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Contract Report to the European Space Agency

ECMWF report: First steps towards using SMOS soil moisture in the European Flood Awareness System

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ESA/ESRIN Contract 4000125399/18/I-BG

European Centre for Medium-Range Weather Forecasts
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Executive Summary

In this report we present the first steps towards testing the use of SMOS neural network soil moisture in the European Flood Awareness System (EFAS) for the SMOS-Operational Emergency Management (SMOS-E) ESA contract (tasks TH1-005, TH1-010 and TH1-015). Currently, EFAS flood forecasts are made from an initial soil moisture produced by the LISFLOOD hydrological model, which is driven by 24-hour precipitation and near-surface temperature and wind observations. In the first part of this report, we compare the EFAS initial soil moisture product with the ECMWF SMOS neural network soil moisture, in order to understand the similarities and differences and the potential of SMOS for improving the initialisation in EFAS. Both soil moisture products are also compared to the ERA5 reanalysis soil moisture. Secondly, we present results of bias correcting SMOS to EFAS through CDF-matching, a necessary step for SMOS soil moisture to be used directly in EFAS.

Results show that SMOS soil moisture has high correlations to ERA5 in most of Europe (>0.6), with values that are similar to North America and Australia where SMOS is thought to have its best performance. This justifies testing the use of SMOS soil moisture for flood forecasting in Europe. SMOS has low correlations to both ERA5 and EFAS in parts of Northern Europe (Norway, Sweden, Finland, Iceland), however, indicating that there may be less benefits to using SMOS data for flood forecasting in these regions. Results also indicate lower anomaly correlations for SMOS compared to the other datasets, as well as probable biases in both EFAS and ERA5. The lower anomaly correlations for SMOS are likely at least partially due to a higher noise compared to EFAS and ERA5, as well as to sudden drops in soil moisture that were observed in the time series of different gridpoints. These latter drops in soil moisture would need to be filtered before SMOS could be used directly in EFAS, e.g. using a first guess check.

Results of the CDF-matching show that this bias correction method works well for most gridpoints, with the exception of some areas where there are strong interannual variations in the seasonal soil moisture cycle. This occurs particularly in Iceland, and for some gridpoints in North Africa, and in these areas the data would need to be filtered before SMOS soil moisture could be used directly in EFAS. This could also be done using a first guess check.

Finally, in this report we discuss options for the next steps of the project, and make recommendations for different experiments that could be performed to test the use of SMOS soil moisture in EFAS.

Contents

1 Introduction

In recent years the European Centre for Medium-Range Forecasts (ECMWF) has created opportunities to analyse and predict environmental parameters other than just the weather. Under the European Union (EU) funded Copernicus Programme, ECMWF is now the computational centre for two of the Copernicus Emergency Management Services (CEMS) which provide flood and fire forecasts, including high resolution 5 km flood forecasts in Europe using the European Flood Awareness System (EFAS)[1] (Smith et al., 2016). ECMWF is also involved in the development and operation of the Global Flood Awareness System (GloFAS), providing Global flood forecasts at 10 km resolution. EFAS was first developed by the European Commission in response to an identified need for flood risk and crisis management following significant flooding across Europe in the early 2000s (European Commission, 2002; Thielen et al., 2009; Bartholmes et al., 2009; Burek et al., 2011), and was developed following the initial research activities of de Roo et al. (2003); Gouweleeuw et al. (2005); Pappenberger et al. (2005). From 2003 to 2012, EFAS was developed and tested at the Joint Research Centre (JRC), after which it became part of CEMS in 2011 and was transferred from a research to an operational service in 2012.

The flood forecasts made by EFAS rely on the initialisation of key land surface variables including notably the soil moisture, which are produced daily by the LISFLOOD hydrological model (van der Knijff et al., 2010). This model is driven by in-situ observations of precipitation, 2-metre temperature and wind speed, and has been calibrated to river discharge observations in Europe. LISFLOOD has been found to have an optimal performance in temperate regions, but a significant decline in performance in arid regions such as the Iberian peninsula (Smith et al., 2016), indicating that there are still areas for improvement in determining the initial conditions for EFAS. One possibility for improvement is the use of observations that are more directly related to soil moisture, such as satellite-derived soil moisture. In December 2018, ECMWF began a new contract of work with the European Space Agency (ESA) to test the use of soil moisture products from the Soil Moisture and Ocean Salinity (SMOS) satellite for use in emergency management, including in the EFAS and GloFAS flood forecasting systems. The contract is known as SMOS-Operational Emergency Services, or SMOS-E (contract number 4000125399/18/I-BG). This report is the first SMOS-E report on flood forecasting, presenting results of the first steps towards testing the use of SMOS soil moisture in EFAS. The impact of SMOS soil moisture on GloFAS is also being tested and this will be presented in a separate report.

The SMOS mission was launched in November 2009 and carries the first-ever space-borne 2-D interferometric radiometer providing observations at 1.4 GHz. At this frequency, the atmosphere is almost transparent and measurements over land are very sensitive to soil moisture, even in areas of low vegetation and (to a lesser extent) over forests. During its lifetime, the SMOS mission has suffered from significant Radio-Frequency Interference (RFI) from man-made emitters on the ground which can be difficult to detect and filter. RFI has been particularly strong over Europe, Asia and the middle East but has been significantly reduced over Europe in the last ten years since SMOS was launched. There are a number of different soil moisture products available from SMOS, including level 2 and level 3 soil moisture retrievals and 2 different neural network products. One of these neural network products - the ECMWF SMOS NN product - is produced at ECMWF using a processor trained on the ECMWF soil moisture and temperature analysis fields, and this product will be tested for use in flood forecasting in SMOS-E. The use of SMOS observations in the ECMWF IFS has been shown to lead to small improvements in the soil moisture analysis (Muñoz-Sabater et al., 2019; Rodríguez-Fernández et al., 2019) and the ECMWF SMOS NN product will be actively assimilated in ECMWF operations from summer 2019.

As a first step towards the use of SMOS in EFAS, we present firstly a comparison between the SMOS neural network soil moisture, EFAS soil moisture, and ERA5 reanalysis soil moisture across Europe (tasks TH1-005, TH1-010 and TH1-015). The aim is to understand the similarities and differences between SMOS and EFAS soil moisture, and therefore the potential of SMOS for improving the soil moisture initialisation in EFAS. The

[1] previously the European Flood Alert System

ECMWF ERA5 reanalysis soil moisture provides a useful third point of comparison and, since it is global, can also give an indication of the performance of SMOS soil moisture in Europe in comparison to the rest of the World.

Secondly, we present results of Cumulative Density Function (CDF) matching the SMOS soil moisture to EFAS soil moisture. This is a necessary step towards using SMOS data directly to initialise the soil moisture for EFAS. Since SMOS observations are not available for every EFAS gridpoint in Europe for every day (particularly after applying quality control) they will need to be supplemented by EFAS soil moisture (if used directly), and the CDF-matching is necessary to prevent any sudden jumps in soil moisture due to different mean states and/or different variabilities of the 2 soil moisture products.

The report is structured as follows. Firstly we present a summary of the 3 soil moisture products used in this study, followed by the comparison between SMOS, EFAS and ERA5 soil moistures. Next we present results of SMOS CDF-matching, and finally the conclusions and discussion.

