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The Sodankylä in-situ soil moisture observation network: an example application to Earth Observation data product evaluation

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Abstract

Soil moisture is one of the main drivers in water, energy, and carbon cycles. Both latent and sensible heat fluxes, governing the air temperature and humidity boundary layer over land, are affected by variations in soil moisture. During the last decade there has

- ⁵ been considerable development in remote sensing techniques relating to soil moisture retrievals over large areas. Within the framework of the European Space Agency's (ESA) Climate Change Initiative (CCI) a new soil moisture product has been generated, merging different satellite-based surface soil moisture based products. Such remotely sensed data needs to be validated by means of in-situ observations in different climatic
- ¹⁰ regions. In that context, a comprehensive, distributed network of in-situ measurement stations gathering information on soil moisture, as well as soil temperature, has been set up in recent years at the Finnish Meteorological Institute's (FMI) Sodankylä Arctic research station. The network forms a (CAL-VAL) reference site and is used as a tool to evaluate the validity of satellite retrievals of soil properties.
- In this paper we present the Sodankylä CAL-VAL reference site soil moisture observation network. The procedures for choosing the representative sites for individual soil moisture network stations are discussed, as well as the development of a weighted average of top layer (5–10 cm) soil moisture over the study area. Comparisons of top layer soil moisture around the Sodankylä CAL-VAL site between the years 2012 and 2014
- ²⁰ using ESA CCI soil moisture data against in-situ network observations were conducted. The comparisons were made against a single CCI data product pixel encapsulating the Sodankylä observation sites. Comparisons have been made against both daily CCI soil moisture estimates and against weekly running average values. Soil moisture comparisons are only conducted during snow free and thawed periods, as the presence of
- ²⁵ snow and soil frost interfere with Earth Observation (EO) data based soil moisture retrievals.

While the overall achieved correlation between the CCI data product and in-situ observations was low (0.479), this was largely the result of a single year of observations



(2014) with poor correlation metrics. The best values were achieved in 2012 and 2013 at 0.551 and 0.621. All years exhibit a negative (dry) bias ranging from 0.0346 to 0.046. Averaging CCI soil moisture data from daily to weekly estimates significantly improves both correlation and RMSE, but has little effect on bias. The average correlation between the CCI data product and weighted average in-situ observations improves from 0.479 to 0.637. The improvements in correlation are most pronounced in 2012 and 2013, with an improvement from 0.551 to 0.840 and from 0.621 to 0.813 respectively.

1 Introduction

Soil moisture is one of the main drivers in water, energy, and carbon cycles. Both latent and sensible heat fluxes, governing the air temperature and humidity boundary layer over land, are affected by variations in soil moisture. For these reasons it plays an important role in the climate system (Legates et al., 2011) and thus, soil moisture observations of global coverage and at high temporal resolution are urgently needed to monitor ongoing climate changes. Soil moisture is estimated by either in situ measure-

- ¹⁵ ments, remote sensing techniques (Kerr et al., 2010), or by earth system models e.g. ECHAM5 combined with JSBACH (Roeckner et al., 2003). Though several soil moisture networks have been developed all over the world, with most of them included in the International Soil Moisture Network's (ISMN) database (Dorigo et al., 2011), there is still a lack of high-density soil moisture data in many regions. Therefore, proper initi-
- ation of soil moisture in numerical models is often difficult and regional to global-scale projections of soil moisture remain relatively uncertain compared to other variables of the water cycle (Legates et al., 2011; Stocker et al., 2013).

During the last decade there has been a considerable development of remote sensing techniques of soil moisture enabling large-scale soil moisture observations (Dorigo

et al., 2015). In 2009, the European Space Agency (ESA) launched the Soil Moisture and Ocean Salinity (SMOS) satellite (Kerr et al., 2010), the first space mission dedicated to soil moisture observations. And just recently, NASA's Soil Moisture Active



and Passive (SMAP) mission was launched with the same objective (Entekhabi et al., 2010, 2014). These advancements have placed soil moisture into one of the 50 Essential Climate Variables collected by the Global Climate Observing System to help the work of United Nations Framework Convention on Climate Change (UNFCCC) and

- the Intergovernmental Panel on Climate Change (IPCC) (Dorigo et al., 2015). In that context, the ESA Climate Change Initiative (CCI) soil moisture product was generated, merging different satellite-based and a land surface model surface soil moisture products (Liu et al., 2011, 2012; Wagner et al., 2012). Such remotely sensed data needs to be validated by means of in situ observations in different climatic regions of the world.
- ¹⁰ The multidisciplinary research center of Sodankylä in Northern Finland is considered as one of the most complete terrestrial environment monitoring stations in the Arctic region, collecting data from sub-surface to upper-atmosphere, with continuous observations dating back to 1908. It also hosts a network of automatic soil state observation stations, thus forming such a calibration and validation (CAL-VAL) reference site for ¹⁵ Earth Observation (EO) soil moisture data products.

