722" ;
}

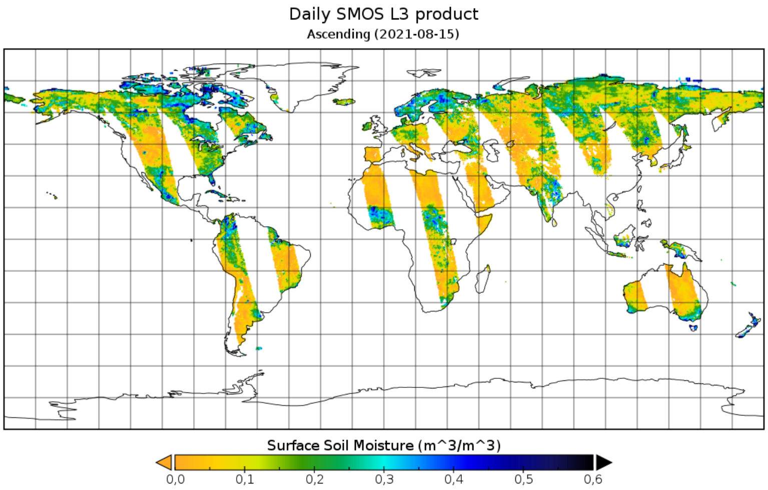
Use the following reference to cite the BEC SMOS L3 soil moisture product:

Pablos, Miriam; González-Haro, Cristina; Portal, Gerard; Piles, Maria; Vall-llossera, Mercè; Portabella, Marcos. 2022. SMOS L3 Surface Soil Moisture binned maps at 25 km EASE-2 (V.4.0) [Dataset]. DIGITAL.CSIC. DOI: 10.20350/digitalCSIC/14722.

3.2.2 Examples

The global SMOS L3 surface soil moisture maps at 25 km EASE-2 of a particular day of summer 2021 are shown in Fig. 1. The soil moisture signature clearly displays different soil moisture conditions over the entire dynamic range of observations, such as wet regions in Canada, part of Alaska, north of USA, Scandinavian Peninsula, Rusia, Amazon, Congo, Thailand, Bangladesh, Vietnam, Indonesia, etc., and dry regions in Sahara, Arabia, Australia, etc.

Since SMOS follows a polar low Earth orbit with a revisit of 3 days, the separation between traces of consecutive ascending or descending half-orbits of a unique day is larger at low latitudes (maximum separation at the Equator) and decreases when approaching high latitudes (being overlapped close to the poles). Apart from Greenland and Antarctica, some data gaps could appear over other land areas with no L2 retrievals due to the presence of frozen soil or by RFI contamination [Oliva *et al.*, 2016].



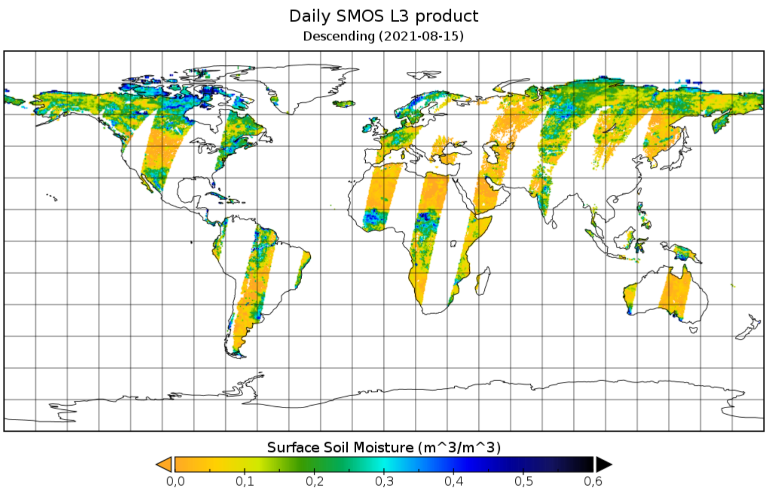
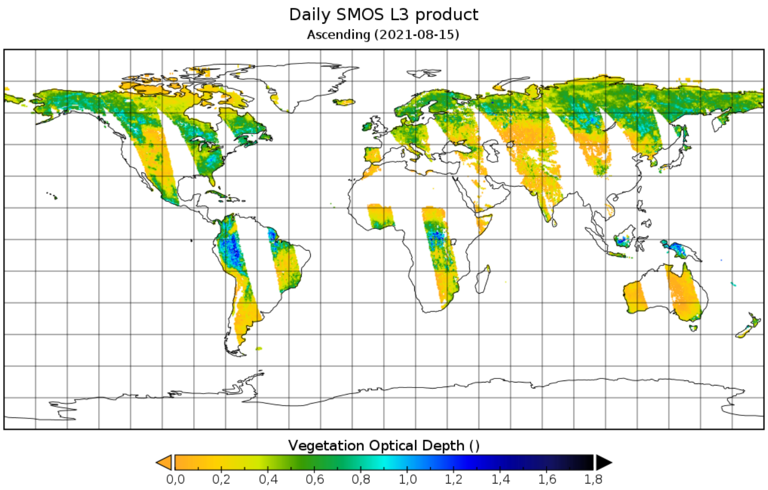


Figure 1: Global daily ascending (top) and descending (bottom) SMOS L3 surface soil moisture at 25 km EASE-2 corresponding to August 15, 2021.

The VOD represents the attenuation of microwave signals naturally emitted by the soil as they pass through the vegetation canopy. It is sensitive to the canopy structure and the amount of living biomass and provides complementary information to soil moisture [Lawrence *et al.*, 2014, Konings *et al.*, 2017, Rodríguez-Fernández *et al.*, 2018].

Figure 2 displays the global SMOS L3 VOD maps at 25 km EASE-2 on a particular day in summer 2021. The northernmost regions covered by tundra, such as the north of Canada, exhibit low VOD but high soil moisture whereas regions covered by boreal and tropical forests show high VOD as well as high soil moisture. There is no VOD data over the Sahara desert and in some regions of Arabia.



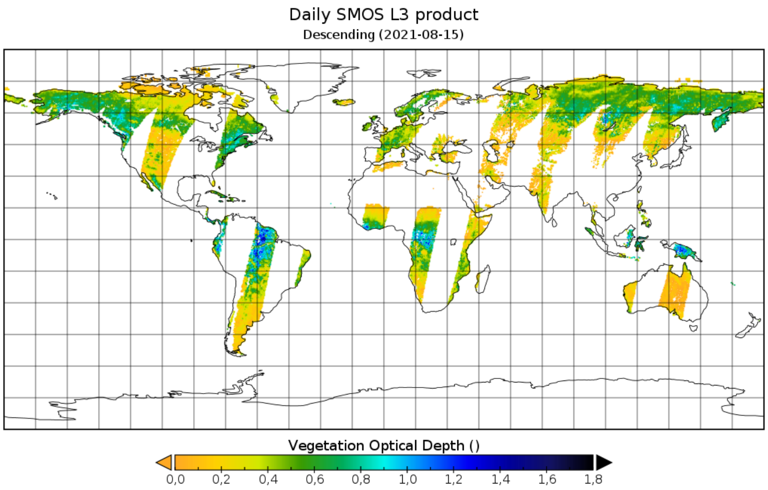


Figure 2: Global daily ascending (top) and descending (bottom) SMOS L3 vegetation optical depth at 25 km EASE-2 corresponding to August 15, 2021.

The 3-day ascending SMOS L3 soil moisture maps at 25 km EASE-2 over North America for 8 days of June 2015 are shown in Fig. 3. They illustrate the soil moisture evolution during the circulation of the Tropical Storm Bill, which was formed on June 16, 2015, and dissipated on June 23, 2015. There were floods due to the heavy rain received in Texas, Oklahoma, Arkansas, Louisiana and some regions on the east coast of the USA, the northeast of Mexico and the southeast of Canada [Pablos *et al.*, 2019].

Note that there is a complete spatial coverage in the 3-day maps (and also in the 9-day, 1-month and 1-year maps) because the averaging period is equal (or higher) than 3 days, which is the SMOS revisit time.

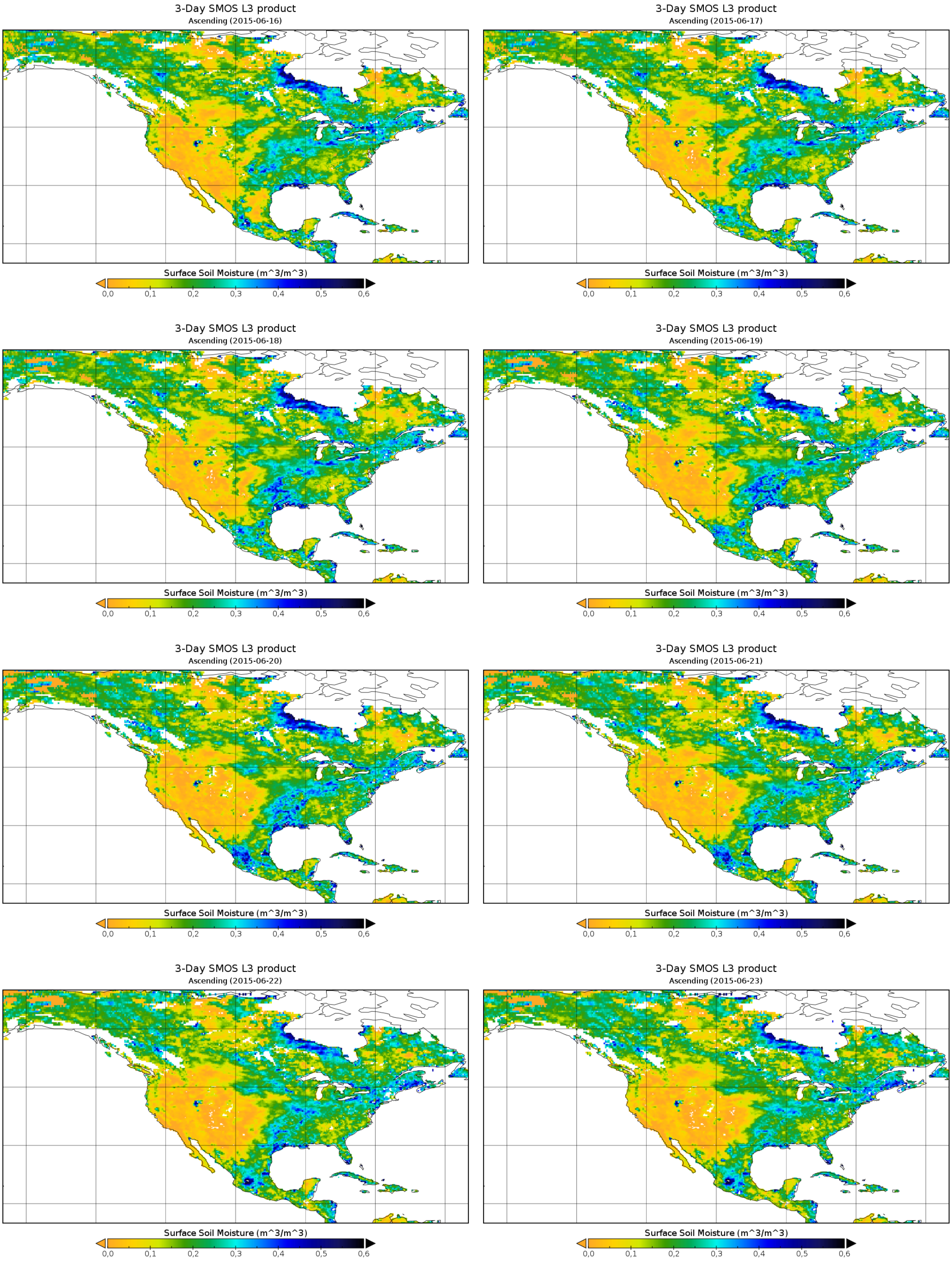


Figure 3: 3-Day ascending SMOS L3 surface soil moisture at 25-km EASE-2 over North America from June 16 to 23, 2015.

The monthly ascending SMOS L3 soil moisture maps over the USA from June 2012 to June 2021 are shown in Fig. 4. As expected, regions on the west of the Great Plains (the Colorado Plateau, the Great Basin, the Columbia Plateau, etc.) are drier than the east areas all the years. However, the monthly mean soil moisture at Central Lowland was very dry in June of 2012, 2017 and 2021, relatively dry in June 2016, 2018 and 2020, and wet for the rest of the years.

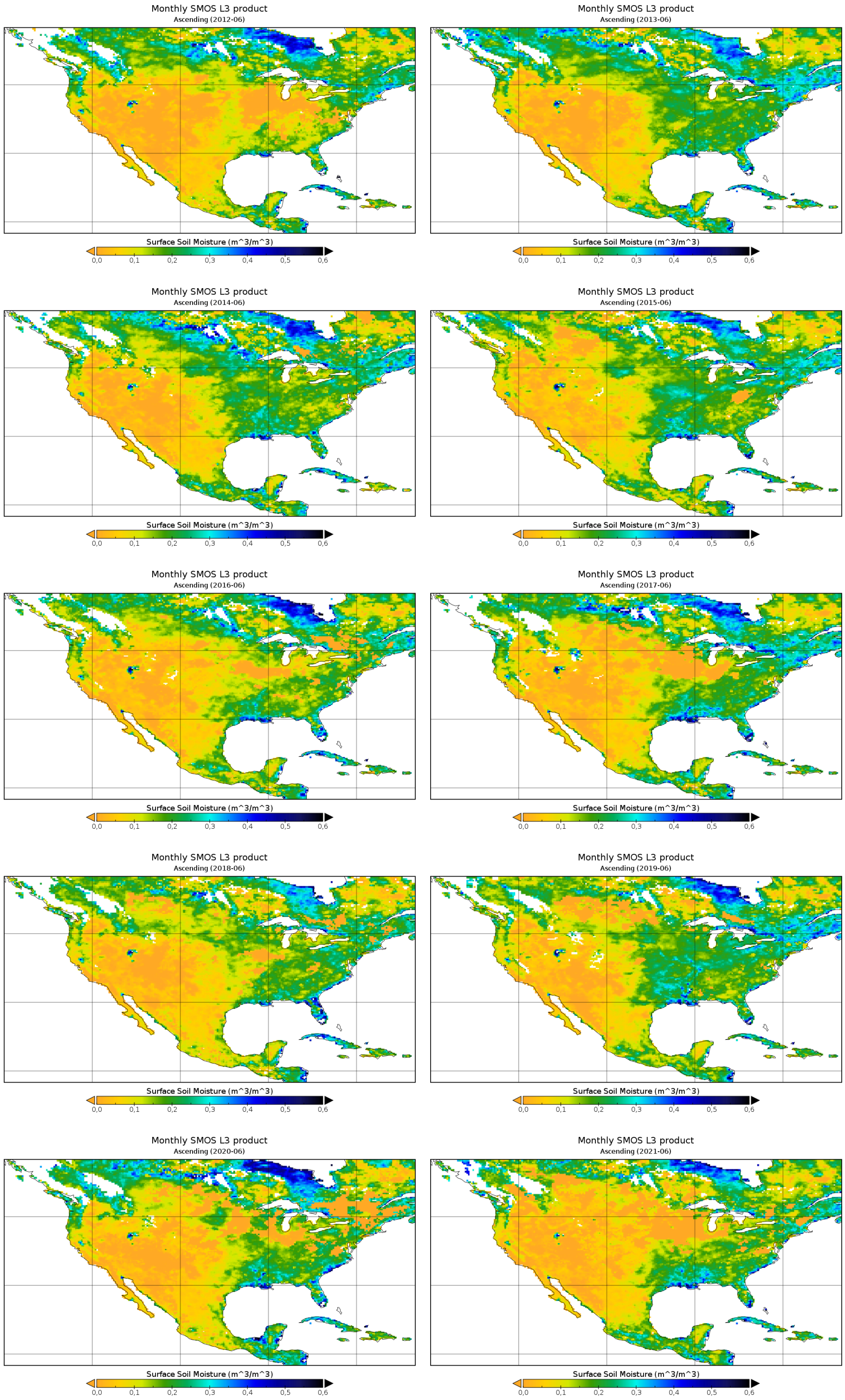


Figure 4: Monthly ascending SMOS L3 surface soil moisture at 25-km EASE-2 over the USA during June for the last 10 years of the mission.

