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GLOBAL SOIL MOISTURE DATA AND ITS POTENTIAL FOR CLIMATOLOGICAL AND METEOROLOGICAL APPLICATIONS

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ABSTRACT

Soil moisture is a key state variable of the global energy and water cycle. Accurate assessment of the soil moisture state and its spatial and temporal dynamics is therefore of crosscutting importance for many disciplines. Considerable technological progress during the last three decades leave no doubt that remote sensing from space afford the possibility of obtaining frequent global sampling of soil moisture over large fractions of the earth surface. Only recently the first global soil moisture data set based on remotely sensed data has been presented. The data set is derived from measurements taken by the ERS scatterometer, a coarse resolution active microwave instrument. First validation studies, using soil moisture data from global climate models and field data, indicate the good overall performance of the derived information. This paper gives an overview of our experiences gained with the ERS scatterometer as a basis to understand the potential of the Advanced Scatterometer ASCAT, which will be the operational continuation of the ERS scatterometers onboard EUMETSATs Polar System METOP.

1. INTRODUCTION

Soil moisture is a key state variable of the global energy and water cycle as it controls the partitioning of incoming radiative energy into sensible and latent heat fluxes. Thus soil moisture is considered to be the second most important boundary condition, second only to the sea surface temperature in the mid-latitudes, and it becomes the most important forcing function in the summer months. Along with snow cover, it is also the most important component of meteorological memory for the climate system over land. By controlling the partitioning of precipitation into infiltration and runoff, soil moisture also acts as a regulator to one of the most fundamental hydrologic processes, discharge. Knowledge of the state of soil moisture and its spatial and temporal dynamics is therefore essential for meteorological, climatologic and hydrological applications. Weather, climate, and extreme events forecast will all benefit from the operational availability of widespread observational data. But also our general understanding of hydrometeorological processes will improve. Still, until recently no convincing approach to global soil moisture monitoring had existed, which has been felt as a pressing deficiency by many. For example, Wei (1995) states: " … *the lack of global measurements and analysis of soil moisture remains an outstanding scientific problem with far reaching significance to mankind".*

Principally, there are many well-established methodologies to measure soil moisture on ground. However, area representative precise *in-situ* measurements are in general expensive and tedious to collect. Therefore, only a few large scale measurement networks providing widespread information exist (Robock, 2000). An alternative to ground based measurement networks are remote sensing techniques. Among the various techniques, especially microwave remote sensing (active and passive) provides the opportunity to collect truly quantitative soil moisture information. Microwaves offer relatively direct means of assessing soil moisture. They exploit, like many *in-situ* observation techniques, the strong relationship between the moisture content and dielectric constant of soil. Technological and methodological progress of recent years have resulted in the approval of dedicated soil moisture missions. ESAs Soil Moisture and Ocean Salinity Mission (SMOS) and NASAs HYDROS are expected to provide a flow of high quality coarse resolution soil moisture data. Apart from these dedicated hydrometeorological missions, a sensor initially designed for ocean applications, the ERS scatterometer, has attracted the attention of the scientific community. Based on ERS scatterometer data the first global remotely sensed soil moisture data set has been derived and was found to be of reasonable accuracy. The ERS scatterometer mission will find continuation on EUMETSATs Polar System METOP, carrying the Advanced Scatterometer ASCAT. The system presents one of the few operational systems with security of long-term tenure and funding. This paper will therefore give an overview of the potential of the Advanced Scatterometer for global soil moisture retrieval.

