SOIL MOISTURE CCI: PRODUCTION OF THE MOST COMPLETE AND CONSISTENT GLOBAL SOIL MOISTURE DATA RECORD

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ABSTRACT

Soil moisture influences hydrological and agricultural processes, runoff generation, drought development and many other processes. It also has an impact on the climate system by controlling land-atmosphere feedbacks. Soil moisture controls evapotranspiration over land, and therefore plays a crucial role in the water, energy, and carbon cycles. In 2010 soil moisture was recognised as an Essential Climate Variable (ECV). ESA's Programme on Global Monitoring of Essential Climate Variables (ECV), better known as the Climate Change Initiative (CCI), was initiated in 2010 for a period of six years. The CCI Programme aims to contribute to the ECV data bases as required by GCOS (Global Climate Observing System) and other international parties. The CCI Soil Moisture project started in January 2012 with the objective to produce the most complete and most consistent global soil moisture data record based on active and passive microwave sensors. This paper introduces the project and presents some results from the first 18 months of activities.

1. BACKGROUND

The CCI soil moisture project focuses on C-band scatterometers (ERS-1/2 scatterometer, MetOp Advanced Scatterometer) and multi-frequency radiometers (SMMR, SSM/I, TMI, AMSR-E, Windsat) as these sensors are characterised by their high suitability for soil moisture retrieval and a long technological heritage. Other microwave sensors suitable for soil moisture retrieval, including the Soil Moisture and Ocean Salinity (SMOS) mission, Synthetic Aperture Radars (SARs) and radar altimeters are not considered in the first phase of the CCI programme due to their recentness and/or their unfavourable spatio-temporal coverage.

Nevertheless, in order to make best use of existing European and international programmes, and to ensure that new sensors such as SMOS can be integrated quite easily in next phase(s) of the CCI programme, the design of the ECV production system is as modular as possible. The main characteristic of the approach is that the merging of the different sensor-specific data sets takes place at the level of the retrieved surface soil moisture data (Level 2). The conversion of the Level 1 backscatter and brightness temperature measurements to surface soil moisture is hence not considered to take place within the ECV production system itself, but before the ECV production system. In this way it becomes possible to make best use of already established Level 2 services of ESA, EUMETSAT, NASA, JAXA, etc. for the different satellites and sensors.

The CCI Soil Moisture project expects that this approach will encourage international cooperation in multiple ways, e.g. in terms of the ECV production process itself or in terms of defining GCOS standards.

2. THE ECV SOIL MOISTURE DATA SET

In June 2012 the project made the first public release of the version 1 ECV soil moisture data set generated within the WACMOS and CCI Soil Moisture projects. The ECV global soil moisture data set has been generated using active and passive microwave space-borne instruments and covers the 32 year period from 1978 to 2010 (Figure 1).

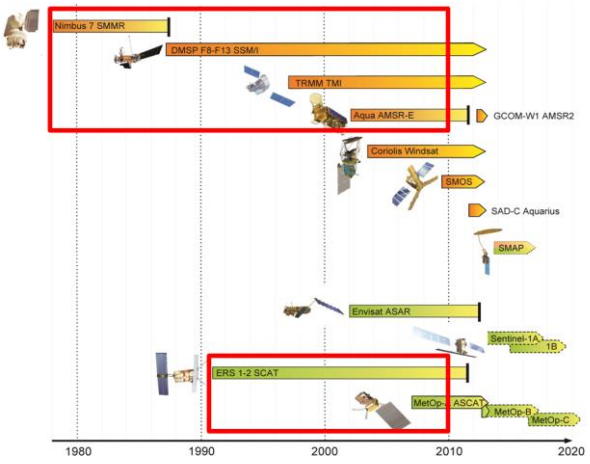

Figure 1. Sensors used for the production of the CCI ECV Soil Moisture data set.

Since its publication more than 700 users[1] requested the ECV soil moisture data with about three new requests daily. The ECV soil moisture data set was globally recognised with user requests originating from over 30 different countries largely stemming from research organisations, but also private companies and public bodies. The users have wide application areas and cover all nine GEO (Group on Earth Observation) societal benefit areas (SBA's) with focus on climate and water applications (Figure 2).