The annual ascending SMOS L3 soil moisture maps from 2012 to 2021 are shown in Fig. 5. These maps provide a global overview of the soil moisture evolution during the last 10 years of the mission.

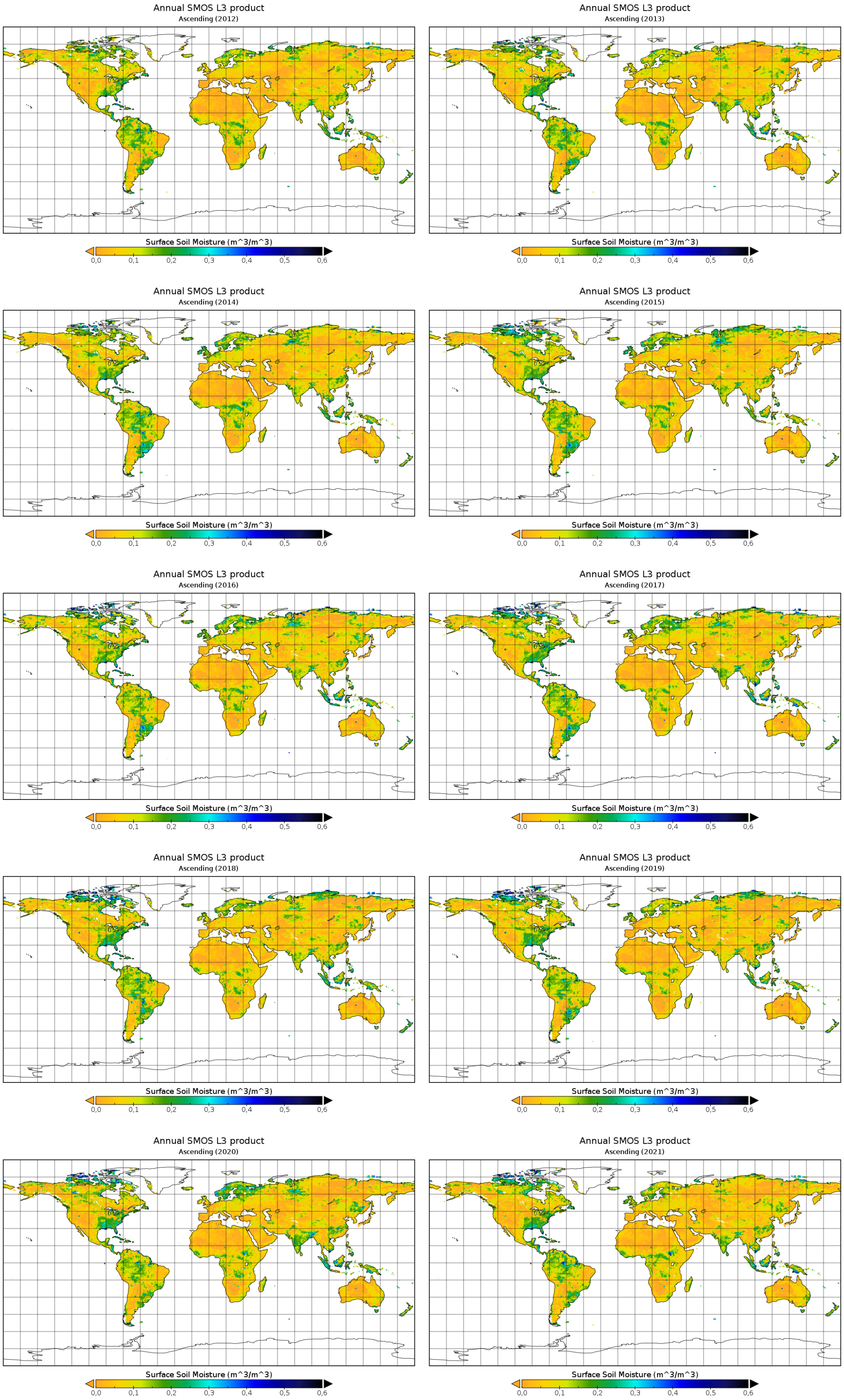


Figure 5: Annual ascending SMOS L3 surface soil moisture from 2012 to 2021.

3.3 L4 soil moisture products

The regional L4 soil moisture maps at 1 km EASE-2 over Europe and Mediterranean countries are daily produced in reprocessed (REP) mode at two different time periods: 1 day and 3 days (see Table 2). Ascending and descending orbits are processed separately. The reprocessed daily L4 soil moisture is produced with a latency of around 3-4 weeks.

A validation study of the BEC L4 soil moisture over a selection of networks within Europe is included in Appendix A. BEC L4 products have been successfully used in a variety of local-scale applications, for instance, to estimate the potential burned area of wildfires [Chaparro *et al.*, 2016], to analyze the decline of drought-prone forests [Chaparro *et al.*, 2017, 2018], to monitor agricultural drought [Pablos *et al.*, 2017], to quantify the water stress effect in light efficiency [Sánchez-Ruiz *et al.*, 2017], to estimate root zone soil moisture [Pablos *et al.*, 2018], and to estimate the yield of rice [Zhan *et al.*, 2020] and other crops [Mateo-Sanchís *et al.*, 2021], among others.

3.3.1 Data definition

The structure of the daily L4 soil moisture files at 1 km EASE-2 is detailed here:

```
netcdf BEC_SM____SMOS__EUM_L4__A_20220101T031400_001km_1d_REP_v6.0 {
dimensions:
    time = UNLIMITED ; // (1 currently)
    lon = 4916 ;
    lat = 3542 ;
variables:
    char crs ;
        crs:long_name = "Coordinate Reference System" ;
        crs:grid_mapping_name = "EASE2_M01km" ;
        crs:description = "Equal Area Scalable Earth version 2.0 (EASE v2.0)
        at 1 km" ;
        crs:cell_area = "1.00090_km_x_1.00090_km" ;
        crs:number_of_columns = 4916s ;
        crs:number_of_rows = 3542s ;
        crs:datum = "WGS_84" ;
        crs:standard_parallel = 30.f ;
        crs:central_meridian = 0.f ;
        crs:false_easting = 0.f ;
        crs:false_northing = 0.f ;
        crs:proj4text = "+proj=cea +lon_0=0 +lat_ts=30 +x_0=0 +y_0=0 +ellps=WGS84
        +towgs84=0,0,0,0,0,0,0 +units=m +no_defs" ;
        crs:epsg = "6933" ;
        crs:ulx = -1060948.73 ;
        crs:uly = 6973404.36 ;
        crs:lrx = 3859451.21 ;
        crs:lry = 3431706.88 ;
    int time(time) ;
        time:long_name = "Time" ;
        time:standard_name = "time" ;
        time:units = "seconds since 1970-1-1 00:00:00" ;
```

```
        time:coordinate_defines = "center" ;
        time:calendar = "gregorian" ;
    float lat(lat) ;
        lat:long_name = "Latitude" ;
        lat:standard_name = "latitude" ;
        lat:units = "degrees_north" ;
        lat:coordinate_defines = "center" ;
    float lon(lon) ;
        lon:long_name = "Longitude" ;
        lon:standard_name = "longitude" ;
        lon:units = "degrees_east" ;
        lon:coordinate_defines = "center" ;
    short SM(time, lat, lon) ;
        SM:long_name = "Surface Soil Moisture" ;
        SM:units = "m^ 3/m^ 3" ;
        SM:scale_factor = 0.0001f ;
        SM:add_offset = 0.f ;
        SM:valid_min = 0.f ;
        SM:valid_max = 0.6f ;
        SM:coordinates = "time lat lon" ;
        SM:missing_value = -999s ;
        SM:_FillValue = -999s ;
    byte quality_flag(time, lat, lon) ;
        quality_flag:long_name = "Quality Flag of Surface Soil Moisture" ;
        quality_flag:description = "The quality flag contains 4 bits (bit3 bit2
        bit1 bit0) If flag=0:  Excellent quality data; if flag>0:  See flag_meanings
        and flag_masks" ;
        quality_flag:flag_meanings =
        "bit0_Brightness_temperature_corrected_by_sea_land_contamination
        bit1_RFI_flagged_in_ESA_L1C_brightness_temperature
        bit2_L3_soil_moisture_with_no_data
        bit3_L4_soil_moisture_without_physical_meaning" ;
        quality_flag:flag_masks = "1b, 2b, 4b, 8b" ;
        quality_flag:coordinates = "time lat lon" ;
        quality_flag:missing_value = -128b ;
        quality_flag:_FillValue = -128b ;
// global attributes:
    :title = "SMOS L4 Surface Soil Moisture downscaled map at 1 km EASE-2" ;
    :institution = "Barcelona Expert Centre (BEC), ICM-CSIC and UPC, Barcelona,
    Spain" ;
    :url = "https://bec.icm.csic.es" ;
    :email = "smos-bec@icm.csic.es" ;
    :copyright = "BEC research products are freely distributed.  If these data
    are used for publication, the following acknowledgment should be included:
    These data were produced by the Barcelona Expert Center (bec.icm.csic.es),
    a joint initiative of the Spanish Research Council (CSIC) and the Technical
    University of Catalonia (UPC), mainly founded by the Spanish National
    Program on Space" ;
    :algorithm = "Downscaling algorithm with adaptive moving window described
```

```
    in Portal et al.  (2018), DOI: 10.1109/JSTARS.2018.2832447";
    :product_version = "6.0" ;
    :Conventions = "CF-1.8" ;
    :TB_source = "ESA SMOS Level 1C v724 and AUX_ECMWF v400" ;
    :SM_source = "BEC SMOS Level 3 v4.0 obtained from ESA SMOS Level 2 v700" ;
    :LST_source = "ECMWF Operational Daily Analysis Skin Temperature 12:00h" ;
    :NDVI_source = "NASA Terra MODIS 16-Day NDVI MOD13A2 v6" ;
    :sensor = "SMOS/MIRAS" ;
    :platform = "PROTEUS" ;
    :time_coverage_start = "20220101T001713 UTC" ;
    :time_coverage_end = "20220101T061047 UTC" ;
    :date_created = "20220630T235933 GMT" ;
    :geospatial_lat_min = 28.00559f ;
    :geospatial_lat_max = 71.99656f ;
    :geospatial_lat_units = "degrees_north" ;
    :geospatial_lon_min = -10.99066f ;
    :geospatial_lon_max = 39.99481f ;
    :geospatial_lon_units = "degrees_east" ;
    :ascending_flag = "A" ;
    :license = "This product is distributed under Creative Commons Attribution
    license (CC BY 4.0).  You are free to share and adapt this product under the
    following terms:  You must give appropriate credit (see copyright), provide
    a link to the license, and indicate if changes were made.  You may do so in
    any reasonable manner, but not in any way that suggests the licensor endorses
    you or your use." ;
    :license_url = "https://creativecommons.org/licenses/by/4.0/" ;
    :DOI = "10.20350/digitalCSIC/14723" ;
}
```

The structure of the 3-day L4 files is the same but adds the N variable that describes the number of daily L4 soil moisture measurements considered in the averaging period. This variable has the following structure:

```
    ubyte N(time, lat, lon) ;
        N:long_name = "Number of L4 Measures" ;
        N:description = "Number of L4 Measures" ;
        N:coordinates = "time lat lon" ;
        N:missing_value = 0UB ;
        N:_FillValue = 0UB ;
```

Since the 3-day L4 soil moisture is the direct average of the daily L4 soil moisture, the 3-day L4 files only include the SM_source global attribute to describe all data sources as:

```
    :SM_source = "Reprocessed Daily BEC SMOS Level 4 SM v6.0" ;
```

The quality_flag variable only has information in the 4 least significant bits (LSB) and the other bits are not used, as described in Table 1.

Bit position	**Bit values**
0	0: Brightness temperature not affected by sea-land contamination. 1: Brightness temperature corrected by sea-land contamination.
1	0: No RFI flagged in ESA L1C brightness temperature. 1: RFI flagged in ESA L1C brightness temperature.
2	0: L3 soil moisture with data obtained from L2 retrievals. 1: L3 soil moisture with data obtained from a linear model.
3	0: L4 soil moisture values within the interval [0,1] m^3/m^3. 1: L4 soil moisture values outside the interval [0,1] m^3/m^3.
4, 5, 6 & 7	Not used.

Table 1: Interpretation of quality_flag variable in daily and 3-day L4 soil moisture files.

In the case of the 3-day L4 files, each bit of the quality_flag is activated if one or more of the soil moisture measures involved in the average are affected.

Use the following reference to cite BEC SMOS L4 soil moisture product:

Pablos, Miriam; González-Haro, Cristina; Portal, Gerard; Piles, Maria; Vall-llossera, Mercè; Portabella, Marcos. 2022. SMOS L4 Surface Soil Moisture downscaled maps at 1 km EASE-2 (reprocessed mode) (V.6.0) [Dataset]. DIGITAL.CSIC. DOI: 10.20350/digitalCSIC/14723.

3.3.2 Examples

The daily ascending and descending SMOS L4 soil moisture maps at 1 km EASE-2 over European and Mediterranean countries on a particular day of summer 2021 are shown in Fig. 6.

