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Editorial

"Advances in Earth observation for water cycle science"

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1 Introduction

Since observing the Earth from space became possible more than forty years ago, satellite Earth Observation (EO) missions have become central to the monitoring and understanding of the Earth system, its different components and how they interact with each other. The continuous growth and improvements in the quality of the data and information provided by satellites has resulted in significant progress and advances in a broad range of scientific and application areas including the understanding and characterisation of the global water cycle hydrology and water management.

The water cycle is a complex process driven mainly by solar radiation. The evaporation of water from open water and wet soil surfaces is controlled by energy and water availability and near-surface atmospheric conditions (air temperature, humidity and wind-speed), while transpiration of water is primarily controlled by vegetation. The result of evaporation and transpiration is the presence of water vapour in the atmosphere, a prerequisite for cloud formation. If cloud condensation nuclei are present and if the atmospheric state allows for condensation, clouds are formed which are then globally distributed by winds. In the presence of precipitating clouds, water returns back to the Earth's surface where it accumulates in rivers, lakes and oceans. Surface water may also infiltrate into the soil, moistening the soil layers and accumulating as groundwater replenishing aquifers. Aquifers can store water for several (thousands of) years, provide water for human activities, or discharge it naturally to the surface or to the oceans. The response of the hydrological cycle to global warming is expected to be far reaching (Bengtsson, 2010), and because different physical processes control the change in water vapour and consequently evaporation and precipitation, a more extreme distribution of precipitation is expected leading to, in general, wet areas become wetter and dry areas become dryer (IPCC, 2008).

In this context, relying on accurate and continuous observations of the long-term dynamics of the different key variables governing the energy and water cycle processes from global to local scale is essential to further increase not only our understanding of the different components of the water cycle both in its spatial and temporal variability, but also to characterise the processes and interactions between the terrestrial and atmospheric aspects of the energy and water cycle, and how this coupling may influence climate variability and predictability. Such global and continuous observations can only be secured by the effective use of Earth Observation (EO) satellites as a major complement to in-situ observation networks.

In the years to come, EO technology will enter into a new era, where the increasing number of more sophisticated missions will provide scientists with an unprecedented capacity to observe and monitor the different components of the water cycle from the local to the global scales. Already today, global observations of several key parameters governing the global water cycle (e.g. precipitation, soil moisture, water vapor, evaporation and transpiration, water levels, gravity-derived groundwater measurements, etc. ...) are feasible. In addition, significant progress has been made in the area of data assimilation enhancing the capabilities to integrate EO-based products into suitable land surface and hydrological models; hence opening new opportunities for science and applications.

The full exploitation of the potential in earth observation is becoming critical not only for science but also for operational and political reasons. In fact, global synoptic information on water resources availability and quality represents a critical support to water governance, management and planning, and it is a priority in order to enhance our capability to predict and adapt to climate change.

As a synthesis of these recent advances, this special issue "Earth observation and water cycle science" aims at collecting a number of scientific results demonstrating the potential and exploring the limits of EO technology as a key tool to advance our current knowledge on the water cycle at different scales in space and time; to better characterize and model the different components of the hydrological cycle from global to regional (basin) scales; and to support global water cycle predictions and water resources management. After an overview of novel EO missions (Sect. 2), the scientific advances reported in the papers of this special issue will be briefly summarized in Sect. 3. Section 4 will provide outlook to future opportunities.

2 Novel EO missions for water cycle science and hydrology

In the coming years, data from many new EO missions will become available to the scientific community. Here a short overview of EO missions suitable for monitoring different components of the water cycle – namely soil moisture, ocean salinity, water surface elevation, precipitation, water vapour, clouds and aerosols, snow, and land surface temperature – will be given.