2. SOIL MOISTURE FROM SCATTEROMETERS

Scatterometers are active microwave sensors (radars) designed to retrieve wind speed and direction over the oceans. However, it is increasingly acknowledged that the unique technical characteristics of the sensors are also beneficial for monitoring highly dynamic geophysical processes over land. The ERS scatterometers are radars operated in C-band. They have been flown on the European Remote Sensing Satellites ERS-1 and ERS-2 operated by the European Space Agency. The instrument has been providing global coverage since the launch of ERS-1 in 1991, with a revisit time of about 3-4 days, acquiring imagery independent of cloud cover and of the sun as source of illumination. The fundamental reason why any microwave technique, and in particular the ERS and METOP scatterometers, offer the opportunity to measure soil moisture in a relatively direct manner is the high sensitivity of microwaves to the water content in the soil surface layer due to the pronounced increase in the soil dielectric constant with increasing water content. This is specifically the case in the low frequency region (1-10 GHz). However, scattering from land surfaces also depends on other factors. The benefit of using the ERS and METOP scatterometers for soil moisture retrieval is their unique sensor design, which enables direct accounting for the confounding effects of surface roughness, vegetation and dielectric properties. Following are the outstanding sensor characteristics: 1) The multi-incidence angle viewing capability which allows separating vegetation and soil moisture effects which both influence the measured backscatter coefficient, 2) The high temporal sampling rate which allows monitoring of highly dynamic processes such as the soil moisture process 3) The excellent radiometric accuracy which results in a low noise level and allows analysing multi annual time series.

For retrieval of soil moisture from ERS scatterometer data, a change detection algorithm tailored to the sensor characteristics has been developed by Wagner et al. (1999). The algorithm exploits, similar to the algorithm foreseen for SMOS, the multiple viewing capabilities of the sensor in order to separate soil moisture and vegetation effects. It also allows accounting for the effects of heterogeneous land cover and surface roughness. Unlike more complex theoretical or semi-empirical approaches often preferred for retrieval purposes, change detection is attractive for global applications because applied to radar backscatter time series it represents an indirect way of accounting for surface roughness effects. Particularly at the spatial scale of scatterometers (tens of kilometres), surface roughness changes due to farming activities or other effects can be assumed to have negligible effects on the scatterometer recorded backscatter time series. Also, change detection applied to ERS scatterometer data accounts for heterogeneous land cover since many land cover classes such as forests, dense shrubs, urban areas and small inland water bodies are characterised by relatively stable C-band backscatter values and hence do not need to be separately modelled. On the other hand, the model must consider vegetation growth and decay over grassland and agricultural regions since this may cause backscatter to change by several decibels. The increase in biomass may increase or decrease backscatter depending on the incidence angle and soil moisture conditions. An increase in backscatter is typically encountered at high incidence angles and dry soil conditions, whereas a decrease at low incidence angles and wet soil moisture conditions. Since this effect is captured by the multi-incidence observations of the ERS scatterometer it becomes possible to quantitatively correct for the effects of vegetation phenology. As a result, time series of the topsoil moisture content are obtained.

3. FROM ERS TO METOP

The successor of the ERS Scatterometer will be the Advanced Scatterometer which will be flown on a series of three METOP satellites. METOP is a joint project of the European Space Agency and the European Organisation for the Exploitation of Meteorological Satellites. The design of ASCAT is based on the successful concept of the ERS scatterometers. Like its predecessors, ASCAT will use fan-beam antennas operating in C-band. However the experience acquired with nearly one decade of operations of the ERS scatterometers and technological advances have lead to significant improvements.
The most prominent improvement of ASCAT will be an increased spatial and temporal resolution. Although it is planned that the initial data product of ASCAT will be made available at 50 km resolution (like for the ERS scatterometers) EUMETSAT plans to distribute data also in a scientific format at 25 km resolution. To improve the temporal resolution ASCAT will use six antennas which cover two swaths to the left and right of the satellite track instead of three antennas with only one swath which was the case for ERS. Additionally ASCAT will provide continuous data acquisition without sharing operation time with other sensors. As a result, the instrument acquires data from 82 % of the earth surface within one day, which will significantly increase the temporal sampling rate compared to the ERS Scatterometer. It can also be expected that improved instrument design will result in higher stability and reliability of the data. Finally, EUMETSATs Polar System satellites, which will carry the ASCAT sensor, are planned as an operational system with security of long-term tenure and funding starting its operation with the METOP-1 satellite in 2005. Currently a series of three satellites is planned for a nominal lifetime of 14 years. Given the similarity between the ERS scatterometers and the ASCAT scatterometers, the methods developed for the ERS scatterometer should be directly applicable for ASCAT after an initial test phase. It can therefore be expected that a consistent data set of the soil hydrology starting with 1991 will be available to the scientific community.