The objective of this paper is to (1) present this soil moisture observation network established within the Sodankylä CAL-VAL reference site, and (2) apply this in-situ dataset to validate ESA's CCI soil moisture product over the site. The procedures for choosing the representative sites for individual soil moisture network stations are dis-

²⁰ cussed, as well as the development of a weighted average of top layer (5–10 cm) soil moisture over the study area, taking into account different soil types found within the region. Comparisons of in-situ soil moisture observations against ESA CCI soil moisture (Liu et al., 2011, 2012; Wagner et al., 2012) data are presented and discussed.

Ongoing SMOS CAL-VAL activities by means of the Sodankylä in-situ soil moisture dataset (e.g. algorithm adaptions for organic substrate, soil moisture retrieval under forest and wetlands) will be the subject of another article planned for the near future.



2 Sodankylä region soils and landscape

The Sodankylä region represents a typical Northern boreal forest/taiga environment; 71 % of the surrounding landscape, within an 80 km radius, is forested with open and forested bogs representing 18 %. The landscape is relatively flat with moderate hills reaching 505 m a.m.s.l. (metres above mean sea level), while the lowest point within the area is at a height of 91 m a.m.s.l.

Soils within the Sodankylä region have only been formed fairly recently, after the last, Weichselian glaciation, period (Sippola, 2005; Yli-Halla, 2002). Owing to rather weak development due to weathering-resistant felsic parent material and a cool climate, the soils of the Sodankylä region have been classified according to national standards and mapped, primarily by GTK (Geological Survey of Finland) according to grain size and content of organic matter. Little attention has been paid to pedogenic classification. Grain size and organic matter based classification serves practical soil-related activities in Finland well; however this makes it difficult to present soil data from Finland in an

international context. During the last few years, national soil classes have been related to the Food and Agriculture Organization of the United Nations' (FAO) World Reference Base (WRB) pedogenic classification systems by MTT (Agrifood Research Finland). We have combined national GTK Quaternary deposits map data with northern Finland MTT pedogenic soil map units, Corine 2006 land cover information and in-situ field
 campaigns to produce a new detailed pedogenic soil map of the Sodankylä region.

Glacial till (moraine) is the most widespread deposit in the region and is primarily covered by sparse and relatively dense pine forests. Peatlands, formed in depressions in glacial till and moist semi-organic soils with mixed forests (mostly Pine, Spruce and Birch) are also widespread. Podzolization is the primary pedogenic process within the

²⁵ region, although the Podzolization process is clearly fairly week in parts of the region. As is the case in other parts of Finland, soils developed on sandy and loamy glacial till are often weakly podzolized and marginally meet the requirements of Podzols of the WRB system (Yli-Halla and Mokma, 2002).



Weakly Podzolized, Haplic Podzols, accounting for 55% of the area, with varying grain sizes are present through-out the region, except for the central riverbed plain. The general distribution of organic soils (Histosols), accounting for 18% of the area, clearly follows a North-West to South-East diagonal, with the northern portion of the area containing larger and more extensive areas of organic and semi-organic (Umbric Gleysol) soils. Semi-organic Umbric Gleysols soils cover 14% of the Sodankylä area. Fine sandy-loam soils, determined in our classification as Haplic Arenosols are found predominantly within the immediate proximity of large rivers, particularly in places where the river channel has changed its shape, exposing old channel bed materials.
¹⁰ Haplic Arenosols account for 1.6% of the area. Terminal moraines at the edge of the greatest extent of past glaciers have formed deposits of silty parent material for forming Eutric Regosols. As can be observed from Fig. 4 this soil type only covers a small

portion of the area (2%). The remainders of soil types within the Sodankylä region consist predominantly of exposed bedrock (6%) and Leptosols formed through both glacial erosion and weathering. They are found mainly on hill tops and on slopes and are generally devoid of trees and are incapable of holding water.

3 In-situ measurements, sites and representativeness

3.1 Network setup

The soil moisture stations within the Sodankylä CAL-VAL site are based on Campbell
 Scientific Ltd. CR850 and CR1000 dataloggers. The electromagnetic (EM) sensors utilized are Decagon 5TE and more recently Campbell Scientific Ltd. CS655 digital soil moisture sensors measuring dielectric constant, electric conductivity and temperature of the soil. The measurement principle in Decagon 5TE is based on capacitance technique in which the sensor supplies a 70 MHz oscillating wave to the sensor prongs that
 changes according to the dielectric of the material (Vaz et al., 2013; Decagon Devices Inc., 2014). The CS655 measurement is based on the so called transmission line oscil-



lation (TLO) technique in which the sensor sends electromagnetic pulses along its two stainless steel rods at a frequency of 175 MHz. The sensor then measures the time period the signal takes to propagate to the end of the rods and back. As the water content in soil increases the propagation velocity of the signal decreases because of increasing

dielectric permittivity (Vaz et al., 2013; Campbell Scientific Ltd., 2015). Both sensors have calibration equations that convert the raw EM data to bulk dielectric conductivity. (Decagon Devices Inc., 2014; Campbell Scientific Ltd., 2015).