Soil moisture: the Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001, 2010), launched successfully on 2 November 2009, aims to provide soil moisture information with accuracies of 4 % in volume with 3 days of revisiting time and spatial resolutions better than 50 km. The SMOS mission is ESA's second Earth Explorer Opportunity mission and carries a single payload, an L band 2-D interferometric radiometer in the 1400–1427 MHz protected band. Its measurements will be complemented by NASA's Soil Moisture Active and Passive mission (SMAP) planned for launch in 2014–2015 (Entekhabi et al., 2010). The SMAP observatory consists of a multi-polarization L-band radar and a radiometer that share a 6-m deployable-mesh reflector antenna. Combined observations from the radar and radiometer is expected to provide accurate estimation of soil moisture at hydrometeorological (10 km) and hydroclimatological (40 km) spatial scales. These new mission will complement existing datasets derived from passive and active microwave information, opening new opportunities to advance towards the creation of a long-term essential climate variable data record on soil moisture.

Sea surface salinity: besides soil moisture information, SMOS provides also sea surface salinity (SSS), which represents a valuable piece of information to understand the global water cycle and its dynamics. SMOS ocean observations have been recently complemented by AQUARIUS, a NASA mission aiming at producing global salinity maps at 0.2 psu accuracy on a monthly basis at 150-km resolution. AQUARIUS payload includes a Passive Salinity Sensor L-Band Radiometer operating at 1.4 GHz supported by an Active Surface Roughness Sensor L-Band Scatterometer operating at 1.2 GHz, using real aperture and a 2.5-m composite reflector antenna.

Water surface elevations: due to the continuous thinning of the in-situ stream gauge networks in several parts of the world, satellite observations of water surface elevations would be much needed to better understand the spatio-temporal variability of surface fresh water. Satellite altimetry has already been applied to the study of the water levels of rivers and lakes but the coarse resolution and poor temporal coverage of the available nadir altimeter data has to some extent limited the ability in addressing key hydrological questions on water storage and discharge. ESA's Cryosat-2 altimetry data (Wingham et al., 2006) is now been tested as a new tool to improve current observations provided by traditional altimetry. However, the experimental nature of this mission and the poor coverage over land areas (due to the fact that the primary scientific objective of this mission is mainly focused over the poles) will not allow the exploitation of the Cryosat-2 dataset for operational applications. This problem is expected to be solved in the future with the advent of the Sentinel-3 mission, a joint undertaking by ESA and the European Union within the context of the Global Monitoring for Environment and Security (GMES) programme, which will incorporate an altimeter payload based on the new Cryosat-2 measuring concept providing new perspectives for operational inland water levels retrieval. This information will hopefully be complemented by the data provided by the planned Surface Water and Ocean Topography (SWOT) satellite mission with its wide-swath altimetry technology as a means of completely covering the world's oceans and freshwater bodies with repeated high-resolution elevation measurements. Over land, the SWOT satellite instrument will produce a water mask able to resolve 100 m wide rivers and 1 km^2 lakes, wetlands, or reservoirs.

Precipitation: precipitation is the primary source of freshwater influencing the water, energy and ocean circulation cycles, playing a key role in extreme weather events such as hurricanes, floods, droughts, and landslides. A new mission, namely, the Global Precipitation Measurement (GPM) mission, is under development aiming at overcoming some of the major gaps today in this type of global observations. GPM, planned to be launched in 2013, is an international satellite mission involving NASA and JAXA, designed to unify and advance precipitation measurements from a constellation of dedicated and operational sensors to provide "next-generation" precipitation estimates characterized by more accurate instantaneous precipitation measurement (especially for light rain and cold-season solid precipitation) and more frequent sampling by an expanded constellation of microwave radiometers including operational humidity sounders over land.

Water vapour: water vapour can be measured with many operational satellite sensors. For example, the Infrared Atmospheric Sounding Interferometer (IASI) and the Atmospheric Infrared Sounder (AIRS) instruments provide a new category of infrared profiling instruments that are of unprecedented value for improved knowledge on water vapour profiles with global coverage. More on the research side, the PREMIER (Process Exploration through Measurements of Infrared and millimetre-wave Emitted Radiation) concept aims at advancing in our understanding of the processes that link trace gases, radiation and chemistry in the upper troposphere and lower stratosphere. The radiative effects of water and clouds are at a maximum in this region.

