New data products provided by SMOS have been opening the door for novel applications (Image - MetroTiff)

→ SMOS OVER LAND

New applications for ESA's water mission

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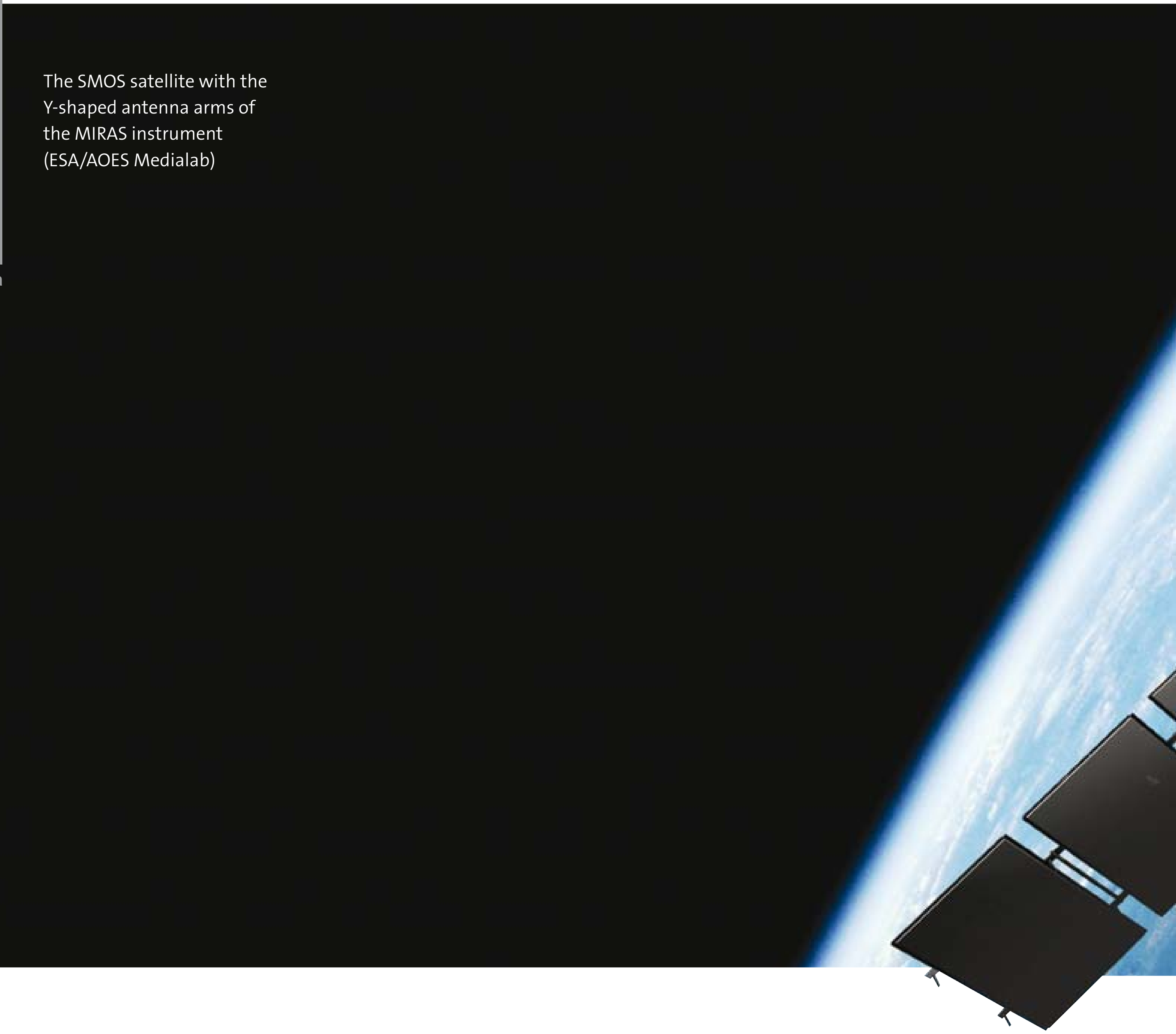
After three years in space, the number and variety of applications of ESA's water mission SMOS have exceeded expectations. Novel data products have been opening the door for new application areas.