2 Soil moisture products

2.1 SMOS neural network soil moisture

The SMOS satellite is polar orbiting with an equatorial crossing time of 06:00 for the ascending pass and 18:00 for the descending pass, a revisit time of 3 days at the Equator, and a horizontal pixel resolution of $\sim$ 50 - 120 km. Dual-polarisation, multi-angular level 1 brightness temperatures (T_B) from SMOS are distributed by ESA to ECMWF in near real time where they are transformed into soil moisture using a Neural Network (NN) processor. Two soil moisture products are available: one where the NN processor was trained on level 2 soil moisture (Rodríguez-Fernández et al., 2017), and one where it was trained on the ECMWF soil moisture analysis fields (top layer, 0 - 7cm). The latter product is used in the following study. The soil moisture analysis used to train the NN processor is very similar to the ERA5 analysis, meaning that we would expect the products to have the same global mean and variation in soil moisture, but with local differences.

SMOS soil moisture data are available over snow-free land after snow depth and land surface mask filters have been applied, as described by Rodríguez-Fernández et al. (2017). Soil moisture values are provided along with associated uncertainties and a flag indicating the probability of RFI (based on the RFI probability provided with T_B data as well as brightness temperature threshold checks).

2.2 ERA5 soil moisture reanalysis

ERA5 is the latest ECMWF reanalysis and is produced within the Copernicus Climate Change Service (C3S) (Hersbach et al., 2018). It includes global atmospheric and surface reanalysis fields from 1950 to the present, and is produced using a fixed data assimilation system based on cycle 41r2 of the IFS (operational in 2016, prior to the introduction of SMOS neural network assimilation) at a horizontal resolution of 30 km. The land data assimilation system used in ERA5 includes a 2-Dimensional Optimal Interpolation (2D-OI) for the analysis of prognostic snow variables, and a Simplified Extended Kalman Filter (SEKF) data assimilation system for the soil moisture analysis. As described by de Rosnay et al. (2013), screen level in-situ observations (2-metre temperature and 2-metre relative humidity) and soil moisture products from the ASCAT scatterometer instrument are assimilated to produce a soil moisture analysis at 6-hourly intervals in a 12-hour assimilation window, and for 3 soil layers (0 - 7 cm, 7 - 28 cm, 28 - 100 cm). A time-step of 10-minutes is used for the forecast model, accounting for temporal differences in soil moisture across the assimilation window. The analysis is a weighted average of observations and short-range forecasts from the previous cycle (background), with the weighting determined by the observation and background error covariance matrices. Short-range forecasts are produced using the HTESSEL hydrological model (Balsamo et al., 2009), coupled to the forecast model for the atmosphere. The ERA5 soil moisture analysis thus accounts for uncertainties in the observations and soil moisture forecasts, and benefits from both land surface observations as well as atmospheric observations, through the coupling of the land and atmospheric forecasts.

2.3 EFAS soil moisture

The soil moisture used in EFAS is produced using the LISFLOOD hydrological model, driven by in-situ observations of precipitation, temperature and near-surface wind as input. The coverage of real-time precipitation stations is shown in Fig. 1, showing a high density of stations particularly in Germany, France and Northern Spain. Soil moisture values are produced every 24 hours (along with Snow Water Equivalent and river water volume) at 06:00 UTC across Europe and at a resolution of 5 km. Values at the end of the previous cycle are taken as the starting soil moisture, and this is then modified by LISFLOOD using the input observations. The observed precipitation accumulated over 24-hours is distributed by LISFLOOD into: snow cover, soil moisture (3 layers of topsoil and 2 of subsoil), groundwater (upper, lower) and surface runoff into the river channel. Processes such as snow melt, soil freezing and evapotranspiration are also modelled. The LISFLOOD model was calibrated to observed river discharge data for different river catchments using observations at 693 gauging stations in Europe. The catchment boundaries and the locations of calibration sites are shown in Fig. 2 (reproduced from Smith et al. (2016)). For each catchment, calibration was performed for 9 - 13 parameters controlling snowmelt, infiltration, preferential bypass flow through the soil matrix, percolation to the lower and deeper groundwater zones, residence times in the soil and subsurface reservoirs and river routing. Note that some constraints were applied in the derivation of these parameters, to keep them within an expected range. The calibration exercise was validated against data from the same sites at a later time (2013, Fig. 2) and a recalibration was recently carried out including more recent observations. The calibration led to a good fit to river flow observations at most locations with the exception of Spain and areas around the Baltic coasts (Smith et al., 2016). Note that calibration was not performed for catchments with no available observations, using instead default values from the literature.

Like ERA5, EFAS soil moisture is produced using a combination of observations and a hydrological model but there are some key differences between the methods, models and the observations used. ERA5 is influenced by many more observations and has a more sophisticated use of these observations through data assimilation. For example, observation uncertainties are accounted for, and the temporal variation of soil moisture is modelled with a 10-minute timestep, in contrast to every 24-hours for EFAS.

There are also differences in the hydrological models used. Subsurface water fluxes are simulated in a more physical manner by HTESSEL (directly solving Darcy's law) (Balsamo et al., 2009) whereas LISFLOOD makes some simplifying assumptions (van der Knijff et al., 2010). On the other hand LISFLOOD accounts for horizontal flow to rivers, which is necessary for flood forecasting and is not accounted for in HTESSEL. Note that GloFAS uses HTESSEL but with the horizontal flow component of LISFLOOD, for the global flood forecasts.

Finally there are some differences due to the intended use of the soil moisture variables - EFAS soil moisture is used to initialise flood forecasting whereas ERA5 soil moisture supports atmospheric weather forecasting. ERA5 soil moisture is strongly affected by screen level variables of 2-m relative humidity and 2-m temperature which leads to a soil moisture that is physically consistent with near-surface atmospheric measurements, and ultimately better atmospheric forecasts. EFAS soil moisture on the other hand is largely driven by in-situ precipitation observations (not assimilated in the IFS) and a hydrological model that is calibrated to river flow.