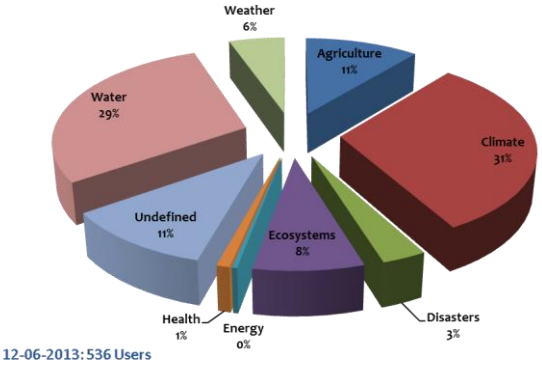

Figure 2. ECV Soil Moisture data set registered users work in all nine GEO Societal Benefit Areas.

Soil moisture is now seen to be one of the crucial earth observation data sets. Within the nine SBAs of Agriculture, Climate, Disasters, Ecosystems, Energy, Health, Water, Biodiversity and Weather, soil moisture is one of only three of the twenty five highest ranked earth observation parameters that is seen as a priority for all SBA's [1]. Only soil moisture, rainfall, and surface air temperature are listed as top priority, Earth Observation (EO) derived parameters, in all SBA's with soil moisture being the second most important parameter trailing slightly behind precipitation.

3. METHODOLOGY IN A NUTSHELL

The production system is described in detail in the ATBD document [2]. It starts from Level 1 calibrated backscatter values and Level 1 calibrated brightness temperatures for scatterometers and radiometers, respectively. The design of the production system is based on several scientific and system requirements. The most important scientific argument is the fact the retrieval from single sensors is best understood and implemented by dedicated groups specialised in the respective sensor and retrieval technique. Therefore, the ECV production system requires a modular system design where new or updated Level 2 data sets can be easily ingested, quality controlled, and assimilated in the ECV production.

In Phase 1 of the project, only input Level 2 products, based on the TU Wien method (for scatterometers), and the VUA-NASA LPRM algorithm (for radiometers) are considered. This results in the following structure of the ECV production system:

1. Level 2 soil moisture retrieval for single radiometer data sets using the VUA-NASA method [3].

2. Level 2 soil moisture retrieval for individual scatterometer data sets using the TU Vienna method first proposed by [4].

3. Fusion of the passive Level 2 data into a homogenised passive surface soil moisture ECV.

4. Fusion of the active Level 2 data sets into a homogenised active surface soil moisture ECV.

5. Rescaling of active and passive data to GLDAS-Noah reference

6. Testing sensitivity to vegetation density

7. Fusion of the merged active and passive data sets into homogenised active & passive surface soil moisture ECV.

A flowchart of the methodology to derive the ECV is shown in Figure 3.

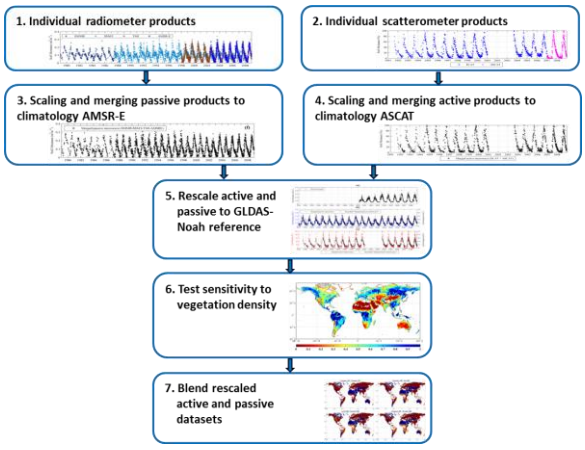

Figure 3. The methodology to derive the ECV Soil Moisture data set in a nutshell.

[1] As of 2013-09-04

4. UNDERSTANDING THE USER REQUIREMENTS

This novel ECV soil moisture product should benefit a wide range of applications and users, thus a thorough user requirement analysis was performed at the beginning of the project. Specific user requirement for the use of EO derived soil moisture products were derived for each of the nine societal benefit areas (communities).

A thorough a priori understanding of user requirements is helpful to direct the user requirement analysis and result in a solid product specification. Thus, the specific activities of the user requirement analysis included a literature review of the documented user requirements to date as well as an analysis of a user questionnaire that was made available online in October 2012. Sixty five users participated in completing and submitted the questionnaire. Users who downloaded the first ECV soil moisture data set were invited to evaluate and document, through the online questionnaire, their specific requirements, thereby incorporating their knowledge and expertise. The results of this user requirement analysis lay the foundation for a user requirement catalogue, defining all required details of the soil moisture ECV product that continues to drive further product development.