Launched in 2009, SMOS, standing for Soil Moisture and Ocean Salinity, is observing key elements of Earth's water cycle. SMOS is the second Earth Explorer Opportunity mission to be developed as part of ESA's Living Planet Programme. Designed to operate for three years in orbit, SMOS is in very good shape technically at the end of its nominal mission lifetime and is thus able to continue to provide data beyond 2012.

One of its main features is a pioneering instrument called MIRAS, the first synthetic aperture L-band radiometer ever operated from space. This instrument works on the same principle as an array of astronomical radio telescopes – but it points back to Earth, not out into space. It features 69 separate radiometer receivers assembled on three arms in a Y-shaped configuration. As well as demonstrating the use of this new instrument, the data acquired from this mission will contribute to furthering our knowledge of Earth's water cycle.

Soil moisture and sea-surface salinity are two variables in Earth's water cycle that scientists need on a global scale for a variety of applications, such as oceanographic,



The SMOS satellite with the Y-shaped antenna arms of the MIRAS instrument (ESA/AOES Medialab)

meteorological and hydrological forecasting, as well as research into climate change.

Moisture and salinity decrease the 'emissivity' of soil and seawater respectively, and thereby affect microwave radiation emitted from Earth's surface. To observe soil moisture over Earth's landmasses and salinity over the oceans, SMOS effectively measures the microwave radiation emitted from Earth's surface. MIRAS picks up faint microwave emissions to map levels of moisture in the ground and the saltiness of the oceans, and these are provided as 2D images, or 'snapshots', of 'brightness temperature'. SMOS makes these measurements in the L-band (electromagnetic waves with a wavelength of 21 cm)

> **"The enthusiasm in the corresponding scientific communities with the number and variety of applications has clearly exceeded our expectations."**

because it is particularly well suited for observing the ocean and land surfaces.

Measurements made in this band are hardly affected by the atmosphere and clouds, and even vegetation looks transparent over large regions of the world. Because this radiation partly originates from inside the water and the soil, the properties of the top layers can be determined down to a depth of several centimetres.

SMOS is also the first ESA Earth Explorer mission with a dedicated near-real-time processing chain for its brightness temperature observations in its operational ground segment. This means that the observations have to be delivered to the end user within 180 minutes of sensing. This fast data processing is a prerequisite for many users who produce forecasts, such as weather centres and hydrological agencies.

To date, SMOS is performing very well according to its system requirements for the satellite and the ground segment. The derived Level 2 soil moisture datasets meet the mission requirements and have been widely used by the science community.

However, a measure of success for an Earth Explorer satellite mission could also be its potential impact for operational applications and on its added socio-economic value.

SMOS data are currently being used in weather and flood forecasting. Drought monitoring systems based on SMOS