The relationship between dielectric permittivity and volumetric water content in mineral soils by Topp et al. (1980) is used to revert sensor output to soil moisture. Based

- on comparison with volumetric soil moisture estimates from gravimetric sampling, the Topp equation yields satisfying results in case of mineral soils of low organic matter content. Considerable effort has been placed on calibration of the Decagon 5TE soil moisture sensors measuring the volumetric water content in organic layers within the Sodankylä area. As a result of these efforts, a new calibration function has been de rived and recently applied to soil moisture measurements in organic layers (Bircher
- et al., 2015). Equal efforts for the more recently installed Campbell Scientific CS655 sensors are underway and planned for summer 2016.

Each station has one vertical measuring profile and two additional horizontal measuring points. The vertical profiles have five sensors placed close to the station at the following depths: -80, -40, -20, -10, -5 cm in mineral soils, and -40, -30, -20, -10, -5 cm in organic bog type soils. These measuring points have been installed some ten meters from the station in opposing directions, in order to catch small scale variations

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in soil moisture of the uppermost layer.

Currently eight soil moisture stations have been installed around the Sodankylä CAL-VAL site. See Table 1 for a list of the stations and their soil/land cover types, sensor types and different soil calibrations used. Figure 1 depicts the locations of the CAL-VAL sites.

The options and requirements governing in-situ observation site locations have evolved over time from 2011 onwards. In the beginning the aim was to only represent



the immediate surroundings of the FMI Arctic Research Center. The initial site installations in 2011 reflect this approach and provide relatively good local coverage. Following wider area field campaigns in 2014 it was acknowledged that the in-situ network should be expanded to cover a more diverse range of soil and land cover types. Therefore, two

⁵ (HA Forest 2 and HP-F Forest 1) new in-situ sites were established. New observation sites will be installed during 2016, providing improved representativeness of the soil moisture observation network as a whole.

3.2 Creation of an area-representative in-situ soil moisture average

Based on land cover and soil type information, an area-representative average of the in-situ observations within the Sodankylä area have been derived for comparison with EO data based soil moisture estimates, in this case the ESA CCI soil moisture product. One ESA CCI soil moisture pixel of ~ 25 km × 25 km size, best covering the Sodankylä CAL-VAL site, was selected. In-situ soil moisture weights were defined based on percentages of composite classes of prevailing soil type and land cover information within

- the area. Soil moisture from the individual network stations was then multiplied with these weights in order to create an average value, representative for the ESA CCI pixel. Table 2 gives an overview over the applied weights. The latter were continuously redistributed when new stations were added to the network. In order to verify both the representativeness of the in-situ observation sites and the accuracy of our
- soil type classification, field measurement campaigns were conducted between 24– 25 June 2014 and on 12 October 2015. Field soil moisture measurements were made at 228 points on all major soil types within and below the organic litter layer (O and A-horizons) representing depths of approximately 5 and 10 cm on average. The measurements were conducted with hand held ML2X theta probes. Pictures of the top soil
- ²⁵ profile and surrounding area were also taken. As expected, the field measurements of soil moisture in each soil type exhibit a large degree of local variability. Despite this variability a clear trend in average soil moisture for each soil type can be observed, with heavier (Eutric Regosol and Umbric Gleysol) soils generally holding more water



compared to lighter (Haplic Podzol and Haplic Arenosol) soils. Moreover, the field campaigns were also able to distinguish differences in Haplic Podzol water holding capacity, with coarse Haplic Podzol being able to hold on average slightly less water than fine Haplic Podzol, see Fig. 5.

- As a result of the field campaigns as well as the new soil type classification and mapping effort, the need to expand the Sodankylä in-situ observation network to improve the representative coverage of the Sodankylä CAL-VAL area was recognized. At the time of the first field campaign (June 2014) the in-situ observation network was found to cover an estimated 42% of the selected ESA CCI soil moisture pixel in terms of
- soil types and land cover. This conclusion was drawn in hindsight after comparing field campaign measurements against the results of the new soil type classification and mapping effort. Following new station (HA Forest 2 and HP-F Forest 1) installations in October 2014, this coverage was increased to between 64 and 89%, depending on the strictness of Haplic Podzol definitions between fine and coarse types. Further new stations are due to be installed in 2016, with the aim of achieving close to 100%
- representative coverage.