User requirements were recorded as users specified their required parameters for a number of precise product attributes. The following attributes were requested and analysed for each user group (defined by SBA category of product application); the geophysical parameters of interest, their required (and minimum acceptable) accuracy and stability, error characteristics expressed in terms of the ability to detect climate change over the natural variation in physical terms, expected and minimum acceptable resolution and coverage in time (observation cycle) and space, product format, metadata, quality flags/indicators and grid and projection.

It is already well understood that the definition of user requirements is best undertaken in an iterative process requiring both the active participation of users and EO data producers. Particularly at the early stages of the development of new EO products the requirements as formulated by both the producers and the users may be unrealistic. Only once real (i.e. not just simulated) EO data products become abundantly available the utility of EO products for different applications can be thoroughly assessed. The validation of the EO data quality and the development of alternative use cases by independent research teams is a very essential part in this process. This also means that meaningful user requirements can only be formulated after many years of research and development efforts. The user requirements analysis performed in the frame of the CCI Soil Moisture project is based on a wealth of a priori understanding about soil moisture data sets and profits from the fact that a first ECV soil moisture data set was already released in the CCI soil moisture project.

It became clear that most of the user requirements are already addressed with the current, first, version of the ECV soil moisture product, produced in the frame of the CCI project. Knowledge gained with this extensive user survey will serve as a basis to also meet the remaining user needs, such as a more frequent updating of the data set and an enhanced flagging. Besides, the Comprehensive Error Characterisation report (CECR) [5] could be updated with the latest knowledge on product performance, as outlined by several recent publications.

Current users are generally satisfied with the existing product, only product stability information is currently not provided. However, it became clear from the user requirement analysis that this parameter is either not clearly understood or not very important for the majority of users. Nevertheless, currently a study is being performed to obtain a clearer statement on this.

This user survey highlighted the key requirements and showed that the existing data set is already sufficient for many applications in all SBAs. To ensure that the soil moisture data set is used by a large user community an updated version of the ECV data set will be provided that aims to address all key requirements of users in all SBAs Requirements that were found to be of less importance such as product stability will be investigated, but it was useful to learn that some parameters initially thought to be of interest by the producers of the data set were indeed not so critical for users. The user requirements analysis has benefited from a close cooperation with the Climate Research Group engaged in the ECV CCI SM project.

5. THE ROUND ROBIN EXERCISE

The scientific community, alongside the user community, were invited to actively participate in the CCI Soil Moisture project. The goals of the Round Robin (RR) exercise, carried out in the frame of the project, were to encourage the active participation of the international science community in CCI soil moisture activities, and identify the “best” algorithms to be used in the ECV product generation. The Round Robin can be divided in two parts: 1) the Round Robin exercise where any interested person can participate and develop Level 2 soil moisture algorithms based on the material contained in the Round Robin data package, and 2) the Round Robin evaluation carried out by members of the CCI soil moisture project consortium.

The Round Robin was carried out at the beginning of the soil moisture CCI project, from May 2012 to December 2012. This public and open process benefited from the knowledge of the research community that works with soil moisture data sets. Consequently, the soil moisture CCI project welcomed every researcher and institution with the will to participate and contribute with their algorithms to this exercise.

Various external research groups applied their methodologies on the Level 2 data sets and demonstrated their performance. The Round Robin enabled the comparison of different algorithms and provided insight into their capacity to meet the targeted criteria defined in the product specification document.
The entire effort was organized to be as transparent as possible. All participants worked within a standardized environment: they had the same information about context and objective and worked with the same data set. The scope of the exercise, the input data set, the expected output, the validation data set and the evaluation methodology were defined in advance and are described in the Round-Robin Protocol document [6].

6. PRODUCT INTER-COMPARISON AND SELECTION

The assessment of the different algorithms participating in the Round Robin (RR) exercises for AMSR-E and ASCAT followed the rules defined in the RR protocol. The assessment was conducted with the RR evaluation and the results are summarized in the Product-Inter-Comparison and Selection Report [7]. The skill of the algorithms in terms of conventional evaluation measures (correlation, centered (unbiased) root mean square difference (RMSD) and standard deviation) was evaluated at 75 in-situ soil moisture sites from the International Soil Moisture Network as reference and summarized in Taylor plots. Furthermore, the triple collocation method was applied to estimate the error of the remotely sensed soil moisture (using in-situ and GLDAS model output as reference) and to assess the representativeness of the considered 75 validation in-situ sites. The RR evaluations were conducted separately for AMSR-E and ASCAT Level 2 products for the time period 2007-2010. The participating algorithms were all treated in the same way, i.e. the inter-comparison is based on equal spatial and temporal data sets. Scaled daily and scaled monthly absolute soil moisture as well as the corresponding short- and long-term soil moisture anomalies was investigated.

