ESA-GEWEX
EARTH OBSERVATION AND WATER CYCLE SCIENCE PRIORITIES

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List of Abbreviations

AMSR	Advanced Microwave Scanning Radiometer
AMSR2	Advanced Microwave Scanning Radiometer-2
AMSU	A/B Advanced Microwave Sounding Unit
ATMS	Advanced Technology Microwave Sounder
AVHRR	Advanced Very High Resolution Radiometer
CMIP	Coupled Model Intercomparison Project
CPR	Cloud Profiling Radar
DPR	Dual-frequency Precipitation Radar
EarthCARE	Earth Clouds Aerosols and Radiation Explorer
ECV	Essential Climate Variable
ESA	European Space Agency
ESMR	Electrically Scanning Microwave Radiometer
GCOM-w1	Global Change Observatory Mission-Water1
GEO	Geostationary Earth Orbit
GEWEX	Global Energy and Water Cycle Experiment
GMI	GOM Microwave Imager
GPM	Global Precipitation Measurement mission
GRACE	Gravity Recovery and Climate Experiment
IGOS	Integrated Global Observing Strategy
IMERG	Integrated Multi-satellitE Retrievals for GPM
IR	Infrared
JAXA	Japan Aerospace Exploration Agency
MERIS	MEdium Resolution Imaging Spectrometer
MetOp	Meteorological Operational *satellite* programme
MetOp-SG	Meteorological Operational *satellite* programme – Second Generation
MHS	Microwave Humidity Sounder
MLS	Microwave Limb Sounder

MODIS	Moderate-Resolution Imaging Spectroradiometer
MTG	Meteosat Third Generation
MW	Microwave
MWI	MicroWave Imaging radiometer
NASA	National Aeronautics and Space Administration
NRCS	Normalized Radar Cross-Section
OLCI	Ocean and Land Colour Instrument
PBL	Planetary Boundary Layer
PMW	Passive Microwave
PR	Precipitation Radar
SAPHIR	Sondeur Atmosphérique du Profil d'Humidité Intertropicale par Radiométrie
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SMAP	Soil Moisture Active Passive
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SSMI	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SWOT	Surface Water & Ocean Topography
TCWV	Total Column Water Vapour
TMI	TRMM Microwave Imager
TMPA	TRMM Multi-satellite Precipitation Analysis
TRMM	Tropical Rainfall Measuring Mission
UTLS	Upper Troposphere Lower Stratosphere
VHRR	Very High Resolution Radiometer
VIIRS	Visible Infrared Imaging Radiometer Suite
Vis	Visible
WCRP	World Climate Research Programme

Meeting abstracts book and presentations
A link to all meeting presentations and abstract book can be found here:

http://www.eo4water2015.info

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1. Objectives of this document

This documents collects and elaborates on the major discussion points gathered during the ESA-GEWEX conference on Earth Observation (EO) for Water Cycle Science that took place the 23rd – 26th October at ESA-ESRIN, Frascati, Italy.

The meeting, with a participation of more than 200 experts, was aimed at reviewing and discussing the existing scientific knowledge gaps and research priority areas for the water cycle where EO may contribute in the next decade.

The outcome of the meeting and its conclusions will contribute to guide scientific activities on water cycle research, supporting the water scientific community and GEWEX strategic objectives.

This document, together with additional inputs, will contribute to establish a strong water science component in the upcoming programmatic elements of ESA (for the 2017-2021 timeframe).

The current document elaborates on the meeting discussions as well as on the different information exchanges with the participants and other experts during and after the meeting.

It is worth mentioning that the meeting did not cover all areas of research and science in the context of water cycle research, and that this document only provides a partial outlook, addressing some of the main Earth Observation contributions to water cycle science priorities. Key relevant research domains such as hydrology or the energy cycle have not been extensively discussed at the meeting and as such will only be briefly discussed in this paper. Some of these specific areas have been covered by dedicated workshops: e.g.,

- Third Space for Hydrology Workshop, "Surface Water Storage and Runoff: Modelling, In-Situ data and Remote Sensing", 15-17 September 2015;
- Conference "Salinity and Freshwater Changes in the Ocean", Hamburg, 12-15 October 2015

The meeting and this document focus mainly on scientific aspects and research needs. Needs for the services and operational aspects were not discussed in detail at the meeting and are only mentioned in this document when pertinent but are not described at length.

Although services are only hinted at in this document, the scientific advances and research developments discussed below (in terms of novel missions, new methods and algorithms, innovative products, and enhanced knowledge of Earth system processes) represent some of the main areas to be further developed for the next generation of EO applications and information services for the water cycle.

2. Introduction

The water cycle is a complex process driven chiefly by solar radiation. The evaporation of water from open water (including oceans) and land is controlled by energy and water availability and near-surface atmospheric conditions (air temperature, humidity and wind-speed), while transpiration of water is also controlled by plants. 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 also infiltrates into the soil, moistening the soil layers, accumulating as groundwater and replenishing aquifers. Aquifers can store water for many 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). Since different physical processes control changes in water vapour and evaporation/precipitation, an impact on the distribution of extreme precipitation events is expected, generally leading to wet areas becoming wetter and dry areas becoming dryer. As such, changes in the hydrological cycle, as a consequence of global warming, may be more severe than temperature changes, due primarily to large increases in extreme precipitation rates (Lenderink and van Meijgaard, 2010) and more extreme droughts.

In this context, it is of great importance to obtain accurate and continuous observations of the long-term dynamics of the different key variables governing the processes above, from global to local scale. This will further increase our understanding of the different components of the water cycle, both in its spatial and temporal variability. This will also enhance our capacity to better characterize the different processes and interactions between the terrestrial, ocean and atmospheric branches of the energy and water cycle, and how this coupling may influence climate variability and predictability. Such global and continuous observations can only be effectively applied through the integrated use of Earth Observation (EO) satellites complementing in-situ observation networks and modeling.

In recent years, EO technology has proved to be a major source of data to retrieve an increasing number of hydro-climatic variables, including radiation and cloud properties (Schulz et al., 2009), precipitation (Kummerow et al., 2001; Huffman et al., 2007; Kidd and Levizzani, 2010), evaporation (Kalma et al., 2008; Jiménez et al., 2011), soil moisture (Aires and Prigent, 2006; De Jeu et al., 2008), water vapour (Schulz et al., 2009), ground water storage (Rodell et al., 2007) and many others (see for example, GEO, 2005; ESA, 2006; CEOS, 2009; Su, 2010). Such measurements not only have enhanced our capabilities to predict the variations in the global energy and water cycle but also open the door to new applications where EO may become a critical element for water management, agriculture or the prediction of water-related natural hazards and sustainable human development (GEO, 2007; IPCC, 2008).

However, despite considerable research progresses in understanding the water cycle over the last decade, many gaps remain in observational capabilities and scientific knowledge. These gaps presently limit our ability to understand and interpret on-going processes, prediction capabilities and forecasting of the water cycle, thereby hampering evidence-based decision-making. Addressing these gaps represents a key priority in order to establish a solid scientific basis for the development of future climate services on water, as outlined in the Roadmap for Climate Services published by the European Commission (EC, 2015).

ESA, NASA, JAXA and several other space agencies and institutions have dedicated significant efforts at addressing different observational needs for water cycle research and applications. The recent availability of dedicated missions such as SMOS, AQUARIUS, SMAP, CryoSat, GPM, GCOM-w1, the advent of the Sentinel series, and the upcoming availability of missions such as EarthCARE, SWOT, IceSat-2, GRACE Follow-On, MetOp SG or MTG will complement and enhance the existing long-term record of observations, contributing to improving our knowledge of the different processes involved in the water cycle as well as our capacity to predict the water cycle dynamics.

This unprecedented observational capability is a major opportunity for the international community and dedicated efforts will be devoted at maximising the scientific return of the massive synergies offered by this unique multi-mission observational capacity.

In this context, international collaboration and coordination will be a key element in the coming years in order to advance towards the development of the future space infrastructure as well as for the establishment of a solid science basis that may drive future applications and information services in the water cycle domain.

3. EO and Science Priorities for the Water Cycle

3.1 The global water cycle

Only about 2.5% of the water in our planet is freshwater (Oki and Kanae, 2006) and only a small amount of it (around 1%) is accessible for human consumption (since approximately 70% and 30% is stored, respectively, as ice in glaciers and ice sheets or as deep groundwater). Furthermore, accessible freshwater is an extremely fragile resource: in fact, processes affecting only a small part of the water balance can largely impact on accessible fresh water.

