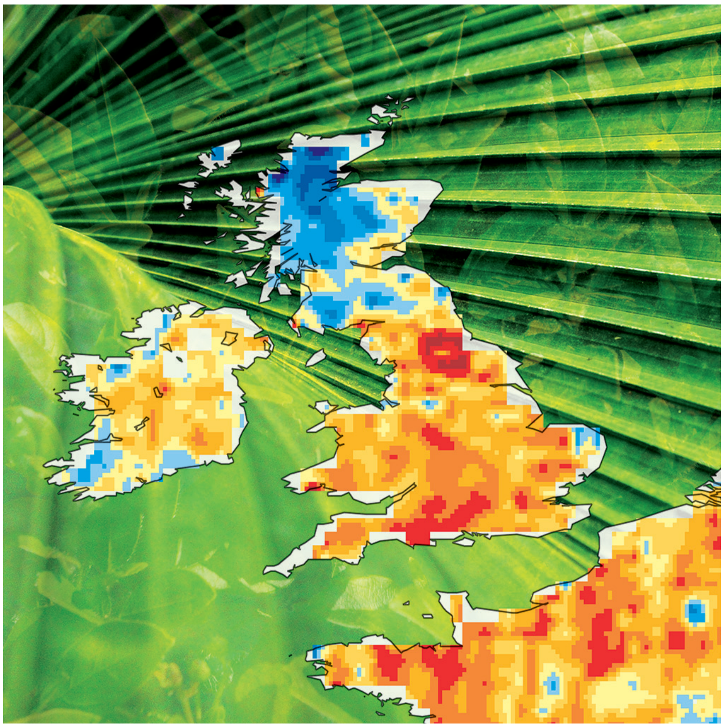
ECMWF Feature article

from Newsletter Number 127 – Spring 2011

METEOROLOGY

Use of SMOS data at ECMWF



www.ecmwf.int/en/about/news-centre/media-resources

doi:10.21957/bo6vggj9

This article appeared in the Meteorology section of ECMWF Newsletter No. 127 – Spring 2011, pp. 23–27.

Use of SMOS data at ECMWF

Joaquín Muñoz Sabater, Patricia de Rosnay, Anne Fouilloux

On 2 November 2009, the Soil Moisture and Ocean Salinity (SMOS) mission was successfully launched from Plesetsk (Russia). This was the second Earth Explorer mission of the European Space Agency (ESA) Living Planet Programme. The most important challenge of this mission is to deliver scientific data with information about the water content of continental surfaces and the salinity content of the oceans. The mission's requirements are to retrieve volumetric soil moisture from the observed radiances with an accuracy of 4% and a spatial resolution of 40–50 km, and salinity in open waters with 0.1 psu accuracy for a 10–30 day average and an open ocean area of 200 km×200 km.

SMOS is a sun-synchronous dawn/dusk polar orbiting satellite flying at an altitude of 758 km. Onboard, a 2D-interferometric radiometer images the entire surface of the Earth between 1.400–1.427 GHz (L-band) once every three days (*Kerr et al.*, 2010). This is the first time that such technology has been used to obtain information about the emission from the surface of the Earth.

SMOS observations can potentially be of great benefit for ECMWF. They are the satellite data most sensitive to soil moisture both with relatively good spatial and temporal resolutions. Although the information they provide is limited to the most superficial soil layer, this data can be assimilated in the Extended Kalman Filter (EKF) soil moisture analysis of ECMWF (*Drusch et al.*, 2008, *de Rosnay et al.*, 2011) to correct the value of the root-zone soil moisture. A better initialization of the root-zone soil moisture has proven to have an impact on short- to medium-range weather forecasts (*Ferranti & Viterbo*, 2006). Currently, the EKF is used operationally at ECMWF to adjust the soil moisture state through the assimilation of 2-metre temperature and relative humidity observations.

The SMOS team working at ECMWF provides operational monitoring of SMOS data and the next objective is to assimilate this data using the EKF. For SMOS, continuous monitoring in near real time (NRT) is especially important. This is because the ambitious technique used to extract information about soil moisture and ocean salinity needs to be tested and validated before an operational mission can be designed. For ECMWF, the main objective will be to investigate the ability of SMOS data to improve the forecast skill.

