Global Observations of the Water Cycle

Background Paper for the GCOS All Panel meeting, 18-22 March 2019.

Authors: S. Dietrich, J.A. Johannessen, S. Briggs, Wouter Dorigo, S. Egglestone, Isabelle Gärtner-Roer, G.C. Hegerl, K. Hills, H. Kramer, U. Looser, F. Paul, C. Ruz Vargas, U. Schneider

BOX 1: Closing the global water cycle	
Targets	Close water cycle globally within 5% on annual timescales
Who	Operators of GCOS-related systems, including data centres
Time frame	Ongoing
Performance indicator	Regular assessment of the uncertainties in estimated turbulent flux of latent heat

Content

1 Background

Life on Earth is intimately connected to availability of water and its variability. However, the demands on water resources and potential extreme damage from droughts and floods are increasing steadily with world population. According to IPCC's conclusion in the 5th assessment report it is likely that human activities influenced the global water cycle since 1960 (Bindoff et al., 2013), with further evidence since. However, observational uncertainties, combined with a low signal-to-noise ratio due to strong natural climate variability render estimates of the human contribution to recent trends uncertain, and overall affect detection and attribution of change. Challenges to quantify changes in the global water cycle were most recently reviewed by (Hegerl et al., 2015).

The GCOS Implementation Plan 2016 produced thus targets based on closing the three major climate cycles water, carbon and energy as well as the biosphere with associated uncertainty targets on annual time scales (GCOS, 2016).

The water cycle, also known as the hydrological cycle, describes the continuous movement of water on, above and below the surface of the Earth. The key processes that influence this cycle include (Fig. 1):

- Evaporation, transpiration and water vapor generation;
- Atmospheric transport of water vapour;
- Precipitation;
- Storage and release by the cryosphere, lakes and reservoirs and as groundwater;
- Water flow on the surface (e.g. rivers);
- River discharges to the ocean;
- Groundwater discharges to the oceans;
- Groundwater recharge by percolating precipitation

Fluxes in the water cycle are driven by the absorption and release of energy, hence there is a close connection between the water and energy cycles, and with it, between precipitation and temperature across the atmosphere. When water evaporates, it takes up energy from its surroundings and cools the environment. When it condenses, it releases energy and warms the environment..

The components of the water cycle are given above and the cycle is illustrated below (Figure 1).

Especially over land, in-situ data provide long-term records of changes in the different components of the water cycle. Global data centres, often operating under the auspices of UN organizations, collect world-wide water data, harmonize them and make the global data sets again publicly available (Table 1). Time series from in-situ observations are in some cases long-enough to allow for detection of climate trends and variability (e.g. for precipitation or river discharge). However, it is important to note that reliable long-term transpiration (sea) and evapotranspiration data (terrestrial) are typically much shorter (10-15 years).

<Please add information about satellite obs here>

Comment [SU1]: Maybe make reference to the data centres he like GRDC, GPCC, IGRAC??

Comment [WD2]: There are mor limitations than just the period o the time series.

Comment [HG3]: There is some stuff in my Bams paper if we ne to snitch it, and I have an updat grant proposal. Let me know if y need its its not been written by so I hesitate and would rather somebody else writes it

The maintenance and improvement of observational capabilities is thus key to understanding human influences on the large-scale water cycle (Hegerl et al., 2015).

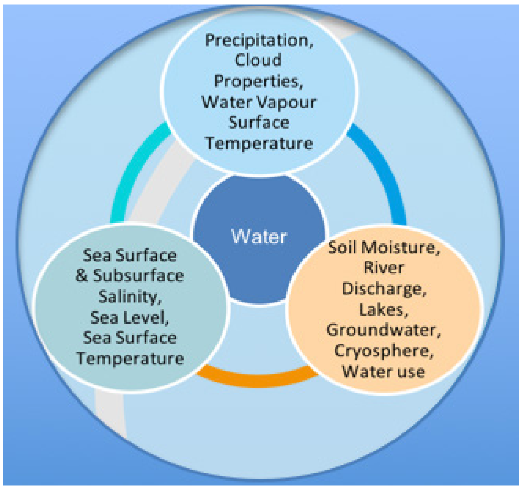

Figure 1 Key atmosphere, ocean, cryosphere, and land components of the water cycle (ref. GCOS presentation).