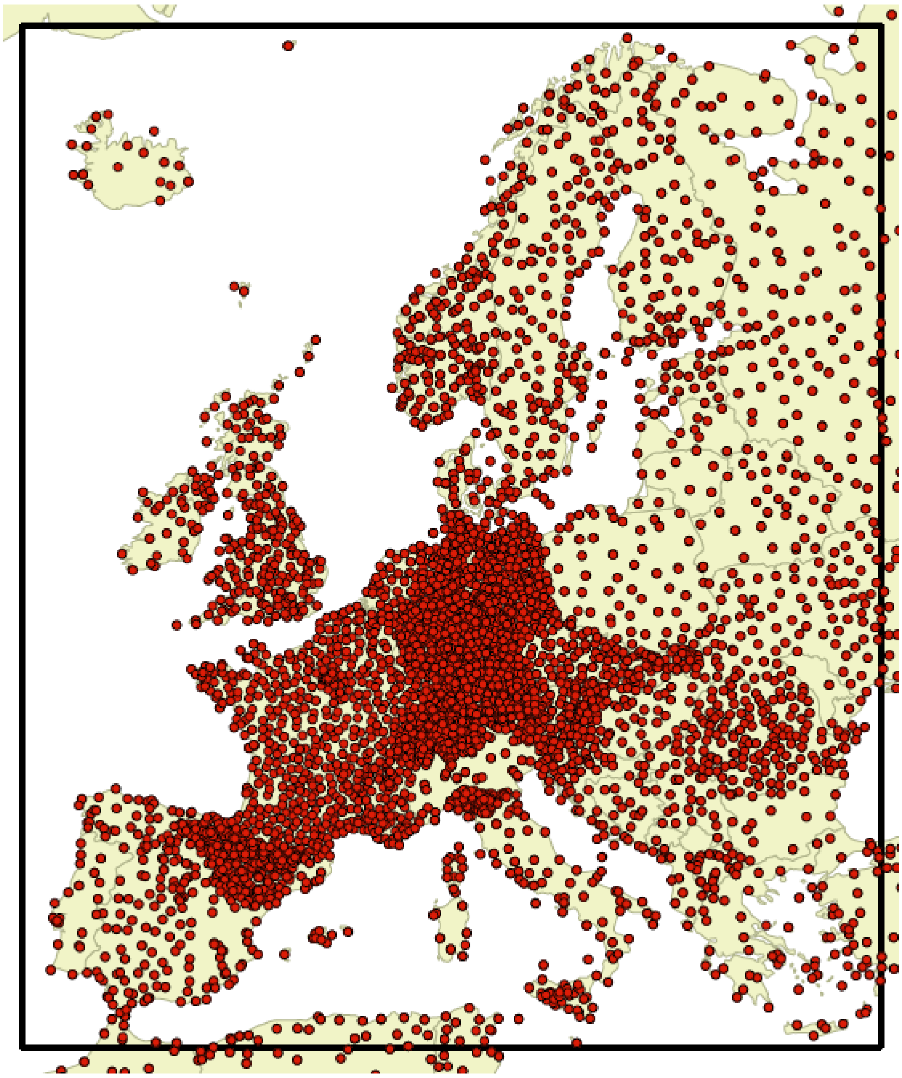

Figure 1: Reproduced from Smith et al. (2016) (Fig. 3): Coverage of EFAS real-time precipitation stations.

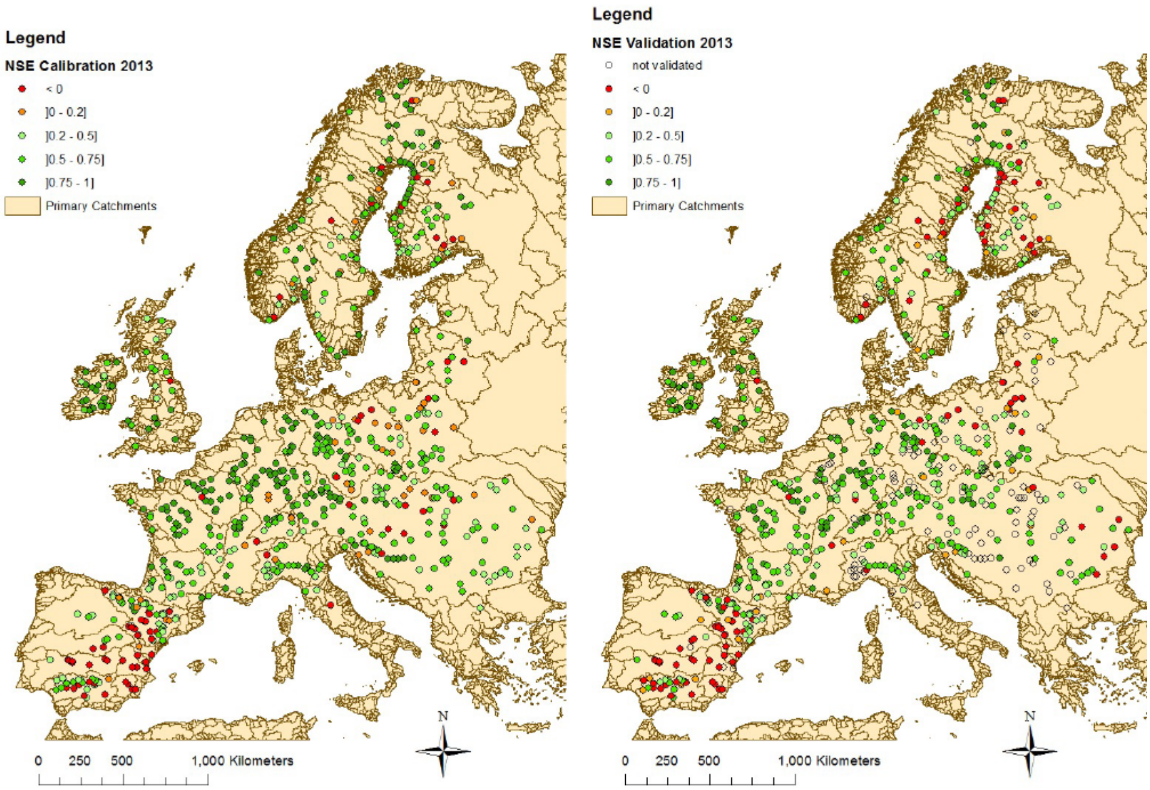

Figure 2: Reproduced from Smith et al. (2016) (Fig. 5): The Nash-Suttcliffe efficiency of LISFLOOD at the 693 sites for the original calibration (left) and validation (right) for 2013.

3 First steps towards using SMOS soil moisture in EFAS

3.1 Method

A comparison between the different soil moisture products was carried out for the period 1 January 2016 - 31 December 2018, corresponding to dates where the ECMWF SMOS soil moisture neural network product is currently available. Before comparison, soil moisture values from the top soil layers of EFAS and ERA5 (0 - 5 cm and 0 - 7 cm respectively) were interpolated to the SMOS regular lat/lon grid of 0.25 degree intervals and a filtering was applied to SMOS data. The 5 km EFAS soil moisture was transformed onto the 0.25/0.25 degree grid by averaging all EFAS points over land within a 0.25/0.25 degree box around each SMOS gridpoint. The 30 km ERA5 soil moisture analysis was transformed onto the SMOS grid using the ECMWF Meteorological Interpolation and Regridding (MIR) interpolation routines which perform a linear interpolation based on a triangular mesh. SMOS data were filtered for RFI using the RFI probability flag given in the SMOS NN product, with additional checks on the soil moisture and uncertainties, as described in Table 1. These latter checks removed erroneous values in 2017 where the soil moisture was set to 0.0 m^3/m^3. There was an additional filter to remove SMOS soil moisture values derived from the average of 2 overpasses, however this removed very few points.

Pearson's correlation coefficient (R), the anomaly correlation and the mean and standard deviation of differences between the 3 products were computed for the full period and for different seasons. The anomaly correlations were calculated as Pearson's correlation coefficient after a 30-day moving average was removed from each dataset. For intercomparisons of the 3 products (over Europe) the data were first filtered to keep only values at times where SMOS, EFAS and ERA5 soil moisture are all available. Since the EFAS product is only available at 06:00 UTC we therefore kept ERA5 soil moisture only at this time, and SMOS observations available at 06:00 UTC $\pm$ 3 hours.

Table 1: Filtering applied to SMOS, ERA5 and EFAS before comparison of soil moistures. SMOS filtering is based on the RFI probability flag, the soil moisture (SM) values and the soil moisture uncertainties (σ). A slightly different filtering was applied to different comparisons, as indicated.