Why a passive mission in L-band to sense soil moisture?

Over the last two decades, remotely-sensed microwave observations from 1 to 10 GHz have been used to obtain information about the water content of a shallow near-surface layer. In this microwave region, attenuation from clouds and vegetation is smaller than at higher frequencies. Remote sensing of soil moisture (as with many other variables) can be carried out for two types of sensors: active and passive. Active instruments emit an electromagnetic pulse to illuminate the scene they observe. Then they measure the radiation that is reflected or backscattered from that scene. In contrast, passive instruments measure directly the radiation emitted by the Earth. Factors such as vegetation or soil roughness are less significant in passive remote sensing of microwaves. In addition, L-band has the advantage of having little sensitivity to the water vapour in clouds and rain in the atmosphere, even for adverse weather conditions. Therefore SMOS (using a passive L-band instrument) should have the capability to monitor the soil moisture under conditions where other sensors have problems.

The high cost and technological challenge of arranging a large antenna in L-band has prevented an earlier mission based on this technology. For SMOS, an antenna of approximately 8 metres in diameter is necessary to comply with the spatial resolution requirements of the mission. In SMOS this problem has been overcome by applying the interferometric technique. Instead of one large antenna, sixty nine small receivers installed in three arms collect the radiation emitted by the Earth's surface between 1.400 and 1.427 GHz. By combining the signals received by the small receivers, a two-dimensional image of the Earth's surface brightness temperature (which is proportional to the radiation emitted by the surface) can be reconstructed.

ECMWF will use SMOS data in synergy with active measurements, in particular with a global soil moisture index product derived from the C-band (5.255 GHz) active microwave data of the Advanced Scatterometer instrument (ASCAT), onboard the MetOp platform, to better constrain the soil moisture state.

 doi:10.21957/bo6vggj9

Which product is used at ECMWF?

ECMWF is receiving the data from the SMOS Data Processing Ground Segment in NRT. It constitutes geographically sorted swath-based maps of brightness temperatures. The geolocated product received at ECMWF is arranged in an equal-area grid system called ISEA 4H9. For this grid, the centres of the cell grids have almost an equal spacing of 15 km over land. Over oceans the grid has a coarser resolution, which is half of the resolution over land, as oceans are more homogeneous than continental surfaces.

The data arrives organized in snapshots, each being generated every 1.2 seconds. After the end of the commissioning phase it was decided that SMOS would measure in the so called full polarization mode. This means that for the first 1.2 seconds all the receivers in the three arms are in the same polarisation mode (and then obtaining pure horizontal or vertical polarized observations; i.e. when the orientation of the electric field of the electromagnetic waves received at the three arms is parallel or perpendicular to the satellite antenna reference frame, respectively), whereas in the following 1.2 seconds the receivers in an arm switch the polarisation. For the first 1.2 seconds approximately 4,800 observations are found within a snapshot, whereas this quantity can be doubled in the next 1.2 seconds. Each of these observations is provided in a node (or grid point) of the ISEA grid.

Developments towards an operational monitoring chain

To take full advantage of the NRT product, ECMWF implemented this new data type within the Integrated Forecasting System (IFS). This was a challenging task for several reasons. For SMOS, the interferometric technique observes the same area at different angles as the satellite moves along the track. Up to 150 records of brightness temperatures observed at incidence angles between 0° and 65° are provided for each location. So the angular resolution of the observations is very high. This measuring principle has two consequences: (a) it provides a unique dataset with new features very different to any other source of satellite data used for NWP and (b) it produces a very large volume of data which cannot all be ingested into the IFS. This raises a great concern about the feasibility of integrating SMOS data in the IFS. However, SMOS data is still compatible with the current structure of the IFS if the amount of data is significantly reduced. Data thinning is essential in this context. The thinning approach for SMOS data needs to avoid redundant observations and reduce drastically the volume of the original dataset, while keeping the angular distribution of the observations.