2 Closing the water cycle

The GCOS target for closing the global water cycle (Box 1) is within 5% annually. According to GCOS-200, the important requirement to close the water cycle is the turbulent flux of latent heat (evaporation) from ocean and land to the atmosphere. Precipitation over the ocean are poorly understood, although within climate models, the strongest signals of wet getting wetter and dry getting drier are anticipated over ocean (see Collins et al., 2013 (IPCC ch12; Hegerl et al 2015), with land surface and vegetation feedbacks complicating prediction and attribution of changes over land (e.g. Greve et al.). Long Island records support precipitation sensitivity in climate models (Polson et al., 2016). Precipitation changes over land in many regions with less dense monitoring networks are also poorly understood. Though fluxes from land are more difficult to observe on a global basis, given their heterogeneity, the current set of ECVs, including precipitation, river discharge, water vapour, sea level, soil moisture and groundwater, should be sufficient to close the global water cycle. Ocean salinity observations provide an independent insight into the changing water cycle (Bindoff et al., 2013; Hegerl et al., 2015).

The evaluation of the global water cycle was most lately assed by different approaches: (a) by the analysis of in-situ observations using data of the Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2017) and (b) the application of flux estimates from satellite measurements and data-integrating models (Rodell et al., 2015).

In the majority of cases, the observed annual surface and atmospheric water budgets over the continents and oceans close with much less than 10% residual. Observed residuals and optimized uncertainty estimates are considerably larger for monthly surface and atmospheric water budget closure, often nearing or exceeding 20% (Rodell et al., 2015).

The warming of nearly 1 K relative to pre-industrial temperatures is expected to be accompanied by a 2%–3% increase in global (land and ocean) precipitation. However, a comparison of climatology for 30-year reference periods from 1931–1960 up to 1981–2010 reveals no significant trend for land surface precipitation. This may be caused by the large variability of precipitation, the varying data coverage over time and other issues related to the sampling of rain-gauge networks (Schneider et al., 2017).

A closure of the global water cycle on a 10% level on annual time scales is possible at the moment.

Performance indicator: Regular assessment of the uncertainties in estimated turbulent flux of latent heat

Comment [WD4]: Where does th number come from? The numbe in the graphic have an uncertain of ~10%, so I guess you'd like t do better.

Comment [HG5]: Greve P, Orlowsky B, Mueller B, Sheffield Reichstein M and Seneviratne S I 2014 Global assessment of trends in wetting and drying over land Nat. Geosci. 7 716–21

Comment [HG6]: Very optional!!! Polson D., Hegerl G.C. and Solomon S. Precipitation sensitivity to warming estimated from long island records. Environ. Res. Lett. 11 (2016 074024 doi:10.1088/1748-9326/11/7/074024

Comment [WD7]: Sufficient wha

Comment [StD8]: Please comm

What is needed to reach the tar

Comment [StD9]: Who can contribute here?