4. SOIL MOISTURE PRODUCTS

Currently two soil moisture products are derived from ERS scatterometer data, surface soil moisture and profile soil moisture. The surface moisture is a relative measure of soil moisture in the first centimetre of the soil ranging between 0 and 100, representing the degree of saturation. Soil moisture can only be retrieved under snow-free conditions. Over dense tropical forest retrieval is not possible which affects about 6.5 % of the land surface area. Also in sand desert areas spurious effects are observed in the backscattered signal. These are related to azimuthal viewing effects which are currently not correctly treated in the retrieval and therefore masked. The other product is the profile soil moisture or Soil Water Index (SWI). The *SWI* is a relative measure of the soil moisture content of the 1 meter soil layer ranging between 0 and 100 (Figure 1).
In order to retrieve soil moisture measurements over greater depths (up to about one meter) a two-layer water balance model, which only considers the exchange of soil water between the topmost remotely sensed layer and the “reservoir” below, was used to establish a relationship between the topsoil series and the profile soil moisture content (Wagner et al., 1999). The water content in the soil profile is estimated by convoluting the surface soil moisture series with an exponential filter. The derived profile soil moisture time series has a spectrum similar to that of a red-noise process, which is often used to describe the statistical properties of modelled and *in-situ* soil moisture data. If soil hydrologic properties are known (wilting level, field capacity and total water holding capacity) the SWI can be related to the volumetric soil moisture content.

5. NEAR REAL TIME CAPABILITIES

Scatterometers are designed to continuously record and transmit data to the ground stations. Due to the low data bit rate, the processing load is moderate and an operational application of the proposed technique is realistic. A prototype near real time operator for soil moisture retrieval has already been tested and implemented for the ERS scatterometer to monitor soil moisture conditions over Africa and Central Asia for the Food and Agriculture Organisation of the United Nations. The system has been operated for nearly six month and delivered soil moisture data on a weekly basis. Unfortunately, the system had to be discontinued after the ERS scatterometer mission has temporarily been stopped due to technical problems.

Given the very similar technical characteristics of the ERS and the Advanced scatterometer it is possible to use the existing algorithms to deliver operational 25 km soil moisture products in quasi-real time (2-3 hours after reception) with an expected accuracy of about 0.05 m^3m^{-3}. Every day to every other day the Advanced scatterometer could deliver an update of the status of the regional soil moisture conditions within a few hours after data reception. Technically near real time processing can be started immediately after the Advanced scatterometer is in an operational phase. The required datasets for retrieving soil moisture from ASCAT data can be set up using historic ERS scatterometer measurements (for reliable soil moisture retrieval knowledge of backscattering characteristics for each point of the earth surface is required which is extracted from long time series spanning several years of data). Given the similarities between the sensors, using the historic backscatter data should not constrain the retrieval of soil moisture from ASCAT data. An optimisation of the retrieval will be achieved by frequent reanalysis of the historic backscatter knowledgebase incorporating data from ASCAT.