The practical implication of under representation of the various soil types within the region by the in-situ observation network is that some other in-situ observation site must be used as a surrogate and assigned a weight that corresponds to the weight

- of the missing area if comparisons against EO based soil moisture estimates prior to 2015 are to be made. Preferably the surrogate in-situ site's soil should resemble the soil textural properties of the missing soil type as closely as possible. According to our soil type classification, the missing in-situ soil type references prior to 2015 are Haplic Podzol (fine) and Haplic Podzol (coarse). As Haplic Arenosol is very similar in terms
- of soil textural properties to Haplic Podzol, and since the vegetation covering this soil type generally consists of similar Pine forests, we chose the HA Forest1 site on Haplic Arenosol as the surrogate. This site tends to hold more water than the HA Open 1 site and although generally not as moist as the HP-F Forest 1 site, it, out of all the options, most closely resembles that of the HP-F Forest 1 site. Figure 6 illustrates the



impact of the new station (HP-F Forest 1) installation on spatially weighted average top soil (5 cm depth) moisture in comparison to average soil moisture without the new station between 1 June and 30 September 2015. As expected using the HA Forest 1 as the surrogate for Haplic Podzol soils (fine and coarse) results in generally lower soil
 ⁵ moisture levels. Figure 6 also illustrates the difference in soil moisture observations be-

tween the surrogate; HA Forest 1 site, and the actual HP-F Forest 1 site independently. Although the difference in the two is quite pronounced, the overall weighted affect is less notable.

4 The ESA CCI soil moisture product

¹⁰ The ESA's CCI soil moisture data represents a homogenised and merged product of surface soil moisture with global coverage. The product currently covers the years 1978 to 2014 with daily timesteps at a spatial resolution of 0.25°, spanning the entire period covered by the individual sensors. The Active CCI soil moisture product is produced by merging scatterometer data, derived from AMI-WS (prior to 2007) and ASCAT in-¹⁵ struments. The Passive product is based on merging derived soil moisture data from SMMR, SSM/I, TMI, AMSR-E, and AMSR2 instruments (Chung et al., 2014b).

The generation of the ESA CCI soil moisture data set involves three steps; (1) merging the original passive microwave soil moisture products into one product, (2) merging the original active microwave soil moisture products into one product, and (3) blend-

- ing the two merged products into one final dataset together with the GLDAS model estimates. The input datasets for generating the merged soil moisture product consist of, (1) Scatterometer-based soil moisture products, (2) Radiometer-based soil moisture products, (3) Modelled 0–10 cm soil moisture from the Noah land surface model of the Global Land Data Assimilation System version 1. In step 3 the active and passive datasets are blended together by re-scaling both to GLDAS-Noah soil moisture data
- ²⁵ datasets are blended together by re-scaling both to GLDAS-Noah soil moisture data values with a cumulative distribution function (CDF) matching approach. This imposes



GLDAS-Noah model based absolute value ranges on the original EO observations, but does not have an affect on the original EO data dynamics (Chung et al., 2014b).

Active and passive datasets are combined into the merged CCI data product based on data availability and their sensitivity to vegetation (i.e. vegetation density). An av-

- ⁵ erage vegetation optical depth (VOD) value is obtained from the Land Parameter Retrieval Model (LPRM) (Owe et al., 2008; Meesters et al., 2005). The VOD value is used to identify sparsely vegetated areas from moderately vegetated areas. The active soil moisture product is used in areas with high VOD values (i.e. higher than a predefined threshold), whereas the passive product is used in areas with low VOD values, i.e.
- in semiarid and arid regions.(Chung et al., 2014b; Wagner et al., 2012). For the So-10 dankylä region only active microwave data is used, since from the perspective of the CCI product merging algorithm, the Sodankylä region falls within a region with moderate vegetation density exceeding the predefined threshold value. The daily summer period overpass times of ASCAT, over the Sodankylä study area, between the years ¹⁵ 2012 and 2014 are 07:00 UTC (44 times), 08:00 UTC (2 times), 10:00 UTC (5 times),
 - 16:00 UTC (94 times), 17:00 UTC (50 times), 18:00 UTC (26 times) and 19:00 UTC (170 times).

Comparisons and results 5

Comparisons of top layer soil moisture around the Sodankylä CAL-VAL site between

- the years 2012 and 2014 using ESA CCI soil moisture data against in-situ network 20 observations were conducted. The comparisons were made against a single CCI data product pixel encapsulating the Sodankylä observation sites. Soil type classification based map unit areas within the CCI data pixel were used to derive in-situ observation weights. The respective weights for each in-situ observation site are provided in
- Table 2. Since ESA CCI data is, at the time of writing, only available prior to 2015, our 25 comparisons are made against in-situ weights using the HA Forest 1 site as a surrogate for the HP-F Forest 1 site as described in Sect. 3.