For AMSR-E, the following five institutions participated with their retrieved Level 2 products: VU University Amsterdam (VUA; C- and X-band), University of Montana (UMT), National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA). Ascending and descending paths are considered separately. This resulted in ten participating AMSR-E algorithms. For ASCAT the following four institutions provided Level 2 data: Vienna University of Technology (TU Wien), Institute of Applied Physics (IFAC-CNR), European Academy of Bozen/Bolzano (EURAC; delivered the algorithm Bayes and SVR) and the Finnish Meteorological Institute (FMI; delivered with and without auxiliary data), resulting in six algorithms assessed in the RR evaluation for retrieval from active microwave systems

The assessment of the different algorithms for the conventional measures and triple collocation method showed that none of the participating algorithm outperforms the other. All algorithms compare rather well. In particular, their mean performances for the scaled daily short- and long-term soil moisture anomalies are very similar. Moreover, this indicates that all participating algorithms seem to describe the physics behind the retrieval in a very similar way, despite large differences in the algorithms. Consequently, a “best” algorithm could not be chosen. The resulting outcome of the RR was that the ECV system will be implemented based upon the VUA method for retrieval of soil moisture from the passive systems and the TU Wien method for the active systems.

With respect to the representativeness of the in-situ sites for remotely sensed coarse-scale soil moisture, the triple collocation method concluded that the limited representativeness does not affect the error estimates for the satellite products.

7. PRODUCT VALIDATION

The validation of the final CCI ECV soil moisture product is an important mechanism to evaluate and characterize the errors and uncertainties of the established long-term soil moisture time series [8].

The validation will be performed with in-situ or other appropriate data sets that were not used for the production of the CCI product. However, it is a multi-faceted undertaking because there is no global reference data set that can be considered as a “truth” for the EO based surface soil moisture retrievals. In-situ soil moisture measurements, often referred to “ground-truth”, as they are assembled in the International Soil Moisture Network (ISMN) will not provide the final answer to the accuracy of the ECV soil moisture product.

Indeed these measurements have two major problems that need to be considered: the different measurement depths (microwave sensors sense within 0.5-5 cm while

in-situ sensors are typically installed at least at 5 cm depth) and the scaling problem (microwave sensors sense in the order of hundreds of km^2 while in-situ sensors represent a few dm^2). Moreover, the ISMN soil moisture data set is not available globally. Therefore, additional reference data sets and mathematical tools such as triple collocation or data assimilation are necessary to capture the various aspects necessary for a complete validation including the characterization of errors and uncertainties.

The final CCI ECV soil moisture product, due for release in mid-2014, will consist of three soil moisture time series (one active, one passive and one merged) with daily temporal resolution and a spatial resolution of 0.25°. Their assessment will be performed with appropriate data sets that are independent from the production of the CCI product using a range of statistical approaches. The final validation of the product will be carried out from December 2013 to August 2014.

8. OUTLOOK

Half way through the first project phase it can be stated that the developed ECV Soil Moisture data set is useful for a variety of applications and that the established methods of merging the active and passive data provide good results. Extensive validation activities will be carried out in 2014 but first results show that validation based on in-situ data appears to be an extremely delicate task. Such validation activities can be supported by land surface models. Good correlations with in-situ data and reanalysis were obtained in areas with a strong seasonal cycle (close to the Equator, Australia, and Central Asia). Overall, the quality of the CCI ECV Soil Moisture data set is consistent over time with respect to ERA-Land with slight increase in performance towards recent periods for $p<0.05$ for all periods. The current data set is far from perfect but an increasingly better understanding of flaws is already achieved. Current results have also shown that the data set can be useful for a better understanding of vegetation activity. A key issue for future research is to gain a better understanding of the driving mechanisms of soil moisture variability. Therefore, links and active engagement with several other CCI projects and data sets such as Sea Surface Temperature, Sea Level, Land cover and change as well as fires is of importance and initial collaborative activities will be instigated.

Acknowledgements
The CCI Soil Moisture project is part of ESA's Climate Change Initiative (CCI) programme that will run from 2009 to 2016. The aim of the programme is to realise the full potential of the long-term global Earth Observation archives that ESA, together with its member states, has established over the last thirty years, as a significant and timely contribution to the ECV databases required by United Nations Framework Convention on Climate Change (UNFCCC). For more information please see http://www.esa-cci.org/.

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