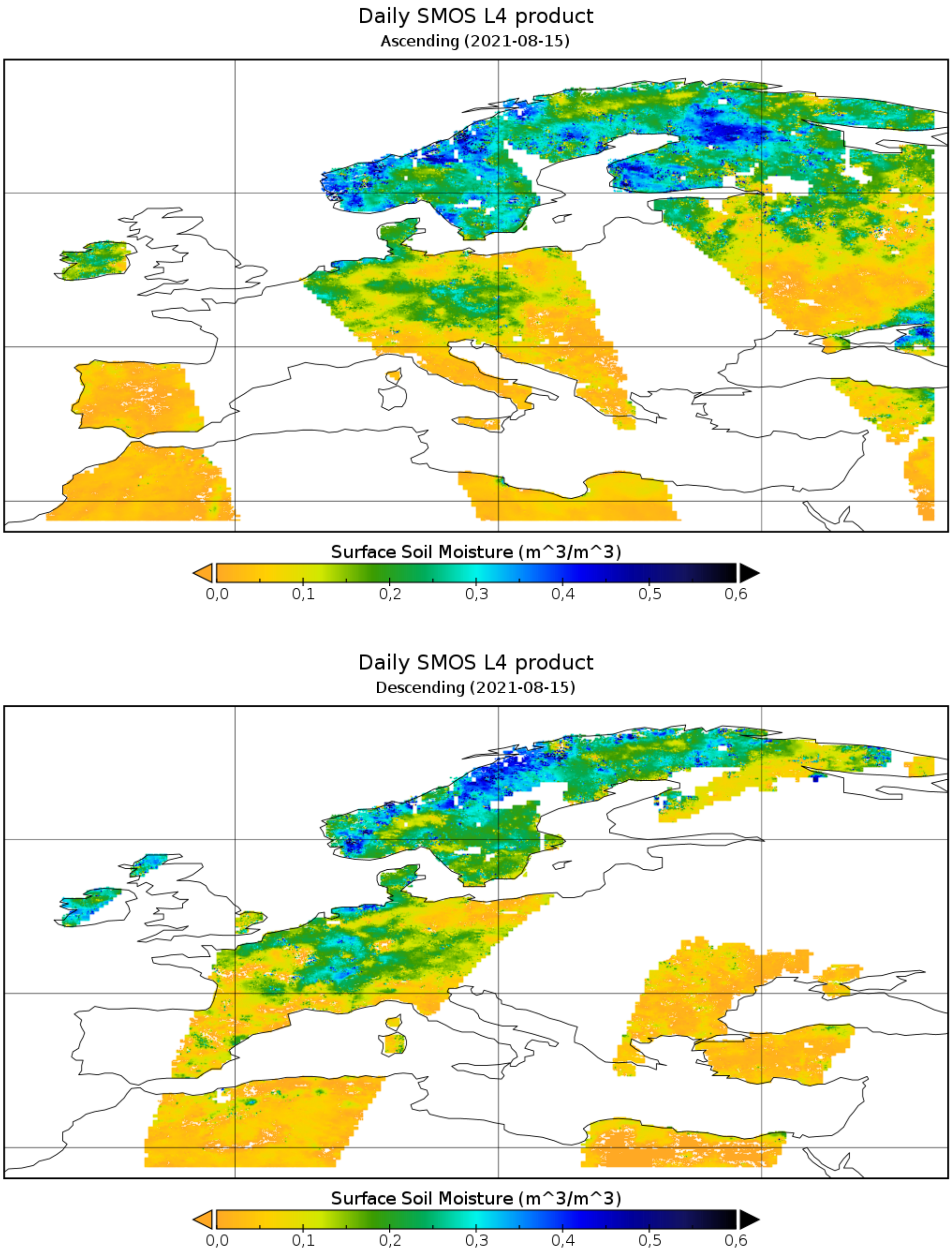


Figure 6: Daily ascending (top) and descending (bottom) SMOS L4 surface soil moisture at 1 km EASE-2 over Europe on August 15, 2021.

The 3-day ascending and descending L4 soil moisture maps over European and Mediterranean countries for the same day are shown in Fig. 7. Note the enhanced spatial resolution with respect to the 3-day L3 soil moisture included in Fig. 8.

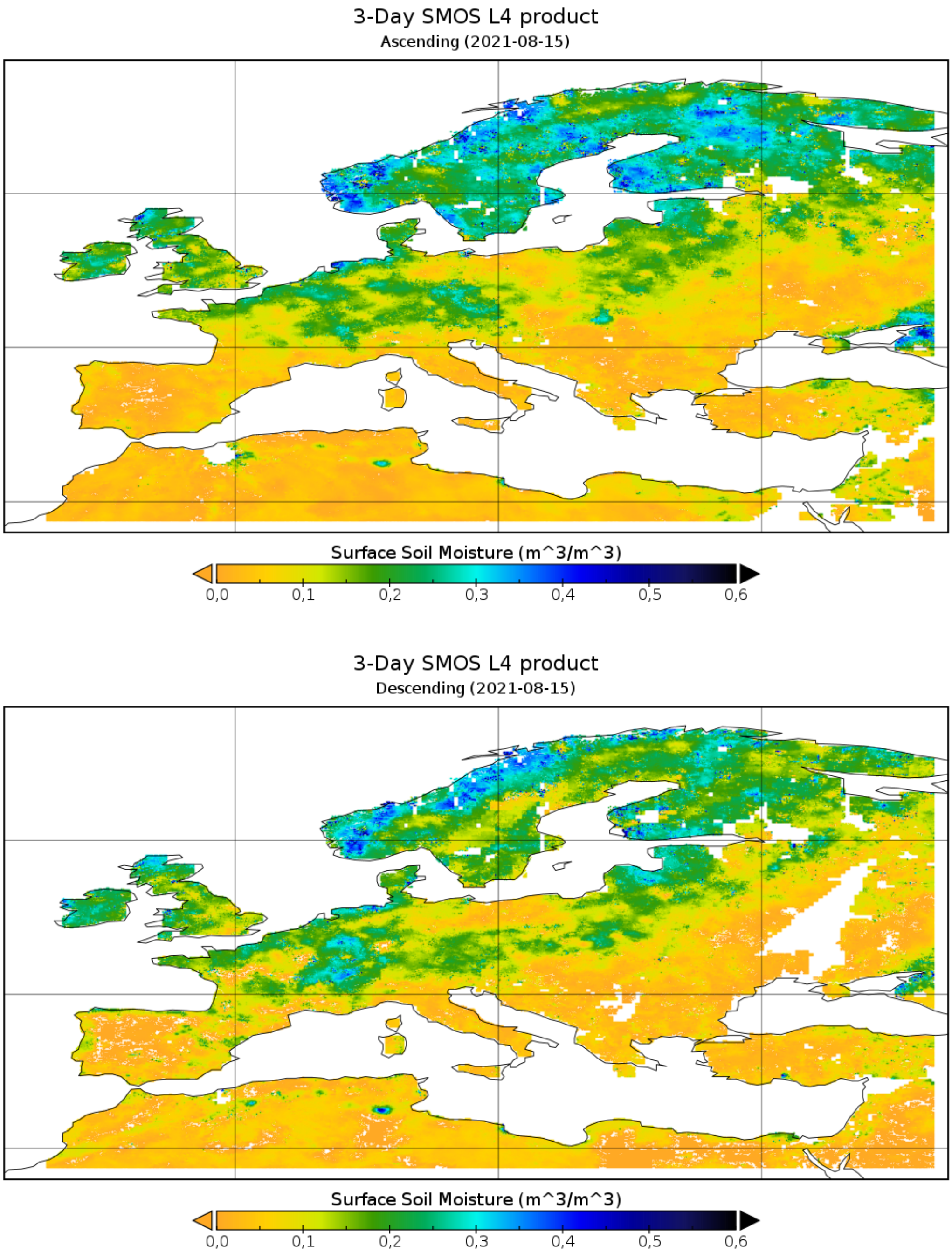


Figure 7: 3-Day ascending (top) and descending (bottom) SMOS L4 surface soil moisture at 1 km EASE-2 over Europe on August 15, 2021.

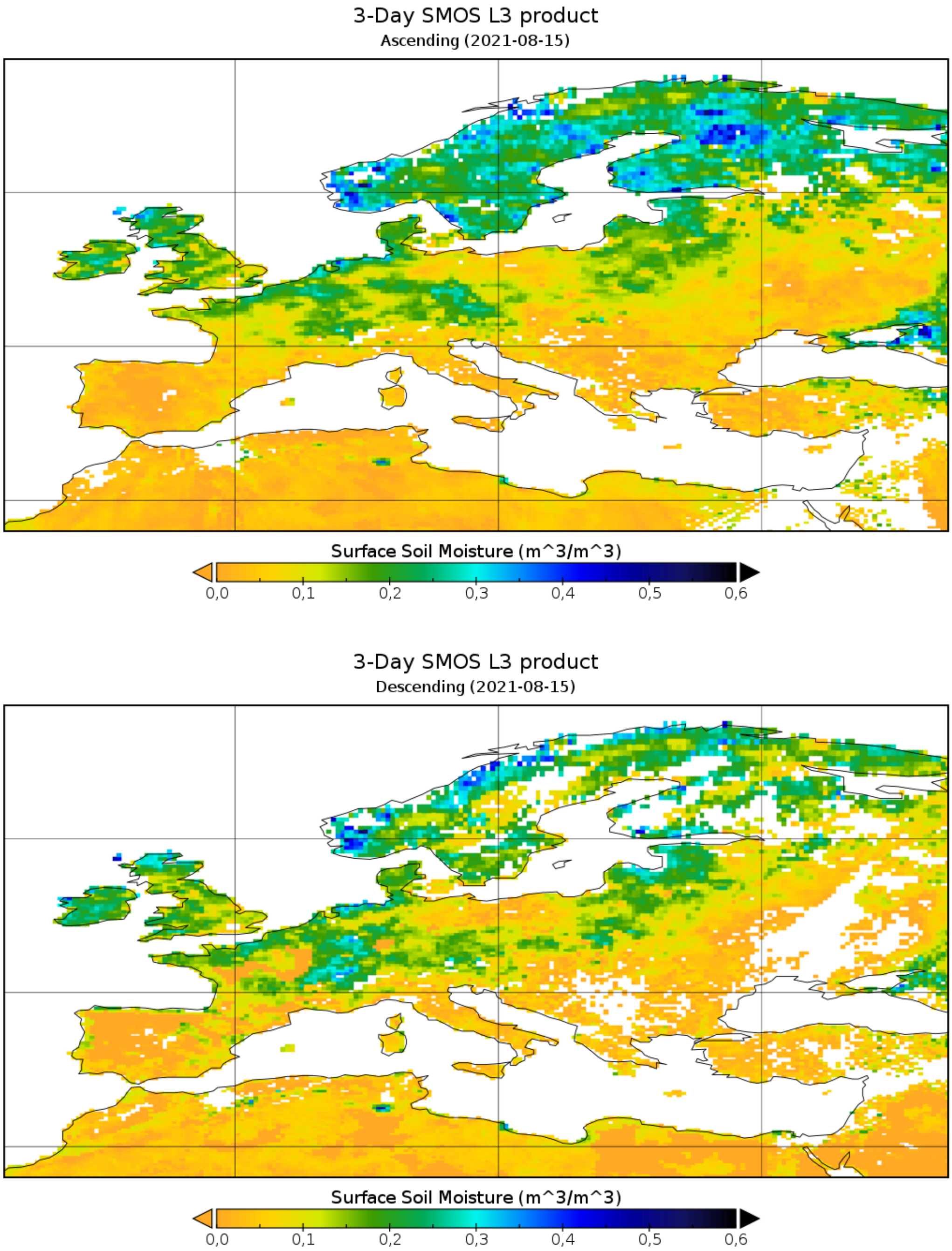


Figure 8: 3-Day ascending (top) and descending (bottom) SMOS L3 surface soil moisture at 25 km EASE-2 over Europe on August 15, 2021.

3.4 Summary of soil moisture products

All BEC soil moisture products and their correspondence with the SMOS DPGS products and other auxiliary data are summarized in Tables 2 and 3, respectively. Note that the currently available soil moisture files are L3 v4.0 and L4 v6.0.

Product	Variable	Spatial resolution (grid)	Production rate (mode)	Temporal resolution	Orbit
L3	surface soil moisture & vegetation optical depth	25 km (EASE-2)	daily	1 day	ascending
					descending
				3 days	ascending
					descending
			every 3 days	9 days	ascending
					descending
			monthly	1 month	ascending
					descending
			annually	1 year	ascending
					descending
L4	surface soil moisture	1 km (EASE-2)	daily (reprocessed)	1 day	ascending
					descending
				3 day	ascending
					descending

Table 2: SMOS soil moisture products distributed by BEC.

Product	Version	DPGS processor	Other data
L3	v1.0	L2 v551	–
	v2.0	L2 v620	–
	v3.0	L2 v650	–
	v4.0	**L2 v700**	–
L4	v1.0	L1C v505 & L2 v551	Terra MOD11A1 v5, Aqua MYD11A1 v5 & Terra MOD13A2 v5
	v2.0	L1C v620 & L2 v620	Aqua MYD11A1 v5 & Terra MOD13A2 v5
	v3.0	L1C v620 & L2 v620	ECMWF ERA-Interim & Terra MOD13A2 v5
	v4.0	L1C v620 & L2 v650	Operational ECMWF & Terra MOD13A2 v6
	v5.0	L1C v620 & L2 v650	Operational ECMWF, Terra MOD13A2 v6 & Terra MOD13A4N v6
	v6.0	**L1C v724 & L2 v700**	**Operational ECMWF & Terra MOD13A2 v6**

Table 3: Correspondance between BEC and ESA DPGS products.

A list of the missing daily L3 and L4 soil moisture files and the reason for not being produced are included in Tables 4 and 5, respectively. Note the dependency on lower-level products from ESA.

Ascending		**Descending**	
Date	**Reason**	**Date**	**Reason**
2010-12-27	No L2 data	2010-12-27	No L2 data
2010-12-28	No L2 data	2010-12-28	No L2 data
2010-12-29	No L2 data	2010-12-29	No L2 data
2010-12-30	No L2 data	2010-12-30	No L2 data
2010-12-31	No L2 data	2010-12-31	No L2 data

Table 4: Missing daily global SMOS L3 soil moisture files.

Ascending		**Descending**	
Date	**Reason**	**Date**	**Reason**
—	—	2010-06-06	Neither L1C nor L2 data
2010-06-07	Neither L1C nor L2 data	—	—
2010-06-18	Neither L1C nor L2 data	—	—
2010-12-27	Neither L1C nor L2 data	2010-12-27	Neither L1C nor L2 data
2010-12-28	Neither L1C nor L2 data	2010-12-28	Neither L1C nor L2 data
2010-12-29	Neither L1C nor L2 data	2010-12-29	Neither L1C nor L2 data
2010-12-30	Neither L1C nor L2 data	2010-12-30	Neither L1C nor L2 data
2010-12-31	Neither L1C nor L2 data	2010-12-31	Neither L1C nor L2 data
2011-01-01	Neither L1C nor L2 data	2011-01-01	Neither L1C nor L2 data
2011-02-01	Neither L1C nor L2 data	2011-02-01	Neither L1C nor L2 data
2011-02-05	Neither L1C nor L2 data	2011-02-05	Neither L1C nor L2 data
2011-03-01	Neither L1C nor L2 data	—	—
2011-05-18	Neither L1C nor L2 data	—	—
2019-09-10	No AUX_ECMWF data	—	—
—	—	2020-11-18	Neither L1C nor L2 data

Table 5: Missing daily SMOS L4 soil moisture files over European and Mediterranean countries

3.5 Data Access

BEC data is freely available to users upon registration in our secure FTP (sFTP) service. Registration is free; just fill the form in https://bec.icm.csic.es/bec-ftp-service-registration to complete registration.

If your browser is sFTP compatible, you can browse directly from the following address: sftp://becftp.icm.csic.es:27500.

If you employ an FTP client (as FileZilla), use the following configuration:

- Host: sftp://becftp.icm.csic.es
- Username: your username
- Password: your password
- Port: 27500

For more information about the BEC sFTP service, please visit our website: https://bec.icm.csic.es/bec-ftp-service. For any further assistance, do not hesitate to contact us by email to smos-bec@icm.csic.es.