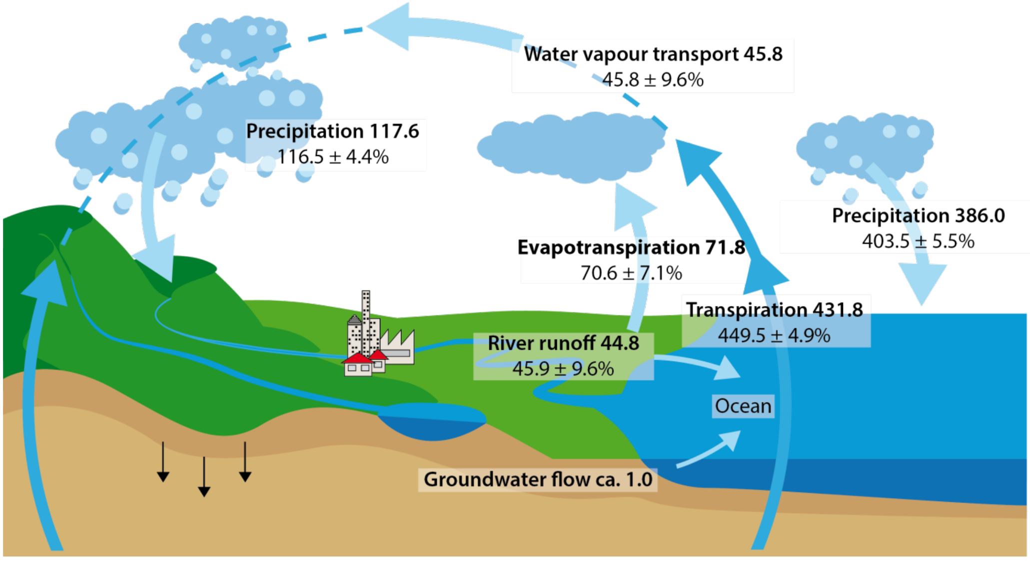

Figure 2. Mean annual fluxes (10^3 km^3 yr^{-1}) of the global water cycle, and associated uncertainties, during the first decade of the millennium including estimates that have been optimized by forcing water and energy budget closure, taking into account uncertainty in the original estimates (Rodell et al., 2015). The uncertainties are here expressed as relative errors for comparison with the GCOS target of closing the water cycle on 5%.

Comment [StD10]: Fluxes are indicated. Water storage in lake glaciers, soil moisture etc should be added. Same is true for sea level …

3 Core ECVs

3.1 Precipitation

- *Precipitation over land* is measured quite well by the dense networks of rain-gauges operated by many countries. Overall the number of rain-gauges operated around the world is roughly about 200,000, of which the GPCC has currently data from more than 118,000 stations in its data base. Since the rain-gauge measurements represent only point measurements the data have to be transferred to a grid by using an interpolation scheme/objective analysis method, with substantial uncertainty over complex terrain or in poorly sampled regions. The gridded precipitation analyses are accompanied by a sampling error. In addition to that the rain-gauge measurements are also influenced by the systematic gauge measuring error, mainly caused by wind-effects on the precipitation, which is particularly large for snowfall.
- Several countries are operating RADAR networks in addition to the rain-gauge networks, but currently there is no global assessment in sight.
- *Precipitation over oceans* can be assessed by satellite observations offering complementary means of rainfall estimation beyond the reach of in-situ weather stations. However satellites estimates are not free of errors. Geostationary satellites (GEO) using IR have the ability to uniformly and continuously monitor clouds, but not with an instrument sensitive to raindrops beneath the cloud layer they observe. Low Earth orbiting (LEO) satellites carrying microwave instruments are superior in the detection skill of precipitating particles, but sample only intermittently and thus can miss important parts of the diurnal cycle in precipitation.
- Among the rainfall datasets widely adopted across the user community are "merged" products constructed with observations from multiple GEO and/or LEO satellites with or without gauge networks in hopes to compensate the drawbacks inherent in individual observations (i.e. GPCP, HOAPS).Current trends indicate episodes of extreme rainfall, as well as droughts, may be increasing, but are poorly observed. Note that for drought, changes depend on the drought indicator used, with different changes under anthropogenic forcing for indicators that account for temperatures from those that diagnose rainfall only (e.g. Trenberth et al)

3.2 River runoff

In situ systems offer the most complete basis for river discharge monitoring and most countries monitor river discharge. However, many are reluctant to share data. Data holdings at GRDC, the international repository for river discharge therefore show large regional differences in both density of coverage and availability of recent data.

Based on past availability of data, GRDC has proposed a baseline network of river discharge stations near the mouths of the largest rivers of the world. These stations, a subset of existing gauging stations around the world, collectively form a GCOS Baseline Network, the Global Terrestrial Network for River Discharge (GTN-R). Data from them capture about 70% of the global freshwater flux from rivers into the oceans.

Comment [StD11]: Dear colleagues,
please add a short paragraph: estimation of the spatial tempor coverage of the measurements If possible for in-situ and sat observations.

Please also fill out the tables.

Please also include relevant literature.

Comment [SU12]: Becker, A.; Fing P.; Meyer-Christoffer, A.; Rudolf, B.; Schamm, K.; Schneider, U.; Ziese, M description of the global land-surface precipitatio data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 190 present. Earth Syst. Sci. Data **2013**, 921–998.

Schneider, U.; Becker, A.; Finger, P. Meyer-Christoffer, A.; Ziese, M.; Rud B. GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. Theor. Appl. Climatol. **2014**, 1 15–40. [

Comment [HG13]: my understanding is this is a calibration problem should this b said? Radar seems very promising...

Comment [SU14]: Adler, R. F., J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, Rudolf, U. Schneider, S. Curti D. Bolvin, A. Gruber, J. Susskind, and P. Arkin, 2003 The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979- present). *J. Hydrometeor*, 4, 1147-1167.

