ECMWF/ESA workshop on using low frequency passive microwave measurements in research and operational applications

The workshop was held on 4-6 December 2017 at ECMWF with approximately 60 participants from the carbon, ocean, land, and polar research communities. A number of operational agencies and services were represented, including the UK MetOffice, Météo France, the Finish Meteorological Institute, the Danish Meteorological Institute, EUMETSAT, the Copernicus Marine Environment Monitoring Service and Mercator. In four dedicated sessions key applications and scientific achievements based on low frequency passive microwave (LFPM) remote sensing were discussed.

The key outcomes of the workshop discussions across the different domains and applications are the following recommendations:

1. Continuity
A wide range of operational applications already benefit from Low Frequency Passive Microwave (LFPM) measurements (e.g. sea ice monitoring and ship routing, fire risk estimates and food security, NWP, and ocean monitoring) and a number of pre-operational services are being developed (e.g. in the field of hydrology, agricultural monitoring, and severe storm forecasting). All service providers require continued observations especially in L- and C-band to guarantee high-quality, synergistic products. **Missions with at least similar or better performances than SMOS, SMAP, and AMSR shall be implemented as soon as possible minimizing the risk of a data gap for operational applications already being based on such measurements.**

2. Native Spatial Resolution
Although LFPM measurements at spatial resolutions of around 50 × 50 km^2 have already been used successfully in many applications, the native spatial resolution was identified as the major limitation to progress further. Data assimilation and downscaling approaches combining measurements from different sensors and models can lead to information at the relevant (finer) spatial scales. **However, in order to observe physical processes, for example over ocean in high latitudes at their native spatial resolution, measurements at ~ 10 × 10 km^2 shall be targeted.**

3. Combination of Microwave Sensors
Many – if not most – applications benefit from the combined use of measurements obtained at different frequencies. **Two combinations are considered as favorable: Collocated measurements of passive and active systems at the same frequency (either at L- or at C-band) and collocated passive microwave measurements at L-, C- and X-band.** P-band observations are considered beneficial to address new science, in particular for cryospheric applications.

4. Orbit and Overpass Times
For some applications, e.g. related to soil moisture, certain orbits and overpass times are favorable. Other applications may benefit from complementing observations from other sensors to resolve the daily cycle for example **A critical analysis of the orbit/overpass times related to the key mission objectives shall be performed for future LFPM mission concepts.**

5. Radio Frequency Interference
Radio Frequency Interference (RFI) has been identified as a major limiting factor across the microwave spectrum (including L, C and X Band) even in protected bands. Instruments on future mission concepts **shall allow detecting RFI directly in the measurements.**

Summary of the workshop presentations:

F. Rabier (ECMWF Director General) opened the workshop and welcomed all participants. She gave an overview of ECMWF's core activities related to global numerical weather forecasts, supercomputing and data archiving, education and training, and – since 2015 – operating the Copernicus Atmospheric Monitoring and Climate Change Services on behalf of the EU. ECMWF has been a key user of satellite data collaborating closely with space agencies. Approximately 98% of the observations used at ECMWF are based on satellite data. F. Rabier stressed the fact that SMOS observations are being used operationally in ECMWF's forecasting system.

As an introduction and before moving to the thematic sessions, Y. Kerr (CESBIO) presented the state-of-the-art of L-band radiometry highlighting the large number of achievements and results stemming from the measurements of ESA's SMOS and NASA's SMAP and Aquarius missions. Importantly, and despite the fact that these measurements are based on different instruments' designs though sharing the same spectral band, the measurements coming from these three l-Band missions agree very well. However and in contradiction with the success of a large variety of applications and the demonstrated technological readiness, there is currently no follow-on L-Band mission planned. Data continuity, the key requirement of operational users – has not been met and a gap in the data record seems to be highly likely.

The first Thematic Session focused on research and applications related to **Carbon and Climate**. J.-N. Thepaut (ECMWF) introduced the Copernicus Climate Change Service (C3S) and its portfolio comprising of observations, climate reanalysis, and model outputs, namely multi-model seasonal forecast products. While GCOS has specified the Essential Climate Variables (ECV) and the corresponding observation requirements, the actual climate data records will be generated building on past and current capabilities. Consequently, various organisations and agencies, providing relevant data sets and expertise, are involved in the implementation and production of the ECVs, organized in 5 thematic so-called "lots". Combining models and observations within the ERA5 reanalysis will allow delivering 4D representation of the Earth System at 31 km spatial resolution globally. ECMWF, the UK Met Office, and Météo France currently provide seasonal forecasts for selected ECVs. SMOS observations are being used for the generation of the soil moisture and sea ice thickness ECVs. Monitoring sea ice and ice sheets through a combination of passive microwave imagers and altimetry was identified as a future observation priority by C3S.