In this context, understanding the global and regional dynamics of the water cycle, its different processes and its spatial and temporal variability, represents a major condition to subsequently evaluate potential consequences of climate change and their potential impacts on human societies and ecosystems.

Available observational records (both from satellite and in-situ networks) provide evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change. In particular, each degree of warming is projected to decrease renewable water resources by at least 20% for an additional 7% of the global population (Schewe et al., 2014).

The IPCC technical paper on Climate Change and Water (Bates et al., 2008), reports on recent results from climate simulations for the 21st century, which consistently project precipitation increase at high latitudes and part of the tropics, with decrease in some subtropical and lower mid-latitude regions. This will alter river runoff in a similar manner with projected annual average increases at high-latitudes and some wet tropical areas and decrease over some dry regions at mid-latitudes and in the dry tropics, impacting many semi-arid and arid areas (e.g., Mediterranean, western USA, southern Africa or north-eastern Brazil), which may suffer a decrease of water resources.

These expected changes may impact the intensity and variability of floods and droughts in many areas with an increase on heavy precipitation events and risk of floods as well as extreme droughts and drying processes in continental interiors during summer, especially in the sub-tropics, low and mid-latitudes, increasing wild fire risk and causing a major impact on human population, leading to a decreased food security and increased vulnerability of poor rural farmers, especially in the arid and semi-arid tropics and Asian and African megadeltas (Bates et al., 2008).

Functioning, operation and management of existing water infrastructure (e.g., hydropower, flood defence, drainage, irrigations) will not only be stressed by the above changes, but will be further exacerbated by population growth and increased water demands, rendering mitigation and adaptation measures a critical aspects that may influence several policy areas such as energy, health, food security and nature conservation.

In order to face these challenges, enhanced and continuous observations (satellite and in-situ) as well as their processing into products and information must be linked to dedicated efforts to improve understanding and modelling of the hydrological cycle at scales of relevance to decision making.

In spite of significant international efforts, several knowledge gaps still exist due to the limitations in the current observation systems (both satellite and in-situ), as well as deficiencies in models and lack of understanding on key processes:

- In-situ data over certain regions are very scarce.
- Several processes are still not well understood: missing physics in models and related feedbacks – e.g. convection-related feedbacks, aerosol effects, soil water feedbacks, ecosystem feedbacks.
- Current satellite observations present limitations to resolved key water cycle components – e.g., snowfall, snow water equivalent (SWE), evaporation, deeper root zone water.
- Resolution of both model and observations (e.g., higher spatial resolution hydrological and atmospheric models (~1km), accounting for water management practices, enhanced observations achieving more accurate higher temporal and (horizontal and vertical) spatial resolutions);
- Physically consistent combination of outcomes from models with observations is often missing, especially with respect to parameters and components of the water cycle.

Several studies on the global water cycle address only specific aspects and relatively few studies have attempted to provide a synthesized view on the global and energy-water cycles (Trenberth et al., 2007, Oki and Kanae 2006, Trenberth and Fasullo, 2013, Rodell et al., 2015; Stephens & L'Ecuyer, 2015, L'Ecuyer et al., 2015) showing imbalances that forced the authors to make adjustments to our best estimate fluxes (on the order of 10 to 15 W/m2). In addition, the water cycle is considered as a purely physical system in isolation from human activities, which may significantly impact several processes in the hydrological cycle. Perhaps, the most obvious example is the building of dams that limit streamflow. It is critical to understand to what extent human intervention impacts the water cycle and how the activities that shape one part of the cycle affect other parts.

In this complex context, the WCRP has elaborated a number of key questions or grand challenges (Trenberth and Asrar, 2014) that summarise the major scientific needs of the water cycle community for the next 5 to 10 years:

- How can we better understand and predict precipitation variability and changes?
    - How well can precipitation be described by various observing systems and what basic measurement deficiencies and model assumptions determine the uncertainty estimates at various space and time scales?
    - How do changes in land use, urbanization and air pollution affect precipitation amounts, intensities and redistribution in time and space?
    - How much confidence do we have in global and regional climate predictions of precipitation?
- How do changes in the land surface and hydrology influence past and future changes in water availability and security?
    -
    - How do changes in climate affect terrestrial ecosystems, hydrological processes, water resources and water quality, especially water temperature?
    - How can new observations lead to improvements in water management?
- How does a warming world affect climate extremes, and especially droughts, floods and heat waves and how do land processes, in particular, contribute?
    - What are the short-term, mid-term and strategic requirements for the existing observing systems and data sets, and which observations are needed to accurately quantify trends in the intensity and frequency of extremes on different space/time scales?
    - How can models be improved in their simulation and predictions or projections of the magnitude and frequency of extremes?
    - How can the phenomena responsible for extremes be better simulated in models?
    - How can we promote development of applications for improved extremes tracking and warning systems?
- How can understanding of water and energy exchanges in the current and changing climate be improved and conveyed?
    - Can we balance the energy/water budget at the top-of-atmosphere?
    - Can we balance the energy/water budget at the surface of the Earth?
    - Can we further track the changes over time?
    - Can we relate the changes in surface energy/water budget with atmospheric-oceanic processes and long-term variability?
    - Can we improve confidence in feedbacks associated with cloud-aerosol-precipitation interactions in the climate system?

3.2 The atmospheric component of the water cycle

3.2.1 Precipitation

Precipitation represents a key component of the water cycle. Its variability and behavior require frequent, closely spaced observations for adequate representation. Such observations are not possible through surface-based measurements over much of the globe, particularly over oceans or developing economic regions. Consequently, on a global scale it is necessary to rely upon satellite-based techniques to derive precipitation estimates with adequate temporal coverage through suites of sensors flying on a variety of satellites:

- Technique based on Visible/Infrared (cloud top properties): e.g., AVHRR, VIIRS, SEVIRI, MODIS.
- Techniques based on Passive Microwave (water vapour & hydrometeors): e.g., SSMI, SSMIS, TMI, AMSR, AMSR2, GMI, AMSU A/B, MHS, ATMS, SAPHIR.
- Techniques based on Active Microwave (hydrometeors): e.g., PR, CPR, DPR.

For global precipitation monitoring and hydrological applications combined MW-IR techniques are currently employed (e.g. TMPA or IMERG) to exploit the higher temporal sampling of the GEO observations. However, these integrated products suffer from structural errors of its components and more attention to these is necessary before estimates for a truly integrated water cycle picture can emerge.

The exploitation of the complete Global Precipitation Measuring (GPM) constellation of passive microwave (PMW) radiometers and radars (providing 3-hourly precipitation coverage over 80% of the globe) provides outstanding rain estimates. This represents a great opportunity to enhance our knowledge and capabilities to characterize rain processes. As a way forward is worth noting that limited information content (primarily from radiometers) requires that more emphasis is placed on elucidating and quantifying structural errors – which can be highlighted via **independent** products or **integrated** assessments.

In general terms, current precipitation estimates are good. It is possible to obtain very good matches between the spatial coverage and rainfall intensity at the instantaneous scale. However, because of the inherent intermittency of precipitation, it is vital to gather improved information on frequency, intensity, amount, type (e.g., rain vs snow) and extremes, as a function of space and various thresholds and time scales (e.g., 50, 100, 500 and 1000 mm over 1 hour, vs, 1 day, vs 5 days rain events). Further efforts are needed in order to address the following aspects:

- Enhancing estimates of light and shallow precipitation;
- Enhancing characterization of small-scale (shower) events;
- Special emphasis should be put in ensuring all-region capability – including cold regions and cold seasons, and dealing with snow. To address this aspect, further research is required as this represents one of the main gaps in retrievals today;
- Caution needed in wholesale bias-correction of retrievals;
- It is worth noting that estimates of precipitation from satellite provide instantaneous rates which then need to be accumulated to obtain amounts; this makes them fundamentally different from rain gauge measurements. Hence it is essential to recognize that there are fundamental differences in the observations or measurements. We need to understand the differences, before accounting for them.
- To adequately deal with intermittency and extremes, it's essential to achieve global hourly precipitation amounts.

Looking at the future, the following requirements should be considered in view of developing the next generation of precipitation missions:

Resolution: commensurate with the phenomena being measured.