The following tree diagram shows the complete paths of the repository to the global SMOS L3 soil moisture v4.0 and to the regional SMOS L4 soil moisture v6.0, respectively.

```
becftpdata
└ LAND
  └ SM
    └ SMOS
      ├ Global
      │ └ v4.0
      │   └ L3
      │     ├ 3days
      │     │ ├ ASC
      │     │ │ ├ 2010
      │     │ │ ├ ...
      │     │ │ └ 2022
      │     │ └ DES
      │     ├ 9days
      │     ├ annual
      │     ├ daily
      │     └ monthly
      └ Europe_and_Mediterranean
        └ v6.0
          └ L4
            ├ 3days
            │ └ REP
            │   ├ ASC
            │   │ ├ 2010
            │   │ ├ ...
            │   │ └ 2022
            │   └ DES
            └ daily
```

A QUALITY ASSESSMENT

This section includes the results obtained from the validation of SMOS L3 v4.0 and L4 v6.0 soil moisture products and their previous versions (L3 v3.0 and L4 v5.0) against *in-situ* soil moisture time series and their spatial analysis over Europe from 2015 to 2016.

A.1 Validation of soil moisture with in situ measurements

Five soil moisture networks were selected over Europe to validate the L3 and L4 products. They are located in different climates [Kottek *et al.*, 2006] and topographic complexities:

- **REMEDHUS: Soil Moisture Measurements Stations Network of the University of Salamanca**
  REMEDHUS is a dense network placed at the river Duero Basin, at the north Plateau of the Iberian Peninsula, Spain [Sánchez *et al.*, 2012]. It includes 24 stations (HydraProbes) installed at 5 cm depth, measuring hourly soil moisture and soil temperature. Its climate is warm-summer Mediterranean.
- **SMOSMANIA: Soil Moisture Observing System-Meteorological Automatic Network Integrated Application**
  SMOSMANIA is a sparse network located in the south of France, along a transect between the Atlantic Ocean and the Mediterranea Sea [Calvet *et al.*, 2007]. It is equipped with 22 stations (ThetaProbes ML2X and ML3), measuring soil moisture and soil temperature at the first top 5 cm of the soil every 12 minutes. The region has contrasting climatic conditions, varying from the humid oceanic climate in the West to the hot-summer Mediterranean climate in the East.
- **HOBE: Hydrological Observatory**
  HOBE is a dense network established at the Skjern River Catchment, Denmark [Bircher *et al.*, 2012]. It has 32 stations (Decagon 5TE) installed at 5 cm depth, which measure soil moisture and soil temperature at 30 minutes intervals. The climate is humid oceanic, with mild summers and wet all year.
- **RSMN: Continous Soil Moisture and Temperature Ground-based Observation Network**
  RSMN is a sparse network homogeneously distributed at Romania [Zeng *et al.*, 2016]. It includes 20 stations (Decagon 5TM), measuring hourly soil moisture and soil temperature at 5 cm below the soil surface. This area has a humid continental climate.
- **FMI: Finnish Meteorological Institute**
  FMI is placed at the Sodankylä Arctic research region, Findland [Ikonen *et al.*, 2016]. It has 8 stations (ThetaProbe ML2X, CS655 and Decagon 5TE) at a depth of 5 cm, which measure soil moisture and soil temperature every 60 minutes. The climate is subarctic, with cool summers and wet around precipitation.

The location of these five soil moisture networks is displayed in Fig. 9. *In-situ* soil moisture data was provided by the International Soil Moisture Network (ISMN) [Dorigo *et al.*, 2011]. In all stations, good quality soil moisture measurements were selected with the corresponding flag and daily averaged. The validation analysis was performed by means of the comparison of the soil moisture time-series of the L3 pixel (25 km) and L4 pixel (1 km) overlapping a particular ground station with the *in-situ* soil moisture time-series.

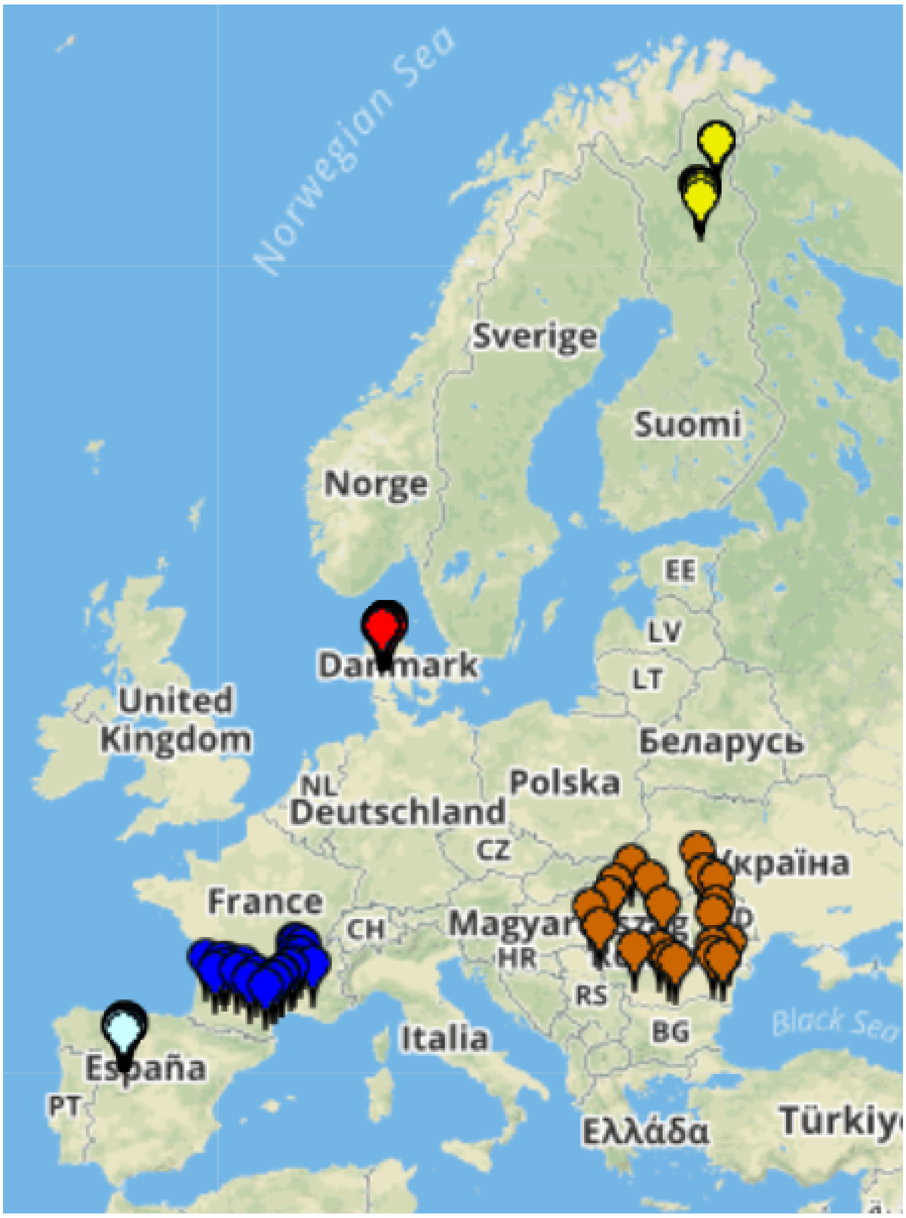


Figure 9: Location of the five soil moisture networks (cyan: REMEDHUS, blue: SMOSMANIA, red: HOBE, orange: RSMN, and yellow: FMI) over Europe.

Four statistical metrics were calculated: the Pearson correlation coefficient (R), the Root Mean Square Error (RMSE), the unbiased Root Mean Square Error (ubRMSE) and the bias [Entekhabi *et al.*, 2010]. Data from a total of 22 stations of REMEHUS, 15 stations of SMOSMANIA, 26 stations of HOBE, 16 stations of RSMN and 6 stations of FMI were used. The rest of the available stations in these networks were not utilized because they lead to non-significant correlations (p_{value} <0.01). Additionally, the number of coincident days with available data (N) during the study period was also computed.

For each network, the correlation and errors of the SMOS L3 surface soil moisture corresponding to the last and previous versions at each station were displayed in Figs. 10, 12, 14, 16 and 18 for ascending and Figs. 11, 13, 15, 17 and 19 for descending half-orbits. The correlation of the L3 v4.0 product is equal to or better than that of the v3.0 in all the networks and orbits, even showing a very notable increase in SMOSMANIA. Regarding the errors, the ubRMSE is similar or very similar in most networks, except in SMOSMANIA, where the ubRMSE of the v4.0 significantly decreases with respect to that of v3.0. The RMSE of the L3 v4.0 is also similar to or slightly higher than that of the v3.0 due to a slight bias increase in all networks and orbits. Notwithstanding, a lower RMSE is obtained when comparing the descending L3 v4.0 with *in-situ* data over FMI. This evidences that, in general, the quality of the new SMOS L3 product is equal to or higher than that of the previous version.

The correlation and errors of the L4 soil moisture v5.0 and v6.0 at each ground station were shown in Figs. 20, 22, 24, 26 and 28 for the SMOS ascending passes and Figs. 21, 23, 25, 27 and 29 for the descending ones. In REMEDHUS, there are no significant differences between the statistics corresponding to the last or the previous version neither in ascending nor descending orbits. In SMOSMANIA, the statistics of both versions of the L4 are consistent with those obtained with the L3 product, presenting higher correlations, lower ubRMSE, and similar or slightly higher RMSE for L4 v6.0 compared to v5.0. In both HOBE and RSMN, the correlation of the v6.0 is equal to or higher than that of the v5.0 for most of the stations, while the errors are very similar or exhibit a very slight increase. However, in FMI, both correlations and errors of the L4 v5.0 are better than that of the last version.

The average of the statistical scores for each network are summarized in Tables 6 and 7 for ascending and descending orbits, respectively. Considering the last version of the products, the highest correlations are obtained over SMOSMANIA (mean of 0.75 and 0.74 for L3 v4.0 and L4 v6.0 in both orbits, respectively) and the lowest correlations are obtained over FMI (0.46 and 0.39 in ascending and 0.51 and 0.49 in descending). In ascending, the lowest ubRMSE is obtained over SMOSMANIA (0.055 and 0.056 m^3/m^3 for L3 and L4, respectively) and the highest over FMI (0.067 and 0.100 m^3/m^3). There is a positive bias in HOBE, RSMN and FMI, which reveals an overestimation of the satellite soil moisture against the *in-situ* measurements. There is a negative bias en REMEDHUS and SMOSMANIA. In descending, the lowest ubRMSE is also computed over SMOSMANIA (0.058 and 0.059 m^3/m^3 for L3 and L4, respectively) and the highest over FMI (0.096 and 0.104 m^3/m^3). The bias shows a positive mean over RSMN and FMI, whereas REMEDHUS, SMOSMANIA and HOBE underestimate soil moisture. However, considering the absolute value of the mean, the largest bias is obtained over FMI for both ascending and descending orbits.

In general, both the correlations and root-mean-squared-errors for the L4 surface soil moisture are similar to those obtained for the L3 regardless of the network analyzed indicating that the applied downscaling algorithm is not having a significant impact on the soil moisture accuracy obtained by the radiometer-only product (L3) at the selected locations. In all networks, except in FMI, the ascending orbits of the last version of the products (L3 v4.0 and L4 v6.0) perform slightly better than descending orbits in terms of R and (ub)RMSE.

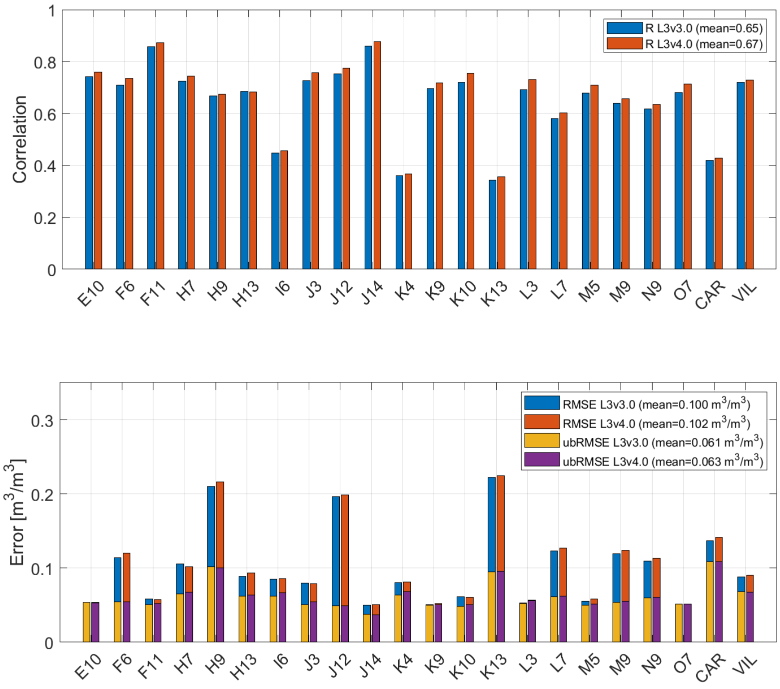


Figure 10: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L3 surface soil moisture v3.0 and v4.0 over REMEDHUS.

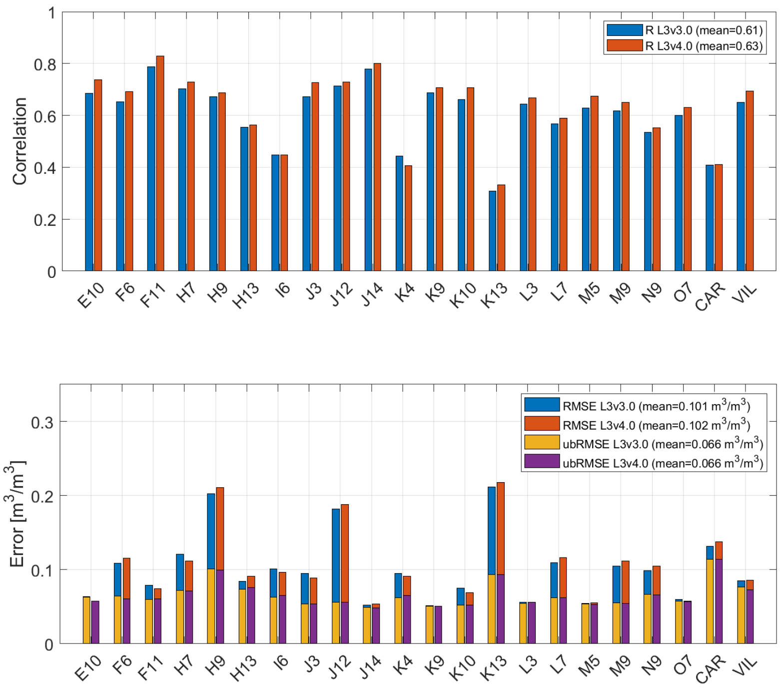


Figure 11: Same as Fig. 10, but for descending orbits.