Type of comparison	Times considered	Filtering
Global comparison of SMOS and ERA5	All available	Remove SMOS RFI probability $> 20\%$ Remove SMOS SM > 0.7 m^3/m^3, SM < 0.01 m^3/m^3 Remove SMOS $\sigma > 0.2$ m^3/m^3
Comparison of SMOS, EFAS, ERA5 in Europe	06:00 UTC $\pm$ 3 hours	Remove SMOS RFI probability $> 20\%$ Remove SMOS SM > 0.7 m^3/m^3 or < 0.01 m^3/m^3 Remove SMOS $\sigma > 0.2$ m^3/m^3 Keep EFAS, ERA5 and SMOS soil moisture only where all 3 are available
Time series of SMOS, ERA5, EFAS in Europe	All available	Remove SMOS RFI probability $> 20\%$ Remove SMOS SM > 0.7 m^3/m^3 or < 0.01 m^3/m^3 Remove SMOS $\sigma > 0.2$ m^3/m^3

3.2 Results

We evaluated firstly the performance of SMOS over Europe, by verifying SMOS soil moisture against ERA5 and comparing statistics to other parts of the Globe. The SMOS instrument is expected to have its best performance in Australia and North America, due to the lack of RFI in these areas and due to large areas of bare soil or low vegetation where the measurements are most sensitive to surface soil moisture (in comparison to forested areas for example). Results indicate that SMOS has a high correlation to ERA5 over most of Europe (above 0.6) and low standard deviation of differences, similar to values obtained over North America and Australia (Fig. 3). This suggests a similar performance in Europe compared to other parts of the World and justifies testing the use of SMOS soil moisture for flood forecasting in EFAS. The anomaly correlation is slightly lower over Europe than over North America and Australia, however, suggesting a slightly lower correlation in Europe for the more short-term variations in SMOS and ERA5 soil moisture.

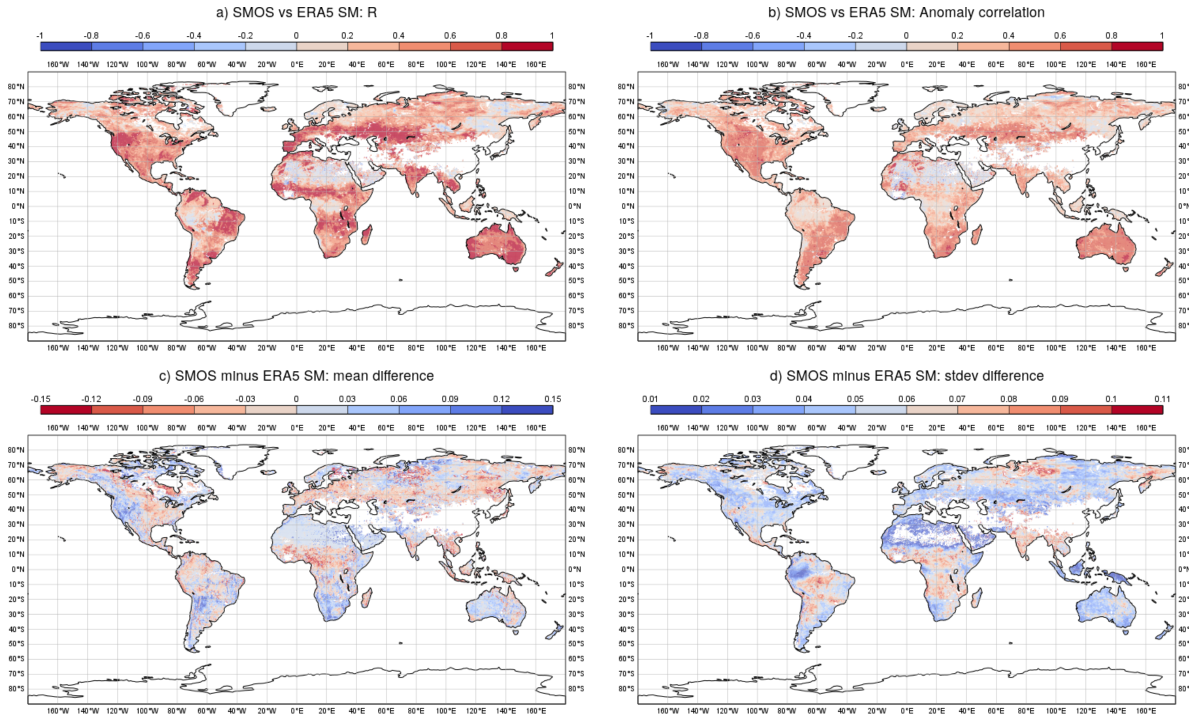

Figure 3: a) Pearson's correlation coefficient, b) Anomaly correlation coefficent, c) mean difference and d) standard deviation of difference for SMOS and ERA5 soil moisture in 2016. Values are shown for all data after SMOS quality control.

Next, we compared the 3 different soil moisture products (SMOS vs ERA5, EFAS vs ERA5 and SMOS vs EFAS) in Europe, by comparing Pearson's correlation coefficient, anomaly correlations and mean differences in soil moisture. Results show that all 3 products have similarly high values of the Pearson's correlation coefficient in most of Europe (values > 0.6, Fig. 4), but with lower values for SMOS compared to both ERA5 and EFAS in parts of Northern Europe, including in Norway, Sweden, Finland, Iceland, Scotland and Ireland. These lower correlations for SMOS in Northern Europe are likely due to difficulties in deriving soil moisture from SMOS in these areas, where there are a lot of lakes and areas of dense forest, and suggests there may be less benefits to using the SMOS data for flood forecasting in Northern Europe.

SMOS also has consistently lower anomaly correlations in Europe compared to the other datasets, as shown by Fig. 5. This indicates that the more short-term soil-moisture variations are more correlated between EFAS and ERA5, with SMOS being the outlier. This is likely at least partially due to a higher noise for SMOS as well as some sudden drops in soil moisture that are observed in time series at different gridpoints around Europe (e.g. Fig. 6a, b, d, e). A higher noise would not be surprising, since SMOS soil moisture is based on a single observation type whereas ERA5 and EFAS soil moistures are produced through a combination of model and observations. However, the sudden drops in soil moisture are unphysical and indicate erroneous soil moisture values, perhaps due to a problem in the neural network processor such as numerical instabilities. These drops in soil moisture would need to be filtered out before SMOS soil moisture could be used in flood forecasting, for example using a first guess check to remove any values that are different by more than a given threshold from