- Temporally: *Better than 3h, ideally <1h - lifetime of precipitation systems (e.g. diurnal cycle)*
- Spatially: *Better than 5 km – necessary for precipitation structure and hydrological applications*.

Accuracy: necessary to meet user expectations.

- Observational: *long-term well calibrated sensors*
- Retrieval: *temporally/spatially dependent*
- Range: *full spectrum of precipitation intensities and types*

In this context, having an international multi-agency strategic plan will be critical going forward for **precipitation**, as much of the needed input data are derived from different agencies. Such a plan should include the possibility of, for example, geostationary satellites, formation flying or constellations of small satellites, necessary to provide the long term products needed for climate. For example, simply redistributing current satellite platforms in time would enable 1-hourly coverage, but clustering of satellites leaves gaps.

Due to the pivotal role of precipitation in the water cycle it is strongly recommended that precipitation is included in the list of ESA's ECVs.

It is also very important to emphasize the integrated nature of the water cycle variables, with the recommendations that products should also be more integrated at their basic level as was illustrated with a potential benefit of merging precipitation from direct measurements with inferences made possible by changes in soil moisture (e.g., approaches based on exploiting soil moisture to enhance precipitation estimates through data assimilation), runoff and streamflow.

In this context, further developments to build the next generation of water cycle missions and products shall be oriented to processes and synthesis as well as single parameters and products. An example of this is the cloud-aerosol and precipitation processes that must be better understood to not only improve current products (e.g. structural errors) but also to better understand the core mechanisms that affect the water distribution so that these can be confidently predicted into the future. Cloud and precipitation observations, for instance, should be done in conjunction with other variables to better understand and characterize the associated processes and feedbacks (see also Section 3.2.3): e.g.,

- Cloud microstructure and phase;
- Cloud updrafts;
- Cloud active aerosols;
- Cloud base temperature;
- Thermodynamic atmospheric profiles - instability, wind shear and humidity.

The development of sensors to enhance the capabilities of current and planned sensors with respect to precipitation (e.g. resolution and sensitivity), as well as those that address the linkages between the different elements of the water cycle is strongly encouraged. This also requires synthesis tools including four-dimensional data assimilation and modeling.

The Earth Care mission has a strong focus on cloud processes forming both an example of where the emphasis should be going forward as well as a natural seed from which more cloud and precipitation process related activities and missions should be built. Space agencies should reenergize their interactions to ensure coordination in future missions designed to observe clouds/precipitation and the processes that govern these so that both measurements and predictions of these important variables can move forward.

3.2.2 Water Vapour

Water vapour plays a dominant role in the water cycle and the climate change debate because it is not only a source of moisture but also because it is a greenhouse gas.

However, observing water vapour over a climatological time period in a consistent and homogeneous manner is challenging. On one hand, networks of ground-based instruments able to retrieve integrated water vapour (IWV) data sets has been available since decades. Typical examples are Global Navigation Satellite System (GNSS) observation networks such as the International GNSS Service (IGS), with continuous GPS (Global Positioning System) observations spanning over the last 15+ years, and the AErosol RObotic NETwork (AERONET), providing long-term observations performed with standardized and well-calibrated sun photometers. Also available are radiosonde archives such as the Analyzed RadioSoundings Archive (ARSA) and Integrated Global Radiosonde Archive (IGRA). On the other hand, though covering a shorter time period than sondes, satellite-based measurements of water vapour profiles already have a time span of more than 30 years (e.g. HIRS or, with shorter temporal coverage, AIRS and IASI). Datasets from different sensors have being merged to create long-term time series (e.g. GOME, SCIAMACHY, and GOME-2, SSM/I and SSMIS, SSM/I+MERIS product from the ESA DUE GlobVapour project or the NVAP-M from the NASA Water Vapor Project of MEaSUREs), even though this may lead to inhomogeneity in the dataset.

The combination and merging of multi-satellite multi-sensor and multi-agency data, as well as reanalysis, is key to improve the quality of currently available climate data records, to help constrain the WCRP Grand Challenges and to better constrain energy and water cycle closure studies.

Among others, the stability of resulting Climate Data Records (CDRs), an improved understanding of the associated uncertainties (uncertainty propagation, sampling uncertainties and others) and the development of consistent retrieval schemes, applicable across satellites and sensors types, are important elements and highly challenging. In order to tackle these challenges the following is needed:

- Sustained satellite missions, which allow continuous observations with heritage channels and enhanced capabilities taking into account latest developments from science and technology innovation. Such missions should avoid orbital drift. The prelaunch characterization needs to be complete, fully documented and with free access to the documents. Sufficient overlap between missions is mandatory for proper intercalibration.
- Sustained funding schemes for science and product development, improvement and continuation, especially also for CDRs.
- Data mining, quality control, recalibration and intercalibration of long term missions should be reinforced.
- Consistency among observing systems should be demonstrated.
- Continue to work on estimating sampling and structural uncertainties on global and regional scales.

- It was emphasized that more efforts should go into process studies using diverse parameters: e.g.,
  - o Focus on the UTLS because this region exhibits important climate sensitivity and CMIP models and reanalysis are too wet with respect to observations (e.g., from MLS);
  - o Focus on subsidence regions to identify uncertainties and ideally to develop innovative ideas to improve the vertical resolution of remote sensing missions. In fact, it is hardly possible with current sensor capabilities to resolve PBL in stratus regions. Also, sensors often have sensitivity issues (not ambiguity issues) at near surface layers. Thus, there is a need for high vertical resolution profiles with dense global coverage. The latter is also important at near surface layers.
- Recommendations for new/enhanced products include:
  - o Combine MERIS, MODIS, OLCI over land and SSM/I, SSMIS and MWI over ocean to generate a high quality global satellite-based TCWV product;
  - o Develop consistent retrieval for all hyperspectral sensors in combination with microwave data for profile retrieval and consider reprocessing.

3.2.3 Cloud-aerosol interactions

Aerosols serve as cloud condensation nuclei (CCN), thus, in combination with cloud base updrafts, they determine convective cloud drop concentrations, N_d. The amount of condensed cloud water increases with cloud depth above its base (D). This causes the cloud drop effective radius (r_e) to increase with D, but at a slower pace for larger N_d, because the cloud water is distributed among larger number of smaller cloud droplets. Since drop coalescence rate depends on r_e^5, significant rain starts when r_e exceeds ~ 14 μm. The D at which r_e exceeds any given size increases linearly with N_d (Freud and Rosenfeld, 2012). This means that cloud must grow deeper to start raining in more polluted air masses. In polluted deep convective clouds with warm base the delay of rain initiation to above the freezing level leads to more supercooled water that freeze into large ice hydrometeors that release more latent heat aloft and invigorates the convective clouds, thus redistributing the rain to more intense over shorter time and smaller area (Rosenfeld et al., 2008). This affects the vertical motions and can modify weather circulation patterns (Fan et al., 2012), modifies tropical (Rosenfeld et al., 2012) extratropical cyclones (Wang et al., 2014) and lead to greater occurrences of severe convective storms (Rosenfeld and Bell, 2011). Aerosols can act also as ice forming nuclei. Their incorporation in supercooled clouds can enhance their precipitation under some circumstances, especially in orographic clouds (Fan et al., 2014).

The radiative effects of aerosols can change the vertical heating profiles of the atmosphere. Larger aerosol optical depth (AOD) scatters and absorbs more solar radiation which suppresses surface heating and evaporation, thus leading to smaller precipitation amounts (Ramanathan et al., 2001). The redistribution of solar heating can lead also to redistribution of precipitation, which in some cases was documented to lead to catastrophic floods (Fan et al., 2015).

To document the processes by which these aerosol cloud integrations affect the hydrological cycle, satellite measurements and retrievals are recommended to include the following properties:

- Aerosol optical depth, absorption, type and vertical extent.
- Cloud type - convective or stratiform, coupled to the boundary layer or elevated.
- Cloud base height and temperature.
- Cloud base drop concentrations.
- Cloud base updraft.
- Cloud condensation nuclei concentration as a function of supersaturation.
- Cloud drop effective radius as a function of depth above their base.
- Cloud glaciation temperature.
- Cloud depth and top temperature.
- Cloud top rising rates and updrafts.
- Ice forming nuclei.