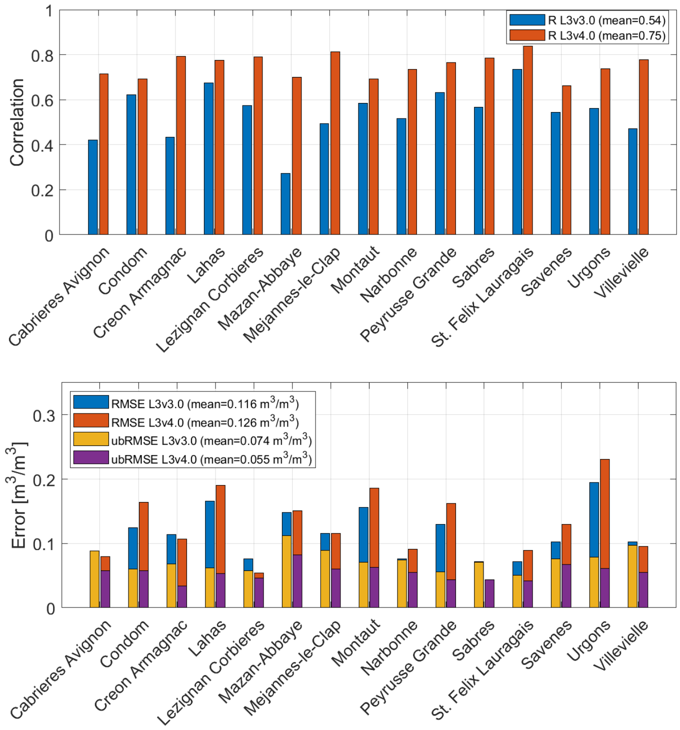


Figure 12: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L3 surface soil moisture v3.0 and v4.0 over SMOSMANIA.

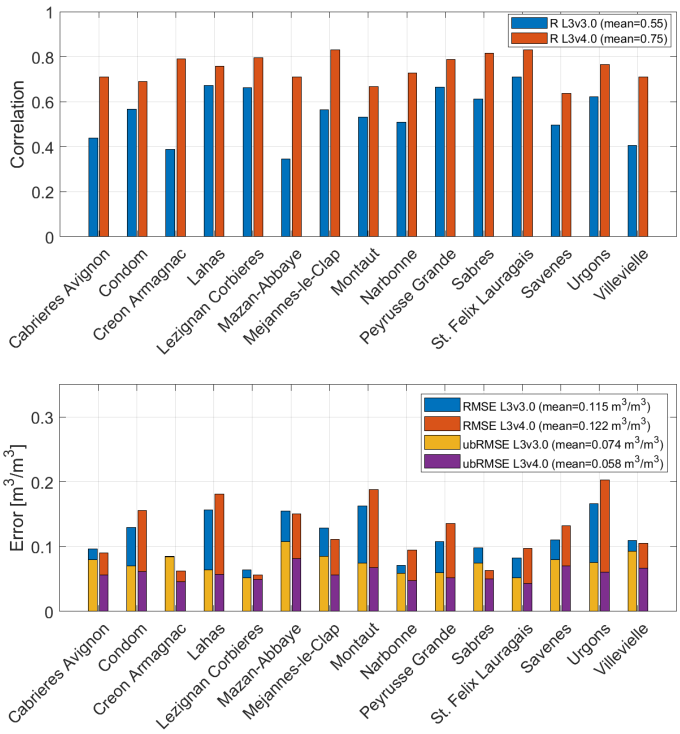


Figure 13: Same as Fig. 12, but for descending orbits.

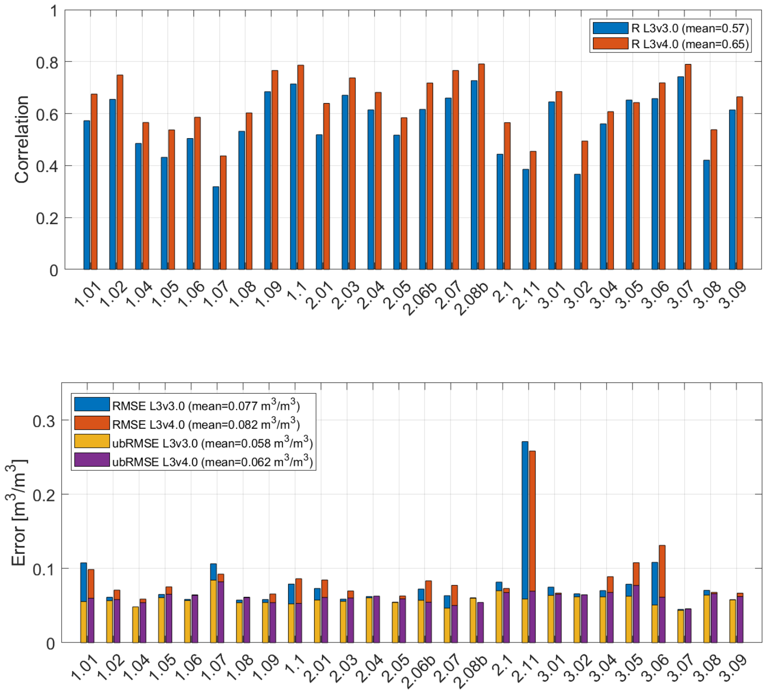


Figure 14: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L3 surface soil moisture v3.0 and v4.0 over HOBE.

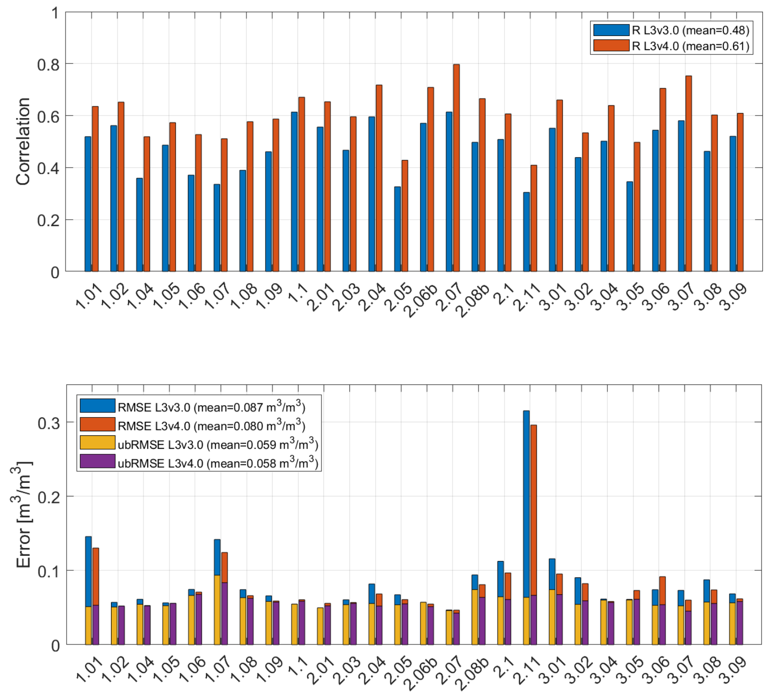


Figure 15: Same as Fig. 14, but for descending orbits.

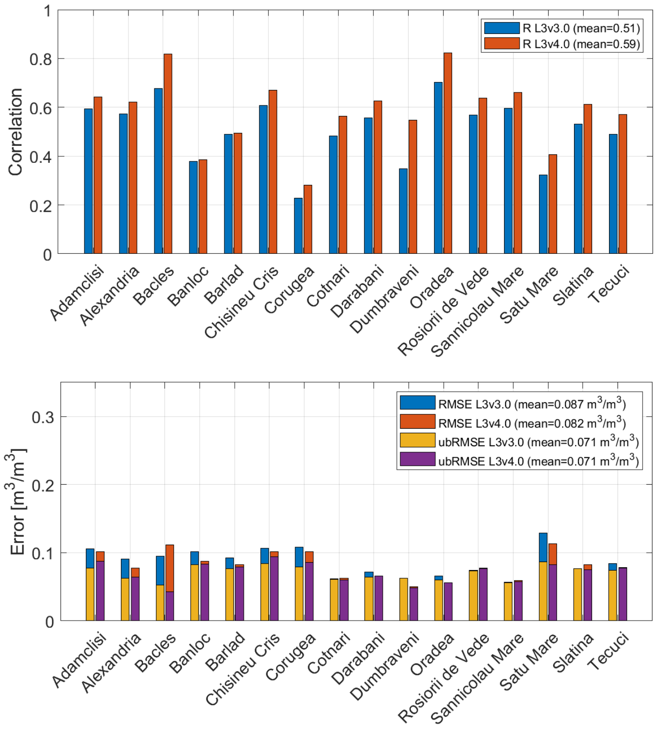


Figure 16: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L3 surface soil moisture v3.0 and v4.0 over RSMN.

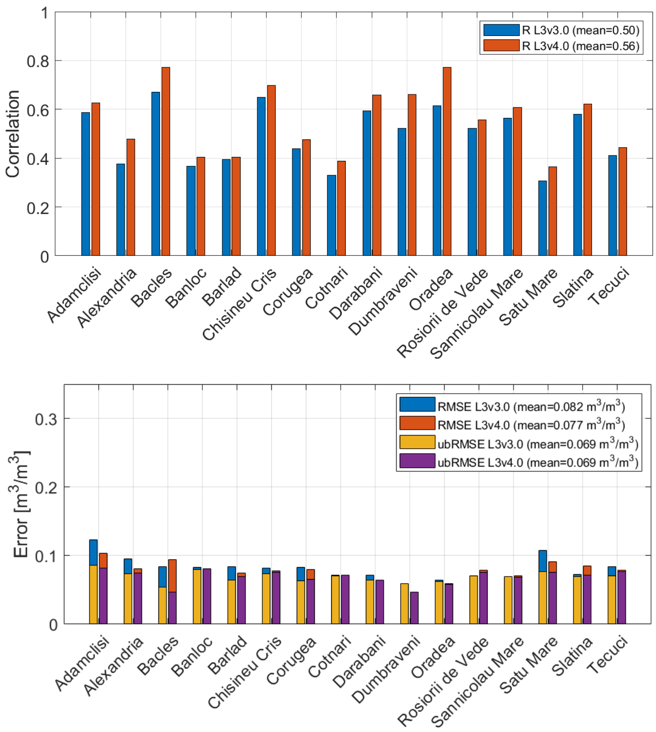


Figure 17: Same as Fig. 16, but for descending orbits.

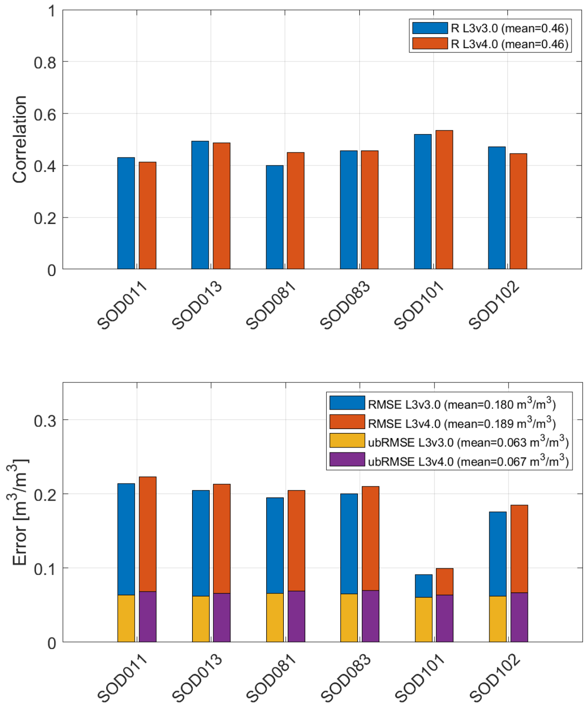


Figure 18: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L3 surface soil moisture v3.0 and v4.0 over FMI.

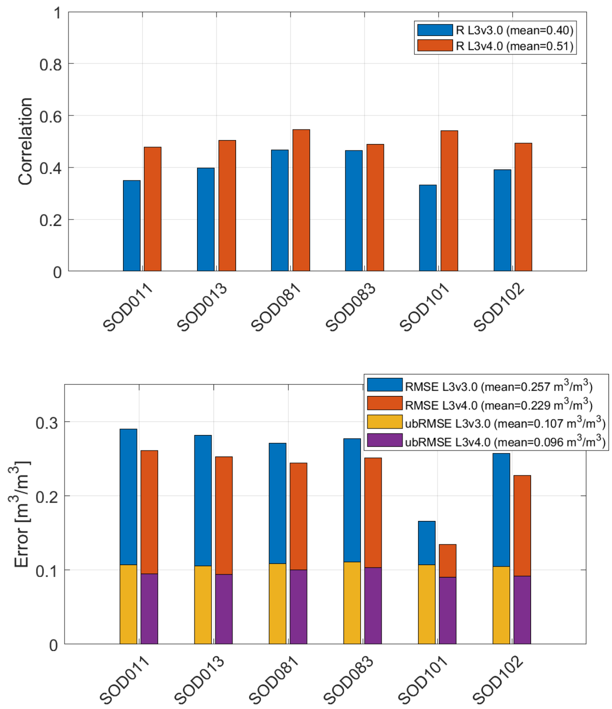


Figure 19: Same as Fig. 18, but for descending orbits.

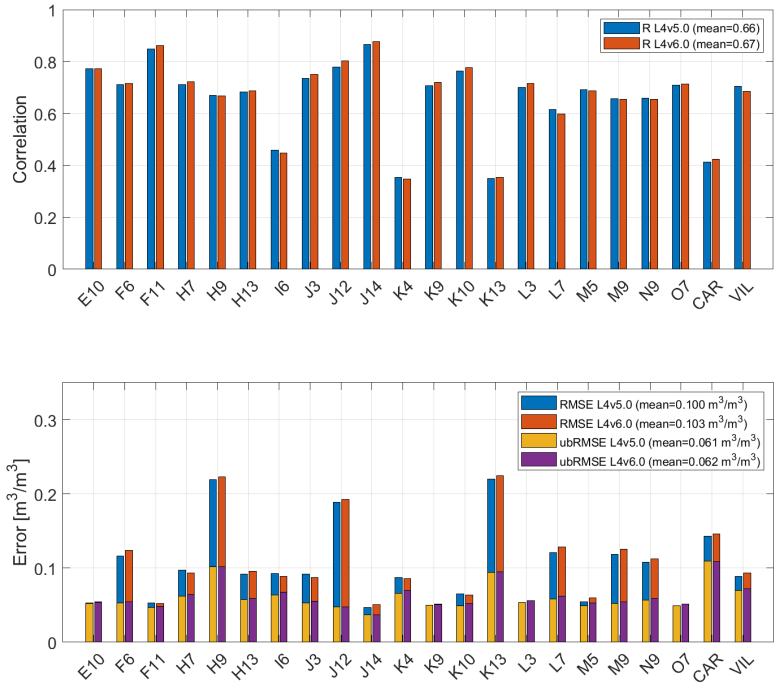


Figure 20: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L4 surface soil moisture v5.0 and v6.0 over REMEDHUS.