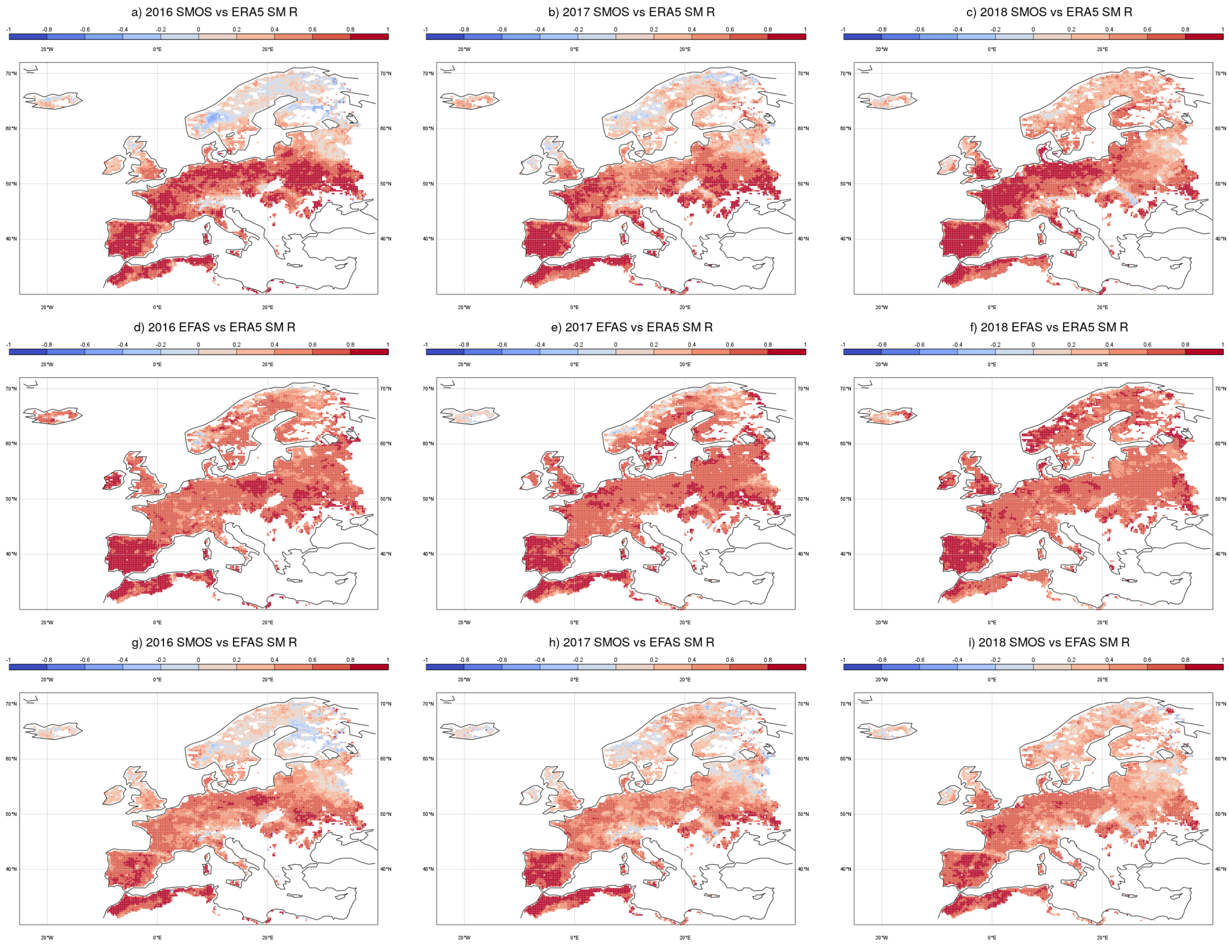

Figure 4: Pearson's correlation coefficient between SMOS and ERA5 soil moisture (top), EFAS and ERA5 soil moisture (middle) and SMOS and EFAS soil moisture (bottom) for (left-to-right) 2016, 2017 and 2018, in Europe. Values are shown after filtering SMOS observations, and for the subset of data where SMOS, EFAS and ERA5 observations are all available.

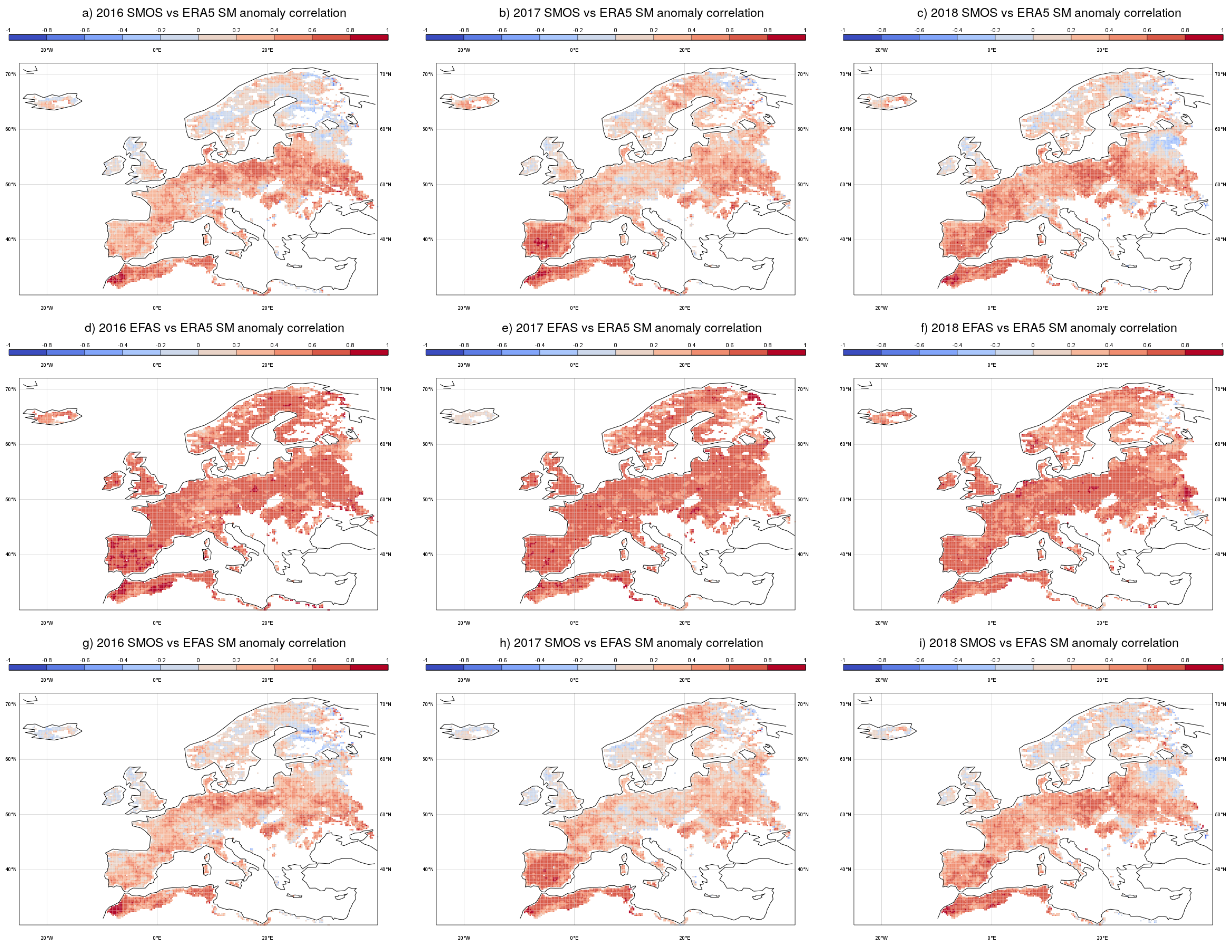

Figure 5: As Fig. 4 but for anomaly correlations.

