Report on “Satellite inspired hydrology in an uncertain future: A H SAF and HEPEX workshop”

Introduction:

More than a hundred modellers and satellite data specialists in the field of hydrology came together at ECMWF from 25 to 28 November to debate new ideas and deepen collaborations. The workshop on ‘satellite-inspired hydrology in an uncertain future’ was organised jointly by the EUMETSAT Satellite Application Facility for hydrology and water management (H SAF) and the HEPEX community of specialists in hydrological ensemble prediction. ECMWF has a stake in both: for H SAF, ECMWF develops, produces and maintains the root zone soil moisture product, while the Centre’s scientists involved in flood risk prediction are active players in HEPEX. Recommendations are given below, followed by a summary of the oral presentations.

At the end of the workshop there were demonstrational sessions dedicated to H SAF and HEPEX products. During these sessions the trainers of the H SAF and HEPEX communities had the possibility to interact directly with the users.

Plenary discussion and recommendations:

The plenary discussion and general discussion during the conference allowed to identify areas where significant improvements and progress can be made. These are summarized as bullet points below:

- H SAF is encouraged to consider using machine learning in their product developments;
- H SAF products should provide information on products uncertainties;
- H SAF should make available daily surface soil moisture products in addition to the current sub-daily products;
- The number of H SAF products should be reduced by combining products (e.g. ASCAT-A/B/C) where appropriate;
- H SAF data should be made available in user friendly formats (e.g. regular lat-lon netCDF);
- H SAF and HEPEX should foster collaboration with developing countries (e.g through the H SAF visiting scientist programme, and/or by sharing products);
- Hydrological validation should be strengthened by implementing more case studies e.g. considering more catchments, different climatological conditions, hydrological models and assimilation techniques;
- NWP centres should assimilate radar precipitation products over Europe. For this to happen, all European countries should make available their raw volume data and work towards a consistent quality control and format;
- Both the H SAF and HEPEX communities should explore the use of satellite-based precipitation products for flood forecasting.
- Further collaboration between H SAF and HEPEX (e.g. via the H SAF VS programme, regular workshop as this one) would be beneficial for both projects;
- H SAF is encouraged to promote the production of long-term data series which are of high interest for flood forecasts.

- Both the H SAF and HEPEX communities should focus on extreme events, for example through event-based modelling
- Developing use cases for H SAF satellite data in hydrology would be helpful to strengthen the collaboration with the hydrological community.
- H SAF is encouraged to work to reduce the effect of the cloudy pixels on the snow products.

These recommendations are highly relevant in the context of the preparation of H SAF CDOP4 (Continuous Development and Operations Phase-4, 2022-2027).

Summary of oral presentations:

The workshop began with presentations on **H SAF products and quality assessment**. Both surface and root-zone H SAF soil moisture (SM) products are derived from active microwave observations from scatterometers. The ASCAT-derived surface SM near-real-time (NRT), climate data record (CDR) and offline products are available from Metop-A and Metop-B at 12.5 and 25 km sampling. Metop-C H SAF soil moisture data will be available from 2020. There will be a continuation of ASCAT to the EUMETSAT second generation of polar orbiting satellites (EPS-SG) from 2022. The root-zone SM NRT and CDR products assimilate ASCAT-derived surface SM into H SAF/ECMWF land data assimilation system (LDAS), with resolutions of 25 km and 16 km for the NRT and data record respectively. New 10 km resolution NRT and CDR root-zone SM products are in development. In situ soil moisture observations provide a direct but spatially and temporally sparse reference for the validation. Triple colocation provides global estimates of performance but makes various assumptions (e.g. uncorrelated errors) that are not always accurate. Hydrovalidation methods assess the performance indirectly by validating the output (e.g. river discharge) from ingesting the SM into hydrological models. Overall the performances are generally good for the surface and the root-zone H SAF products, although in some areas (e.g. mountainous, deserts, frozen areas) the satellite-based soil moisture products are not reliable.

H SAF precipitation products are mainly based on the exploitation of current (AMSU-MHS, SSMIS, ATMS, AMSR-2, GMI) and future, (e.g., MWI, MWS) microwave radiometers on board a constellation of Low Earth Orbit (LEO) satellites. The goal is to achieve the best temporal and spatial coverage by converting microwave radiation measurements, directly related to emission/scattering properties of liquid/solid hydrometeors, into surface precipitation rates. For NRT monitoring and applications, products based on a combination of geostationary infrared observations with passive microwave (PMW) are also delivered. Ground data (71 radar and about 8000 rain gauge) and triple/quadruple colocation are used to validate the performance, together with hydrovalidation case studies.