Adler, R.F.; Sapiano, M.R.P.; Huffman, G.J.; Wang, J.-J.; G

Comment [SU15]: There is currently a special issue in preparation that is addressing changes in precipitation extreme in the context climate change "Focus on Extreme Precipitation Observations and Process Understanding" in Environmenta Res. Letters

Comment [HG16]: Trenberth K, Dai, G. van der Schrier, P. D. Jones, J. Barichivich, K. R. Briffa, and J. Sheffield, 20 Global warming and changes in drought. Nat. Climate Change, 4, 17–22, doi:10.1038/nclimate20

The GCOS Status Report (GCOS-195) mentions for Action T6 that the development of GTN-R is proceeding, but progress is slow due to limited resources and the reluctance of many NHSs to contribute to GTN-R by verifying the station selection and providing river-discharge data in a timely fashion.

Long-term, regular measurements of upstream river discharge on a more detailed spatial scale than GTN-R within countries and catchment areas are necessary to assess potential impacts of climate change on river discharge in terms of river management, water supply, transport and ecosystems. A parallel project to GTN-R is the WMO CHy "Climate sensitive stations" network, comprising stations with minimum human impact that can be used as reference stations to detect change signals.

As observations are sparsely reported in many areas, model approaches are used as well to estimate freshwater fluxes to the world oceans. GRDC re-calculated the Global Freshwater Fluxes into the World Oceans (GRDC,2014) based on results from the global hydrological model *WaterGAP* (Doell et al., 2003) for 0.5° grid cell resolution. The annual freshwater inputs to the oceans are also aggregated per decades and the reporting periods 1961-90 and 1971-00. The mean annual discharge for the period 1960 -2009 has been calculated at 41 867 km³/a.

3.3 Soil moisture

As noted in the last GCOS Status Report (GCOS-195), there has been significant progress in the implementation of this ECV. Its two related actions, namely Action T13 (Development of a globally gridded near-surface soil moisture data from satellites) and Action T14 (Develop a Global Terrestrial Network for Soil Moisture), have been largely completed according to or even exceeding expectations. The main implementation mechanisms have been the ESA Climate Change Initiative (CCI) for Action T13, and the ESA-funded International Soil Moisture Network for Action T14. However, large uncertainties and gaps still exist for both observation strategies.

For the in-situ component, stations measuring soil moisture are virtually absent in Latin America, Africa, Asia, Antarctica, and northern latitudes in general. In situ observations are sparse before the year 2000 while many stations measure soil moisture only at the surface, while soil moisture in deeper layers largely controls the important fluxes transpiration (through vegetation) and groundwater recharge.

Satellites provide nearly contiguous soil moisture observations worldwide. After 2002, data availability has substantially improved, with soil moisture observations being available almost every day anywhere on Earth. However, satellites only measure the top few centimetres of the soil column and models are needed to propagate the surface measurements to deeper soil layers. Moreover, satellite observations are obstructed by dense vegetation and complicated in very dry regions, over organic soils, or close to coast lines. Seasonal gaps in the observations exist for snow-covered and frozen areas, while permanent gaps exist in areas with permanent ice cover.

3.4 Groundwater

The state of groundwater monitoring is highly variable around the world. Developed countries usually have a national groundwater monitoring programme in place that collects data of both groundwater levels and groundwater quality with a defined frequency in selected locations. However, in many parts of the world poor in-situ monitoring capabilities remain, with scattered and un-representative groundwater

Comment [StD17]: ref

Comment [StD18]: Do you have addressed the uncertainty alrea Could be a task for the 2019 version that is in planning.

Comment [WD19]: Dorigo, W. A Wagner, W., Hohensinn, R., Hah S., Paulik, C., Xaver, A., Gruber A., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A., and Jackson, T. (2011). The International Soil Moisture Network: a data hosting facility global in situ soil moisture measurements, Hydrology and Earth System Sciences, 15, 167 1698, doi: 10.5194/hess-15-167 2011.