Some of these properties appear to be currently unattainable, but concepts and ideas for satellite missions that can measure them are being developed by some of the co-authors of this report, and are well within the presently available technology.

For the way forward in this topic, it is also worth mentioning the new GEWEX Cloud-Aerosol-Precipitation Initiative aiming at performing a global assessment of the impacts of variations in aerosol loading on precipitation as a function of varying environments.

3.3 The land component of the water cycle

The land component of the water cycle includes complex processes and links to the atmosphere and oceans that require different types of observations from satellites and in-situ networks. Today, satellites only provide a partial view of the different variables that characterize the water cycle over land. Key measurements such as lakes and river heights measurements, soil moisture, precipitation (see Section 3.2.1 above), ground water storage or heat fluxes (see Section 3.5.1 below) are currently provided by satellites with different levels of coverage, accuracy, temporal and spatial resolutions. In this context, the following recommendations for further work can be made (heat fluxes and precipitation are treated in their dedicated Sections):

- **Snow mass and water equivalent:** Although there is an urgent need to determine a robust method for providing information on global terrestrial snow mass, existing spaceborne sensors are unable to retrieve this parameter at high spatial and temporal resolution scales. Actually the observational needs in terms of spatial and temporal resolution have been addressed in the IGOS Cryosphere Theme Report (2007) but cannot be met by conventional/current satellites and products (e.g., daily or every 2-days northern hemisphere coverage at a moderate, ~1 km, resolution for operational land surface data assimilation, NWP and hydrological forecasts). In order to meet the accuracy requirements of SWE for the different states of the global snow cover, dual or multi-sensor approaches, including formation flying with existing and planned missions should be assessed through experimental campaigns and theoretical studies. This includes investigations of dual or even multi-frequency observables from lower frequency L-band systems to higher frequency Ka-band systems (including exploiting the interferometric phase and tomography techniques) for the determination of key snow and cryospheric parameters. The need of a new mission based on different techniques must be also evaluated. Airborne LiDAR data might provide an exceptionally valuable suborbital data source for Cal/Val and process studies of snow depth. Furthermore, a better integration of snow retrievals with physical and electromagnetic snow/soil models is required as well as coordinated field experiments on the representation of the snow microstructure and its evolution. Special attention should be paid to the development of robust algorithms on mountainous regions where retrievals are more challenging.

- **Enhancing soil moisture observations and products:** Concerning soil moisture observations and products, it is important to:

    - Continuously advance in the consolidation and refinement of the different methods and algorithms to derive surface soil moisture and root-zone soil moisture products;
    - Explore the potential offered by the synergistic use of different missions (e.g., SMOS, SMAP, SAR systems);
    - Foster the contribution of existing missions (e.g., SMOS, SMAP) to long-term records of soil moisture, directly responding to the needs of the climate community.
    - Foster and promote the development and demonstration of different applications in close collaboration with the end-user community. This may help not only to identify the limits and advantages of current systems but also to expand the user base in view of preparing the next generation of soil moisture missions.

- Explore the potential of new SAR systems (e.g., Sentinel 1, TerraSAR-L) to provide higher resolution products.
- Advance towards a process understanding at local to regional scales (e.g. study the interactions of soil moisture and vegetation) by exploiting the synergies with optical and thermal data.
- Concerning future soil moisture missions, it is recommended to initiate dedicated activities aimed at collecting and consolidating the user requirements (end-user information needs) for different applications and user communities (e.g., climate, agriculture, hydrology, etc..) that may drive the technical specifications (observation requirements) of the future observational systems. Different user communities may have different needs leading to contrasting observational requirements (e.g., spatial resolution vs frequency of acquisitions) and different technological solutions. Exploring different technological options and mission concepts to address the specific information needs of the different communities through dedicated exploratory studies, in-situ and airborne campaigns and potentially dedicated Observational System Simulation Experiments is a priority.

- **Enhancing river, lake and reservoir storage observations:** Much progress has been made over the past decade with respect to the operational mapping of open water with both optical and SAR imagery (Liebe et al. 2005; Annor et al., 2009). When the relation between surface area and stored volumes are known, this allows for monitoring of storage in lakes and reservoirs, which has important science and societal value. By combining surface area measurements with water height measurements, stored volumes can be determined without in situ bathymetrical knowledge. The combination of open water surface mapping and water heights will be an important source of hydrological information. In addition, retrievals of changes in water levels from satellite has been consolidated in the last decade as a successful application. Recently, CryoSat has opened the door to the exploration of the SAR altimetry capabilities for river and lake water level heights. The next advent of SWOT will further open the door to a new and global observation capacity with an enormous potential for hydrology applications as well as for global water cycle research. It is of critical importance to further advance in the elaboration of advance methods to exploit this novel data as well as to prepare for the synergistic use of the different altimeter and imaging systems that will be flying in the future.

- **River discharge monitoring:** Some 80% of the world's population and 65% of its river ecosystems are threatened by insecure water supply, yet global knowledge of the river discharges upon which these depend is surprisingly poor. River discharge is one of the most accurately measured components of the hydrological cycle from gauge measurements but access to river discharge is typically limited. Estimates of absolute river discharge (in cubic meters per second) are mostly derived from ground-based information but can also be obtained from satellite remote sensing (e.g., altimetry) complementing information to the existing discharge monitoring network. Future, **higher resolution sensors** (SWOT) may have the potential to overcome limitations of current systems (e.g., in terms of coverage, resolution). However, it is also required to improve existing models as well as to foster the effective assimilation of available satellite data into hydrological models with the ultimate target to enhance global estimates of river discharge to the oceans.

- **Groundwater storage:** Groundwater is a vital resource as well as a useful indicator of hydroclimatic variability. It typically varies more slowly and on larger spatial scales than the near-surface components of the water cycle, yet it exhibits significant interannual variability, integrating the effects of water cycle variations on timescales of weeks to decades. While ground based observations are unavailable in most of the world, GRACE demonstrated that groundwater storage changes could be monitored from space, albeit at much lower resolution (150,000 km^2 and monthly) than other remote sensing observations. GRACE Follow On is scheduled to launch in 2017, extending this unique and important data record. Beyond GRACE Follow On, data continuity should continue to be the highest priority, while advanced gravimetry techniques that could potentially improve the spatial and temporal resolution of the measurements (such as satellite constellations and cold atom gradiometers) should be explored. In this context, inter-agency collaboration is strongly recommended. Furthermore, assimilation of GRACE data into land surface models, which enables spatial and temporal downscaling and vertical disaggregation of the terrestrial water storage observations, should continue to be pursued as an alternative to high resolution measurements for satisfying the needs of the hydrological community in terms of spatial scales and accuracies towards fostering operational hydrology services.

- **The boundary layer observations:** The Planetary Boundary Layer (PBL) is a critical component of Earth System Science. There is an established and growing need for routine PBL measurements over land for a range of applications: Hydrology, Clouds & Convection, Pollution & Chemistry or Land-Atmosphere Interactions & Coupling. The connection of surface hydrology to clouds and precipitation relies on proper quantification of heat and moisture transport through the coupled system via the PBL. Today's spaceborne instruments have limited PBL sensitivity: e.g.,

- Hyperspectral Sounders (e.g. AIRS/IASI) are the most capable in term spectral resolution but have not been tailored for PBL sounding and are confounded by surface emissivity.
- Lidar (e.g. CALIPSO) can obtain high vertical resolution, but is limited in return time and spatial sampling and does not provide thermodynamic state information.
- Geostationary (e.g. GOES-R) have frequent temporal sampling, coarse spectral bands and PBL resolution.
- GPS-RO (e.g. COSMIC) shows promise for PBL retrieval, but is limited by sampling and confounding issues related to humidity/topography.

In this context, observations of PBL height, temperature, and humidity are necessary for evaluation and development of Land-Atmosphere coupling in weather and climate models.