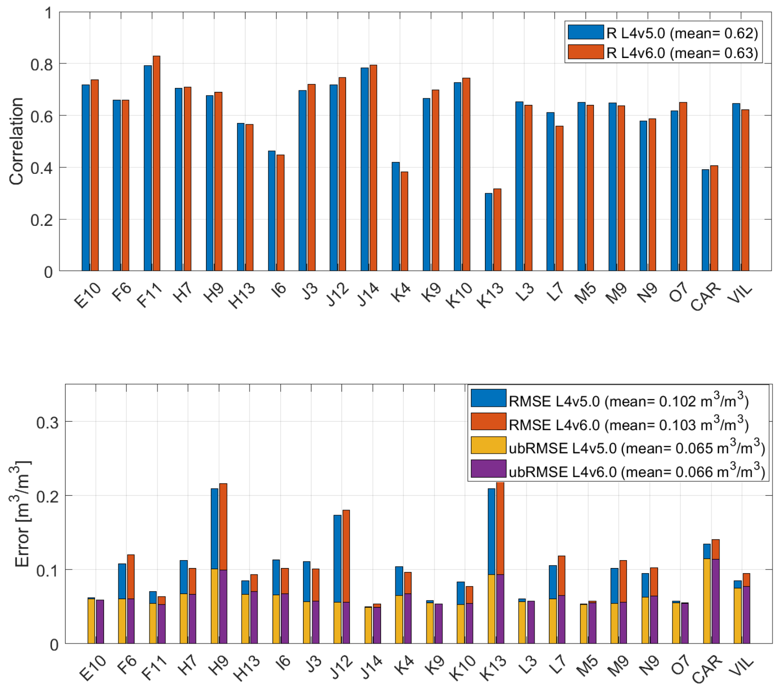


Figure 21: Same as Fig. 20, but for descending orbits.

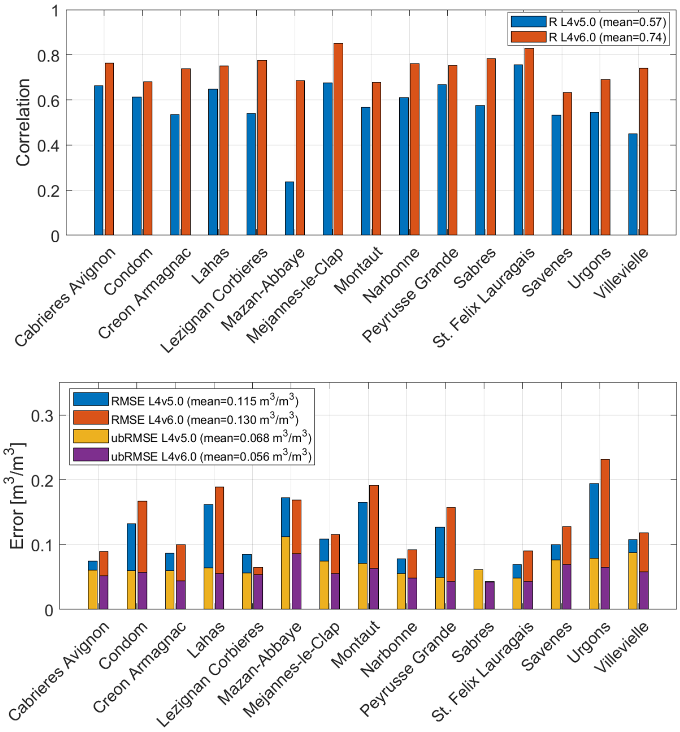


Figure 22: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L4 surface soil moisture v5.0 and v6.0 over SMOSMANIA.

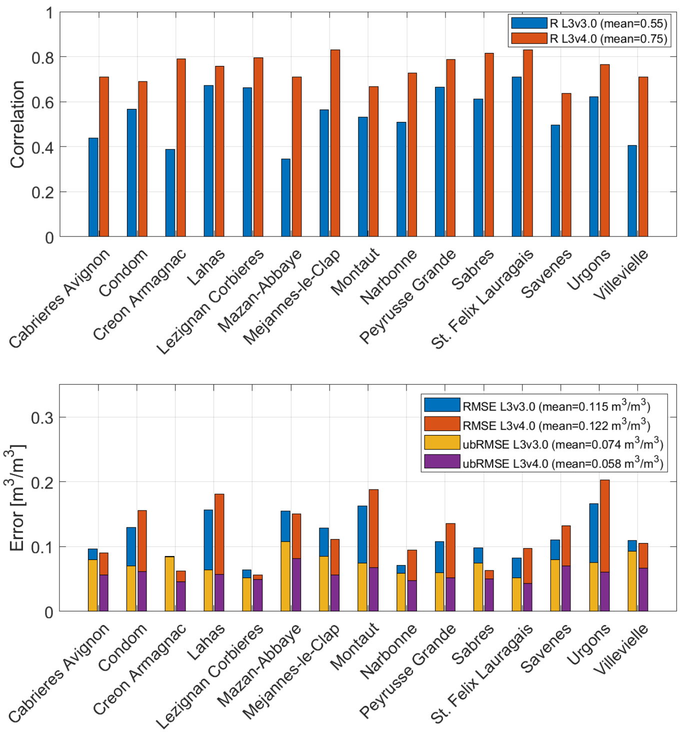


Figure 23: Same as Fig. 12, but for descending orbits.

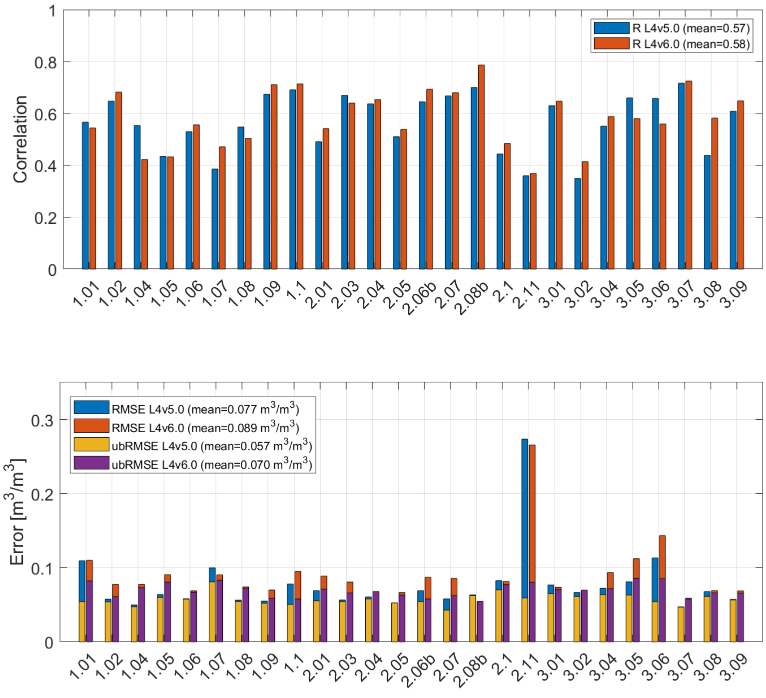


Figure 24: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L4 surface soil moisture v5.0 and v6.0 over HOBE.

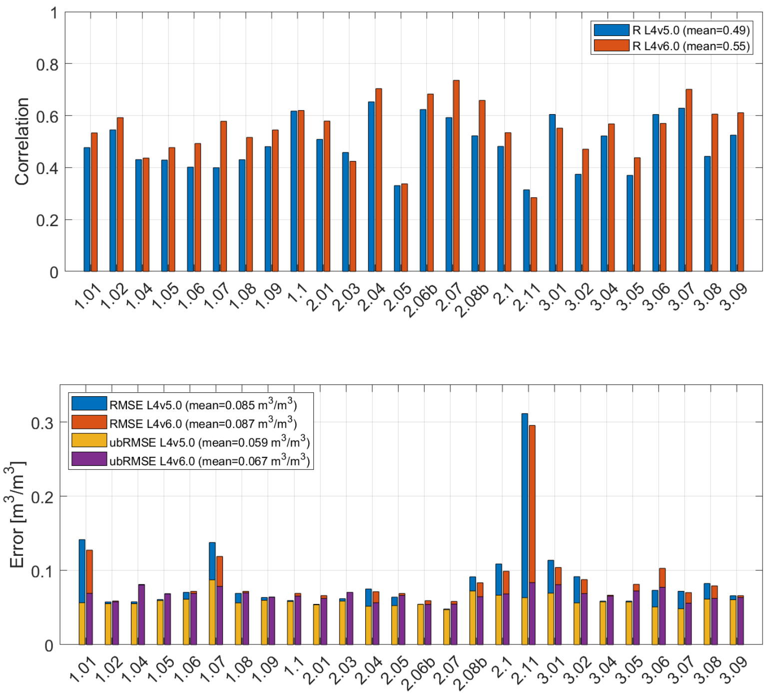


Figure 25: Same as Fig. 24, but for descending orbits.

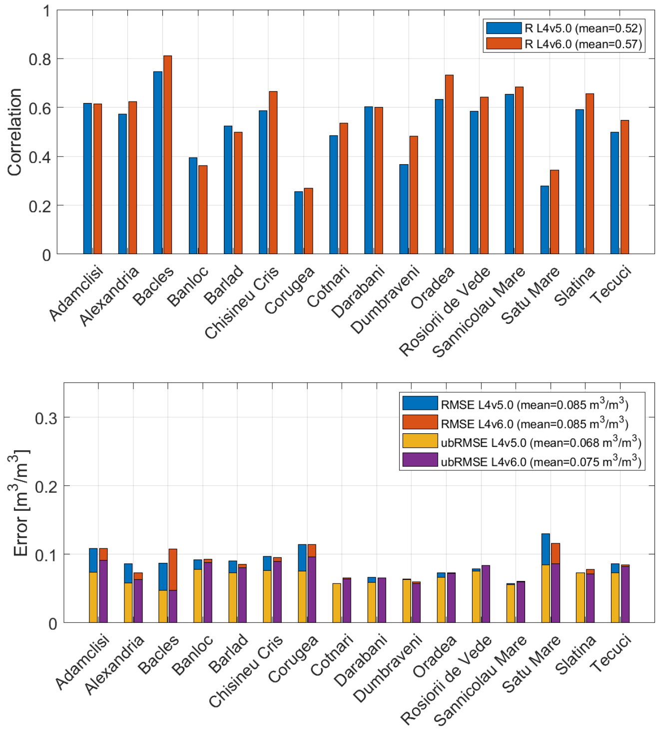


Figure 26: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L4 surface soil moisture v5.0 and v6.0 over RSMN.

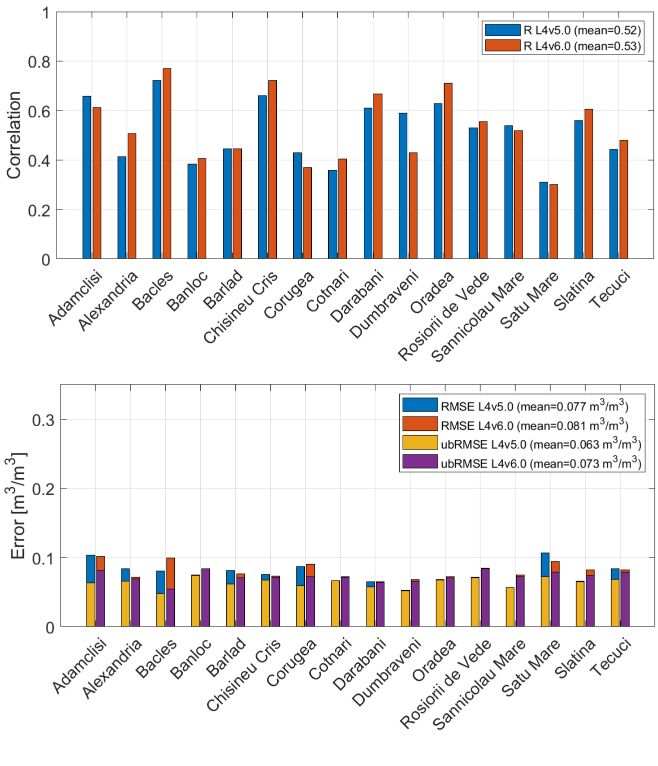


Figure 27: Same as Fig. 26, but for descending orbits.

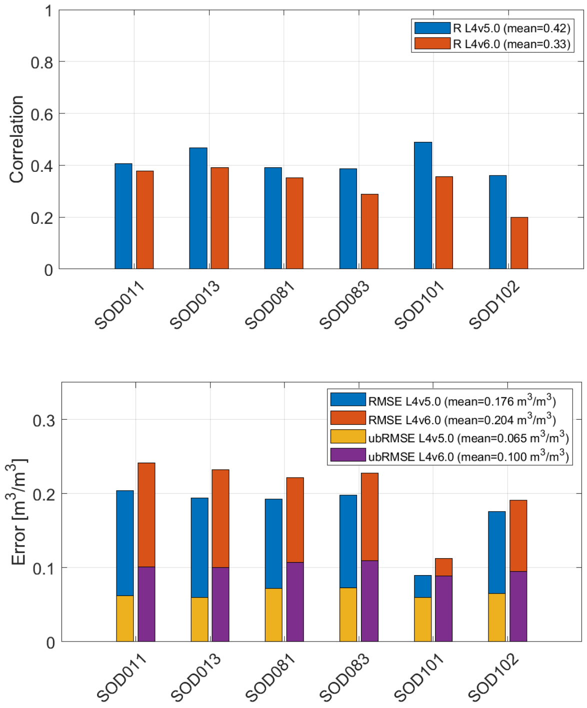


Figure 28: Correlation (top) and error (bottom) obtained from validation of ascending SMOS L4 surface soil moisture v5.0 and v6.0 over FMI.

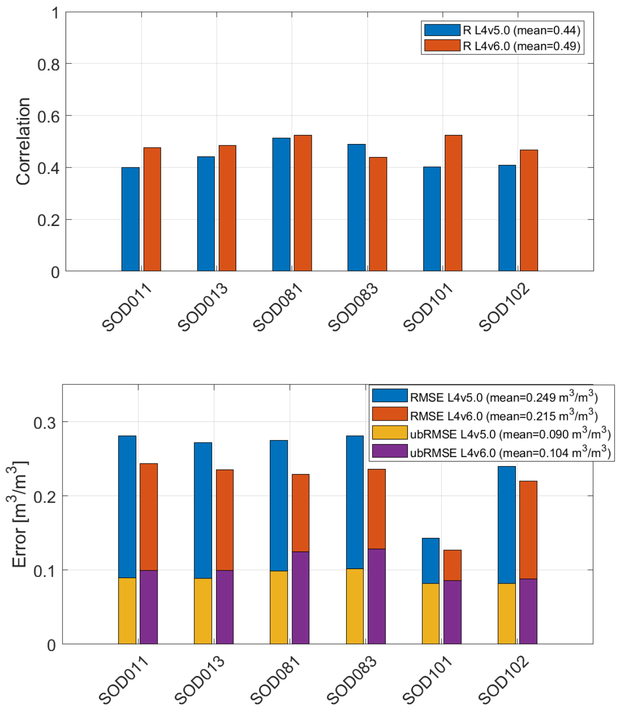


Figure 29: Same as Fig. 28, but for descending orbits.