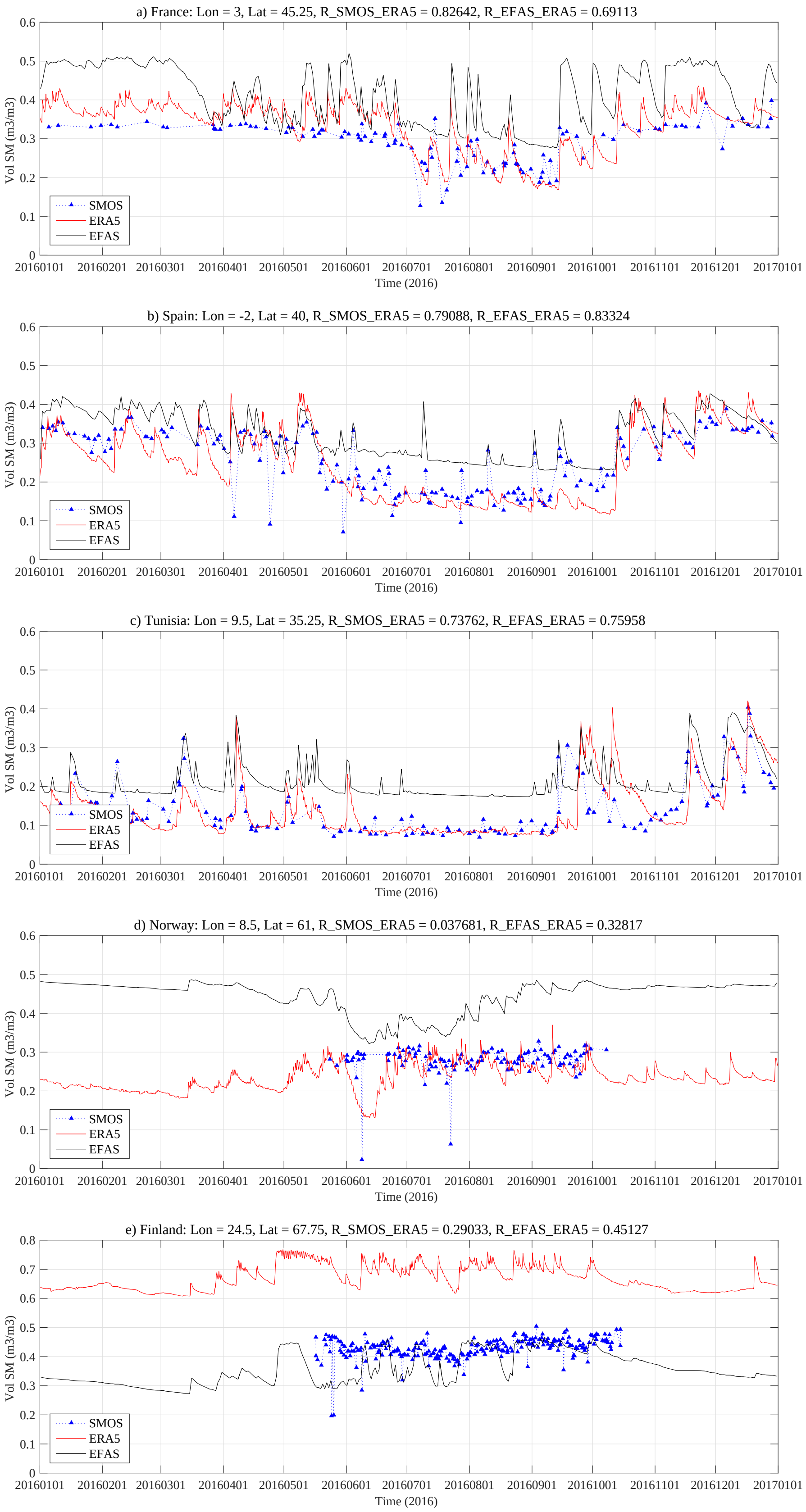

Figure 6: Timeseries of SMOS, ERA5 and EFAS soil moisture for 2016 at grid points in France, Spain, Tunisia, Norway and Finland. The latitudes and longitudes of the grid points are indicated in the titles, along with the 2016 Pearson's correlation coefficients between SMOS and ERA5 and between EFAS and ERA5 at these grid points. Values are shown for all available data, after filtering SMOS observations.

EFAS soil moisture (similar to the checks applied routinely in the land surface data assimilation system). Such a check would need to be performed after bias correction, however.

Maps of the mean differences in soil moisture (SMOS minus ERA5 and EFAS minus ERA5 shown in Fig. 7) show some systematic differences between the 3 soil moisture products. SMOS observations are generally drier than ERA5 by about 0.03 - 0.06 m^3/m^3, which is consistent with previous studies indicating that SMOS tends to dry the ECMWF analysis (e.g. as shown for brightness temperature assimilation by Muñoz-Sabater et al. (2019)). EFAS is generally wetter than both ERA5 and SMOS in Spain, North Africa and Northern Europe (Sweden, Norway and Iceland). In Spain and North Africa this is due to a lack of drying for EFAS in the summer months in comparison to SMOS and ERA5, as shown by soil moisture time series in these regions (e.g. Fig. 6b and c). A similar lack of drying is also observed in parts of France (e.g. Fig. 6a), and it may indicate that the LISFLOOD model is not removing enough soil moisture from the top soil layer in dry regions. It would be useful to confirm this in future work.

There are also systematic differences between the soil moisture products in Northern Europe. EFAS is generally much wetter than both ERA5 and SMOS in Sweden, Norway and Iceland, where EFAS has higher soil moisture values (0.4 - 0.6 m^3/m^3) throughout the year (see e.g. Fig. 6d and Fig. 7d - i). These values are suspiciously high and likely indicate that the EFAS soil moisture is too wet in these areas, perhaps due to shortcomings in the LISFLOOD model, or due to errors in the observations used to drive the model. However, in parts of Finland ERA5 has a very high soil moisture compared to both EFAS and SMOS (Fig. 7 and Fig. 6e), with values around 0.6 - 0.8 m^3/m^3. This is due to a known difficulty in the IFS model, where the soil moisture is generally too high for organic soil types, which are found in this region.

The differences in bias between EFAS and SMOS (and ERA5) highlight the importance of bias-correcting SMOS data to EFAS, in order for it to be directly used for soil moisture initialisation. This will be discussed in the next section.

4 CDF matching the SMOS data to EFAS

In this section, we present results of the SMOS bias correction calculated using a CDF-matching technique. CDF-matching is applied in the land surface data assimilation at ECMWF, and it ensures that the mean and variation in all soil moisture observations are the same as the mean and variations of the model at each gridpoint location (see e.g. de Rosnay et al. (2019)). SMOS soil moisture was CDF-matched to EFAS soil moisture as follows. At each gridpoint location and for each day of the year, the CDF-matching parameters A and B were calculated, as:

$$A = \langle SM_{EFAS} \rangle - \langle SM_{SMOS} \rangle . \frac{StDev(SM_{EFAS})}{StDev(SM_{SMOS})}, \tag{1}$$

$$B = \frac{StDev(SM_{EFAS})}{StDev(SM_{SMOS})}, \tag{2}$$

where $\langle SM_{EFAS} \rangle$ and $StDev(SM_{EFAS})$ are respectively the mean and standard deviation of EFAS soil moisture, and $\langle SM_{SMOS} \rangle$ and $StDev(SM_{SMOS})$ are the mean and standard deviation of SMOS soil moisture.