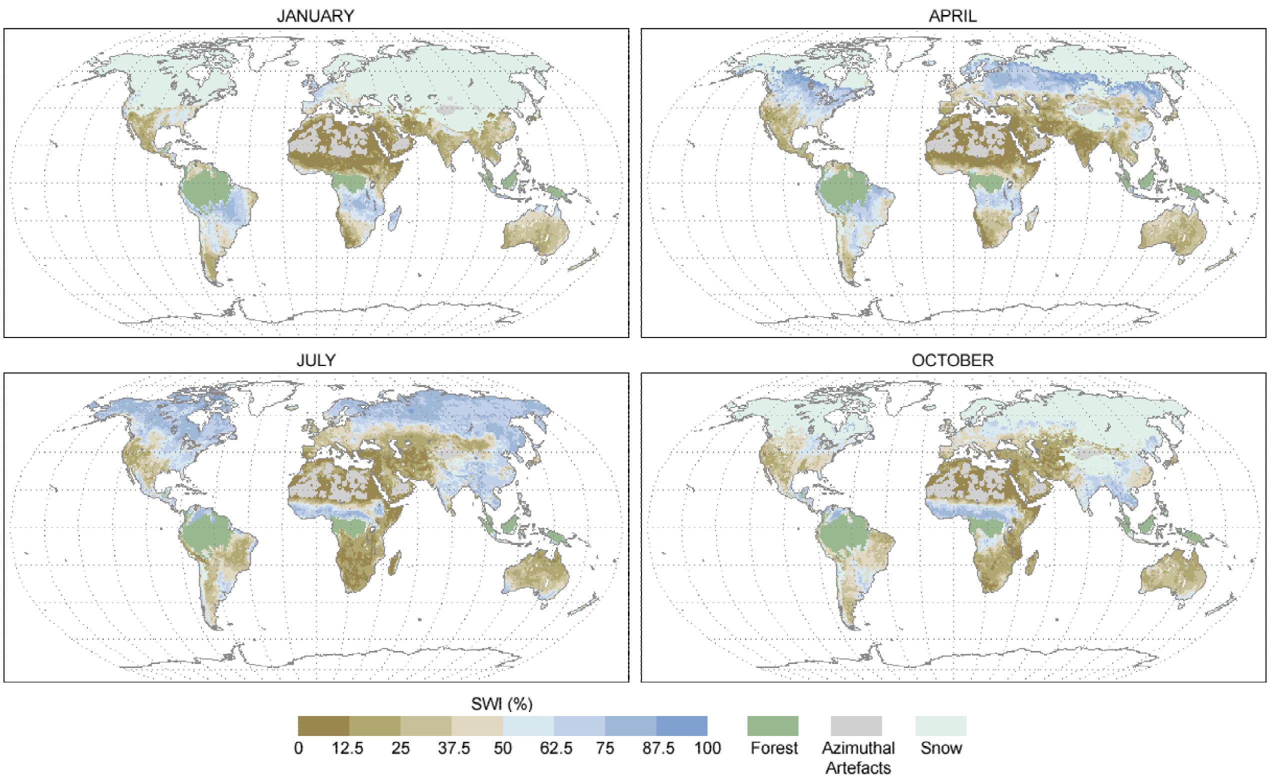

Figure 1. Mean monthly Soil Water Index derived from ERS scatterometer data for January, April, July, and October. Brown colour tones indicate dry conditions, blue colour tones indicate wet conditions.

6. ACCURACY

To assess the quality of scatterometer derived soil moisture, data has been compared extensively with soil moisture information from various sources. Wagner et al. (2003) compared scatterometer derived monthly soil moisture estimates with global gridded precipitation data and global modelled soil moisture of the 0-50 cm layer. The study showed that there is reasonable agreement between the different datasets especially under tropical and temperate climates. Only in extreme climates such as deserts and the arctic, spurious effects have been observed. Given, that the accuracy of the gridded precipitation and the modelled soil moisture is not known it is not possible to draw any quantitative conclusions. Considering that the datasets are independent it is however reasonable to assume that a high agreement indicate regions of good data quality and that in such a case upper limits of the accuracy of the scatterometer derived soil moisture can be inferred. This upper limit has been determined to be in the range of 0.03-0.07 m^3 m^{-3}. The comparison with gridded precipitation also showed that reasonable agreement can only be achieved over areas with high station density. This observation led to the impression that remotely sensed soil moisture, being independent of the availability of ground data, can improve our capabilities to monitor extreme soil moisture conditions especially in regions with sparse station networks. Dirnmeyer et al. (2003) have compared the scatterometer data set with seven other global wetness products, three produced by land surface model calculations, three from coupled land atmosphere reanalysis, and the NOAA/NESDIS data set derived from SSM/I radiometer data. They found that, while the SSM/I data have clearly a different character than all of the other data sets, the ERS scatterometer data revealed many similarities with the modeled wetness products. In another study Campling and De Belder (2003) found that there is a significant correlation between the ERS soil moisture data and the ERA-40 reanalysis data set produced by the European Centre for Medium Range Weather