Network	Product	R	RMSE (m^3/m^3)	ubRMSE (m^3/m^3)	bias (m^3/m^3)	N (days)
REMEDHUS	L3 v3.0	0.65	0.100	0.061	-0.042	311.50
	L3 v4.0	0.67	0.102	0.063	-0.047	
	L4 v5.0	0.66	0.100	0.061	-0.042	
	L4 v6.0	0.67	0.103	0.062	-0.047	
SMOSMANIA	L3 v3.0	0.54	0.116	0.074	-0.071	286.73
	L3 v4.0	0.75	0.126	0.055	-0.106	
	L4 v5.0	0.57	0.115	0.068	-0.079	
	L4 v6.0	0.74	0.130	0.056	-0.109	
HOBE	L3 v3.0	0.57	0.077	0.058	-0.006	269.35
	L3 v4.0	0.65	0.082	0.062	0.012	
	L4 v5.0	0.57	0.077	0.057	-0.006	
	L4 v6.0	0.58	0.089	0.070	0.014	
RSMN	L3 v3.0	0.51	0.087	0.071	0.033	221.25
	L3 v4.0	0.59	0.082	0.071	0.008	
	L4 v5.0	0.52	0.085	0.068	0.036	
	L4 v6.0	0.57	0.085	0.075	0.011	
FMI	L3 v3.0	0.46	0.180	0.063	0.168	265.33
	L3 v4.0	0.46	0.189	0.067	0.176	
	L4 v5.0	0.42	0.176	0.065	0.162	
	L4 v6.0	0.33	0.204	0.100	0.176	

Table 6: Mean value of statistics for ascending orbits.

Network	Product	R	RMSE (m^3/m^3)	ubRMSE (m^3/m^3)	bias (m^3/m^3)	N (days)
REMEDHUS	L3 v3.0	0.61	0.101	0.066	-0.026	295.91
	L3 v4.0	0.63	0.102	0.066	-0.035	
	L4 v5.0	0.62	0.102	0.065	-0.023	
	L4 v6.0	0.63	0.103	0.066	-0.035	
SMOSMANIA	L3 v3.0	0.55	0.115	0.074	-0.070	301.07
	L3 v4.0	0.75	0.122	0.058	-0.096	
	L4 v5.0	0.57	0.115	0.069	-0.074	
	L4 v6.0	0.74	0.124	0.059	-0.098	
HOBE	L3 v3.0	0.48	0.086	0.059	-0.048	143.31
	L3 v4.0	0.61	0.080	0.058	-0.031	
	L4 v5.0	0.49	0.085	0.059	-0.044	
	L4 v6.0	0.55	0.087	0.067	-0.027	
RSMN	L3 v3.0	0.50	0.081	0.069	0.027	131
	L3 v4.0	0.56	0.077	0.069	0.004	
	L4 v5.0	0.52	0.077	0.063	0.027	
	L4 v6.0	0.53	0.081	0.073	0.005	
FMI	L3 v3.0	0.40	0.257	0.107	0.233	114
	L3 v4.0	0.51	0.229	0.096	0.206	
	L4 v5.0	0.44	0.249	0.090	0.231	
	L4 v6.0	0.49	0.215	0.104	0.187	

Table 7: Mean value of statistics for descending orbits.

A.2 Spatial analysis of soil moisture

In order to analyze the spatial features of L3 v4.0 and L4 v6.0 soil moisture maps, their yearly mean and standard deviation (std) were computed. The patterns found in the mean L3 soil moisture are also observed in the mean L4 for both 2015 and 2016 (Figs 30 and 31 for ascending and descending orbits, respectively). Note the enhanced spatial resolution of the L4 product with respect to that of the L3.

As expected, high latitude regions (Sweden, Finland, Norway, Netherlands, Denmark, Ireland, United Kingdom, etc.) are wetter than those located in the south of Europe (Spain, Portugal, Italy, Croatia, Bosnia and Herzegovina, Montenegro, Albania, Greece, Macedonia, etc.). Additionally, the main mountain ranges (Scandinavian, Pyrenees, Alps, Carpathians, Apennines and Balkan mountains) are clearly distinguished in both products by their low values of soil moisture. This is because topography has a significant impact on the L2 soil moisture retrievals, which is translated to the L3 and, consequently, to the L4 product.

Regarding differences among years, the mean soil moisture in 2015 is slightly lower than that in 2016, especially over the Iberian Peninsula and the East European Plain. In general, the std L3 soil moisture is similar to the std L4 (Figs 32 and 33 for ascending and descending, respectively).

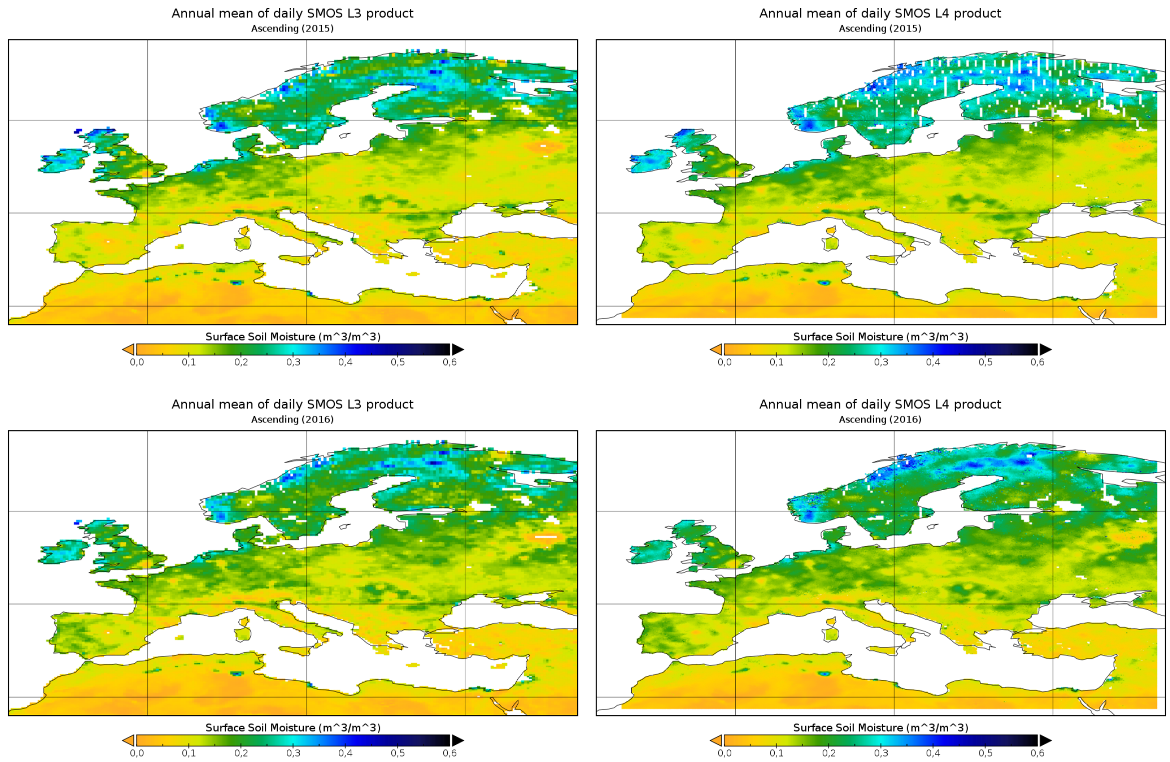


Figure 30: Annual mean ascending SMOS L3 (left) and L4 (right) soil moisture maps over Europe for 2015 (top) and 2016 (bottom).

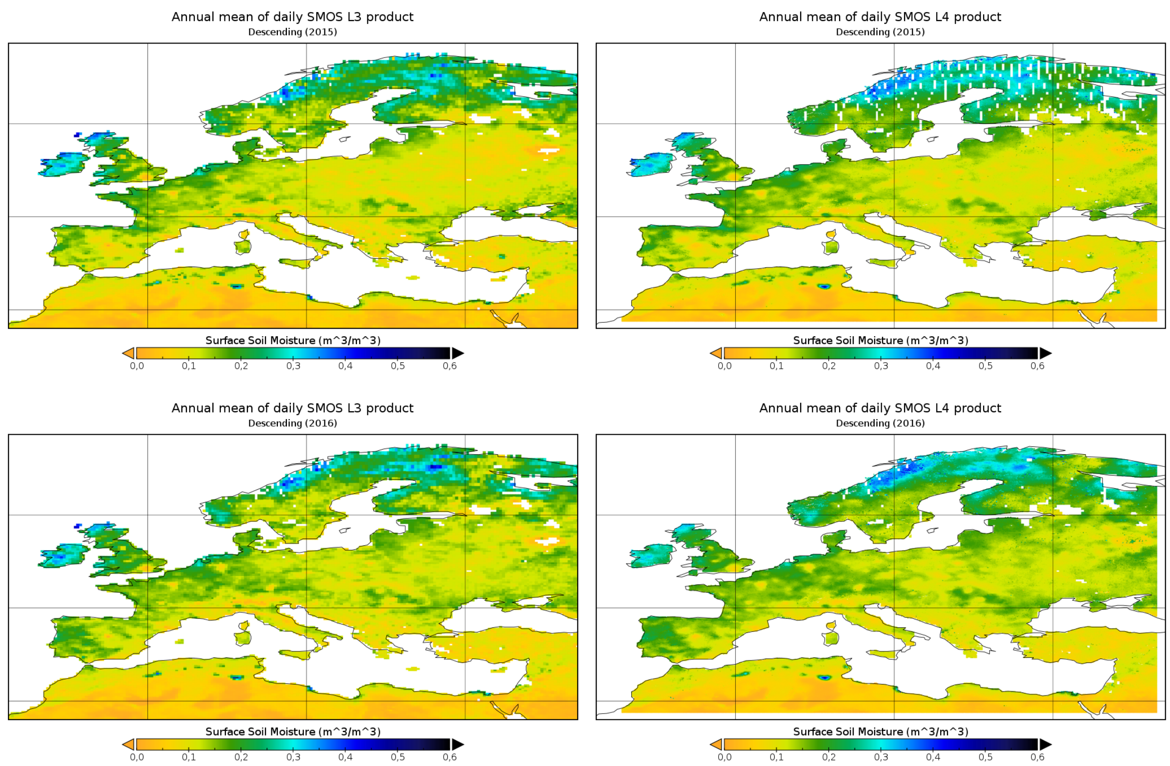


Figure 31: Same as Fig. 30, but for descending orbits.

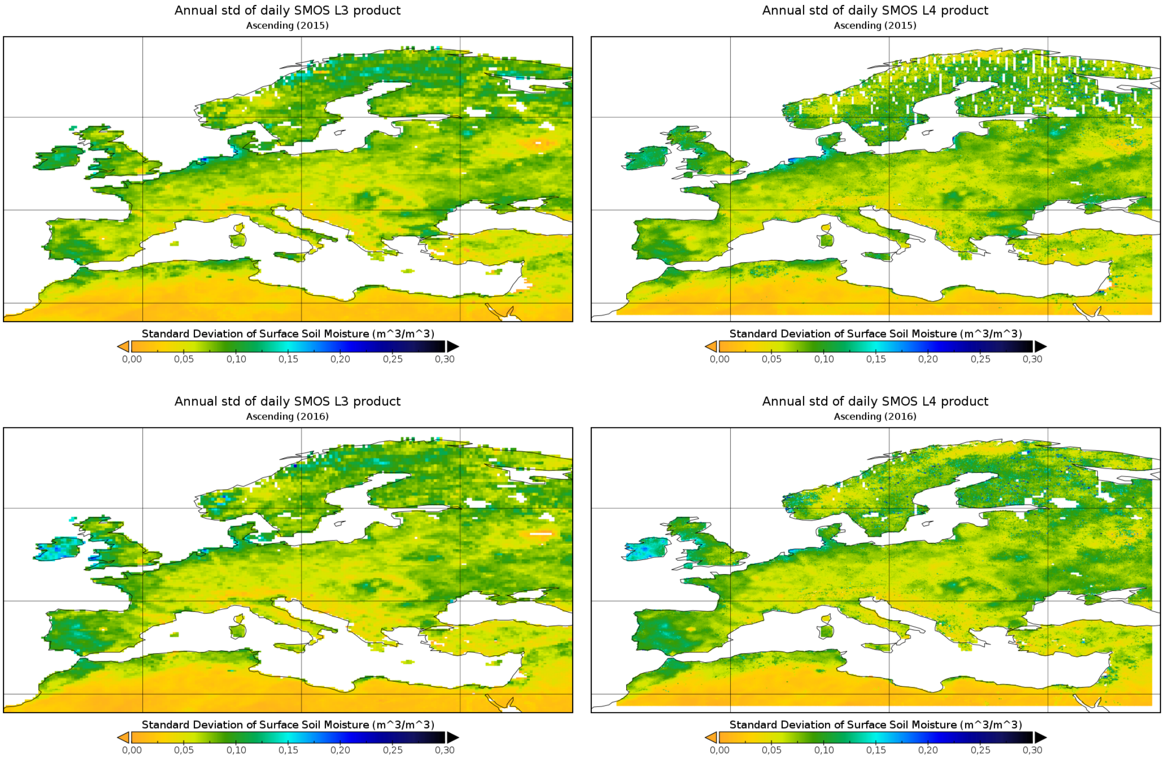


Figure 32: Annual std ascending SMOS L3 (left) and L4 (right) soil moisture maps over Europe for 2015 (top) and 2016 (bottom).

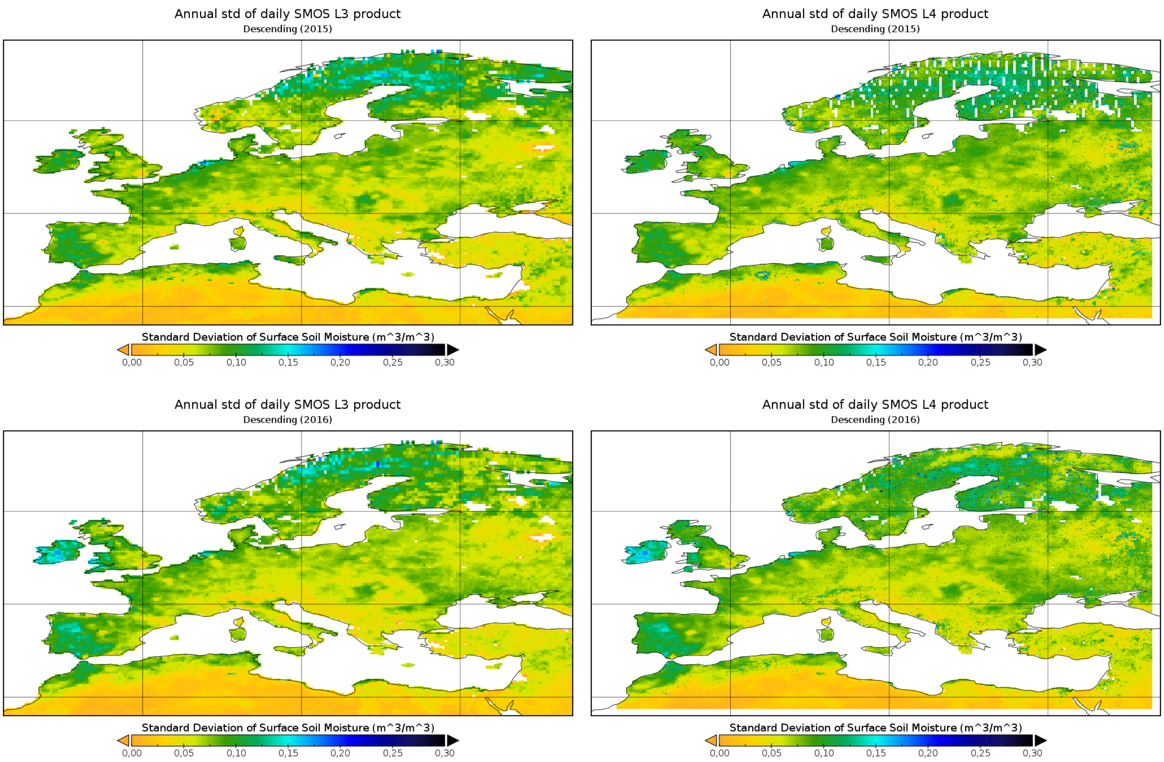


Figure 33: Same as Fig. 32, but for descending orbits.