Operational snow products have been developed since 2008 within H SAF, namely H10 (Snow detection (snow mask) by VIS/IR radiometry), H11 (dry/wet by MW radiometry), H12 (Effective snow cover by VIS/IR radiometry AVHRR), H13 (Snow Water Equivalent by MW radiometry), H31 (Snow detection by VIS/IR radiometry) and H32 (Effective snow cover by VIS/IR radiometry AVHRR). The development of new snow products is in progress. Considering different characteristics of snow for mountainous and flat areas, various algorithms are used in producing the snow products, and then the products are merged to have a single snow product. Snow water equivalent (SWE) from microwave radiometry product needs improvement in terms of microwave signal penetration depth limitations. H65 will address these improvements. The performances of snow products that are validated using snow stations and high-resolution data from Sentinel2 are generally good. Additionally, hydrovalidation results emphasize the added value of data assimilation (DA).

Session 1 focused on **remote sensing, hydrological modelling and data assimilation**, including flood mapping, remote sensing of soil moisture, snow and precipitation, heavy precipitation H SAF products, HEPEX perspectives, the European Flood Awareness System (EFAS) and the Global Flood Awareness System (GLOFAS). There was a focus on hydrological variables retrieval from space and model integration to improve land surface monitoring in severe conditions, flood detection and forecasting. For example, the global land surface data assimilation system (LDAS-Monde) at Météo-France was used to initialize land surface forecasts of leaf area index and soil moisture for drought predictions. A range of observations are available at various temporal and spatial scales, which increases the importance for accurate uncertainty characterization of merged products. Examples include the multi-microwave satellite precipitation product (IMERG) developed by North American Space Agency (NASA), which uses a Kalman filter technique to blend information and is calibrated using ground data. Opportunities and challenges of future satellites were presented, including the Meteosat third generation of geostationary satellites (MTG), the second generation of EUMETSAT polar orbiting satellites (EPS-SG), the Earthcare mission, new Sentinel satellites and the Surface Water and Ocean Topography (SWOT) mission. Future missions are likely to take advantage of smaller satellites with shorter lifetimes (e.g. CubeSats), which are substantially less expensive and faster to build than conventional satellites.

The H SAF P-IN-SEVIRI product (with high temporal and spatial resolution), is the only merged product derived from GEO IR observations calibrated with MW precipitation rate, currently available in NRT over the MSG full disk.

Machine learning can facilitate satellite retrievals, forward modelling, post-processing and uncertainty quantification, such as the estimation of error covariances from microwave-channel observations.

Session 2 focused on **hydrological validation and benchmarking**, including recent advances in satellite snow cover data, applications of satellite data, closing the hydrological water budget and satellite data to improve flood forecasting.

There is now a wealth of data and know-how in satellite-based snow remote sensing. Optical and Passive microwave sensors are well suited for snow cover monitoring, including snow cover extent and snow water equivalent, from high resolution regional to moderate/coarse resolution global scales. A methodology has also been developed for using MODIS data for determining degree-day factors of snow melt. In Europe, a large range of operational snow products are developed by H SAF whilst the European Space Agency (ESA) is developing data record products such as the ESA-snow Climate Change Initiative (CCI). Long term trends show a small decrease in northern hemisphere snow mass since the late 1970s. Validation of snow products is essential but requires careful consideration of model biases, inter-variability between different datasets and the sparseness and intermittency of in situ reference observations.

Soil moisture retrievals from the Soil Moisture Ocean Salinity mission (SMOS) are available at approximately 30 km resolution. The assimilation of SMOS-derived soil moisture has been tested for the initialization of GLOFAS forecasts. A small neutral impact was found on river discharge, but the transfer of useful information from soil moisture to hydrological models is challenging due to strong nonlinearities and model errors. Another application demonstrated that Soil Moisture retrieved from the Active Passive Mission (SMAP) can detect forest fires.

A new purely observational approach has been used to optimize satellite datasets to improve estimates of the global water budget. This can be used to estimate missing components, such as total water storage and groundwater flow.