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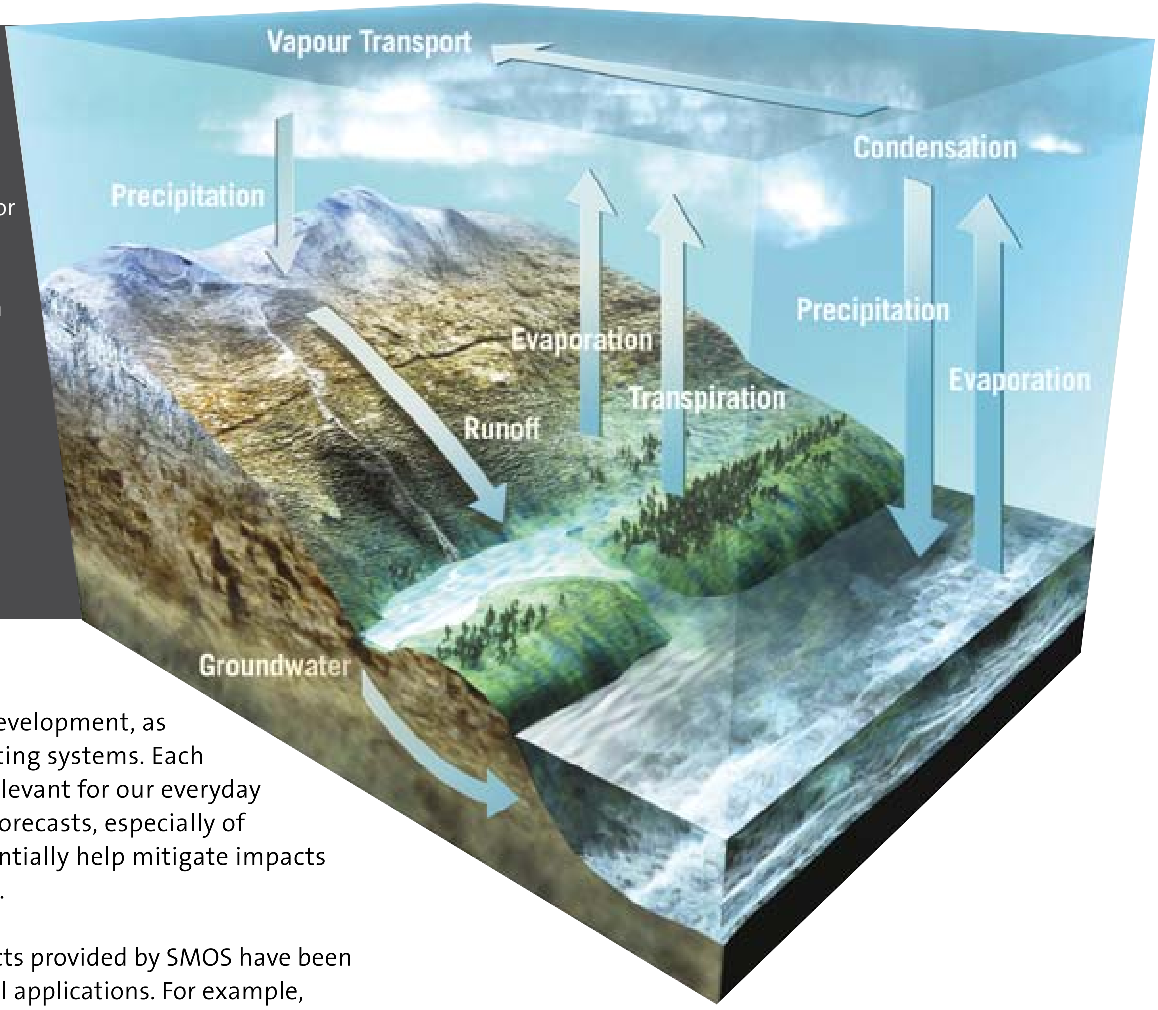
Soil moisture and ocean salinity are the key geophysical parameters for enhanced understanding of the terrestrial water balance, ocean circulation and climate change



observations are under development, as well as crop yield forecasting systems. Each of these areas is highly relevant for our everyday lives. Improved weather forecasts, especially of extreme events, can potentially help mitigate impacts and save billions of euros.

Recently, new data products provided by SMOS have been opening the door for novel applications. For example, it was found that the freeze-thaw cycle of soils can be determined, and this could result in the improved monitoring of the active surface layer in permafrost regions and a more accurate description of the gas exchange between land surfaces and the atmosphere, which is highly relevant for our climate system.

Applications

Soil moisture is a key variable determining the exchange of water and energy between the land surface and the atmosphere. SMOS soil moisture data have their own scientific value, because they provide an independent estimate of the current state of the land surface. Monitoring the spatial and temporal global dynamics of soil moisture is important for a variety of applications, such as water resources management, weather forecasting, agriculture, flood prediction and climate research. An additional socio-economic value of these Earth observation data comes from their use in forecasting systems and the subsequent decision-making process.

To reduce forecasting uncertainty, satellite observations can be used in data assimilation systems to improve the accuracy of the initial conditions. For our daily weather forecasts, out to a few days ahead, soil moisture mainly influences the development of air temperature and humidity in the lower atmosphere. Locally, convection, the formation of clouds and subsequent precipitation events, can be modified or triggered by the amount of water in the soil and its availability for the atmosphere as well.

“Improved weather forecasts, especially of extreme events, can potentially help mitigate impacts and save billions of euros.”

↑ The drought-stricken Debar Lake, 150 km west of Skopje in Macedonia. The western Balkans have been hit by an ongoing heat wave this September that has seen temperatures over 42°C, triggering hundreds of wildfires (Miller and Farmer Assoc.)

Early studies by ECMWF indicated that the use of satellite-derived soil moisture estimates reduces the errors in the temperature and humidity forecasts and influences a variety of weather parameters.