Cloud-aerosol interaction: the EarthCARE mission aims to improve the representation and understanding of the Earth's radiative balance in climate and numerical weather forecast models by acquiring vertical profiles of clouds and aerosols, as well as the radiances at the top of the atmosphere. EarthCARE observations will lead to more reliable climate predictions and better weather forecasts through the improved representation of processes involving clouds, aerosol and radiation. Aerosols control cloud properties, clouds control the production of precipitation and vigorous convection influences stratospheric humidity. Cloud feedbacks are one of the main causes of the uncertainty in predictions of future climate. A better representation of clouds-aerosol-radiation processes in models (NWP and climate) is therefore needed.

Snow: the candidate ESA Earth Explorer mission COld REgions Hydrology High-resolution Observatory (CoReH2O) has been selected for scientific and technical feasibility studies (Phase-A) and focuses on cold region processes. This mission will in particular perform spatially detailed repeat measurements of snow and ice properties. A main objective is the observation of snow water equivalent, in order to improve the modelling of snow and ice processes and to advance the prediction of stream flow in regions where snow and glacier melt is an important component of the water balance. A dual frequency SAR, operating at X-band (9.6 GHz) and Ku-band (17.2 GHz), VV and VH polarizations, with a swath width of about 100 km, has been selected for this mission.

Land surface temperature: land surface temperature (LST) is strongly coupled to the moisture and vegetation conditions. Geostationary meteorological satellite systems (e.g. GOES, METEOSAT, FY-2B, MSG) provide nearly global coverage of LST at kilometre spatial scale and sub-hourly temporal frequency. The proposed Landsat Data Continuity Mission (LDCM) and Hyperspectral Infrared Imager (HyspIRI) mission will provide global LST coverage with a biweekly (LDCM) to less than 6 day (HyspIRI) repeat cycle at sub-field-scale resolution (∼60 m). Used in combination, this LST information may provide unique capabilities for evaluating the water cycle at spatial scales commensurate to ground observations and provide a way of validating and up-scaling to water and energy fluxes produced by microwave and other coarse resolution sensors.

3 Advances on the use of EO technology for water cycle science

This section provides an overview of the different papers collected in this special issue. They provide a good panorama of some of the recent scientific efforts carried out by the international scientific community to advance our understanding of the water cycle by exploiting the advantages of EO technology. It is worth nothing that the discussion below provides only a partial view of the current state of the art, as the discussion is mainly focused on the papers included in this special issue. In fact, many important parameters, observations and open scientific issues are not tackled in detail. However, the sample of works included in this issue provides an excellent showcase of some of the main areas of research where the community is focusing their efforts at present time.

A significant part of this special issue is dedicated to evaporation and transpiration. Evaporation/transpiration (ET) is the process whereby water is transferred from the surface to the atmosphere (Kalma et al., 2008) as a combination of soil and water evaporation and vegetation transpiration. Where evaporation is only controlled by the physical processes of diffusion and advection, transpiration is also controlled by biological process, like photosynthesis. Evaporation and transpiration is unique in providing the link between energy, water and plant growth and as such it is vital in the energy, water and carbon cycle processes (Bowen, 1926; Penman, 1948; Montheith, 1965; Famiglietti and Wood, 1994). By returning available water at the surface to the atmosphere, terrestrial evaporation and transpiration regulates the biological environment and its water use efficiency. In addition, evaporation and transpiration is a key quantity for the estimation of crop yield, irrigation water management, drought assessment, fire susceptibility, convective precipitation patterns as well as catchment water budgets.

Several papers report impacts and uncertainties of different parameterisations required to estimate ET, namely those related to in-canopy wind profile formulations by Cammalleri et al. (2010) and those using default parameterisation in SEBS model (Su, 2002) to derive evaporation and transpiration in a heterogeneous study area in South Africa by Gibson et al. (2011).

Anderson et al. (2011) reports mapping daily terrestrial evaporation at field to continental scales using geostationary and polar orbiting satellite imagery, while Miralles et al. (2011) presents a model for global land-surface evaporation using satellite-based observations as some input.