Session 3 covered **hydrological data assimilation for NWP**. The relative contribution of all-sky radiances on NWP forecast skill have steadily improved over the past 5 years and now make up about 20% of the forecast sensitivity to observation impact at ECMWF. Their assimilation adjusts atmospheric humidity to better fit radiances, which can indirectly improve cloud or precipitation. The assimilation of rain rates from NEXRAD precipitation composites (combined radar and rain gauges) is operational over the US and provides positive impacts on short-range NWP forecasts. Whilst Europe generally has a good coverage of radar observations, some countries are still reluctant to release their raw volume data to the wider NWP community (including ECMWF). Recent experimental results from assimilating OPERA precipitation composites over Europe (EUMETNET) in ECMWF's IFS are encouraging, provided the proper screening, attenuation correction and other bias correction are applied prior to the assimilation. Many other parts of the world lack radar data altogether, especially in Africa and South America.

Land surface data assimilation in NWP started at the global scale and has recently been extended to high resolution regional models. At the UK Met Office, a simplified Extended Kalman filter (SEKF) assimilates MetOp ASCAT-derived soil moisture in the 1.5-km resolution UK regional model (UKV). Although the resulting NWP impact appears to be neutral over the UK, improvements in river discharge result from ingesting the soil moisture into a hydrological model. A new soil temperature analysis has also been implemented in the SEKF, leading to small improvements in NWP forecasts of screen-level temperature and humidity. Furthermore, a new optimal interpolation snow-depth analysis in the UKV has led to more realistic snow depth values, but with no significant NWP impact. Over Austria, the combination of ASCAT and synthetic aperture radar (SAR) derived soil moisture observations (SCATSAR) have been assimilated into the SURFEX model at 2.5 km resolution, providing some improvements in NWP forecast skill.

Session 4 presented **impacts of hydrological uncertainty, hydrological forecasting and modelling**. This covered the impacts of realism and data assimilation in hydrological models and the dissemination of information to stakeholders.

Increasing model realism does not always lead to better hydrological forecasts. An example demonstrated that introducing a more realistic relationship between the temperature and the precipitation type (snow or rain) in a bucket-type hydrological model did not improve the snow representation, possibly because the elevations and the temperature lapse rate were not accurately specified.

A distributed hydrological model has been developed for assimilating H SAF or other hydrological products (IMPREX-H SAF testbed). The assimilation of water levels of Swiss lakes either with direct insertion or with an Ensemble Kalman filter (EnKF) can yield considerably better forecasts. The joint assimilation of streamflow and soil moisture could be implemented operationally in the future to obtain better hydrological forecasts.

A proof-of-concept synthetic study demonstrated that the assimilation of SAR-derived flood extent with a particle filter can improve streamflow forecasting, water elevation and flood extent. However, real case studies are needed to corroborate these findings.

Whether or not other sources of information are available, satellite data can be a great way to inform decision making. Indeed, Pixalytics is an independent consultancy company, which informs decision making in Uganda concerning water availability through the Drought and

Flood Mitigation Service. Currently surface soil moisture products from H SAF are used and there is scope to use the H SAF root-zone soil moisture products in the future.

Session 5 covered **novel hydrological data sources and assimilation techniques**. Machine learning may complement models and traditional DA techniques. Neural networks have been trained based on the nonlinear regression between passive microwave observations from satellites (e.g. SMOS, SMAP) and modelled soil moisture. Subsequently, soil moisture is retrieved directly from the satellite observations without the need for a radiative transfer model. Indeed, SMOS neural networks and SMAP neural networks examples were demonstrated. Another application of machine learning with multilayer perceptrons for performing data assimilation in a simple rainfall-runoff model was successfully demonstrated, but extreme learning machines (with no iterative training) were less effective.

One example demonstrated that the direct assimilation of Digital Elevation Models from LIDAR observations in hydraulic models using a particle filter can lead to improvements in flood extent mapping downstream from the observed location. Another interesting presentation investigated the sequential and variational assimilation of satellite snow data through a conceptual hydrological model in a mountainous catchment. It was found that the assimilation of snow observations (H SAF products) together with discharge improved the snow and discharge outputs in the HBV model compared to an open loop run. Moving Horizon based Variational methods performed better than Sequential Kalman Filtering methods. Future work will extend the models to NWP predictions (deterministic and probabilistic) for real time forecasting.