Comment [WD20]: Ochsner, T., Cosh, M., Cuenca, R., Dorigo, W Draper, C., Hagimoto, Y., Kerr, Y Larson, K., Njoku, E., Small, E., Zreda, M. (2013). The state-of-the-art in large scale monitoring soil moisture. Soil Science Socie of America Journal, 77 (6), 1888 1919, doi:10.2136/sssaj2013.03.0093

Comment [WD21]: Gruber, A., Dorigo, W.A., Zwieback, S., Xav A. Wagner, W. (2013). Characterizing coarse-scale representativeness of in-situ soi moisture measurements from th International Soil Moisture Network. Vadose Zone Journal, (2), doi:10.2136/vzj2012.0170

Comment [WD22]: Dorigo, W., Wagner, W., Albergel, C., Albre F., Balsamo, G., Brocca, L., Chu D., Ertl, M., Forkel, M., Gruber, Haas, E., Hamer, P.D., Hirschi, M Ikonen, J., de Jeu, R., Kidd, R., Lahoz, W., Liu, Y.Y., Miralles, D. Mistelbauer, T., Nicolai-Shaw, N Parinussa, R., Pratola, C., Reime C., van der Schalie, R., Seneviratne, S.I., Smolander, T. & Lecomte, P. (2017). ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. Remote Sensing of Environment 203, 185-215, doi: 10.1016/j.rse.2017.07.001

Comment [StD23]: Igrac ref

monitoring wells. Other problems as the difficult access to collected data, and the scarcity of information about aquifers such as specific yield or storage capacity, pose an even higher burden to carry out a proper groundwater resources assessment. Areas with the largest uncertainties are in Northern and Western Africa, Central Asia, and Central and South America.

One alternative method to monitor groundwater is through satellite observations. For instance, the Gravity Recovery and Climate Experiment (GRACE) satellite has been widely used to estimate groundwater storage variations in combination with in-situ measurements, other satellite methods, and models. However, GRACE is able to detect changes in groundwater storage only at a large scale (more than 100 km2). The combination of in-situ and satellite monitoring methods, plus advancements in both fields, seems to be the best approach to measure the variations of groundwater in Earth in the coming future.

The use of models represent an alternative to the use of real data, both in-situ and derived from satellite measurements. However, groundwater models (or hydrological models that integrate groundwater) have to be considered with caution. For instance, when modelling groundwater recharge: groundwater is replenished in the environment through precipitation, which means that estimations on global groundwater recharge depend on estimating the distribution and amount of global precipitation. But climate change makes more difficult to predict how precipitation will change in the coming years, and hence, groundwater recharge. Moreover, the melting of glaciers and thawing of permafrost will have an effect in groundwater recharge, however, these phenomena are still being studied and are not well understood at a global level, especially when connected to other circumstances (e.g. forest fires, as studied by Zipper et al, 2018).

Another example is the integration of groundwater in Land Surface Models (LSMs), which are used to simulate the fluxes of water at the Earth surface-atmosphere interface. The most current LSMs do not explicitly consider the lateral groundwater flow process, which limits the level of realism in simulations of groundwater dynamics globally (Zeng et al, 2018). Some recent studies have incorporated this factor, as the one carried out by Zeng et al in 2018. However, the presence of several important uncertainties suggests that future research in this area in needed.

3.5 Water vapour

3.6 Sea level

3.7 Salinity

3.8 Evaporation from land

3.9 Glaciers

Changes in glaciers and ice caps provide some of the clearest evidence of climate change. Their decline will cause serious impacts on many societies that are dependent on glacier meltwater. The Global Terrestrial Network for Glaciers (GTN-G), based on century-long world-wide observations, has developed an integrated, multi-level strategy for global observations. This strategy combines detailed process-oriented in situ studies (annual mass balance measurements) with satellite-based coverage of large glacier ensembles in entire mountain systems (i.e., glacier inventories combined with digital elevation

Comment [StD24]: ref

Comment [StD25]: ref

Comment [StD26]: GCOS-Sec: please forward

Comment [StD27]: Sea Level Budget Closure Assessment Rep

Sea level Budget closure of CCI:
https://tu-dresden.de/bu/umwelt/geo/ipg/f/forschung/projekte/slbc_cci/se level-budget-closure-esa-cci-programme?set_language=en

Thanks Wouter ;)

Comment [StD28]: GCOS-Sec: please forward

Shall we use it?

models). The GTN-G is a collaboration among the World Glacier Monitoring Service (WGMS, which operates under the auspices of the ISC (WDS), the IACS of the International Union of Geodesy and Geophysics (IUGG), UNEP, UNESCO, and WMO), the Global Land Ice Measurement from Space (GLIMS) initiative, and the National Snow and Ice Data Center (NSIDC) at Boulder Colorado, USA.