Presentations from A. Watson, J. Shuttler, and M. Scholze focused on CO_2 fluxes over ocean a land. All three speakers highlighted the need for an improved understanding of the spatial and temporal dynamics of the global carbon cycle.

Over the ocean, parameters of interest are Colored Dissolved Organic Matter (CDOM) and Total Alkalinity, which depend – among others – on salinity, Sea Surface Temperature (SST), wind speed and as a consequence surface parameters such as foam, with most of these parameters being provided by passive microwave data in synergy with optical sensors directly. In addition, sea ice parameters are of importance for the carbon exchange between the ocean and the atmosphere.

Pilot studies on using L-band observations to address some of scientific questions related to the marine carbon cycle were successful and resulted for example in the FluxEngine Toolbox with passive microwave measurements being identified as a key element. Earth Observation data are even more powerful when combined with in-situ measurements and numerical models, preferably in a full data assimilation or re-analysis framework.

Over land, it has been demonstrated that soil moisture and vegetation optical depth estimates can be used successfully in constraining global carbon models. Assimilating SMOS derived products in addition to in-situ measurements of CO_2 concentrations further improved the representation of soil moisture in the carbon model and further reduced relative uncertainty for carbon fluxes (NEP & NPP) for a number of test regions. Potentially, soil freeze and thaw data will provide further improvements quantifying carbon exchange between land and atmosphere.

The second Thematic Session focused on research and applications related to **Polar and the Cryosphere.**

Four talks from S. Tietsche (ECMWF), L. Bertino (NERSC), L. Kaleschke (University of Hamburg) and R. Tonboe (DMI) addressed Arctic sea ice. K. Rautiainen (FMI) complemented the session presenting results over land. The importance of sea ice and freeze and thaw state of the soil was again emphasized in this session. At FMI, a SMOS-based soil freeze and thaw product has been developed and the corresponding operational processor is being implemented for systematic data provision. The verification against in-situ observations and model estimates has shown good performance of this satellite based product. When compared against methane budgets obtained over North America, good temporal correlation between soil freezing and the decrease in natural methane emission was found. Passive microwave observations at L-band were found to be extremely useful for monitoring the soil freeze and thaw transition.

L. Kaleschke (University of Hamburg)and R. Tonboe (DMI) addressed the retrieval of sea ice thickness and snow on ice from passive microwave measurements. While the SMOS-based sea ice thickness product is well established and has been generated operationally f since 2014, snow on ice represents a further challenge. Collocated high quality measurements of snow, ice and brightness temperatures, provided by synergistic measurement in the microwave domain, are needed to advance and eventually build robust operational retrieval algorithms.

The presentations from L. Bertino (NERCS) and S. Tietsche (ECMWF) focused on the exploitation of SMOS based ice thickness data in operational applications. S. Tietsche (ECMWF) stressed the fact that sea ice is a key factor for improving polar observing, modelling and predictions of thin sea ice. Since uncertainties in sea ice thickness translates into uncertainties into forecasted sea ice concentration , both parameters have an impact on large-scale atmospheric circulation and thus forecasts ranging from days to seasons. S. Tietsche (ECMWF) showed comparisons between the ECMWF sea ice model and observations and concluded that low frequency microwave radiances are currently the only way to observe the thickness of thin sea ice with sufficient spatial and temporal coverage. In the Arctic Monitoring Forecasting Centre (ARC MFC), SMOS sea ice thickness estimates merged with CryoSat2 data have been assimilated also including a number of other satellite data sets. The analyses showed a better fit to independent observations and resulted in a minor improvement of the ice drift. Other model state estimates, i.e. ice edge, SST, SSS or sea level, were not degraded, which is a very good result. As for any operational application, continuity of L-band observations was highlighted as the main requirement.

The third Thematic Session focused on research and applications related to **the Terrestrial Water Cycle and Hydrology.**

C. Baugh (ECMWF) opened this session with a presentation on the Copernicus Emergency Management Service related to floods. There are currently two systems being operated in parallel: the European Flood Awareness System (EFAS) based on the raster based hydrological model LISFLOOD and the Global Flood Awareness System (GLOFAS) based on the grid based land surface model HTESSEL, used by the ECMWF forecasting system. Both systems use the 1D flow routing from LISFLOOD. GLOFAS already uses the data assimilation system operated at ECMWF, thus including SMOS data. Apart from assimilating brightness temperatures,, information from passive microwave observations on flood extent, irrigation, and rainfall could be incorporated. Continuity of L-band observations, preferably at a spatial resolution of 10 km for hydrological applications, is needed.

R. Reichle (NASA) summarized research activities related to the assimilation of low frequency microwave observations into land surface models. Observations from active systems, i.e.