Forecasts (ECMWF) for the major cultivated regions of the globe. On the other hand, low correlations were observed over high-latitude regions and desert areas. Over some test sites it was observed that ERA-40 rainfall deviated strongly from observed rainfall, in which case ERA-40 modelled soil moisture data appeared to be unrealistic.

A quantitative assessment of the quality of the soil moisture product was carried out by Scipal (2002) using over 45000 soil moisture measurements from 372 stations worldwide. Samples were taken at agrometeorological large-scale measurement networks located in Russia, Ukraine, China, Mongolia and the US, covering a wide range of soil types and climatic regions. For Ukraine, Russia and Illinois soil moisture samples from a depth of 1m were compared. In India and China, soil moisture samples from a depth of 50 and 60 cm respectively were used, as samples of deeper layers were not available. Statistical analysis indicated an accuracy of scatterometer derived soil moisture for the 1m layer between 0.049 m^3m^{-3} and 0.084 m^3m^{-3} depending on the measurement network. The average accuracy was determined to be 0.054 m^3m^{-3}. Even better values have been determined for soil moisture anomalies with an average accuracy of 0.032 m^3m^{-3}. A more detailed study, was carried out by Ceballos et al. (2003) who compared scatterometer derived soil moisture to field observations from the REMEDHUS network. All stations of the REMEDHUS network are within one scatterometer pixel therefore allowing a more detailed assessment of soil moisture conditions of the covered region. For the comparison, data from twenty stations were averaged. The resulting time series compared well with scatterometer derived soil moisture. The coefficient of estimation R^2 for the average soil moisture profile (0-100 cm) reached a value of 0.74 and the mean square error (RMS error) was 2.2 vol.%.

7. OTHER SOIL MOISTURE MISSIONS

The insistent request for soil moisture data coupled with technological and methodological progress of recent years have resulted in the approval of dedicated soil moisture missions. In the next couple of years several satellite missions, both operational and experimental will be available to observe global hydrometeorological processes (Figure 2). Two missions which have received much attention in recent years are the experimental satellite missions SMOS and HYDROS. SMOS is ESA's second Earth Explorer Opportunity Mission and will make passive measurements at a spatial resolution of about 40 km. HYDROS is a NASA Earth System Science Pathfinder mission and will combine a radiometer (40 km) and a radar (3 and 10 km). Foreseen launch dates are 2007 and 2010 respectively. As a lower microwave frequency is beneficial for soil moisture retrieval (longer wavelengths are more able to penetrate vegetation), both missions are operated in L-band. These two missions will perform first-of-a-kind exploratory measurements and aim to measure soil moisture with an accuracy of 0.04 m^3m^{-3}. Besides these two dedicated soil moisture missions there are other operational radiometer systems which have been found capable of soil moisture retrieval.

Among the latest generation of radiometers is the Advanced Microwave Scanning Radiometers, AMSR-E, which was launched in 2002 onboard the AQUA satellite. This instrument receives at 6 frequencies ranging from 6.9 GHz (C-Band) to 89.0 GHz, with a spatial resolution ranging between 56 km (6.9 GHz) and 5.4 km (89 GHz). One general problem with the AMSR and similar radiometers planned for the future such as the Conical-scanning Microwave Imager/Sounder (CMIS), which have their lowest frequency channel in C-band, is that within this frequency band there is no international allocation for the passive Earth Exploration Satellite Service (EESS). Therefore, retrieval from C-band brightness temperature data may be hampered by Radio Frequency Interference (RFI) over populated areas. One advantage of radiometers compared to radars is that the retrieval from passive data appears to be less confounded by surface roughness effects than from active data. However, no globally consistent soil moisture data set has yet been derived from spaceborne radiometers. Therefore, the achievable accuracy and potential problems can at the present not be thoroughly assessed.