From the more than 8 Gb of daily data that can reach ECMWF archives, only 5 to 10% can realistically be ingested into the IFS. An optimal trade-off between number of incidence angles and volume of data is to keep only six incidence angles with a margin of ±0.5°. These angles are 10°, 20°, 30°, 40°, 50° and 60°. They are continuously being monitored and the results are publicly available in NRT at:

- http://www.ecmwf.int/research/ESA_projects/SMOS/monitoring/smos_monitor.html.

This is an excellent tool to assess and analyse the angular and polarised evolution of the data as a function of time. For more detailed information see *Sabater et al.* (2009, 2010).

The forecast model's estimate of the SMOS data (the model equivalent) is computed at the model grid points. In the case of SMOS, this has several advantages.

- All the background fields necessary to simulate brightness temperatures at the top of the atmosphere are computed and available at model grid points. Thus, it avoids interpolating physical quantities to observation location.
- Other satellite data sensitive to soil moisture, such as AMSR-E data in C-band, is also available at model grid points, making a comparison possible with other satellite data.

The Community Microwave Emission Model (CMEM) is currently used to simulate the soil emission in L-band. Further information about CMEM and its current configuration can be found at:

- http://www.ecmwf.int/research/ESA_projects/SMOS/cmem/cmem_index.html.

Monitoring results

Daily monitoring of observed brightness temperatures

SMOS data has been regularly monitored since the launch of the satellite. Daily maps of brightness temperatures have been produced and published on the ECMWF SMOS website mentioned above. These maps were especially of interest during the commissioning phase when a series of calibration events took place. As an example, Figure 1a shows global maps of brightness temperatures at 40° incidence angle for the vertical polarisation, as measured by SMOS, on 28 November 2009. This data corresponded to data from the 'Switch-On Phase'. Figure 1b shows data approximately four weeks later, on 20 December 2009, just after a major calibration event took place.

The plots in Figure 1 clearly show a significant improvement in the quality of the observations. The early mission data was very noisy (presented as dark red in the Figure 1a) and with significant geo-location problems, which was completely normal at that phase. However, the data in late December (Figure 1b) was of much better quality and more in agreement with expectations. Furthermore, the edges of the satellite track looked colder than the inner part. This is the area which corresponds to the extended alias-free field of view (EAFOV), which is a post-processed area to benefit from global coverage every three days, but with the drawback of being of lesser quality. These plots were useful to observe anomalies in the data, especially important during the commissioning phase. They were supported until November 2010. From this date onwards, global statistics have been produced in NRT.