ASCAT and Sentinel-1, were included in the analysis. In summary, the results confirmed that LFPM are sensitive to the terrestrial water cycle and useful for model diagnostics, calibration and data assimilation. They have the demonstrated potential to improve flood forecasts and carbon flux estimates. In general, passive L-band data had improved skills compared to passive C- or X-band data. However, the best results were obtained when observations from passive and active instruments were assimilated together. L-Band passive microwave radiances and ASCAT backscatter should be assimilated rather than retrieved (geophysical) products, such as soil moisture.

N. Rodriguez (CESBIO) summarized the research activities related to using the operationally available SMOS soil moisture product being based on brightness temperatures available in near-real time (3 hours from sensing) and a Neural Network approach, using the output of the geophysical retrieval of soil moisture as a training data set. Currently, this data is applied for operational assimilation and first results imply a moderate improvements to the soil moisture analysis and the subsequent forecasts in the Northern Hemisphere.

Applications related to agriculture and hydrology were presented by M.J. Escorihuela (isardSAT) and A. Al Bitar (CESBIO). Both showed disaggregated soil moisture products based on SMOS data together with data from other active and passive sensors at 1 km spatial resolution. Applications benefitting from such a combination are for example land surface hydrology including drought monitoring, food security, irrigation and water management. A particular interesting application is the prediction of desert locust presence in North Africa where it was demonstrated that using SMOS based information can increase the forecast lead-time from 1 month to 2 to 3 months.

The fourths Thematic Session focused on research and applications related to the **Ocean.**
E. Rémy outlined the use of LFPM measurements in the Copernicus Marine Environment Service (CMEMS) and Mercator. In general, this type of measurements is used in data assimilation and processing related to Sea Surface Temperature (SST), sea ice, and Sea surface Salinity (SSS). Out of these three parameters, SST related applications are probably most mature and LFPM sensors are an essential component of the global constellation of SST sensors as they provide information also under the presence of clouds and aerosols. They are of particular importance in areas with persistent cloud coverage and at high latitudes. E.Rémy noted that the future of LFPM SST is very uncertain and CMEMS cannot solely rely on contributing missions from the US or Japan for its operational service. The assimilation of sea ice concentration derived from LFPM observation is also well established and first tests with the SMOS/CryoSat2 merged sea ice thickness product were successful. Continuous data availability for both data streams is again a key requirement. Within the SMOS-Nino 2015 ESA STSE project the assimilation of SSS into the forecasting systems of Mercator and the UK Met Office have been tested. First results from this study suggest that the assimilation of SSS data from SMOS have a positive impact on the ocean analysis and the forecast. A. O'Carroll (EUMETSAT) supported these conclusions when presenting the use and impact of LFPM data on SST estimates. A wide range of operational applications using SST fields benefit from the unique capabilities provided through passive microwave measurements. Especially the availability of measurements from the 6-7 GHz channel was stressed as an essential requirement for good data quality in high-latitudes. Not only the continuity but also the redundancy of current mission capabilities were identified as critical requirements.

N. Reul (IFREMER) and T. Lee (NASA) both presented an impressive record of scientific results and achievements based on the L-band measurements and sea surface salinity estimates coming from the SMOS and Aquarius missions. Oceanic processes and features like hurricane haline wakes, tropical instability waves, Rosby waves, mesoscale eddies, fronts, cross-shelf exchanges, dynamics of salinity zones and river plumes have been detected and analyzed. Climate variability that can be described through phenomena like ENSO and the Madden-Julian_Oscillation was observed as well as large scale interactions between ocean and atmosphere and land. Both speakers identified high-latitude oceans and closed seas as future target areas requiring improved accuracy and higher spatial resolution measurements. Again, continuity of L-band observations was listed as the most important requirement.

F. Collard (ODL) gave the last presentation in this session on high wind speed retrievals from LFPM measurements. LFPM observations are all weather tools and the effect of precipitation and ice clouds on the observed signal is decreasing with increasing wavelength. L-band has a large sensitivity to ocean roughness and features like white caps and foam, which are directly linked to wind speed. A comprehensive database of tropical and extra-tropical cyclones was generated and analyzed showing the complementary information provided by L-band measurements when compared to observations from active sensors, such as ASCAT. The radius of wind speeds exceeding 64 knots could only be analyzed with L-band observations whereas ASCAT only in selected cases could yield the 50 knots radius with a substantial loss of sensitivity at 34 knots. Incorporating these measurements in data assimilation systems is an ongoing task. Again, the combination of measurements from active and passive systems like SMOS and Sentinel-1 seems to be most promising since only SAR high resolution data can capture wind speed changes in the inner wall of a hurricane.