Changes in glacier length, area, volume and mass are observed using in-situ and remote sensing methods. Glacier length changes are available for about 620 glaciers worldwide, measured by more than 400 Principle Investigators in 35 countries. Glaciological mass balances are calculated from ablation stake and snow pit measurements and provide seasonal to annual information on glacier mass change and their contribution to runoff. Such data are available for about 150 glaciers worldwide of which about 40 have more than 30 years of ongoing glaciological mass-balance measurements (so-called reference glaciers (https://wgms.ch/products_ref_glaciers/). The global average of the cumulative mass change amounts to -20 m w.e. (water equivalent) since 1960 and indicates very strong losses in the last two decades (WGMS 2017). Geodetic methods from airborne and space borne platforms provide multi-annual to decadal information on glacier volume changes. Based on assumptions on the density of snow, ice and firn, the observed geodetic volume changes can be converted to mass change and runoff contribution. Glacier volume change and mass balance are a relatively direct reaction to the annual climatic forcing. On the other hand, glacier front variations - derived from both in-situ and remotely sensed observations - are an indirect and delayed response to longer term climatic changes but allow extending the observational series back into the Little Ice Age period and beyond.

According to GTN-G Tier 5, glacier inventories derived from satellite remote sensing in combination with digital elevation models (DEMs) should be repeated at time intervals of a few decades, the typical response time of glaciers to climate change. Current efforts for this activity mainly depend on processing of Landsat and Sentinel 2 data following guidelines provided by GLIMS. An important incentive for the completion of a detailed global glacier inventory comes from the opening of the USGS Landsat archive in 2008 and the free availability of global DEMs from the Shuttle Radar Topography Mission (SRTM) and the ASTER sensor (GDEM). These sources have recently been complimented by free access to Sentinel-2 data and additional DEMs covering the global scale (e.g. ALOS AW3D30, TanDEM-X). Collectively, they allow an increasingly better world-wide monitoring of glacier changes. A DEM is mandatory to derive hydrologic divides for separating contiguous ice masses into glacier entities and subsequently to obtain topographic information (e.g. mean elevation) for each glacier entity. If DEMs from two points in time are available, glacier elevation and hence volume and mass changes can be calculated. When both (glacier outlines and geodetic mass changes) are combined with the network of field-based mass balance measurements, it is possible to determine annual glacier mass changes on a global scale (Zemp et al. in press).

3.10 Ice Sheets

3.11 Lakes

Table 1, the Water Cycle and its uncertainty, (LIT)

Component	Estimated Water Fluxes: Water Flux $10^3 km^3 yr^{-1}$	Uncertainty ± 1 σ	Uncertainty (%)	References and Data Sources	Significant ECV
Precipitation					Precipitation
Water storage in ice and snow				Global ice volume (glaciers and ice caps) of 158000 cubickilometer (uncertainty of 25%) (study by Farinotti et al. 2019, Nature Geoscience) About 1mm/a SLE (sea level elevation) from glacier melt (glaciers and ice caps), glaciers contribute 30% of the observed SLE (Zemp et al. in press, Nature Geoscience)	Glaciers, Ice Caps, Snow
Lakes					Lakes
River discharge	41,867	Not known	Not known	GRDC (2014) Global Freshwater Fluxes into the World Oceans	River Discharge
Water vapour					Surface and Vertical water vapour
Soil moisture	123930	No idea…	likewise	Jones 1997, Global hydrology	Soil Moisture
Groundwater	13,000 - 15,000 *			Taylor et al, 2012	Groundwater
Sea level					Sea Level
Evapotranspiration					Evaporation from Land
Budget imbalance					
Not included: **Total water storage**					
Not included: **salinity**					

*Estimates represent potential recharge fluxes, which does not include focused recharge (that can be important in semi-arid environments)

Comment [WD29]: Some of the variables mentioned, including S are not fluxes.

Comment [WD30]: Estimated to amount of SM. With a lot of assumptions

Comment [CR31]: Highly uncert

Comment [StD32]: Salinity as proxy?