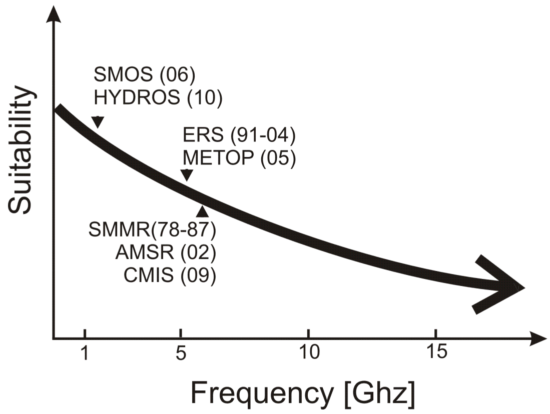

Figure 2: Suitability of satellite missions for soil moisture retrieval.

8. BENEFITS

Soil moisture is regarded to be a key state variable of the global energy and water cycle. It is commonly recognised that, with the operational availability of widespread observational data, our understanding of hydrometeorological processes will improve as well as forcasting of weather, climate, and extreme events. The future generation of satellite systems will for the first time make global operational soil moisture observations a reality. The METOP satellite series of EUMETSATs Polar System with its Advanced Scatterometer onboard will share an outstanding role together with other systems. METOP will be the first operational satellite system with a proven and tested capability to retrieve soil moisture information. Together with its predecessors, the ERS scatterometers, it will be possible to obtain continuous soil moisture information starting with 1991, with an estimated accuracy of 0.06 m^3m^{-3}. The system will also allow near real time processing of data. Such nearly every second day a global assessment of the soil moisture state will be available. The operational character will also have implications on the scientific and commercial exploitation of the data. Given that soil moisture plays a crucial role in various disciplines, a potentially large user community will be attracted. For example making experimental global soil moisture data, derived from the ERS scatterometer sensor, available on the internet has attracted the interest form nearly 60 research institutions with a background in climatology, hydrology, agronomy and ecology.

9. REFERENCES

CAMPLING, P., DE BELDER J. (2003) CLIMSCAT Qualification Report, European Space Agency, Data User Programme 2001, http://dup.esrin.esa.it/projects/summaryp40.asp.

CEBALLOS A., SCIPAL K., WAGNER W., MARTÍNEZ-FERNÁNDEZ J. (2004) Validation of ERS Scatterometer-Derived Soil Moisture Data in the Central Part of the Duero Basin, Spain, Journal of Hydrologic Processes, *in press*.

DIRNMEYER, P. A., GUO Z., GAO X. (2003) Validation and forecast applicability of multi-year global soil wetness products, COLA Technical Report, Center for Ocean-Land-Atmosphere Studies, http://www.iges.org/, 12. December 2003.

ROBOCK A., VINNIKOV K. Y., SRINIVASAN G., ENTIN J. K., HOLLINGER S. E., SPERANSKAYA N. A., LIU S., NAMKHAI A. (2000) The Global Soil Moisture Data Bank. Bull. Amer. Meteorol. Soc., vol 81, pp. 1281-1299.

SCIPAL K. (2002) Global soil moisture retrieval from ERS scatterometer data, Dissertation, Vienna University of Technology.

WAGNER W., LEMOINE G., ROTT H. (1999) A method for estimating soil moisture from ERS Scatterometer and soil data. Remote Sensing of Enviroment, vol 70, pp. 191-207.

WAGNER, W., SCIPAL K., PATHE C., GERTEN D., LUCHT W., RUDOLF B. (2003) Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data, Journal of Geophysical Research – Atmospheres, Vol. 108, No. D19, 4611, doi: 10.1029/2003JD003663.

WEI, M.-Y., Ed., (1995) Soil Moisture: Report of a Workshop Held in Tiburon, California, 25-27 January 1994, NASA Conference Publication 3319, 80 pp.