Modeling evaporation and transpiration at large scale using near-real time MSG SEVIRI derived data is reported by Ghilain et al. (2011).

At local scales, useful for crop management and agricultural applications, Courault et al. (2010) proposes a method for the use of high resolution multitemporal FORMOSAT-2 images with a crop model for biomass and evaporation and transpiration estimation on a field scale. This approach is particularly interesting as a precursor to potential operational systems based on the planned Sentinel-2 missions, which will provide optical high resolution data with unprecedented coverage.

Land surface temperature represents a key input for evaporation and transpiration models. In this special issue, Corbari et al. (2010) show that land surface temperature can be represented adequately in a heterogeneous area through a distributed energy-water balance model and remote sensing data. The benefit of such an approach is clearly that remotely sensed land surface temperature can be used as a direct constraint to optimise the spatial representativeness of a hydrological model by improving the model structure and parameterisation.

Another important component of the water cycle that has been extensively treated in this special issue is soil moisture. In the last few years, the field of microwave remote sensing has matured to the point where we can construct multi-decadal, global, coarse-resolution (25–50 km) soil moisture time series, but their use for climate change studies has still to be proven. An improved soil moisture dataset was presented by Liu et al. (2011) by blending passive and active microwave satellite-based retrievals. This paper is complement to the work proposed by Dorigo et al. (2010), which reports error characteristics in global active and passive microwave soil moisture datasets that is important for model validation and data assimilation.

For soil moisture at finer spatial scales, the correct parameterisation of surface roughness has posed a challenge for accurate soil moisture retrieval. In this context, Lievens et al. (2011) reports recent progress by developing an operational method using C- and L-band SAR data by means of the effective roughness concept proposed originally by Su et al. (1997). With respect to mapping surface soil moisture by SAR systems, Baup et al. (2011) reports progress by using ENVISAT ASAR data and Fieuzal et al. (2011) by combined use of optical and radar satellite data for monitoring irrigation and soil moisture of wheat crops.

As far as precipitation is concerned, two areas of progresses are reported. One is the rainfall retrievals from SEVIRI reflectances by Wolters et al. (2011) as an operational method, and the other is the high-resolution detection and retrieval of precipitation fields from X-band spaceborne synthetic aperture radar by Marzano et al. (2011) which reports the feasibilities if such data would be routinely available. Kidd and Levizzani (2011) provides a state of the art review of the status of satellite precipitation retrievals.

A significant component of this special issue is dedicated to explore the benefits and challenges to assimilate EO data into land surface and hydrological models. This, in fact, represents an important area of research that is attracting more and more the attention of many scientists worldwide. The potential offered by a suitable combination of EO data, models and in-situ data represents a major opportunity for the future.

In this context, to close the water budget, Negrel et al. (2011) reports estimating river discharge from earth observation measurements of river surface hydraulic variables, while Sun et al. (2010) use of satellite observations of river flow width at basin outlet in calibrated rainfall-runoff models for improving river discharge estimation in ungauged basins.

For investigations in interannual variations of the terrestrial water storage, Frappart et al. (2010) reports progress with a multisatellite approach by using an inundation dataset and water level information over rivers and floodplains derived from radar altimetry, as well as the total water storage measured by gravimetry in combination with hydrological model simulations.

Albergel et al. (2010) reports progress in monitoring of water and carbon fluxes using a land data assimilation system with a case study for south-western France, while Brocca et al. (2010) discusses improving runoff prediction through the assimilation of the Advanced Scatterometer (ASCAT) soil moisture product. The use of remotely sensed latent heat fluxes for model error diagnosis is reported by Schuurmans et al. (2011). Dharssi et al. (2011) presents progress in operational assimilation of ASCAT surface soil wetness at the Met Office by showing improvements in soil moisture analysis when assimilating ASCAT surface soil wetness.