- **Synergies and assimilation of EO data in hydrological models:** EO technology represents a major opportunity for operational applications related to land surface hydrology. Since it will never be possible to observe all variables related to the water cycle at the relevant space and time scales, information provided from the various observation systems needs to be combined with numerical models to constrain forecasting systems to the best possible extent. In this context, the following aspects need to be taken into account in order to advance towards process understanding and in the establishment of operational applications:

i) Performance measures quantifying the added value of individual observations on the applications' skill should be established to justify investments and to support the definition of future observation and model systems.

ii) Continued recognition by space agencies about the need for long-term data continuity and multi-sensor data products. Operational agencies will only invest resources in the exploitation of observation data sets if continuity is envisaged. For most land data assimilation applications (and any application – like agricultural drought monitoring - based on the detection of anomalies relative to a fixed climatology) even "excellent" 1-2 year datasets are not likely to be as valuable as "marginal" 5-10 year datasets.

iii) Key satellite observations related to precipitation, water level dynamics and soil moisture are critical data to constrain or force hydrological land surface models. Enhanced measurement capabilities related to these critical variables are needed:

   a. Precipitation estimates shall be improved in term of spatial/temporal resolution, as well as with respect to product uncertainties;

b. Water level dynamics (and potential of getting streamflow) shall be derived for a large number of rivers (> 100 m width). SWOT mission (NASA/CNES) in 2020 will enhance the current situation;
c. Soil moisture estimates shall be improved in term of spatial/temporal resolution, as well as with respect to product uncertainties;

iv) It is critical to pay increasing attention to enhance the temporal resolution of observations. Frequently, priorities are given to high spatial resolution data (<10 m), putting less emphasis on the importance of having temporally dense observations. This is particularly true for the applications where highly dynamic processes are involved, i.e. the prediction\simulation of floods and shallow landslides for the mitigation of hydrogeological risk.

v) Terrestrial ET estimates are still characterized by large uncertainties and only few reliable measurements exits (See Section 3.5.2). This has implications for water resources management (e.g. our ability to track recent growth in irrigation agriculture), water balance studies and climatic trend applications. In the absence of any existing direct ET observations from satellites a major effort is needed to combine the available observational data (e.g. soil moisture, atmospheric water vapour, temperature, absorbed photosynthetically active radiation) and numerical models to improve the ET product quality.

3.4 The Ocean component of the water cycle

Water cycle components over the ocean largely dominate in the contribution to the global freshwater cycle budget. Four major interfaces at which water is exchanged through various processes have to be considered in any ocean fresh water monitoring attempt:

1) Air-sea interface exchanges of water:

- Atmospheric forcing fluxes: Evaporation minus Precipitation, sea-spray and aerosols;
- Horizontal Transport at surface by oceanic circulation;
- Oceanic vertical stratification (buoyancy) modulations and retroactions (feedbacks) on air-sea fluxes

2) Ocean surface-deeper layer interactions:

- Transport of fresh/salty water downward from the surface by turbulent mixing through surface current convergences, wave-induced mixing, double diffusion, diurnal thermal cycles, etc.
- Vertical transport of salt upwards by Ekman pumping, upwelling and inertial waves
- Oceanic vertical stratification (buoyancy) and impact on vertical water fluxes

3) Land-sea water exchanges:

- Run-off and discharges from continental rivers, river plume tractability
- Intrusion of salty ocean water on land masses, sea level rise effects (e.g. Vietnam and rice crisis)

4) Ocean-ice exchanges:

- Seasonal and interannual variations in water exchanges due to melting/freezing of sea ice
- Links with dense water formation & thermohaline circulation

Water exchanges at the four previously listed interfaces involve a large ensemble of physico-chemical processes, which themselves can be best estimated from the regular monitoring of a sub-ensemble of key geophysical variables. Ideally, the challenge of monitoring the freshwater cycle over the ocean would indeed involve observational capabilities for the following key geophysical variables:

- Sea surface salinity
- Sea surface temperature
- Precipitations
- Liquid water content in the atmosphere
- Column water vapor
- Evaporation: latent and sensible heat fluxes (wind stress, SST, air temperature and humidity at a few meters above the sea surface)
- Ocean surface currents
- Sea surface wind stress
- Sea surface state
- River discharge monitoring
- Soil moisture and water storage
- Ocean color and biogenic properties (flux penetration)
- Vertical monitoring of ocean properties (salinity, temperature, density)
- Sea ice thickness, drift, and ice freezing/melting metrics

A dedicated water cycle mission, or group of missions used in synergy, to monitor the freshwater cycle over the ocean shall at least consider the above list of key geophysical variables.

In this context, a list of main challenges in the observation of key variables for the oceanic water cycle is reported below together with priority areas for further work:

- **Sea Surface Salinity:** currently measured from Space by SMOS and SMAP L-band sensor (~40 km, 10-days). Continuity is not ensured. Coastal domains are not covered and spatial resolution is not adapted to coastal variability. SSS accuracy strongly decreases at high latitude and for cold seas (loss of sensitivity). Short term variability cannot be regularly sampled (diurnal freshening induced by tropical rains, etc..). Currently available information is often heavily contaminated in ocean-land and ocean-ice transitions. So main challenges concerning SSS are: **ensure continuity**, **improve measurement accuracy in cold seas**, and **improve space-time resolution to approach the land & ice to sea transition samplings.**

- **Sea Surface Temperature:** SST is well monitored down to meso-scale (1—50 km) by current observing systems (MW and IR) for most oceanic regions. However, for high latitude seas, the Rossby radius of deformation drops to ~ 15 km for meso-scale circulation. Given the high cloud coverage in such regions mostly MW SST observations are available with a resolution of ~25 km. However, there is a need to detect SST changes in the proximity of sea ice, icebergs etc.. with a higher resolution (1-10 km). One of the challenges would therefore be to best monitor SST-driven processes playing a role in the water cycle (e.g. evaporation, thermohaline circulation, air-sea momentum and heat fluxes) by obtaining **higher spatial resolution MW observations of SST (~10 km) at high latitudes**.

- **Rain:** MW passive, IR and MW radar Precipitation missions are efficient in general and permit today to provide Rain rate estimation down to 8 km every half an hour for merged Precipitation products (e.g., CMORPH). This shall be sufficient for most oceanic water cycle budget closure at large and meso-scale. In this context, continuity of observations is an issue. Sub-meso-scale rain variability over the ocean (<10 km) certainly keeps being a challenge. Rain radars from meteorological land stations might help covering the coastal areas. Therefore, there is a critical need to **ensure continuity of rain measurements- improve accuracy.**

- **Evaporation:** (See Section 3.5.1 below)

- **Liquid water and water vapor columnar content in the atmosphere:** Cloud Liquid Water is a measure of the total liquid water contained in a cloud in a vertical column of atmosphere. It does not include solid water (snow, ice). Cloud water links the hydrological and radiative components of the climate system. Cloud water can be retrieved from passive microwave measurements because of its strong spectral signature and polarization signature (Wentz, 1997). Passive microwave observations provide a direct estimate of the total absorption along the sensor viewing path. At 18 and 37 GHz, clouds are semi-transparent allowing for measurement of the total columnar absorption. The absorption is related to the total amount of liquid water in the viewing path, after accounting for oxygen and water vapor absorption. Validation of satellite measured columnar cloud liquid water is a difficult undertaking and remains challenging. The spatial variability of clouds makes comparisons between upward looking ground based radiometers and the large footprint size of the downward looking satellite retrievals problematic.

Over 99% of the atmospheric moisture is in the form of water vapor, and this vapor is the principal source of the atmospheric energy that drives the development of weather systems on short time scales and influences the climate on longer time scales. Water vapor is a critical component of Earth's climate systems and therefore of global water cycle. Because of the strong water vapor absorption line near 22 GHz, within the microwave range, we can use microwave radiometers to measure columnar (atmospheric total) water vapor. This is a very accurate measurement due to the high signal-to-noise ratio for this measurement. With little diurnal variation, the measurements from different satellites at the same location often agree to within a few tenths of a millimeter.

Both variables are important to the water cycle over the ocean and are currently measured by AMSR-2 and WindSat. Challenges involve continuity and validation.

- **Ocean surface currents:** Direct and indirect estimates of Ocean Surface Currents and higher level derived products such as frontal boundaries can be obtained using a variety of satellite sensors including altimetry (both LRM and SARM), gravimetry, SAR, scatterometry, optical (VIS and TIR) and passive microwaves. Sparse in-situ current measurements from drifting and moored buoys, coastal HF-radar installations, Argo floats, gliders and ship observations complement these satellite measurements. Each of these satellite and in-situ based measurement technique has its specific strengths and limitations (e.g., resolution, coverage, accuracy, depth integration, cloud dependence, empirical based retrieval methods, etc.). Currently available products (OSCAR, Globcurrent, AVISO) can be obtained at a maximum space/time resolution of 0.1° , 15 m depth, daily. There are numerous challenges associated to ageostrophy, wind-drift and stokes-drift effects, surface versus depth integrated quantity etc. (see Globcurrent).