Soil moisture also plays an important role in long-range forecasts, such as in monthly and seasonal weather prediction. For example, it could be shown that the 2003 heatwave in Europe followed a very dry spring. Low soil moisture contents over large parts in Europe influenced the onset and the duration of this very extreme event, which led to the deaths of over 30 000 people and damage costing an estimated €11 billion in the farming, livestock and forestry industries alone. Using SMOS data in seasonal forecasting systems will be addressed in a future scientific study starting in 2013.

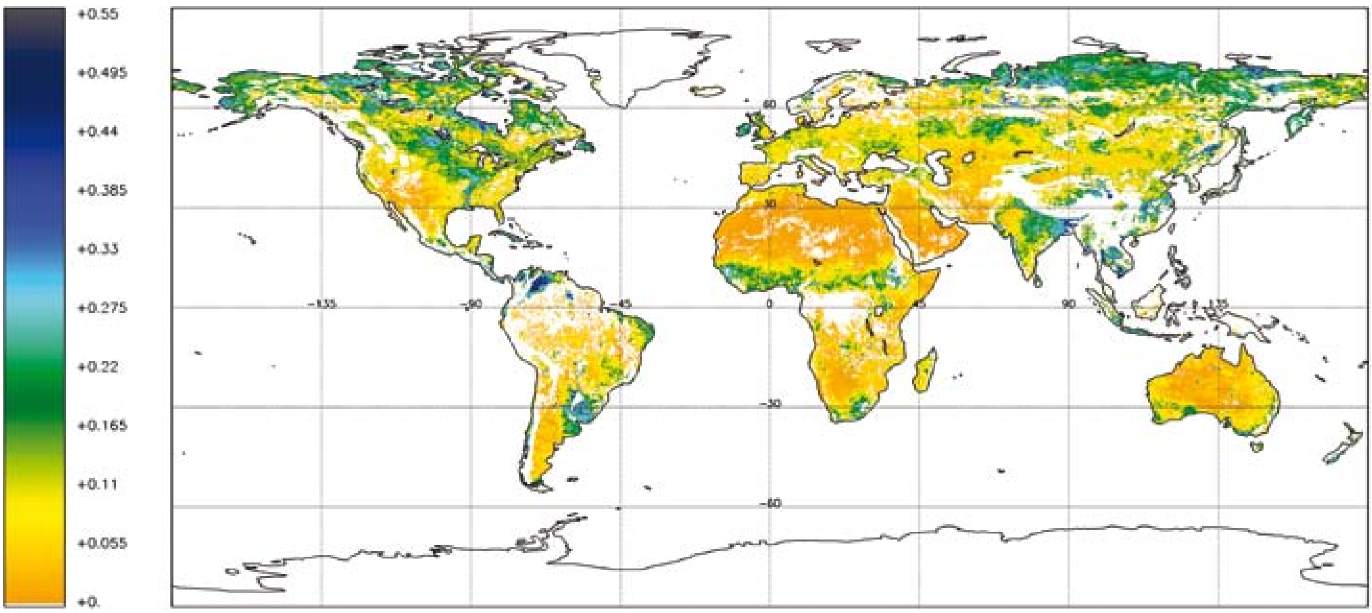
The dynamics of surface soil moisture are an important source of uncertainty in flood forecasting models as well. Floods, as a consequence of too much water runoff, can be generated through saturation excess overland flow and infiltration excess overland flow. In the first case, soil moisture determines how much water can be stored in the soil before runoff and flooding starts. In the second case, soil moisture determines the infiltration capacity and the moment when runoff starts. Knowing the soil moisture distribution before an expected heavy rainfall event will in both cases help to determine whether the water reaching the land surface can infiltrate and be stored in the soil or will cause flooding.