Comparisons have been made against both daily CCI soil moisture estimates and against weekly running average (in-situ and CCI data) values in order to examine the effects of apparent noise in the CCI data product. Top soil moisture for each in-situ site are approximated from 5 cm depths apart from sites on Umbric Gleysol soil (UG

- Forest 1 and UG Forest 2 sites), where the Organic layer is typically much thicker than in e.g. Podzol soils. With these in-situ sites top soil moisture is approximated from 10 cm depths. Soil moisture comparisons are only conducted during snow free and thawed periods, as the presence of snow and soil frost interfere with EO data based soil moisture retrievals (Chung et.al., 2014a) such as is the case with the ESA CCI data product. Snow free and thawed conditions are determined by a data quality filter
- provided as a part of the CCI product itself (Scipal et al., 2005) combined with direct Sodankylä CAL-VAL site snow observations.

Figures 7 and 8 show daily and weekly CCI and in-situ soil moisture time series as well as corresponding scatterplots, respectively, for the years 2012, 2013, and 2014,

- separately. Corresponding statistical metrics can be found in Table 3. The overall correlation between the daily CCI data product and daily weighted average in-situ observations is rather low at 0.479. The best values are achieved in 2012 and 2013 at 0.551 and 0.621, respectively. In 2014 the correlation is very low at only 0.186. The overall unbiased RMSE is generally relatively low at 0.039, with the highest RMSE value
- (0.049) observed for 2014. All years exhibit a negative (dry) bias ranging from 0.0346 to 0.046, with 2013 having the lowest negative bias. Averaging CCI soil moisture data from daily to weekly estimates significantly improves both correlation and RMSE, but has little effect on bias. The average correlation between the CCI data product and weighted average in-situ observations improves from 0.479 to 0.637 and the average
- RMSE decreases from 0.039 to 0.026. The improvements in correlation are most pronounced in 2012 and 2013, with an improvement from 0.551 to 0.840 and from 0.621 to 0.813 respectively. Similarly the RMSE drops from 0.034 to 0.015 in 2012 and from 0.033 to 0.020 in 2013.



The general in-situ observation soil moisture trend during the summer of 2012 is descending, while switching to an ascending trend towards the autumn period. In 2013 the overall in-situ soil moisture observation trend is primarily descending, with the exception of early summer and late autumn. These same general trends are also apparent

in the CCI data product, and therefore the correlations for these years are higher, as compared to 2014. It appears that in 2014 in-situ observations exhibit larger wet-dry variation compared to the years 2012 and 2013, with no clear overall trend. In-situ observation variation and lack of a general trend is however not observable in the CCI data product and the general trend, as in all other years is descending, resulting in considerably poorer correlation with both the daily and weekly weighted average in-situ observations.

6 Discussion and conclusions

of the area as a whole.

A comprehensive, distributed network of in situ measurement stations gathering information on soil moisture, as well as soil temperature, has been set up in recent years
at the FMI Sodankylä Arctic research station. The network forms a tool to evaluate the validity of satellite retrievals of soil properties. The applicability of point-scale measurements to represent an area covered especially by coarse scale passive microwave sensors is always a subject for debate; however, the employed land-cover sensitive scheme in this study addresses the issue by applying weight factors for measurement
stations according to their relative representativeness following a new soil type classification. The classification will also be used to assist in the planning for installation of new stations in the near future, with the aim of achieving improved representativeness

In our study, soil moisture measurements network data was compared in a land cover sensitive scheme to the blended soil moisture product of the ESA Soil Moisture CCI initiative over several summer periods. While the overall achieved correlation for the daily CCI was low (0.479), this was largely the result of a single year of observations



(2014) with poor correlation metrics. Comparisons of weekly CCI estimates to averaged weekly station readings provided improved metrics in terms of correlation and RMSE.

It is apparent from the comparison results that the CCI data product has issues with noise between observation steps. Reduction of CCI data noise by smoothing results

- to a running weekly average improves correlation against weighted average in-situ observations considerably. This could possibly point to issues stemming from CCI data acquisition times. In Sodankylä, and in boreal and sub-arctic zones in general, moisture often condenses over night into morning dew on vegetation. This could interfere with active microwave soil moisture retrievals acquired during the early morning hours.
- In order to investigate this, we created a subset of comparisons where CCI data collected during morning hours were removed. Comparisons were also conducted against hourly in-situ observations corresponding to CCI data overpass times. However, neither one of these comparisons resulted in significant changes in correlation, RMSE or bias. Therefore, it is not clear to us if these shortcomings are related to issues with the
- retrieval algorithm, scaling issues induced by the GLDAS-Noah model or possible issues associated with the LPRM model. The latter however seems less likely according to our findings as diurnal affects of vegetation moisture do not appear to be the cause. The affect of conducting comparisons of daily average in-situ moisture against CCI soil moisture data which is intervallic by nature was also investigated. However as with the removal of observations conducted during morning hours, this also had little effect on
- any statistical metrics.