A challenge in the context of oceanic water cycle monitoring is to better link the oceanic freshwater cycle with the ocean circulation through vertical stratification effects (stability of the upper ocean), surface density variability, air-sea fluxes. Today, incorporating the impacts of SSS variability into the dynamics of ocean currents features is not done systematically, the current estimates being only driven by SSH from altimetry, winds and SST. Another challenge would be that surface current data need to be provided at a similar space and time scale than any other variable involved in estimating water cycle and as close in time as possible to the other observations.

- **Sea surface wind stress:** Surface wind can now be regularly measured by scatterometers. However, there are significant limitations at high winds and in rainy conditions. Wind stress are deduced from the wind speed by using Drag coefficient parametrization that remains uncertain. The high spatio-temporal variability of marine winds requires very frequent surface wind stress vector estimates. Challenges are therefore: improving high wind and rainy condition wind stress estimate quality, gaining understanding in high wind drag coefficients, enhancing space and time resolution in sampling.

- **River discharge monitoring:** (see Section 3.3). A regular mapping of global river discharge will be needed to connect the SSS changes in the open ocean to river runoffs.

- **Soil moisture and water storage link to the oceans**: To fill the gap of connections between freshwater cycle on land and on the ocean, **higher resolution and closer to coast SSS** data will be required and **concomitant acquisition of SSS and Soil Moisture** data (based on L-band radiometry) and **water mass storage** (GRACE) shall be continued in the long term to foster studies relating the mass water storage interannual, seasonal and intra-seasonal variability to freshwater content in the ocean. Very few studies have investigated those links. So one of the challenge is to **perform research** on these topics and potential synergies.

- **Ocean color and biogenic properties (flux penetration):** Ocean color allows the monitoring of large river plume bio-optical characteristics. Because of the conservative principles of river constituents when they dissolve into the ocean, ocean color comes as a natural complement to SSS monitoring of the fresh water river dispersal into the ocean. Challenges in such context include the temporal and spatial coverage of ocean color properties for important rivers in dominantly cloudy conditions, characterization and better understanding of non-conservative mechanisms (photo-bleaching, primary production,..) and the methodologies to connect high-resolution optical versus low-resolution MW SSS.

- **Vertical monitoring of ocean properties (Salinity, Temperature, Density):** These properties are currently only observable by in situ networks, predominantly ARGO floats. Main limitations are spatial coverage (scales > 300km) and time sampling (~10 days) which limit our ability to monitor the freshwater transport towards the ocean interior at meso-scale.

- **Sea ice thickness, drift, and ice freezing/melting metrics:** Space-borne passive microwave observations (SSM/I, AMSR series) have been the most commonly used tool to monitor sea ice over the polar regions. Sea ice is difficult to observe using satellite optical sensors because of the low level of illumination in polar regions and because of frequent cloud cover. Microwave instruments and in particular satellite-borne radars, such as scatterometers or SAR, are of major interest, first because of their large temporal and spatial coverage and second because of their all-weather measurement capability. The combination of these data with passive satellite-borne sensors measurements is very useful for sea ice displacement estimation and relative coverage (concentration) of sea ice. Passive microwave footprints are large, typically 10–60 km depending on frequency, implying that many different components of snow/ice/water can be present in one measurement. Nevertheless, thanks to these sensors, large-scale properties of sea ice are now well monitored.

  Recently, CryoSat-2 and SMOS have been providing information on sea ice thickness. Thickness information is valuable for assessing the overall condition of the sea ice cover. The sensors on these satellites however cannot determine thickness during the summer melt season which is a key season for ice to ocean water transfer.

  Other applications involve interferometry, cross-correlation mapping, altimetry, accumulation rates, and detection of melting that were developed using data from sensors not specifically designed for glaciological purposes. The "hole at the pole," where orbital inclinations fail to cover the most poleward latitudes, limits the data collection capabilities for all but those sensors with extremely wide fields of view, or with large off-nadir pointing capability. This constraint does not present any engineering challenge, and it is hoped that in the future either sensor capabilities will be enhanced or polar-dedicated satellites will be built to provide Earth scientists with truly global coverage. As a minimum, continuation of the current remote-sensing capability, including moderate and high-resolution visible imagers, SAR, and passive microwave imagers and altimeters, is needed to ensure that monitoring and further studying of ice sheets are made increasingly efficient by space-traversing sensors.

3.4.1 **Additional aspects**

In addition to all previous issues, some additional points shall be taken into consideration:

- **Long-term monitoring of water exchanges at the four natural interfaces:** Probably, of all four interfaces, monitoring of land-sea and ice-sea exchanges of water are the most critical in terms of reliable data availability. High resolution observations are indeed needed and important variables for the water cycle at these interfaces are only today obtained at low-spatial resolution microwave sensors (SSS, ice, SST). Limitations of passive MW at strong transitions (coastal, ice sheets) is also an issue.

  The ocean surface-deeper layer interface is difficult to monitor from Space except from depth integrated quantity (sea level height) so that today we have to rely mostly on low resolution in situ observations to characterize exchanges of water between the upper ocean mixed layer and the deeper ocean.

  A challenge is to improve our monitoring capability of air-sea exchanges of water in low and high winds conditions and to better monitor the latent heat and humidity fluxes at this interface.

- **Dealing with the diversity of variables sampling and the need for synergisms:** Water cycle involves an extremely large diversity of multi-scale processes. Monitoring the water cycle on the ocean side therefore implies a synergistic use of multi-sensor observations. The processes involved in the marine branch of the water cycle are sampled by a large ensemble of sensors (passive, active,..) with varying sampling characteristics, strengths and limitations. A first challenge might therefore be to establish the list of processes involved in the water cycle as a function of their space-time variability and the current and foreseen sensor sampling characteristics to monitor those. This would greatly help identifying the missing gaps for best monitoring water exchanges at each of the four ocean interfaces . The second step might then involve synergic methodologies exploiting such different observations to best cover those exchange gates.

- **The role of SSS in revealing the tele-connections between land and ocean:** Sea Surface Salinity (SSS) is an indicator of E-P over oceans and thus of the transfer of water from the ocean to other parts of the climate system. About 1/3 of the water (and latent heat energy) exported from the subtropical gyres ends up on land (especially extreme rains). It also responds to the state of the atmosphere through Ekman advection and wind driven mixing, so may be a hypersensitive indicator of change.

Recent work shows the potential of salinity to be a powerful predictor of rainfall on land, 1-2 seasons ahead, apparently by the delay mechanism of soil moisture. In particular, SSS variability strongly correlates with summer rainfall in Sahel of Africa (East N. Atlantic SSS), US Midwest (West N. Atlantic SSS), US Southwest (N. Pacific SSS), Yangtze River Valley (S. China Sea SSS). The understanding and characterization of the different processes involved and the amplitude and variability of these tele-connections require further research. The availability of SSS measurements from the ARGO float array, and L-Band satellites (Aquarius), SMOS and SMAP offers a major opportunity to explore these aspects and further advance in the complete understanding of these processes.

3.5 Heat fluxes

3.5.1 Ocean Evaporation

Accurately estimating Evaporation from space remains very challenging. The reason is that Evaporation is a function of the latent heat flux, itself dependent on the sea surface temperature, surface winds, air temperature and humidity just above the sea surface. These two latter quantities can only be obtained today from NWP models. SST and marine winds are also key variables to estimate evaporation but can be well estimated from space in general, with a few remaining challenges. There are limitations in the highest and lowest wind speed range from scatterometry and passive observations (rain contamination, NRCS saturation, sea state impacts) so that estimating evaporation in calms and storms still remains a challenge. Wind and SST observation in coastal domains and along the ice shelves and sea ice borders is also critical as mostly microwave SST data are available in high latitude seas and there are spatial resolution limitations of MW products (~25 km); scatterometer winds also loose accuracy in the proximity of the coasts or sea-ice transition. These issues contribute to limit our ability to currently well monitor evaporation in coastal and melting sea ice areas. How to incorporate diurnal SST, winds and specific humidity variability in the evaporation estimates still is a challenge too. As a consequence, currently available Evaporation products (e.g. OAFLUX) rely on NWP model estimations and are produced at low (1°x1°) spatial resolution, daily.