Table 2 Major known sources of uncertainty in the water cycle (LIT)

Source of Uncertainty	Source, timescale, region	Reference
Precipitation (large-scale & convective)		
Snow precipitation		
Water storage as snow		
Water storage as ice	Problem of unknown glacier beds (difficult estimation of glacier thickness)	
Discharge	River discharge monitored by National Hydrological Services. Daily and monthly timeseries up to 200 years. Average timeseries length for more than 9500 stations is 43 years Global coverage with limited updates in Latin America, Central and Northern Africa, Large parts of Asia	
Freshwater release in the ocean		
Lake Volume		
Soil Moisture	International Soil Moisture Network (ISMN): in-situ observations of soil moisture down to 1-2 metres depth, 1950s – present, point locations worldwide. Data availability and quality gradually improve over time, particularly after 2000. Very poor data availability over latin America, Africa, Asia Various satellite products (e.g., SMAP, ESA CCI, SMOS: globally, with improved spatio-temporal coverage after 2002.	https://ismn.geo.tuwien.ac.at/; https://www.esa-soilmoisture-cci.org/; https://nsidc.org/data/SPL2SMP/versions/5
Groundwater	Parameters: In-situ groundwater levels, groundwater quality, change in groundwater storage Time-scale (of uncertainties): last 10 years for groundwater quality, before year 1980 for groundwater levels (rough estimate), prior GRACE period (before 2002) Region: Northern and Western Africa, Central Asia, Central and South America	https://ggmn.un-igrac.org/, https://gemstat.bafg.de/ (for in-situ measurements)
Total water storage		
Evapotranspiration		
Water vapour		
Sea level		

4 Research

The Global Energy and Water Cycle Exchanges (GEWEX) activity of WCRP is to coordinate and facilitate science activities that measure and predict global and regional energy and water variations, trends, and extremes, such as heat waves, floods, and droughts, through improved observations and modelling of land, atmosphere, and their interaction. GEWEX identifies 4 key areas and questions addressing the contributions that water and energy cycle science can make to society, including:

- **Observations and Predictions of Precipitation**: How can we better understand and predict precipitation variability and changes?
- **Global Water Resource Systems**: How do changes in land surface and hydrology influence past and future changes in water availability and security?
- **Changes in Extremes**: How does a warming world affect climate extremes, especially droughts, floods, and heat waves, and how do land area processes, in particular, contribute? This topic is also covered by the WCRP grand challenge on weather and climate extremes which includes a focus on heavy precipitation.
- **Water and Energy Cycles and Processes**: How can understanding of the effects and uncertainties of water and energy exchanges in the current and changing climate be improved and conveyed?

Several panels within GEWEX are set-up to explore these distinct questions such as The Coordinated Energy and Water Cycle Observations Project (CEOP), the GEWEX Radiation Panel (GRP), the GEWEX Modelling and Prediction Panel (GMPP), And the GEWEX Data and Analysis Panel.

<TBD> Other on-going activities are some of the ESA Climate Change Initiative (CCI) projects on ECVs, and the CMIP on precipitation.

Comment [WD33]: There have been several closure experiment at the basin scale, e.g.

Pellet, V., Aires, F., Munier, S., Fernández Prieto, D., Jordá, G., Dorigo, W. A., Polcher, J., and Brocca, L.: Integrating multiple satellite observations into a coherent dataset to monitor the full water cycle – application to t Mediterranean region, Hydrol. Earth Syst. Sci., 23, 465-491, https://doi.org/10.5194/hess-23 465-2019, 2019

Pan, M., Sahoo, A. K., Troy, T. J Vinukollu, R. K., Sheffield, J., an Wood, F. E.: Multisource estimation of long-term terrestri water budget for major global river basins, J. Climate, 25, 319 3206, https://doi.org/10.1175/JCLI-D- 11-00300.1, 2012.

Sheffield, J., Ferguson, C. R., T T. J., Wood, E. F., and McCabe, F.: Closing the terrestrial water budget from satellite remote sensing, Geophys. Res. Lett., 36 1–5, https://doi.org/10.1029/2009GL 7338, 2009.

Comment [WD34]: Add Sea Leve Budget Closure of (ESA CCI Programme)

Comment [HG35]: Related to grand challenge on water in food baskets of the world>?

Comment [WD36]: Mention also Global Soil Wetness project?

Comment [WD37]: There are many more projects

5 Key Questions

Key Questions to start addressing (list is non exhaustive)

1) Can addressing these gaps be *prioritised* in terms of improving the estimates of the water cycle?
2) What *practical* steps can be undertaken/recommended in the short term?
3) Are the existing ECV requirements *adequate*? Do they capture the scales needed?
4) Can we formulate recommendations for improved data *availability*, or novel observation techniques?
5) Next steps?