Combining information on storm tracks, the corresponding precipitation forecasts and SMOS soil

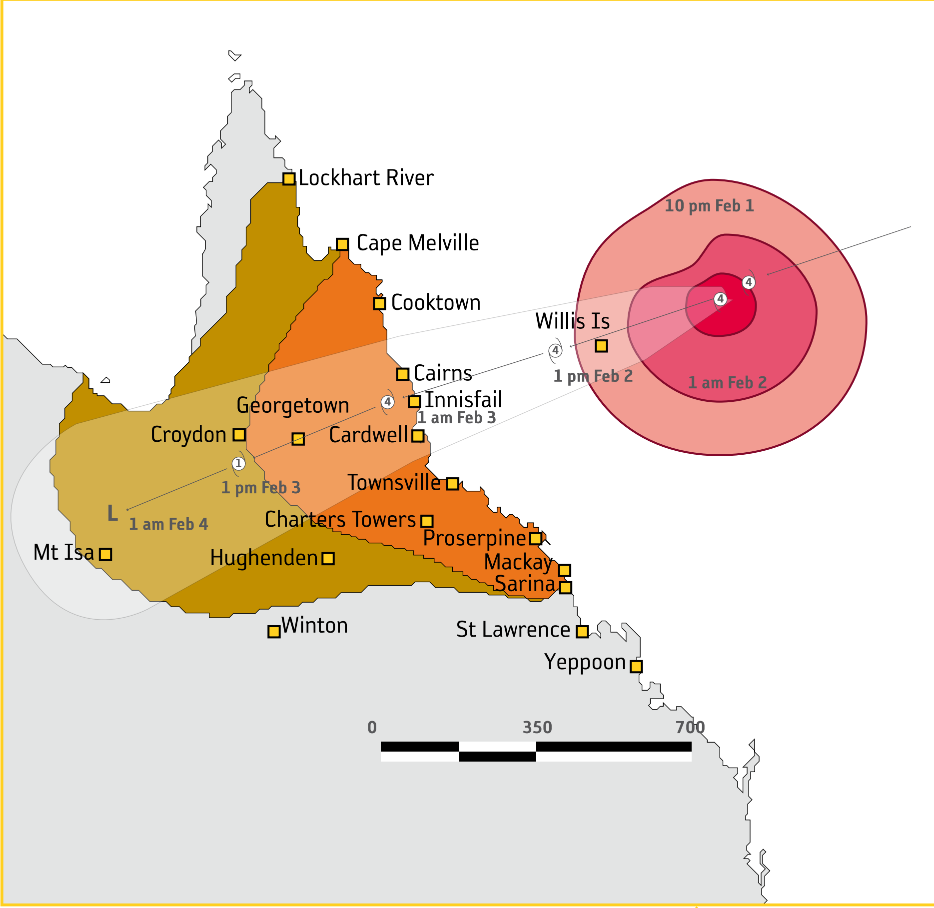
↑ Roofs of houses are visible above flood waters in Brisbane, Australia, during disastrous floods in early 2011 (Reuters/T. Wimborne)

moisture maps can give us flood risk maps, which can be used to mitigate the effects of extreme weather events. The concept was demonstrated using data over Australia's east coast in 2011 and which is being further developed by an international consortium through the 'SMOS + Hydrology' study within ESA's Support to Science Element (STSE) programme.

The growth of vegetation is intrinsically dependent on the amount of plant-available soil moisture for photosynthesis



↑ Global surface soil moisture fields for June 2011, with moisture in m³/m³ (CESBIO/Y. Kerr)