The mean and standard deviation for a given grid-point and day were calculated from a sample containing all soil moistures from 45 days before to 45 days after a given day in each of the 3 years (2016, 2017 and 2018), i.e. using a sample of 91x3 = 273 days of observations for each day of the year and each gridpoint. Note that the same day of the year in 2016, 2017 and 2018 will therefore have the same values of A and B. Only SMOS

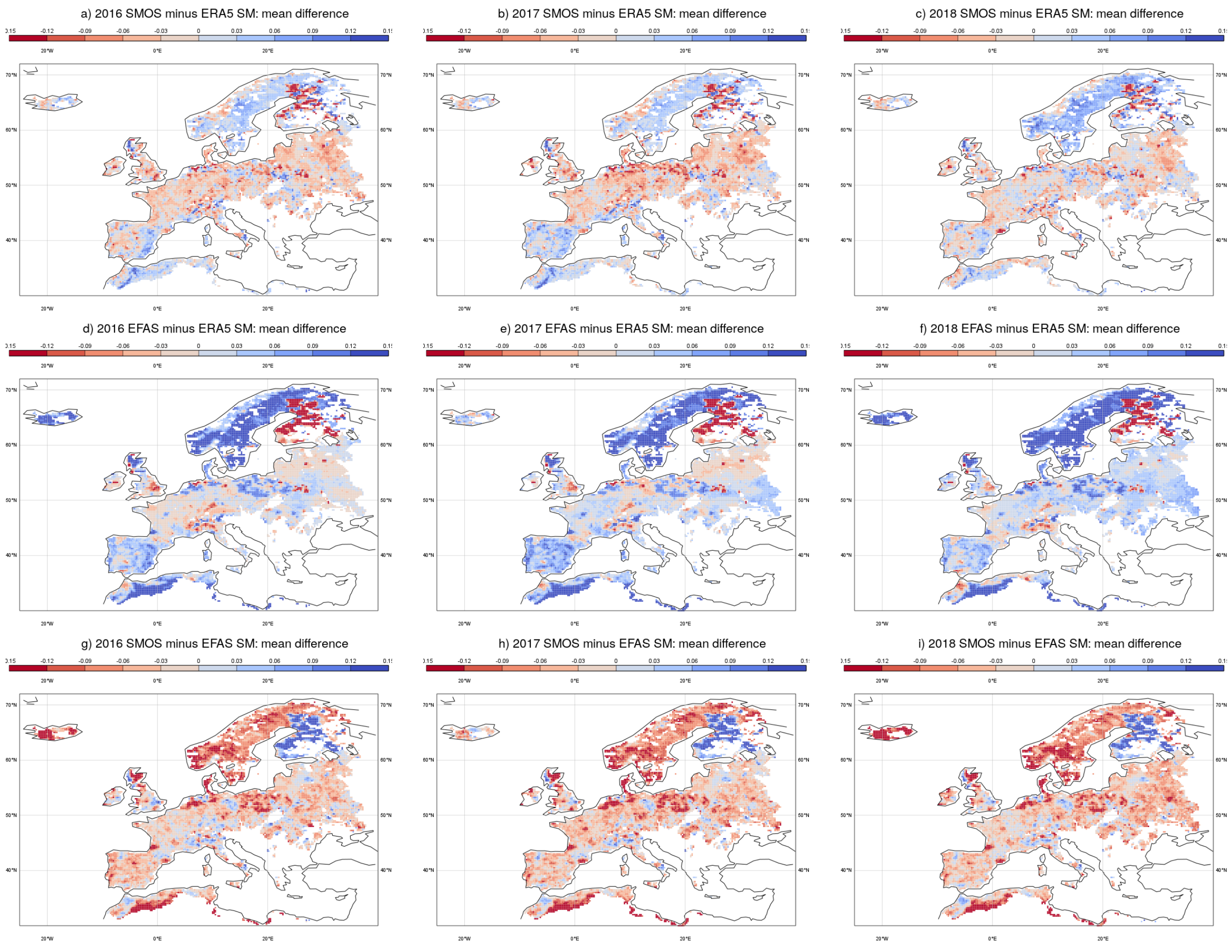

Figure 7: Mean SMOS minus ERA5 (top) and EFAS minus ERA5 (bottom) averaged over (left-to-right) 2016, 2017 and 2018. Values are shown after filtering SMOS data and for times and grid-points where all 3 datasets are available.

observations at 06:00 UTC ± 3 hours were included in the sample, after applying quality control, since EFAS requires soil moisture at 06:00 UTC.

The CDF-matched SMOS soil moisture SM^*_{SMOS} was then calculated as:

$$SM^*_{SMOS} = A + B \cdot SM_{SMOS} \tag{3}$$

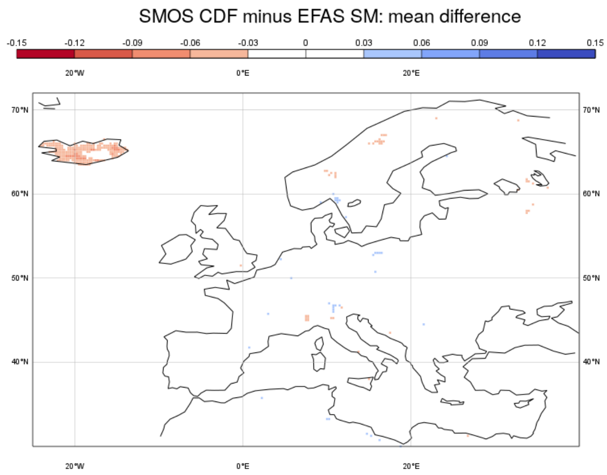

Figure 8: Mean difference between SMOS and EFAS soil moisture in 2016 after CDF-matching for SMOS.

The CDF-matching was found to work well for most grid-points in Europe, with absolute differences of SMOS and EFAS soil moisture of less than 0.03 m^3/m^3 in most gridpoints in Europe after CDF-matching (Fig. 8). Histograms of SMOS - ERA5 also have the same mean and standard deviation as EFAS - ERA5 after CDF-matching, as shown in Fig. 9, as we would expect. Note that the pdf shape of SMOS - ERA5 is still similar to before, however, with changes in only the mean and width. The changes in seasonal mean and standard deviation can also be seen in soil moisture time-series, as shown in Fig. 10a for a point in Spain.

However, for a small number of gridpoints, including most gridpoints in Iceland and some in North Africa, the CDF-matching was less successful due to large interannual variations in the mean seasonal cycle of soil moisture at these locations. This is illustrated in a time series shown for a point in Morocco and a point in Iceland in Fig. 10, where there were significant differences in EFAS soil moisture for the winter seasons in 2016 and 2017. The CDF-matching method does not account for such interannual variabilities and so either the SMOS data should be screened or a CDF-matching approach applied that varies from year-to-year. The latter is only feasible for testing in research experiments, however, and would not be possible for operations in EFAS.

5 Conclusions and Discussion

In this report, the first steps towards using SMOS soil moisture for flood-forecasting in EFAS were presented. Firstly, we compared values from the ECMWF SMOS Neural Network soil moisture product to ERA5 reanalysis soil moisture as well as the soil moisture produced currently by EFAS. SMOS generally shows a good correlation to ERA5 and EFAS in most of Europe, suggesting similar annual soil moisture variations. In some areas of Northern Europe (Norway, Sweden, Finland, Iceland, Scotland and Ireland), however, SMOS has a low correlation to both ERA5 and EFAS. This is likely due to difficulties in deriving soil moisture from SMOS in these regions and there may be less benefits to using the data for flood forecasting in these areas. Anomaly correlations indicate that the short-term variations in SMOS soil moisture are less correlated to ERA5 and EFAS.