The apparent soil moisture scale difference (dry bias) between weighted average in-situ observations and the CCI data product is significant but not very meaningful. This is true even when it is likely that our weighted in-situ average soil moisture level

itself somewhat underestimates overall soil moisture content due to the use of surrogate in-situ sites (as detailed in previous chapters). As part of the steps used to create the merged CCI data product, it is stated that the use of GLDAS-Noah model data to impose absolute soil moisture values to the CCI data product, renders statistical comparison metrics such as root-mean-square-difference and bias somewhat scientifically



meaningless. The CCI soil moisture product should in fact be used, and considered as a reference product for computing correlation statistics, not as an absolute soil moisture content estimate (Wagner et al., 2012).

- Further studies in to the apparent anomalies in the CCI data product and assumption
 made in producing the data product should be conducted. For example, the validity of using a single, inter-annually constant, correction variable to counter the affect of vegetation moisture interference in soil moisture retrieval should be assessed. Although our findings do not directly point to an issue related to this, it could still explain at least part of the noise and variability of soil moisture estimates between the daily timesteps.
 Further comparisons and analysis of CCI soil moisture data over larger (boreal) areas
- ¹⁰ Further comparisons and analysis of CCI soil moisture data over larger (boreal) areas and longer time spans against both in-situ observations and distributed soil moisture model estimates will be performed in future studies.

Data availability

Data from the measuring stations is freely available from the web server of the Finnish
Meteorological Institute URL: http://litdb.fmi.fi. Although the CCI soil moisture data used in this study is not yet freely available to the public a previous version can already by accessed through http://www.esa-soilmoisture-cci.org/node/145. The CCI data version (v02.2) used in this study is scheduled for public release in January 2016. At the time of writing version v02.2 data have gone through basic internal verification by the project
consortium. Corine land cover data is freely available through The European Environment Agency (EEA) at http://www.eea.europa.eu/data-and-maps/. Finnish quaternary deposits map data is available through the Geological Survey of Finland

- (GTK) data distribution service; http://www.gtk.fi/tietopalvelut/rajapintapalvelut/. Agrifood Research Finland (MTT) soil database data (1:250000) is available through
 a Web Feature Service (WFS) provided by the Natural Resources Institute Finland;
 - http://maps.luke.fi/geoserver/.



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References

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- Bircher, S., Andreasen, M., Vuollet, J., Vehviläinen, J., Rautiainen, K., Jonard, F., Weihermüller, L., Zakharova, E., Wigneron, J.-P., and Kerr, Y. H.: Soil moisture sensor calibration for organic soil surface layers, Geosci. Instrum. Method. Data Syst. Discuss., 5, 447–493, doi:10.5194/gid-5-447-2015, 2015.
- Campbell Scientific Ltd.: CS650 & CS655 Soil Water Content Reflectometers, User manual, Campbell Scientific Ltd., 80 Hathern Road, Shepshed, Loughborough, LE12 9GX, UK, 2015.
 Chung, D., Dorigo, W., Hahn, S., Melzer, T., Paulik, C., Reimer, C., Vreugdenhil, M., Wagner, W., and Kidd, R.: Soil Moisture Retrieval from Active Microwave Sensors: Algorithm Theoretical



Baseline Document, Version 2, available at: http://www.esa-soilmoisture-cci.org (last access: 15 October 2015), 2014a.

- Chung, D., Dorigo, W., Hahn, S., Melzer, T., Paulik, C., Reimer, C., Vreugdenhil, M., Wagner, W., and Kidd, R.: ECV Production, Fusion of Soil Moisture Products: Algorithm Theo-
- retical Baseline Document, Version 2, available at: http://www.esa-soilmoisture-cci.org (last access: 15 October 2015), 2014b.

Decagon Devices Inc.: 5TE Water Content, EC and Temperature Sensor, User manual, Decagon Devices Inc., 2365 NE Hopkins Court, Pullman, WA 99163, USA, 2014.

Dorigo, W. A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Dr-

¹⁰ usch, M., Mecklenburg, S., van Oevelen, P., Robock, A., and Jackson, T.: The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements, Hydrol. Earth Syst. Sci., 15, 1675–1698, doi:10.5194/hess-15-1675-2011, 2011.