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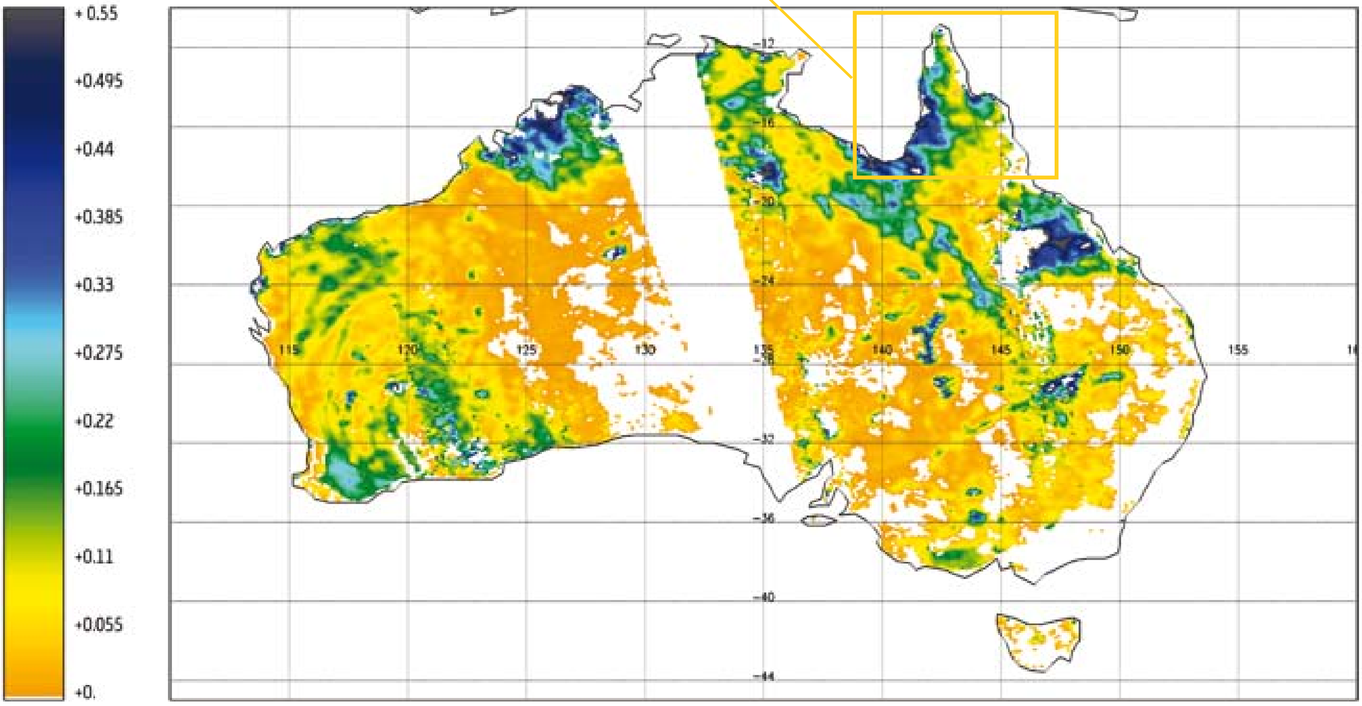
The forecast storm track issued by the Bureau of Meteorology shows that the centre of the storm was expected to hit the coast on 3 February with heavy rainfall. By combining information from the weather forecast and the soil moisture state from SMOS, the risk of severe flooding could be assessed. Here, the risk was assumed to be low because the rain from this storm could be largely absorbed by the relatively dry soil. If the storm had hit the coast further south, where the soil was already saturated, the risk of severe flooding would have been high



↑ SMOS-derived soil moisture conditions in Australia for 29–31 January 2011, just before a tropical storm system hit the northeast coast, with moisture in m³/m³ (CESBIO/Y. Kerr)

→ How do we verify SMOS data?

Brightness temperature data

The key data produced for the user communities are geolocated 'brightness temperatures' for the individual orbits of the satellite. Radiative transfer calculations are needed to extract the information on geophysical parameters, such as surface soil moisture, vegetation opacity or soil frost depth.

Three brightness temperature (Level 1) data streams have been implemented in the ground segment: (1) a near-real time product providing operational power users (such as the European Centre for Medium-range Weather Forecasts, ECMWF) with global observations within three hours of sensing, (2) a near-realtime 'light' product with a reduced spatial coverage over land areas for hydrological applications, and (3) the nominal Level 1C product received by the user within 12 to 48 hours.

Data products have been made available to users operationally since the end of the SMOS commissioning phase in May 2010 and the payload data ground segment is performing to expectations.

Verification and quality control

Verifying these top-of-the-atmosphere brightness temperature observations and assessing the products' accuracy is extremely difficult and is done independently from the in-orbit instrument calibration.