Some efforts have been carried out in the last years in order to advance from sometimes a poorly scientific and research status to an operational level in the use of EO and modelling as an operational water management tool. As an interesting example, the role of satellite observations in an operational context is reviewed by van Dijk and Renzullo (2011) in water resource monitoring systems as practised in Australia.

Finally, it is worth noting the importance of in-situ networks. Without appropriate in-situ observations, the progress on the validation, calibration and development of EO derived geo-information products will not be possible. In this context, Su et al. (2011a) reports the establishment of the Tibetan Plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) and its use for quantifying uncertainties in coarse resolution satellite and model products.

4 Final remarks

The following points provides some conclusions raised from the analysis of the different papers included in this special issue and represent some of the major overall requirements for the future in order to enhance the use and acceptance of EO technology by the hydrological, water cycle and climate communities.

Improve interdisciplinary collaboration and dialogue: this special issue underlines that an integrated approach to observe and characterize the water cycle with all its components will be fundamental to ensure the effective computation of basin-to-global scale water budgets and the full application of EO technology to water cycle science, climate, hydrology and operational water management. In the near future, this interdisciplinary collaboration, the dialogue between the EO and the earth system science, hydrology and climate communities, and a more holistic approach to observe and characterise the water cycle and not only its individual components will be fundamental to ensure the effective computation of basin-to-global scale water budgets and the full application of EO technology into climate research, operational water management and hydrology.

Promote inter-comparison and assessment exercises: the different contributions included in this issue also highlight the large number of methods, techniques and products that have been developed in the last years by the EO community addressing several components of the water cycle. In this context, promoting inter-comparison exercises providing a clear understanding of the validity ranges, uncertainties and limitations of algorithms and retrieved data products represent a major need for the coming future. In this respect it is worth noting the international coordination efforts carried out in the context of the Global Energy and Water Experiment (GEWEX), e.g. LandFlux (Jiménez et al., 2001), GEWEX Water Vapour Project (GVAP), to assess and compare different EO-based products and data sets; hence contributing to promote and facilitate the understanding and acceptance by the climate research community.

Enhance understanding of multi-scale inconsistencies: furthermore, dedicated multi-scale data analysis experiments studying the inter-scale relationships between point measurements on the ground, airborne data sets and observations retrieved at different scales and resolutions from satellites needs to be promoted. A better understanding of the multi-scale inconsistencies between the hydrological and biophysical processes measured in-situ and the final observations and data products obtained from satellites at different resolutions from local to global scales will open new opportunities to develop enhanced methods, algorithms and data products. Reducing multi-scale inconsistencies between in-situ observations and different scales EO-based data products is a major requirement to ensure an effective dialogue between the models characterising biophysical and hydrological processes and the geo-information retrieved from satellites.

Advance in the understanding of the full potential of novel missions: the capacity of current available missions is being complemented by a new generation of scientific and operational satellites that will offer new opportunities for science and operational applications. However, it will be still necessary to further understand the full potential of these novel missions that in many cases are based on new technologies. Further research will be required in order to maximize the scientific impact of those missions as well as to generate robust and enhanced data products that may gain the acceptance of hydrologist and climate modelers in the near future.

Maximize the exploitation of multi-mission multi-product synergies: this growing observational capacity is also increasing the need for dedicated research efforts aimed at exploring the potential for the synergic exploitation of the different and complementary capacities offered by these new sensors. Multi-mission approaches that exploit synergies among different missions and data sets need to be further promoted.

Exploiting data archives towards long-term data records: it is important to emphasize the need for international coordinated efforts for the development of long-term consistent data record governing the water cycle that may exploit the increasing archives of EO data. This effort will require a significant international cooperation.

Promote higher resolution observations and integration into operational hydrology and water management practices at basin scales: current EO technologies have been proven to be a useful tool for studying key water cycle components at large and global scales. However, most of the practical day by day water management decisions are taken at basin and sub-basin levels. It is required to further develop high resolution observation systems being able to provide, with the required frequencies, accuracies and coverage, key parameters, e.g. soil moisture, land surface temperature, which may contribute to enhance the capacity to address basin and local scale hydrological processes for operational water management.

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