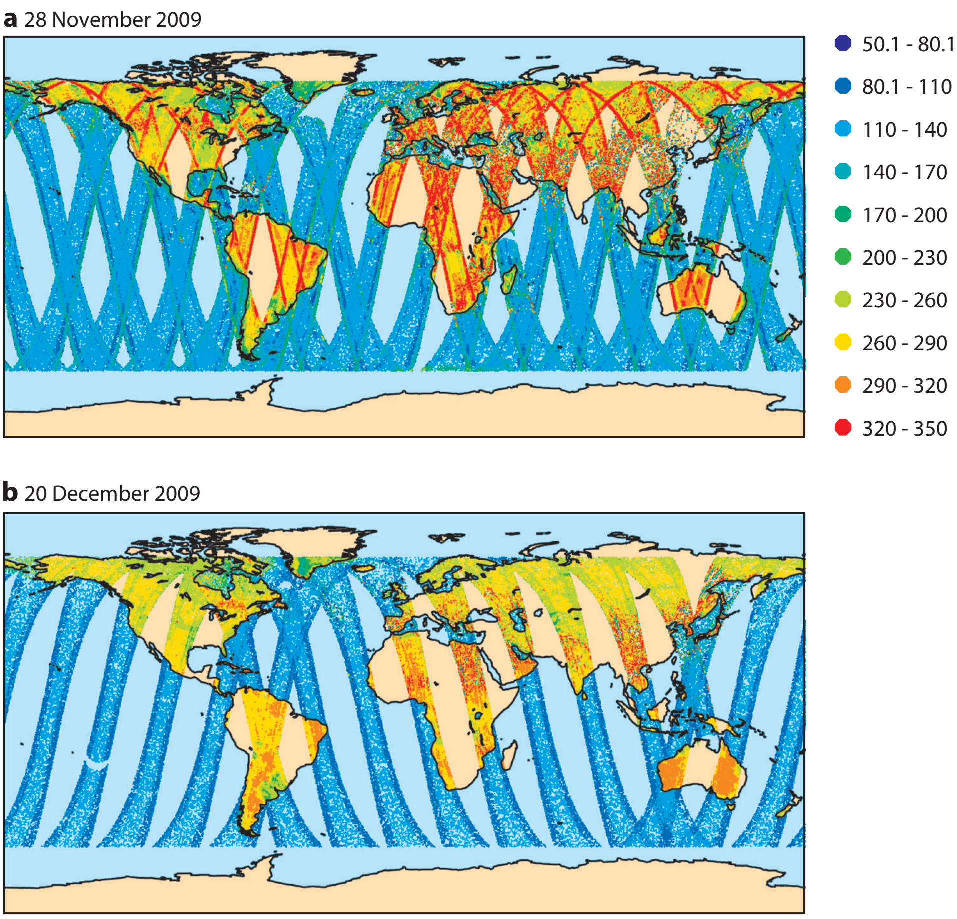


Figure 1 Observed SMOS brightness temperatures (K) at 40° incidence angle and vertical polarisation on (a) 28 November 2009 and (b) 20 December 2009.

doi:10.21957/bo6vggj9

Difference between observations and model equivalents

It is important to monitor the difference between observations and model equivalents (also called first-guess departures). They typically follow a normal distribution with mean value relatively close to zero. This result is very positive as it means that in average ECMWF L-band simulated brightness temperatures are in good agreement with SMOS data. However, the probability distribution functions of first-guess departures also have long tails at both sides, suggesting that a significant number of large differences between model equivalents and observations are still present. The largest wet biases are found in areas with strong orography. This result was expected as the capabilities of CMEM for areas with strong slope, snow and ice are currently inaccurate. The emission over boreal forests, ice and snow covered areas is also significantly overestimated by CMEM. In particular, the snow line over continental surfaces can be monitored very well using the mean values of first-guess departures, as shown in Figure 2.

Concerning the large dry bias, there seems to be two main regions affected: (a) the area near coastlines, where the observed brightness temperatures are strongly influenced by sea water (with much lower values of brightness temperature), and (b) over dry areas observed at large incidence angles. It is well known that roughness effects are not yet well modelled for large incidence angles at the L-band, and in particular for the more sensitive horizontal polarisation. Recent analyses have shown a significant reduction of the tails in the histograms of first-guess departures. The reason is twofold: on the one hand, recent calibrations of the instrument have improved the quality of the observations; on the other hand, the improved model physics used in the current cycle has also improved the ECMWF model equivalents. In particular, the introduction into the IFS cycle 36r4 of a new improved bare soil evaporation scheme, producing more realistic dry values of the soil water content over bare soil, has a significant impact on the ECMWF model equivalents.

Data over oceans

SMOS data is not only being continuously monitored for land masses, but also for oceans. The current L-band emission model over oceans used at ECMWF is quite simple and does not account for contributions due to the galactic noise (which is an ever-present background cosmic radiation, see the figure in Box A) or roughness caused by ocean winds. However, observed radiances have shown a very good correlation with areas covered in sea ice.

Figure 3 shows the average brightness temperatures in grid-boxes of 1° from 5 to 19 November 2010. It can be observed that on average the polar latitudes have higher brightness temperatures than the rest of the oceans. This is the combination of several factors: firstly the water in these zones is colder and fresher with lower salinity (factors which have an influence over the water emission in L-band), but the main reason is due to the sea ice near the poles. Over ice-covered areas the surface emits as if it was drier, which results in substantially higher brightness temperatures. The average brightness temperatures over oceans are very well correlated with maps of sea ice cover; this confirms the ability of SMOS data to also monitor sea ice.