References

Arias, M., & Kerr, Y.H. 2019. *Algorithm Theoretical Basis Document (ATBD) for the SMOS Level 2 Soil Moisture Processor Development Continuation Project, Reference SO-TN-ARG-L2PP-0037, Issue 4.0.* Tech. rept. European Space Agency (ESA).

Bengoa, B., Zapata, M., Ortega, J., & Rodríguez, M. 2020. *SMOS Level 2 and Auxiliary Data Products Specifications, Reference SO-TN-IDR-GS-0006, Issue 8/6.* Tech. rept. European Space Agency (ESA).

Bircher, S., Skou, N., Jensen, K. H., Walker, J. P., & Rasmussen, L. 2012. A soil moisture and temperature network for SMOS validation in Western Denmark. *Hydrology and Earth System Sciences*, **16**(5), 1445–1463.

Brodzik, M.J., & Knowles, K. 2011. *EASE-Grid 2.0 Land-Ocean-Coastline-Ice Masks Derived from Boston University MODIS/Terra Land Cover Data [Dataset: EASE2_M25km.LOCImask_land50_coast0km.1388x584].* Boulder, Colorado USA: NASA National Snow and Ice Data Center Distributed Active Archive Center (NASA NSICD DAAC).

Bueso, D., Piles, M., & Camps-Valls, G. 2020. Nonlinear PCA for Spatio-Temporal Analysis of Earth Observation Data. *IEEE Transactions on Geoscience and Remote Sensing*, **58**(8), 5752–5763.

Calvet, J., Fritz, N., Froissard, F., Suquia, D., Petitpa, A., & Piguet, B. 2007. In situ soil moisture observations for the CAL/VAL of SMOS: the SMOSMANIA network. *Pages 1196–1199 of: IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2007.*

Carlson, T.N., Gillies, R.R., & Perry, E.M. 1994. A method to make use of thermal infrared temperature and NDVI measurements to infer surface soil water content and fractional vegetation cover. *Remote Sensing Reviews*, **9**(1-2), 161–173.

Chaparro, D., Vall-llossera, M., Piles, M., Camps, A., Rüdiger, C., & Riera-Tatché, R. 2016. Predicting the Extent of Wildfires Using Remotely Sensed Soil Moisture and Temperature Trends. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **9**(6), 2818–2829.

Chaparro, D., Vayreda, J., Vall-llossera, M., Banqué, M., Piles, M., Camps, A., & Martínez-Vilalta, J. 2017. The Role of Climatic Anomalies and Soil Moisture in the Decline of Drought-Prone Forests. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **10**(2), 503–514.

Chaparro, D., Piles, M., Martínez-Vilalta, J., Vall-Llossera, M., Vayreda, J., Banqué-Casanovas, M., & Camps, A. 2018. Modelling Forest Decline Using SMOS Soil Moisture and Vegetation Optical Depth. *Pages 1459–1462 of: IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2018.*

Corbella, I., Torres, F., Camps, A., Duffo, N, & Vall-llossera, M. 2009. Brightness-Temperature Retrieval Methods in Synthetic Aperture Radiometers. *IEEE Transactions on Geoscience and Remote Sensing*, **47**(1), 285–294.

Dorigo, W.A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Drusch, M., Mecklenburg, S., Oevelen, P., Robock, A., & Jackson, T.J. 2011. The International Soil Moisture Network: A data hosting facility for global in situ soil moisture measurements. *Hydrology and Earth System Sciences Discussions*, **15**, 1609–1663.

Entekhabi, D., Reichle, R.H., Koster, R.D., & Crow, W.T. 2010. Performance Metrics for Soil Moisture Retrievals and Application Requirements. *Journal of Hydrometeorology*, **11**(3), 832–840.

ESL Level 2 Soil Moisture, & ARGANS. 2021. *Read-me-first note for the release of SMOS Level 2 Soil Moisture data products, Processor version Level 2 Soil Moisture V700*. Tech. rept. European Space Agency (ESA).

Font, J., Camps, A., Borges, A., Martin-Neira, M., Boutin, J., Reul, N., Kerr, Y.H., Hahne, A., & Mechlenburg, S. 2010. SMOS: the challenging sea surface salinity measurement from space. *Proceedings of the IEEE*, **98**(5), 649.

González-Gambau, V. 2012. *Contribution to the characterization of interferometric radiometers devoted to Earth observation: application to the MIRAS/SMOS payload*. Ph.D. thesis, Universitat Politècnica de Catalunya, Barcelona.

González-Zamora, A, Sánchez, N., Martínez-Fernández, J., Gumuzzio, A., Piles, M., & Olmedo, E. 2015. Long-term SMOS soil moisture products: a comprehensive evaluation across scales and methods in the Duero Basin (Spain). *Journal of Physics and Chemistry of the Earth, Parts A/B/C*, **83–84**, 123–136.

Howat, I. 2007. *FILLNANS function of MATLAB Central File Exchange*. https://www.mathworks.com/matlabcentral/fileexchange/15590-fillnans. [Last access: 5-Aug-2022].

Ikonen, J., Vehvilainen, J., Rautiainen, K., Smolander, T., Lemmetyinen, J., Bircher, S., & Pulliainen, J. 2016. The Sodankylä in situ soil moisture observation network: an example application of ESA CCI soil moisture product evaluation. *Geoscientific Instrumentation, Methods and Data Systems*, **5**(1), 95–108.

Kerr, Y.H., Waldteufel, P., Wigneron, J.-P., Delwart, S., Cabot, F., Boutin, J., Escorihuela, M.-J., Font, J., Reul, N., Gruhier, C., Juglea, S.E., Drinkwater, M.R., Hahne, A., Martin-Neira, M., & Mecklenburg, S. 2010. The SMOS mission: new tool for monitoring key elements of the global water cycle. *Proceedings of the IEEE*, **98**, 666–687.

Konings, A.G., Piles, M., Das, N., & Entekhabi, D. 2017. L-band vegetation optical depth and effective scattering albedo estimation from SMAP. *Remote Sensing of Environment*, **198**, 460 – 470.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. 2006. World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, **15**(3), 259–263.

Lawrence, H., Wigneron, J.P., Richaume, P., Novello, N., Grant, J., Mialon, A., Bitar, A. Al, Merlin, O., Guyon, D., Leroux, D., S., & Kerr, Y. 2014. Comparison between SMOS Vegetation Optical Depth products and MODIS vegetation indices over crop zones of the USA. *Remote Sensing of Environment*, **140**, 396 – 406.

Mateo-Sanchís, A., Piles, M., Amorós-López, J., Muñoz-Marí, J., Adsuara, J.E., Moreno-Martínez, Á., & Camps-Valls, G. 2021. Learning main drivers of crop progress and failure in Europe with interpretable machine learning. *International Journal of Applied Earth Observation and Geoinformation*, **104**, 102574.

McMullan, K. D., Brown, M.A., Martin-Neira, M., Rits, W., Ekholm, S., Marti, J., & Lemanczyk, J. 2008. SMOS: The Payload. *IEEE Transactions on Geoscience and Remote Sensing*, **46**(3), 594–605.

Mecklenburg, S., Drusch, M., Kaleschke, L., Rodríguez-Fernández, N., Reul, N., Kerr, Y.H., Font, J., Martin-Neira, M., Oliva, R., Daganzo-Eusebio, E., Grant, J.P., Sabia, R., Macelloni, G., Rautiainen, K., Fauste, J., de Rosnay, P., Munoz-Sabater, J., Verhoest, N., Lievens, H., Delwart, S., Crapolicchio, R., de la Fuente, A., & Kornberg, M. 2016. ESA's Soil Moisture and Ocean Salinity mission: From science to operational applications. *Remote Sensing of Environment*, **180**, 3–18.

Oliva, R., Daganzo, E., Richaume, P., Kerr, Y., Cabot, F., Soldo, Y., Anterrieu, E., Reul, N., Gutierrez, A., Barbosa, J., & Lopes, G. 2016. Status of Radio Frequency Interference (RFI) in the 1400–1427MHz passive band based on six years of SMOS mission. *Remote Sensing of Environment*, **180**, 64–75.

Pablos, M., Martínez-Fernández, J., Piles, M., Sánchez, N., Vall-llossera, M., & Camps, A. 2016a. Multi-Temporal Evaluation of Soil Moisture and Land Surface Temperature Dynamics Using in Situ and Satellite Observations. *Remote Sensing*, **8**(7), 587.

Pablos, M., Piles, M., Sánchez, Nilda, Vall-llossera, M., Martínez-Fernández, J., & Camps, A. 2016b. Impact of day/night time land surface temperature in soil moisture disaggregation algorithms. *European Journal of Remote Sensing*, **49**(1), 899.

Pablos, M., Martínez-Fernández, J., Sánchez, N., & González-Zamora, A. 2017. Temporal and Spatial Comparison of Agricultural Drought Indices from Moderate Resolution Satellite Soil Moisture Data over Northwest Spain. *Remote Sensing*, **9**(11), 1168.

Pablos, M., González-Zamora, A., Sánchez, N., & Martínez-Fernández, J. 2018. Assessment of Root Zone Soil Moisture Estimations from SMAP, SMOS and MODIS Observations. *Remote Sensing*, **10**(7), 981.

Pablos, M., Vall-llossera, M., Piles, M., Camps, A., González-Haro, C., Turiel, A., Herbert, C.J., Chaparro, D., & Portal, G. 2019. Impact of quality filtering approaches in BEC SMOS Level 3 soil moisture products. *In: IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2019*.

Petropoulos, G., Carlson, T.N., Wooster, M.J., & Islam, S. 2009. A review of Ts/VI remote sensing based methods for the retrieval of land surface energy fluxes and soil surface moisture. *Progress in Physical Geography: Earth and Environment*, **33**(2), 224–250.

Piles, M., Camps, A., Vall-llossera, M., Corbella, I., Panciera, R., Rudiger, C., Kerr, Y.H., & Walker, J. 2011. Downscaling SMOS-Derived Soil Moisture Using MODIS Visible/Infrared Data. *IEEE Transactions on Geoscience and Remote Sensing*, **49**(9), 3156–3166.

Piles, M., Vall-llossera, M., Laguna, L., & Camps, A. 2012. A downscaling approach to combine SMOS multi-angular and full-polarimetric observations with MODIS VIS/IR data into high resolution soil moisture maps. *Pages 1247–1250 of: IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2012*.

Piles, M., Vall-llossera, M., Camps, A., Sánchez, N., Martínez-Fernández, J., Martínez, J., González-Gambau, V., & Riera, R. 2013. On the synergy of SMOS and Terra/Aqua MODIS: High resolution soil moisture maps in near real-time. *Pages 3423–3426 of: IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2013*.

Piles, M., Sánchez, N., Vall-llossera, M., Camps, A., Martínez-Fernández, J., Martínez, J., & González-Gambau, V. 2014. A Downscaling Approach for SMOS Land Observations: Evaluation of High-Resolution Soil Moisture Maps Over the Iberian Peninsula. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **7**(9), 3845–3857.

Piles, M, Pou, X., Camps, A., & Vall-llossera, M. 2015. *Quality report: validation of SMOS-BEC L4 high resolution soil moisture products, version 3.0.* Tech. rept. Barcelona Expert Center (BEC).

Piles, M, Ballabrera-Poy, J., & Muñoz Sabater, J. 2019. Dominant Features of Global Surface Soil Moisture Variability Observed by the SMOS Satellite. *Remote Sensing*, **11**(1), 95.

Polcher, J, Piles, M, Gelati, E, Barella-Ortiz, A., & Tello, M. 2016. Comparing surface-soil moisture from the SMOS mission and the ORCHIDEE land-surface model over the Iberian Peninsula. *Remote Sensing of Environment*, **174**, 69–81.

Portal, G., Vall-llossera, M., Piles, M., Camps, A., Chaparro, D., Pablos, M., Rossato, L., & Aabouch, K. 2018a. Microwave and Optical Data Fusion for Global Mapping of Soil Moisture at High Resolution. *Pages 341–344 of: IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2018.*

Portal, G., Vall-llossera, M., Piles, M., Camps, A., Chaparro, D., Pablos, M., & Rossato, L. 2018b. A Spatially Consistent Downscaling Approach for SMOS Using an Adaptive Moving Window. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **11**(6), 1883–1894.

Portal, G., Jagdhuber, T., Vall-llossera, M., Camps, A., Pablos, M., Entekhabi, D., & Piles, M. 2020. Assessment of Multi-Scale SMOS and SMAP Soil Moisture Products across the Iberian Peninsula. *Remote Sensing*, **12**(3), 570.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., & Flannery, B.P. 1992. *Numerical Recipes in C.* Second edn. Cambridge, USA: Cambridge University Press.

Rodríguez-Fernández, N.J., Mialon, A., Mermoz, S., Bouvet, A., Richaume, P., Al Bitar, A., Al-Yaari, A., Brandt, M., Kaminski, T., Le Toan, T., Kerr, Y. H., & Wigneron, J.-P. 2018. An evaluation of SMOS L-band vegetation optical depth (L-VOD) data sets: high sensitivity of L-VOD to above-ground biomass in Africa. *Biogeosciences*, **15**(14), 4627–4645.

Sánchez, N., Martínez-Fernández, J., Scaini, A., & Pérez-Gutiérrez, C. 2012. Validation of the SMOS L2 soil moisture data in the REMEDHUS network (Spain). *IEEE Transactions on Geoscience and Remote Sensing*, **50**(5), 1602–1611.

Sánchez, N., González-Zamora, A., Martínez-Fernández, J., Piles, M., & Pablos, M. 2018. Integrated remote sensing approach to global agricultural drought monitoring. *Agricultural and Forest Meteorology*, **259**, 141–153.

Sánchez-Ruiz, S., Moreno, A., Piles, M., Maselli, F., Carrara, A., Running, S., & Gilabert, M. Amparo. 2017. Quantifying water stress effect on daily light use efficiency in Mediterranean ecosystems using satellite data. *International Journal of Digital Earth*, **10**(6), 623–638.

SMOS Calibration team, & ESL Level 1. 2021. *Read-me-first note for the release of SMOS Level 1 data products, Processor version Level 1 V724, NRT V724.* Tech. rept. European Space Agency (ESA).

Souza, A.G.S.S., Neto, A.R., Rossato, L., Alvalá, R.C.S., & Souza, L.L. 2018. Use of SMOS L3 Soil Moisture Data: Validation and Drought Assessment for Pernambuco State, Northeast Brazil. *Remote Sensing*, **10**(8), 1314.

Zeng, J., Chen, K., Bi, H., & Chen, Q. 2016. A Preliminary Evaluation of the SMAP Radiometer Soil Moisture Product Over United States and Europe Using Ground-Based Measurements. *IEEE Transactions on Geoscience and Remote Sensing*, **54**(8), 4929–4940.

Zhan, Q, Vall-llossera, M, Pablos, M., Camps, A., Portal, G., & Chaparro, D. 2020. Improving the Rice Yield Estimation Using SMOS and CYGNSS GNSS-R Data. *Pages 5254–5257 of: IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2020.*