Three of the challenges concerning better estimation of evaporation over the ocean therefore include:

- Developing new spaceborne/ in situ measurement capabilities for the “above sea surface temperature and humidity” variables;
- Gaining in spatial and temporal resolution of the Evaporation products to at least match the precipitation P merged products sampling of ~1/4°, 3-hourly;
- Improve E estimation at high latitudes and in coastal domains;

3.5.2 Terrestrial Evaporation

The importance of terrestrial evaporation (or '*evapotranspiration*') for hydrology, agriculture and meteorology has long been recognized. As a matter of fact, most of our understanding of the physics of evaporation originated in early experiments during the past two centuries (see e.g. Dalton, 1802; Horton, 1919; Penman, 1948). However, it has been during the last decade that the interest of the scientific community towards land evaporation has increased more dramatically, following the recognition of the key role it plays in climate. Evaporation is highly sensitive to radiative forcing: changes in atmospheric chemical composition impact the magnitude of the flux, ensuring the propagation of anthropogenic forcing to all the components of the hydrological cycle (Wild and Liepert, 2010), hence altering the global availability of water resources. In addition, evaporation regulates climate through a series of feedbacks acting on air temperature, humidity and precipitation (Koster et al., 2006; Seneviratne et al., 2010), thus affecting climate trends (Douville et al., 2012; Sheffield et al., 2012) and hydro-meteorological extremes (Seneviratne et al., 2006; Teuling et al., 2013; Miralles et al., 2014). Furthermore, due to the link between transpiration and photosynthesis, atmospheric carbon concentrations and carbon cycle feedbacks are tightly linked to terrestrial evaporation (Reichstein et al., 2013). Altogether, evaporation stands as a crucial nexus of processes and cycles in the climate system.

The rising interest of the climate community has coincided with an unprecedented availability of global observational data to scrutinize the response of evaporation to climate change impacts and feedbacks. However, given the scarcity of direct *in situ* measurements of evaporation at the global scale, the scientific community has turned its eyes to satellite remote sensing (Kalma et al., 2008; Wang and Dickinson, 2012; Dolman et al., 2014). Consequently, different international activities have focused on the joint advancement of remote sensing technology and evaporation science, including the National Aeronautics and Space Administration (NASA) Energy and Water cycle Study (NEWS), the European Union WATer and global CHange (WATCH) project, the Global Energy and Water-cycle EXperiment (GEWEX) LandFlux initiative, and the European Space Agency (ESA) WAter Cycle Multimission Observation Strategy (WACMOS). Despite continuing progress in the fields of remote sensing and computing, to date, the evaporative flux cannot be directly sensed from space; technology thus lags behind our physical knowledge of evaporation. Nonetheless, taking advantage of this existing knowledge, different models have been proposed to combine the physical variables that are linked to the evaporation process and can be observed from space (e.g. radiation, temperature, soil moisture or vegetation dynamics). Such efforts have yielded a number of global evaporation products (Mu et al., 2007; Zhang et al., 2010; Fisher et al., 2008; Miralles et al., 2011; Jung et al., 2010). These data sets are not to be interpreted as the direct result of satellite observations, but rather as model outputs generated based on satellite forcing data. The reader is directed to Su et al. (2011) or McCabe et al. (2013) for recent reviews of the state of the art.

Despite the recent initiatives dedicated to exploring these evaporation data sets – LandFlux, in particular (Jiménez et al., 2011; Mueller et al., 2013) – the relative merits from each model remain largely unexplored: to date, the lack of inter-model consistency in the choice of forcing data has hampered the attribution of the observed quality of evaporation estimates to differences in the models.

Recent activities in this context, through the GEWEX LandFlux initiative (McCabe et al. 2016) and the ESA WACMOS-ET project (Miralles et al. 2016), have explored this aspect, showing large discrepancies among different methods during conditions of water stress and drought, and deficiencies in the way evaporation is partitioned into its different components. Overall, the observed inter-product variability implies caution in using a single data set for any large-scale application in isolation. The general finding that different models perform better under different conditions highlights the potential for considering biome- or climate-specific composites of models (Ershadi et al. 2014). The generation of a multi-product ensemble, with weighting based on validation analyses and uncertainty assessments, appears the best way forward in our long-term goal to develop a robust observational benchmark data set of continental evaporation.

Here we summarize current challenges and suggest ways to move forward based on common issues highlighted throughout the session presentations and via discussions developed from a number of international initiatives aimed at advancing the production of global terrestrial land turbulent fluxes from satellite observations.

Current challenges to estimate fluxes are partly related to model physics and structural limitations (including access to the data required to force the models). Present product comparisons show that no single model construct is capable of consistently outperforming any other**,** suggesting that future efforts should not only be directed towards improving the model physics and parameterization schemes of retrieval algorithms, but also the development of ensemble averaging techniques based on considering the strengths (and identifying the weaknesses) of available schemes as a pragmatic step forward to produce robust flux estimations across a variety of biomes and land-atmospheric conditions.

The internal consistency of forcing data sets is a recurrent problem for land surface products that demand a large number of inputs, as is the case for many flux estimation methodologies. To what extent does this internal lack of consistency in Earth-Observation (EO) products contribute to the errors when estimating a variable such as the heat fluxes is difficult to judge, as in principle there are still not many EO "integrated" data sets that could facilitate such studies. Therefore, there is a need for the development of internally consistent forcing data products that can provide a mechanism for better understanding the impacts of forcing on model simulations and offer a means to diagnose data induced errors. At a minimum this should focus on the radiative elements of the models, considering this is a recognized area of uncertainty and sensitivity in all of the current flux formulations

Considerable challenges also remain in the assessment and interpretation of flux simulation products. Eddy-covariance approaches represent the gold-standard for flux validation at the field scale, although there are well recognised limitations in the utility of such data for this purpose (e.g., non energy closure issues, sensor limitations under some meteorological and atmospheric conditions, geographical coverage, etc). A critical issue is that the spatial footprint of the eddy-covariance tower sensors (e.g. hundreds of meters) is often much smaller than the resolution of the gridded data from remote sensing, so their use for large scale evaluation remains unclear and calls for the development of alternative metrics or data that can be used to evaluate the products.

Although current GEWEX efforts focus more on generating and evaluating global evaporation products, the agricultural and hydrological community require high-resolution retrievals (defined here as sub-kilometer to tens-meter scale) to respond to the challenges of quantifying water use and availability. Most methodologies assume a scale invariance of the model schemes, with only a few providing the means to explicitly bridge the gap between continental to field scale estimates. Research should be directed towards methodologies that shift between the coarse and fine-scale in a flux-consistent such as the disaggregation methodology described by Anderson et al (2011) to meet the information needs of diverse communities.

Currently, there are relatively few approaches for the direct partitioning of evaporation into its soil (E) and plant (T) contributions. Approaches for determining the transpiration flux are almost exclusively undertaken at the leaf to field scale, with specific instruments (often chamber-based) designed for this task. However, recently a flux partitioning approach being proposed (Scanlon and Kustas, 2013) makes use of the high frequency eddy covariance measurements based on flux-variance similarity theory for estimating E and T, and could be applied to flux measurement networks (FLUXNET) providing a spatial sampling of evaporation partitioning over many different climatic regions. A more precise understanding of local-to-global patterns and distributions of flux water use requires determining the flux partitioning more accurately at a variety of spatial scales. Therefore developing techniques that can be used to validate the accuracy of flux modeling approaches in properly representing these separate processes appears crucial to progress towards more accurate flux estimates.

For the process of transpiration, emerging datasets such as spatial maps of chlorophyll fluorescence could provide new insights. However, there is a current gap in modeling the coupled water-energy-carbon cycles, limiting the uptake of these new datasets for hydrological and related applications. Developing a modeling framework that can integrate plant biophysical response mechanism in a manner that couples with the water and energy cycles represents a key area of needed research that is required to take advantage of these data.