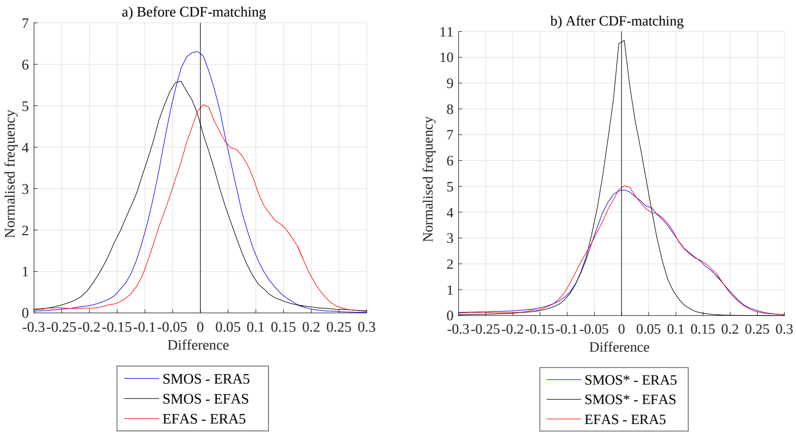

Figure 9: Histograms of differences between the 3 soil moisture products in 2016 for a) before SMOS cdf matching and b) after SMOS cdf matching.

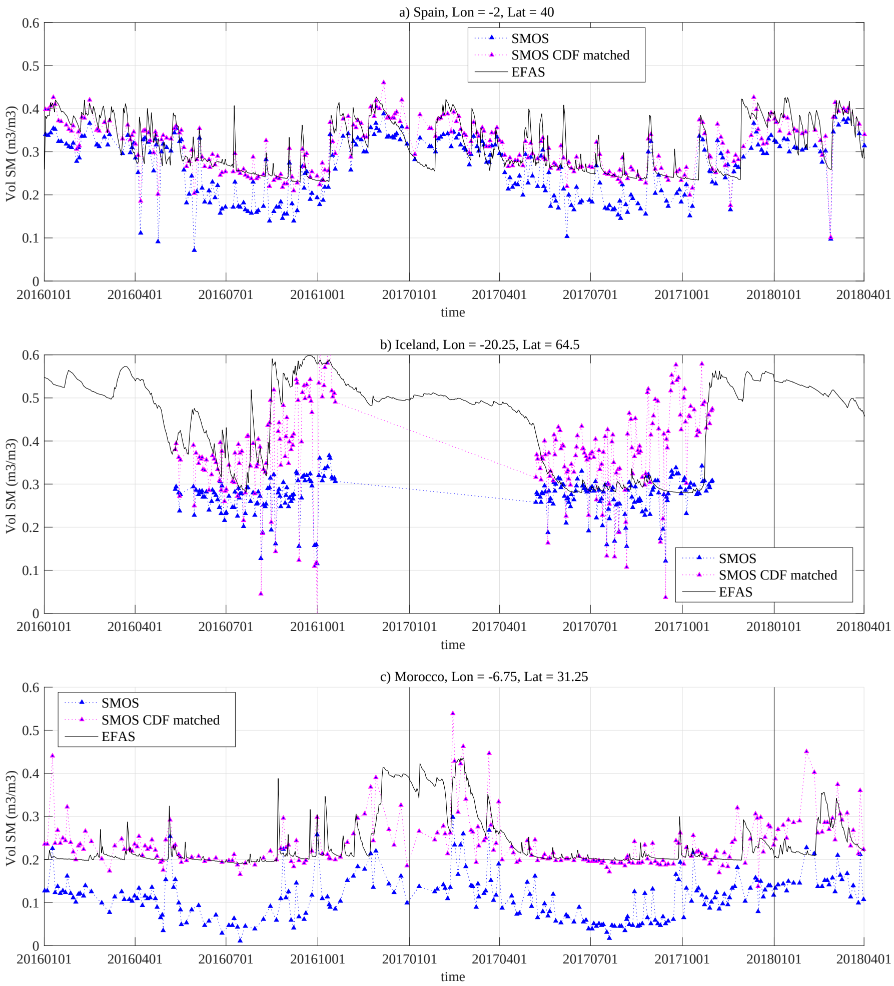

Figure 10: Timeseries of EFAS soil moisture and SMOS soil moisture before and after CDF-matching, for grid-points in a) Spain, b) Iceland and c) Morocco. Note that the gridpoint shown for Spain is the same as shown in Fig. 6.

This is likely at least partially due to noise in the SMOS observations and to unphysical drops in soil moisture that were observed in soil moisture timeseries. SMOS observations would therefore need to be further filtered before being used in flood forecasting e.g. using a first guess check.

Results also indicate some biases in the EFAS soil moisture, particularly over Scandinavia, Iceland and Spain. In Norway, Sweden and Iceland, EFAS soil moisture values were found to be much higher than both SMOS and ERA5 in both summer and winter. In Spain EFAS soil moisture was also generally higher than SMOS and ERA5, due to a lack of drying for the summer season. This latter result is of particular interest since EFAS is known to have a poorer performance against river discharge observations in the Iberian peninsula.

The calculation of CDF-matching parameters, to bias correct SMOS to EFAS was then presented. This is a necessary step for SMOS soil moisture to be used directly to initialise flood forecasts. Results show that CDF-matching led to a reduction in bias between SMOS and EFAS for most gridpoints in Europe, with the exception of Iceland and for a small number of gridpoints in other areas such as North Africa. For these gridpoints, the CDF-matching was less successful for some seasons due to EFAS having a strong interannual variability in the soil moisture seasonal cycle. At these times the SMOS soil moisture values would need to be filtered, which again could be done using a first guess check.

Following the study presented here, the next steps in SMOS-E are to test the impact of SMOS soil moisture on flood forecasts in EFAS. One option for this is to use SMOS soil moisture directly, supplemented by EFAS soil moisture when SMOS observations are not available, as previously described. However, an alternative method would be to use an ECMWF analysis after SMOS has been assimilated for the initialisation of soil moisture, since this has a daily full domain coverage. This would have the additional advantages that the uncertainty in SMOS observations (noise) would be accounted for through data assimilation, and the quality control developed for SMOS in the IFS would be used to remove erroneous data.

Initialising EFAS with an ECMWF analysis soil moisture would also allow us to assess the impact of changing the mean soil moisture state for EFAS, in areas where this study suggested there are likely biases (Spain, Sweden, Norway). This test could confirm whether the EFAS soil moisture really is biased, and might lead to improved forecasts. However, if the biases in these areas are due to LISFLOOD not accurately representing the hydrology of the region, then using more realistic soil moisture values could lead to a degradation in forecast quality, since the forecasts will still be produced by LISFLOOD. Therefore it is envisaged to test the use of SMOS in EFAS by changing the initial soil moisture to two different analysis values, in three separate experiments as follows: 1) a control experiment using EFAS soil moisture, 2) an experiment using the ECMWF analysis soil moisture with SMOS assimilated, and 3) an experiment using the ECMWF analysis soil moisture without the assimilation of SMOS. This will allow us to test changing the mean soil moisture state to that of the IFS and SMOS (experiment 2 minus experiment 1), as well as testing the impact of using SMOS (experiment 3 minus experiment 2).

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