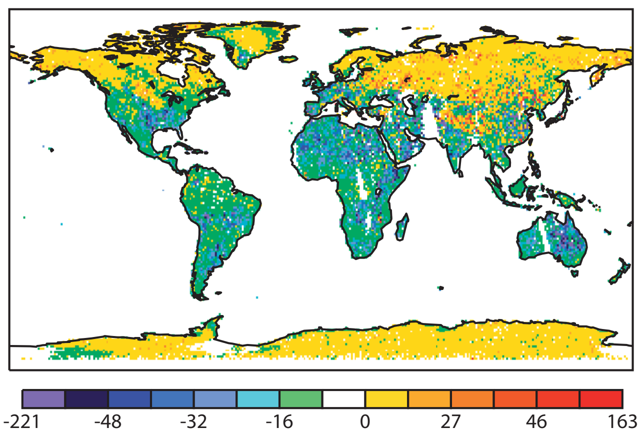
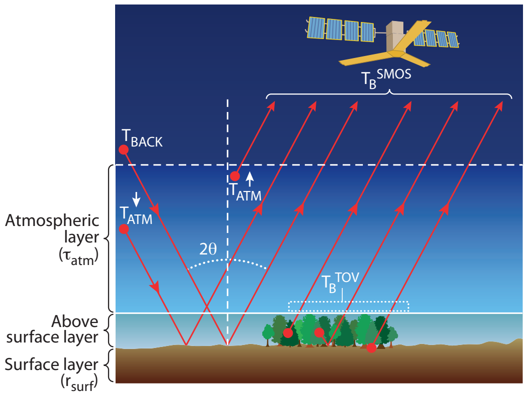


Figure 2 Averaged first-guess departures of brightness temperatures (K) for the first week of March 2010 at 1° spatial resolution. Only observations with an incidence angle of 50° and horizontal polarization are considered in this figure.

doi:10.21957/bo6vggj9

How can soil moisture be retrieved from SMOS observations?

A



The SMOS observation system is a microwave imaging radiometer with aperture synthesis. It collects top-of-the-atmosphere radiances coming from the scene viewed by the SMOS antennas. At the frequency operated by SMOS (1.4 GHz), the brightness temperature (defined as the temperature a blackbody would be in order to produce the radiance received by the sensor) and radiances are directly proportional. Thus, as it is done for many other satellite data, SMOS data is expressed in terms of brightness temperatures rather than in radiances as the units of temperature are easier to interpret than the units of radiances.

The brightness temperatures sensed by the SMOS antennae (T_B^{SMOS}) results from several contributions: (a) surface emission (T_B^{TOV}) attenuated by the atmosphere (τ_{ATM}), (b) the up-welling atmospheric emission ($T_{ATM}^{\uparrow}$), (c) the down-welling atmospheric emission ($T_{ATM}^{\downarrow}$) reflected at the surface and attenuated by the atmosphere, and (d) the cosmic background emission (T_{BACK}) attenuated by the atmosphere, reflected at the surface (r_{SURF}) and attenuated again by the atmosphere. Among all of these contributions, T_B^{TOV} is the most important one. It takes into account the soil emission as well as the emission and the attenuation effects of the vegetation. Soil roughness or the presence of snow also affect the surface emissivity.

The emissivity of the surface is the key variable to retrieve soil moisture. The surface emissivity can be expressed as a function of the dielectric constant of the surface. However, the surface dielectric constant is very different between a dry soil and a wet soil. Detection of soil moisture from a remote sensing platform is based on this principle. The sensitivity of the soil emissivity to soil moisture is optimal at L-band and, although with different magnitude, this is valid for both the horizontal and the vertical polarization. By combining the data from both polarizations unwanted effects in the signal can be removed and soil moisture can be retrieved more accurately.