Dorigo, W. A., Gruber, A., De Jeu, R. A. M., Wagner, W., Stacke, T., Loew, A., Albergel, C., Brocca, L., Chung, D., Parinussa, R. M., and Kidd, R.: Evaluation of the ESA CCI soil moisture product using ground-based observations. Remote Sens. Environ., 162, 380–395.

- moisture product using ground-based observations, Remote Sens. Environ., 162, 380–395, 2015.
 Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N.,
 - Enternabl, D., Njoku, E. G., O'Neili, P. E., Keilogg, K. H., Crow, W. T., Edeisteiri, W. N., Entin, J. K., Goodman, S. D., Jackson, T. J., Johnson, J., Kimball, J., Piepmeier, J. R., Koster, R. D., Martin, N., McDonald, K. C., Moghaddam, M., Moran, S., Reichle, R., Shi, J. C.,
- ²⁰ Spencer, M. W., Thurman, S. W., Tsang, L., and Van Zyl, J.: The Soil Moisture Active Passive (SMAP) mission, P. IEEE, 98, 704–716, 2010.

Entekhabi, D., Yueh, S., O'Neill, P., Kent, K. H., Allen, A., Bindlish, R., Brown, M., Chan, S., Colliander, A., Crow, W. T., Das, N., De Lannoy, G., Dunbar, R. S., Edelstein, W. N., Entin, J. K., Escobar, V., Goodman, S. D., Jackson, T. J., Jai, B., and Johnson, J.: SMAP handbook,

- ²⁵ in: JPL Publication JPL 400-1567, editetd by: J.P. Laboratory, Pasadena, CA, USA, NASA CalTech, 2014.
 - 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., and Mecklenburg, S.: The SMOS mission: new tool for monitoring key elements of the global water cycle, P. IEEE, 98, 666–687, 2010.

30

Legates, D. R., Mahmood, R., Levia, D. F., DeLiberty, T. L., Quiring, S. M., and Houser, C.: Soil moisture: a central and unifying theme in physical geography, Prog. Phys. Geog., 35, 65–86, 2011.



- Liu, Y. Y., Parinussa, R. M., Dorigo, W. A., De Jeu, R. A. M., Wagner, W., van Dijk, A. I. J. M., McCabe, M. F., and Evans, J. P.: Developing an improved soil moisture dataset by blending passive and active microwave satellite-based retrievals, Hydrol. Earth Syst. Sci., 15, 425– 436, doi:10.5194/hess-15-425-2011, 2011.
- Liu, Y. Y., Dorigo, W. A., Parinussa, R. M., de Jeu, R. A. M., Wagner, W., McCabe, M. F., Evans, J. P., and van Dijk, A. I. J. M.: Trend-preserving blending of passive and active microwave soil moisture retrievals, Remote Sens. Environ., 123, 280–297, 2012.
 - Meesters, A., de Jeu, R. A. M., and Owe, M.: Analytical derivation of the vegetation optical depth from the microwave polarization difference index, IEEE Geosci. Remote S., 2, 121–123, 2005.
 - Owe, M., de Jeu, R., and Holmes, T.: Multisensor historical climatology of satellitederived global land surface moisture, J. Geophys. Res.-Earth Surf., 113, F01002, doi:10.1029/2007JF000769, 2008.

10

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S.,

Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., and Tompkins, A.: The Atmospheric General Circulation Model ECHAM 5. PART I: Model Description, Report, Max Plack Insitute for Meteorology, Hamburg, 2003.

Scipal, K., Naeimi, V., and Hasenauer, S.: Definition of Quality Flags, ASCAT Soil Moisture Report Series, Vienna University of Technology, Vienna, 2005.

- Sippola, J. and Yli-Halla, M.: Status of soil mapping in Finland, European Soil Bureau Research Report 9, in: Soil Resources of Europe, 2nd edn., edited by: Jones, R. J. A., Houšková, B., Bullock, P., and Montanarella, L., European SoilBureau Research Report No. 9, EUR 20559 EN, Office for OfficialPublications of the European Communities, Luxembourg, 133–138, 420 pp., 2005.
- Stocker, T. F., Qin, D., Plattner, G.-K., Alexander, L. V., Allen, S. K., Bindoff, N. L., Breion, F.-M., Church, J. A., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J. M., Hartmann, D. L., Jansen, E., Kirtman, B., Knutti, R., Krishna Kumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G. A., Mokhov, I. I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L. D., Vaughan, D. G., and
- 30 Xie, S.-P.: Technical summary, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G- K., Tignor, M., Allen, S. K.,



Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 33–118, 2013.