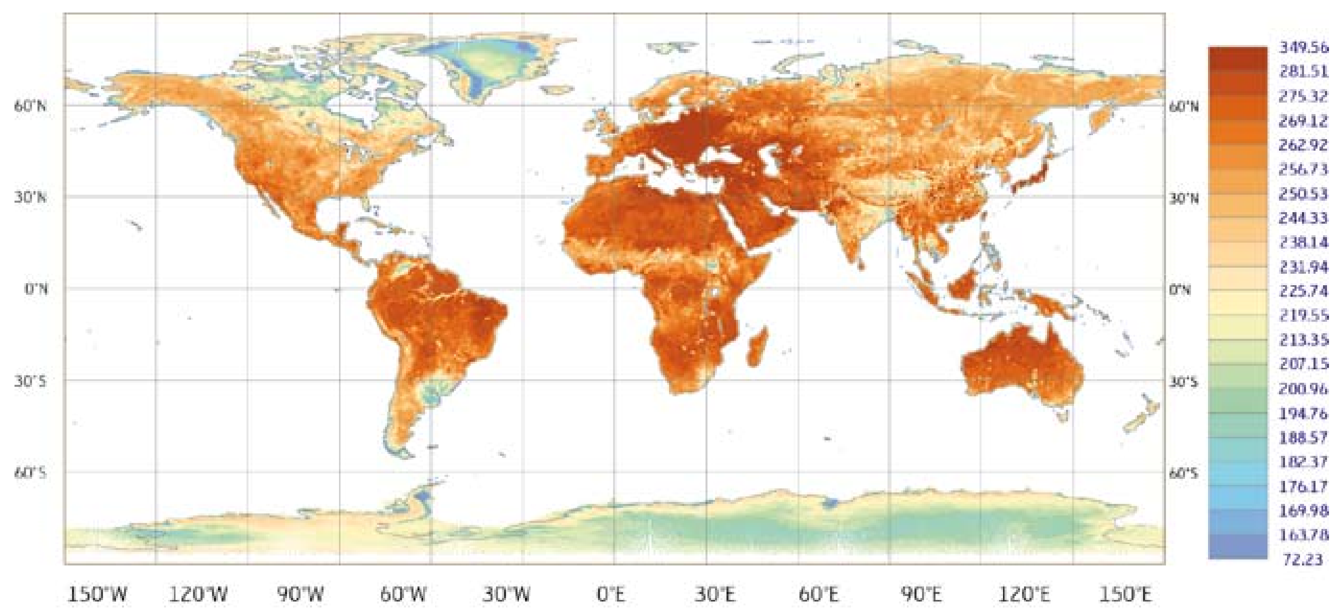
An external homogeneous target is needed, one that is large enough to represent an individual observation of about 2500 km^2, and with dielectric properties that hardly vary with time. This target should also be well positioned with respect to the instrument's observation geometry to ensure systematic and frequent revisits.

One such area that fits these requirements is the East Antarctic Plateau, specifically the area near the Italian/French base of Concordia. This site is particularly well suited for Level 1 product verification because the extinction of radiation of dry snow is low, the upper ice sheet layer is almost transparent for low-frequency microwave observations and the observed signal mainly originates from the thermally stable deep ice layers.

For the evaluation of the satellite data, a radiometer operating at the same frequency was installed on a tower at Concordia and operated from 2008 to 2010. Both instruments, the tower-based radiometer and the SMOS MIRAS, provided data for a direct comparison. Time-series indicate an excellent agreement between the satellite observations and the ground truth.

However, operating a ground-based radiometer over Antarctica is expensive and only feasible for limited periods when there are dedicated campaigns. The ECMWF is performing day-to-day quality control of the brightness temperature observations

↓ Mean SMOS brightness temperatures in Kelvin for September to October 2012 as monitored by ECMWF (www.ecmwf.int/products/forecasts/d/charts)



A view of the tower-based radiometer RadomeX and ice-sheet area at Concordia Station (G. Macelloni/IFAC-CNR)

within their data-monitoring framework. Together with more than 100 million observations per day delivered from satellites, aircrafts, ships, buoys, radiosondes and weather stations, the SMOS observations are compared against modelled brightness temperatures based on the daily weather forecast.

Although this approach does not allow an absolute validation of the SMOS product, trends, jumps and spikes in the satellite observations can be detected against a stable reference, meaning statistics derived from the global forecast fields. In addition, the ECMWF monitoring allows a comparison against similar satellite data, for example from the Special Sensor Microwave/Imager. More than 600 images are produced each day and published for public access through the ECMWF web site for the SMOS quality control only.

and the assimilation of carbon. When soil moisture becomes a limiting factor for these processes, information on this anomaly can provide a leading signal for subsequent problems in vegetative health and a shortfall in plant productivity. Consequently, soil moisture information is commonly used in operational drought forecasting activities. For example, the US Department of Agriculture's Foreign Agricultural Service predicts end-of-season global crop yields for commodity crops. The accuracy of these forecasts is partly limited by the quality of rainfall accumulation data used in the model to predict soil moisture in the plant's root zone. With the data derived from the SMOS mission we should see a significant expansion in our ability to forecast ecosystem productivity and/or agricultural yields by using remotely sensed soil moisture information directly.