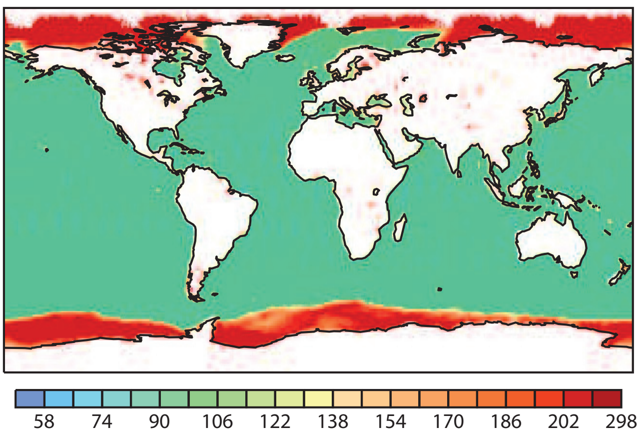


Figure 3 Average SMOS brightness temperatures (K) over oceans at 1° spatial resolution from 5 to 19 November 2010 at a 40° incidence angle and for the vertical polarisation.

doi:10.21957/bo6vggj9

Main problems of the SMOS data

The innovative instrument onboard of SMOS has had to face various problems. The galactic radiation, to which the satellite is continuously being subjected, was the origin of several problems related to the memory (which temporally stores the data in the satellite) and the frequency imbalances of the instrument. More recently, an increase of the temperature of one of the main antennas was observed, thus producing an unwanted trend in the temporal evolution of the brightness temperatures. This is currently under investigation. However, all these problems can be considered small compared to the Radio Frequency Interference (RFI). SMOS data is significantly contaminated by anthropogenic sources in the protected L-band. Many of these sources have a civilian origin, such as radio links, wi-fi networks or surveillance cameras. Efforts made by various ESA teams have made it possible to switch off around 50 sources in Europe which were strongly contaminating the observations.

In Figure 4, the variability of the observations averaged over a week is shown. This figure presents complex patterns related to the state of the soil variables. However, there are some areas mainly in the East of Europe and Asia that present abnormally large variability (in red in the figure). This cannot be explained by the geophysical variability of the observations, but rather by external sources related to RFI.

RFI is not only limited to continental surfaces. Figure 5 shows the average variability of the observations between 5 and 19 November 2010 over oceans. A significant land-sea contamination is observed. There is a very large contamination around the European and Asiatic coasts caused by strong RFI sources over land, which can contaminate the observations up to several hundreds of kilometres offshore. This effect is sharper with increasing incidence angle. To a lesser extent, SMOS observations over sea are also affected in a well-defined latitudinal band of North America due to a series of military radars. Other point sources of RFI are also distributed in several locations over the ocean. The interface between sea ice and open sea water, showing extraordinary dynamics, is also very well captured in this figure, as it can be clearly seen near the south pole. The reason for this is the strong contrast in brightness temperatures between open sea water and water covered by sea ice.

Although the best approach to avoid RFI contamination is to directly switch off the illegal sources at the L-band, this is a slow process as it means requesting the national management authorities to ensure that citizens comply with the International Telecommunication Union regulations. In some countries this is a very difficult process. Currently, several detection and mitigation algorithms are being developed to reduce the impact of RFI on the observations.

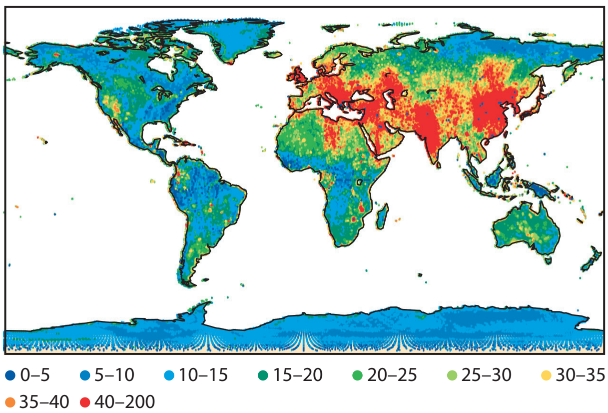


Figure 4 Average standard deviation of the SMOS observed brightness temperatures (K) the first week of October 2010 at horizontal polarization and 40° incidence angle.