- Topp, G. C., Davis, J. L., and Annan, A. P.: Electromagnetic determination of soil water content: measurement in coaxial transmission lines, Water Resour. Res., 16, 574–582, 1980.
- ⁵ Vaz, C. M. P., Jones, S., Meding, M, and Tuller, M.: Evaluation of standard calibration functions for eight electromagnetic soil moisture sensors, Vadose Zone J., 12, 1–16, doi:10.2136/vzj2012.0160, 2013.
 - Wagner, W., Dorigo, W., de Jeu, R., Fernandez, D., Benveniste, J., Haas, E., and Ertl, M.: Fusion of active and passive microwave observations to create an essential climate variable
- data record on soil moisture, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS Annals), Volume I-7, XXII ISPRS Congress, Melbourne, Australia, 25 August–1 September 2012, 315–321, 2012.
 - Yli-Halla, M. and Mokma, D.: Problems encountered when classifying the soils of Finland, European Soil Bureau Research Report 7, 183–189, in: Soil Classification 2001, edited by:
- ¹⁵ Micheli, E., Nachtergaele, F. O., Jones, R. J. A., and Montanarella, L., European Soil Bureau Research Report No. 7, EUR 20398 EN, Office for Official Publications of the European Communities, Luxembourg, 248 pp., 2002.



Table 1. Stations names, representative soil and land cover types and start of observations as month/year. The sensor types are given as; Decagon Devices Inc. 5TE (5TE) and Campbell Scientific Ltd. CS655 (CS655). The last column provides calibration curve information; 1 is factory calibration for mineral soil for 5TE, 2 is custom calibration for organic soil for 5TE (Bircher et al., 2015) and 3 is factory calibration for mineral soil for 5TE solution for CS655.

Station	Soil type	Land cover type	Start	Sensor type	Calibration
HA Open 1 Bog Open 1	Haplic Arenosol Histosol	Pine Forest Opening	11 Aug 11 Aug	5TE 5TE/CS655	1, 2 1 2 3
HA Forest 1	Haplic Arenosol	Pine Forest	11 Aug	5TE	1, 2
Bog Forest 1 UG Forest 1	Histosol Umbric Gleysol	Forested Bog Mixed Forest	11 Aug 11 Aug	5TE 5TE	1,2 1, 2
UG Forest 2	Umbric Gleysol	Mixed Forest	12 Oct	5TE	1,2
HA Forest 2 HP-F Forest 1	Haplic Arenosol Haplic Podzol	Pine Forest	14 Oct 14 Oct	CS655 CS655	3



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Table 2. The respective areal averaging weights used in CCI data comparison/year for each in-situ observation site.

Station	Weight 2012	Weight 2013	Weight 2014	Weight 2015 (not used)
HA Open 1	0.193	0.193	0.193	0.064
Bog Open 1	0.109	0.109	0.109	0.109
HA Forest 1	0.467	0.467	0.467	0.064
Bog Forest 1	0.109	0.109	0.109	0.109
UG Forest 1	0.122	0.061	0.061	0.061
UG Forest 2	-	0.061	0.061	0.061
HA Forest 2	-	-	-	0.064
HP-F Forest 1	_	_	_	0.468

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Table 3. Top soil layer CCI soil moisture data product estimate comparison metrics/year against weighted areal average in-situ observations.

Year/Interval	No. Observations	Correlation	Unbiased RMSE	Bias
2014 (daily)	102	0.186	0.049	-0.046
2014 (weekly)	102	0.166	0.040	-0.046
2013 (daily)	134	0.621	0.033	-0.035
2013 (weekly)	134	0.813	0.020	-0.035
2012 (daily)	128	0.551	0.034	-0.044
2012 (weekly)	128	0.840	0.015	-0.044
2012–2014 (daily)	364	0.479	0.039	-0.041
2012–2014 (weekly)	364	0.637	0.026	-0.041



Figure 1. Locations of the Sodankylä study area, FMI's soil moisture CAL-VAL sites, the field campaign measurement sites and the CCI soil moisture data product pixel.



Discussion Paper





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Figure 3. Distribution of organic (Histosols) and semi-organic (Umbric Gelysols) soils within the Sodankylä region (left) and typical top soil profiles and vegetation (right).





Figure 4. Distribution of other less dominant soils; exposed bedrock, Leptosols, Eutric Regosols and Haplic Arenosols within the Sodankylä region (left) and a typical Arenosol top soil profile and vegetation (right).







Figure 6. Illustration of the impact of the new station (HP-F Forest 1) installation on spatially weighted average top layer soil moisture in comparison to average soil moisture without the new station between 1 June and 30 September 2015.





Figure 7. Timeseries of daily and weekly averaged top soil layer CCI soil moisture data product estimate comparison against daily and weekly averaged, weighted areal average in-situ observations for the years 2012, 2013 and 2014.





Interactive Discussion







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Interactive Discussion