Level 2 soil moisture and verification

A radiative transfer model is used to compute multi-angular brightness temperatures based on a set of 'first guess' geophysical parameters including surface soil moisture. These model values are compared against the observations, using the sum of the squared weighted differences in the so-called 'cost function'. Finding the optimal soil moisture value then minimises the differences. The resulting Level 2 product is volumetric soil moisture representing the top centimetres of the soil on a swath-by-swath basis. From these data, higher-level products can be calculated, for example maps showing the daily distribution of soil moisture or monthly averages.

Verifying these soil moisture products is again a challenge. There are many different ways of taking *in situ* measurements. Soil moisture can be determined by first weighing a soil sample, oven drying it at 105°C and then reweighing it. Knowing the density of water and the sample's volume the loss in mass can be easily transformed into volumetric water content. Other methods comprise electrical resistance blocks, neutron moisture meters, and capacitance and time-domain reflectometry. However, taking and collecting these measurements is time-consuming and costly. In addition, these point measurements do not necessarily support the coarse resolution satellite observations due to the heterogeneity of the soil and the vegetation cover.

↑ Taking *in situ* soil moisture measurements during a five-week campaign in southeast Australia to validate SMOS data (Univ. Melbourne)

In order to collect, quality control and harmonise the local and regional soil moisture data sets, the Technical University of Vienna and ESA established the International Soil Moisture Network (ISMN). The Global Energy and Water Cycle Experiment (GEWEX) coordinate this international initiative in cooperation with the Group of Earth Observation (GEO) and the Committee on Earth Observation Satellites (CEOS). As of now, observations from more than 1200 stations can be downloaded and visualised through the ISMN's web interface under a free and open data policy. The ISMN has more than 500 registered users and has become the world's largest database for *in situ* soil moisture observations. Comparisons between the SMOS derived soil moisture estimates and the *in situ* measurements indicate a good overall performance in line with the expectations.

Frontiers

Soil moisture and ocean salinity have been the two key geophysical parameters driving the SMOS mission concept and its design. The corresponding validation activities and some of the applications have been carefully addressed and planned during the mission preparation phases on the ground and in orbit. However, as the observations have become available, new parameters and exciting applications have been analysed and developed by scientists.

Over the oceans, research into sea-ice thickness and extreme wind speeds associated with storms and hurricanes has been performed successfully. Over land, monitoring the freeze-thaw cycle of soil and detecting frost depth seem feasible. Soil freezing, wintertime evolution of soil frost and thawing are important characteristics influencing the hydrological and climate processes of the large land areas of North America and northern Eurasia.

Changes in the seasonal behaviour of frost have a major effect on the surface energy balance, as well as on the intensity of carbon dioxide (CO_2) and methane (CH_4) fluxes. CH_4 releases from wetlands have been found to increase during recent decades, for example in Siberia because of

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Tundra ponds in Alaska. Because of permafrost (up to 500–600 m thick in places), the land is frozen and holds a lot of water on the surface (Omniterra Images)

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Networks and stations providing *in situ* measurements for the International Soil Moisture Network database. Data are available at www.ipf.tuwien.ac.at/insitu (Wagner, TU Vienna)

the thickening of the seasonally thawed active layer above the permafrost. On the other hand, it has been shown how to relate this information to changes in CO_2.

In the case of boreal forests, the annual CO_2 balance has been found to be highly dependent on conditions during autumn and early winter.

The first soil frost depth datasets based on SMOS observations were derived by the Finnish Meteorological Institute for two consecutive winter periods starting in 2010. Key elements, such as the southward progression of soil freezing in autumn and early winter, were monitored successfully as well as the late onset of winter in northern Europe in 2011.

These results are potentially interesting for climate applications because they could enhance our understanding of the temporal behaviour of the active layer in permafrost regions and the gas exchange process.

More research involving the climate modelling community will be dedicated to this topic over the next few years when multi-year time-series of SMOS observations will allow the analysis of seasonal and inter-annual variations. ■