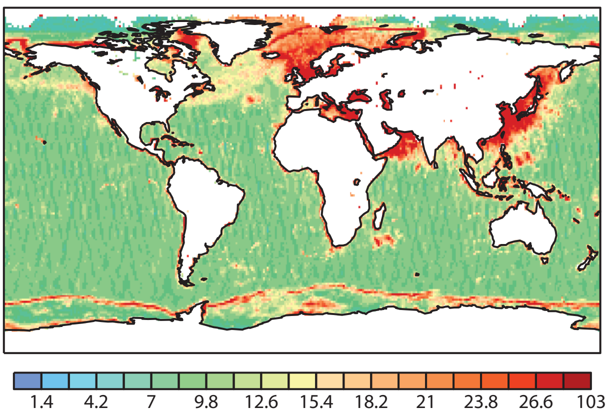


Figure 5 Average of the standard deviation of the SMOS observed brightness temperatures (K) over oceans at 40° incidence angle for the vertical polarisation mode for the period 5 to 19 November 2010.

doi:10.21957/bo6vggj9

Way forward

The potential benefit that the assimilation of SMOS data could bring to the forecast skill will strongly depend on the thinning approach applied to the observations. It is important to try to understand which subset of data carries most information about the soil water content. In addition, SMOS observations are quite noisy as the size of the observed (very heterogeneous) surface of the Earth is very different depending on the incidence angle.

Not only is the optimal use of SMOS data being investigated in view of its assimilation, but also the reduction of noise and significant spatial correlations observed between adjacent observations are being studied. A bias correction scheme, likely based on physical parameters such as roughness or vegetation, will also be developed. It is also envisaged to reduce the bias between SMOS observations and the model equivalent by performing a global calibration of the CMEM parameters which have the strongest influence on the simulated brightness temperatures. The current configuration of the CMEM is based on research which investigated different aspects of the soil emission at local or regional scales. A global re-processed SMOS dataset performed by ESA will be used for validation purposes.

Finally, all these activities, which are aimed at optimally preparing the data for assimilation in the EKF, will be the base for testing the impact that the assimilation of SMOS data has on the forecast skill. This will be tested under several assimilation configurations combining screen-level variables and SMOS data.

Further reading

de Rosnay, **P.**, **M. Drusch**, **G. Balsamo**, **C. Albergel** & **L. Isaksen**, 2011: Extended Kalman Filter soil-moisture analysis in the IFS. *ECMWF Newsletter No. 127*, 12–16.

Drusch, **M.**, **K. Scipal**, **P. de Rosnay**, **G. Balsamo**, **E. Andersson**, **P. Bougeault** & **P. Viterbo**, 2008: Exploitation of satellite data in the surface analysis. *ECMWF Tech. Memo. No. 576*. http://www.ecmwf.int/publications/library/do/references/show?id=88712

Ferranti, **L.** & **P. Viterbo**, 2006: The European summer of 2003: Sensitivity to soil water initial conditions. *J. Climate*, **19**, 3659–3680.

Kerr, **Y.**, **P. Waldteufel**, **J.-P. Wigneron**, **S. Delwart**, **F. Cabot**, **J. Boutin**, **M.-J. Escorihuela**, **J. Font**, **N. Reul**, **C. Gruhier**, **S.E. Juglea**, **M. Drinkwater**, **A. Hahne**, **M. Martin-Neira** & **S. Mecklenburg**, 2010: The SMOS mission: new tools for monitoring key elements of the global water cycle. In *Proc. IEEE 2010*, 98, 666-687, doi:10.1109/JPROC.2010.2043032.

Sabater, **J.M.**, **P.de Rosnay**, **A.Fouilloux**, **M. Dragosavac** & **A. Hofstadler**, 2009: IFS interface. *M1TNP2 ESA Technical Report*. http://www.ecmwf.int/publications/library/do/references/show?id=89524

Sabater, **J.M.**, **P. de Rosnay** & **A. Fouilloux**, 2010: Operational Pre-processing chain, Collocation software development and Offline monitoring suite. *M2TNP1/2/3 ESA Technical Reports*. http://www.ecmwf.int/publications/library/do/references/show?id=89972

 doi:10.21957/bo6vggj9