For coarse flux estimation at the global scale, the large scale simulations derived from some coupled modeling systems (e.g. from operational short term weather prediction and forecasting systems) seem to offer commensurate performance to the Earth-Observation (EO) based modeling systems presented at the session. A valid question is whether developing an over-arching modeling system capable of incorporating (and coupling) all available observations (ground based and satellite alike) would be preferable to a process-based model focused solely on the heat fluxes. Ultimately, the community is not yet in a position to answer this question. But what is clear is that the advances made in land-atmosphere modeling have not arisen in isolation of satellite based processes: indeed, satellite data are absolutely critical to the observed improvements, either directly through data-assimilation based integration, or indirectly through offering evaluation metrics of model performance. In this regard, continued efforts in developing accurate and independent satellite based estimates of evaporative fluxes are critically important, as it is likely to drive further improvements in the application of coupled modeling systems.

Technological advances in nano- and micro-satellites as well as in the research application of unmanned aerial vehicles (UAVs) offer a capacity to meet the demands of communities having a particular interest in high-resolution retrievals of plant health and water use, and bring a wealth of information critical to both the agricultural sector and the research community in terms of better understanding scaling responses, flux partitioning and discrimination of soil and plant conditions. In all of these advances, one key component is lacking: an efficient modeling system that integrates new observations to provide metrics of surface states relevant to the different communities. Developments of science-based applications to take advantage of these new observational platforms are then critical to fully exploit these technological advances.

4. Other key messages

- ***Promoting an holistic approach to water cycle research:*** The water cycle encompasses a broad range of processes and feedbacks among different components of the Earth system. An integrated approach to observe and characterize the water cycle and its different processes in an holistic manner could enable significant advances in water cycle science, climatology, hydrology and operational water management. This would require interdisciplinary collaboration and a renewed focus on processes rather than individual stocks and fluxes. In particular, we should be considering holistic observation systems that attempt near-simultaneous measurements of multiple water cycle variables, including surface and sub-surface waters, following the A-train example in the atmospheric realm. Such an approach could improve our understanding of the water cycle processes, feedbacks and their variability from basin to global scales, address the open questions in hydrology and support the next generation of operational applications for climate, hydrology and water management.

- ***Promoting international collaboration to build the next generation of water cycle observing systems:*** Addressing the coming challenges in water cycle research and applications will require improved international collaboration and coordination of research and development activities. It is strongly recommended that space agencies and funding institutions coordinate their efforts in designing the next generation of water cycle observing systems. They should embrace a water cycle observation constellation concept that maximizes the complementarity of different missions, to address the water cycle as a single complex system, rather than independently developing missions that focus on individual parameters without consideration for complementarity. In this context, formation flying concepts (e.g., A-train, EO-convoy) and international constellations must be further explored in order to define the future observing systems for water cycle research and applications. In this context, the collection and analysis of the user information needs (i.e., from different user communities) shall address the entire water cycle (or the entire set of parameters needed for a certain application area/user sector: e.g., climate, hydrology, agriculture, water management), prioritising observational needs beyond individual geo-physical parameters, identifying the current shortfalls in observations (either not available or insufficient to match the user needs) and exploring the potential technological solutions and mission/system concepts that may provide an holistic solution to the different user needs.

- ***Advancing in understanding the ocean component of the water cycle:*** The ocean component of the water cycle represents a major area of research to be further explored. New satellites observations on sea surface salinity (e.g., from SMOS, AQUARIUS, SMAP) has been recently added to the different observations available to the scientific community (e.g., SST, winds, waves, precipitation, etc...) opening the door to a better understanding of the freshwater fluxes in the ocean, the E-P variability and its tele-connections and impacts on land and atmosphere. More international collaboration to further advance in the understanding and characterization of the role of oceans in the water cycle (e.g., under a dedicated GEWEX initiative) is needed. It is also important taking into account that deriving E-P from the sea surface salinity requires a good estimate of the role of the ocean circulation on the SSS variability. Hence a close connection to CLIVAR is necessary.

- ***Continuous support to in-situ networks:*** There is a critical need to enhanced the systematic acquisition of *in situ* data. This can be also extended to airborne measurements collocated simultaneously with satellite data in order to support basic science as well as satellite observations Cal/Val activities. So far, in situ networks have largely been developed without taking satellite observations into considerations. It may be worthwhile to determine which additional in situ measurements add most value to satellite observations.

- ***Reinforcing the exploitation of EO long-term consistent datasets by the modeling community*** is a major requirement not only for the validation/verification and potential enhancement of model parameterizations, but also to foster data assimilation and improving model predictability in consistency with observations. Advancing in this direction is a prerequisite to establish a solid scientific basis for potential future information services. This requires dedicated efforts to:

    i) ensure the development of long-term consistent EO-based records of essential variables with a proper uncertainty characterization and error structure information covering a wide variety of parameters and adapted to modelers needs. GCOS Essential Climate Variables (ECVs) are a clear example for that and ESA's CCI initiative is advancing in this direction. Ideally, time-dependent and space-dependent uncertainties should be provided. It is also important to account for the spatial correlation of errors;
    ii) support modeling efforts of model validation/verification/ intercomparison in view of maximizing model consistency with observations, validate model parameterizations and enhance model consistency with observations;

iii) further advance in the development of data assimilation schemes for different types of EO-datasets (e.g., addressing key issues such as bias correction, observation operator) and testing the impact of different data streams in models;
iv) ensure a sustained dialogue between the EO and the modeling community as a prerequisite to advance in this direction and
v) maintain and reinforce the open data access and promote data sharing as a best practice to support science.

- ***Capacity building***. A goal for Earth Observation is to ensure a global seamless environmental prediction system for sustainable development of the society; which includes global observations, modelling, prediction and knowledge development. Its sustainability and credibility depend on globally available capacity in understanding and application of earth system science. Education and capacity development are key to the success of the entire effort, which nurture the intellectual leadership and knowledge development. Capacity development is embedded in all activities of our community as priority. A challenge is to ensure long-term and continuing success; in this context, further emphasis is placed on supporting and engaging early career scientists to the core activities of EO science, nurturing the intellectual leadership in interdisciplinary domains. In doing so, the existing gaps in geographical regions, research areas (e.g. understanding the energy cycle in all scales) and infrastructure (e.g. efficient and accessible mechanisms for data/knowledge sharing) should be considered as priority. Also, the community of senior and early career scientists should carry out collective and continuous review on current and future research priorities and relevant requirements. It is a standing necessity to support for fundamental research and infrastructure needs, balanced with responsive actions to requirements by users of scientific knowledge. This naturally requires extensive resources; under the current funding environment, we are facing the critical need for inclusive partnership to foster, nurture and streamline activities to reach the goals in effective and efficient manners. It would also ensure synergies to promote common development agenda across the agencies that are based on key science priorities.

- ***Promoting OSEs (Observing System Experiments) or OSSEs (Observing System Simulation Experiments) for water cycle and hydrology.*** OSSE / OSE are useful tools that have been applied to high-resolution ocean forecasting, seasonal-to-interannual prediction, weather forecasting, and climate analysis and reanalysis to examine the impact of future observations on a particular application. They are flexible tools as they can be used to quantify and compare the benefits from different future observing platforms against each other and to support the design of instruments and mission concepts. In particular the OSSEs can be used to assess the benefit of new missions to the Global Observing System (GOS) or better understand the impact of new observations in terms of predictive skill of forecast models. Although the benefit of OSSEs is significant, they have two shortcomings that have to be taken into account: (1) they are model-dependent and often the skill is evaluated against the models' own analyses; and (2) one needs to avoid the identical twin problem, where the same model is used to determine the "truth" to be sampled to represent future observations, and to perform the data assimilation experiments within the OSSE - in this case the results would be overoptimistic. In the NWP community, this problem was minimised by using the NCEP model as the "truth" and the ECMWF model for the DA runs. However, despite the shortcomings it is recommended to explore the use of these tools to assess novel planned/proposed hydrological cycle satellite missions, building on the expertise from the Ocean, NWP and atmospheric science communities. The costs of an OS(S)E are negligible when compared to a satellite mission.

- ***Promoting the Synergistic Use of Existing Data:*** Despite the fact that several new EO missions have been implemented in the last decades and that the number of observational data sets is continuously growing, very little has been done to use multiple observation data sets in a synergistic way, e.g. in a common model / data assimilation system spanning the different components. Such a system addressing more than one individual parameter is needed (1) to monitor progress made towards overarching research objectives, (2) to define individual missions but also concepts like the A-train, and (3) to quantify mission success. While OS(S)Es can help defining EO systems, only data denial experiments using the full suite of available observations in an application or operational environment can show the value of an individual observation type and justify continuity.

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