First steps are to review current ECV requirements and data sets (see IP). Example questions that can be asked:

5.1.1 Relation land use change and water resources (water-food-energy nexus)

5.1.2 Uncertainties in observations

5.1.3 How well is total water storage covered?

5.1.4 How well are ocean fluxes prescribed regionally?

5.1.5 Are the ECV's prescribed at the scale where it matters?

At the global scale, the water cycle is controlled by atmospheric circulation and water vapor transport patterns, which are determined in part by ocean temperatures and evaporative fluxes. Land-ocean contrasts in these variables lead, among other things, to the development of the annual monsoon.

At continental scales, precipitation at the land surface is balanced by evapotranspiration, surface and subsurface moisture storage, and streamflow. The quantification of streamflow flux and its dependence on complex continental geomorphology and land cover is critical in managing water resources over large areas.

At regional and local scales, convective precipitation is influenced by the structure of the atmosphere near the land surface, orography, the boundary layer, and the land surface cover, which is subject to human modification. At these scales, soil, vegetation, geological, and topographic structures lead to unique streamflow and groundwater behavior.

Variability at decadal and longer time scales is evidenced, for example, in the Pacific Decadal Oscillation at decadal time scales, and in the paleoclimatic record at even longer (decadal to century) time scales.

The El Niño phenomenon, which has significant hydrological impacts throughout the world, has a typical repeat interval of several years. It´s presence is also revealed in the global sea level anomaly. In comparison, the monsoon has significant impact on the regional climate at seasonal to interannual annual timescale. Extreme conditions including droughts and flooding are also known to arise from persistent anomalies in the large-scale atmospheric circulation regime such as shaped by the presence of El Nino. In contrast, individual precipitation events and the physical mechanisms that control them occur over time scales of minutes to hours.

Superimposed on these modes of variability are slow "permanent" trends that may be caused in part by global warming, ice sheet and glacier melting and land cover change. These changes, in turn, are found to contribute to the present observed global mean sea level rise.

5.1.6 Gaps? Inconsistencies? Do we see obvious gaps, datasets with very large uncertainties, and inconsistencies in scales?

The multitude of relevant space and time scales and the complex ways in which they interact is highly challenging for the design of sustainable observing systems and thus limit efforts to quantify the variability of the hydrological cycle with satisfactory accuracy. Quantifying variability at decadal and longer time scales is moreover limited by the length of the instrumental record and the sparseness of useful paleoclimatic proxies. Even variability at shorter time scales is often not well known, owing to incomplete spatial coverage of in situ measurements and complications in interpreting available satellite data. To fill knowledge gaps and remove inconsistencies the following steps are necessary:

- Significant enhancement in the ability to sustainably measure key spatial components of water cycle;
- Strengthening the observing system to provide better understanding of the physical mechanisms and interactive processes that control variability in the water cycle;
- Developing improved physical models and use of data assimilation methods that are critical to:
    - distinguish natural variability in the water cycle from human-induced variability;
    - deliver better hydrological prediction;
    - obtain new insight on coupling of water, carbon, and energy cycles.

5.2 Framing Discussion session:

Integration, how do the disparate observations of the ECVs in the Atmosphere Terrestrial and Ocean come together?

a. *Diverse variables and target scales. Are they comparable/interoperable?*
b. *Measurement approaches and accuracies (inc. satellite, in situ). Can we formulate recommendations for improved data availability, or novel observation techniques?*
c. *Connecting at the interfaces (Atmosphere-Ocean, Land Ocean, Atmosphere-Land). Can we define (and thus observe) ECVs at the interfaces? What role do they play in global and regional budgets?*
d. *Make a list of priority data sets that need to be acquired to achieve the overall goal of 5% of the annual flux?*

The understanding of the water cycle, its variability and how it propagates through atmospheric, land, and oceanic domains is deficient and incomplete. The water cycle is highly complex and require a multi-disciplinary Earth system observation approach in order to integrate disparate observations of the ECVs in the atmosphere, on land including the cryosphere and in the ocean. Many aspects of water cycle variability have never been adequately observed and quantified. This call for the appropriate design and implementation of an interdisciplinary observing system for quantifying the water cycle variability. A comprehensive Earth system monitoring of hydrological variability will advance coupled models with data assimilation and yield more reliable budget studies and ability to reproduce the physical processes controlling water fluxes and storage in each domain. This, in turn, will fill in observational gaps and help quantify uncertainties. Moreover, it will strengthen the capacity for prediction and lead to better understanding of the human interactions with the global water cycle. Better knowledge of the linkage to the energy cycle, CO2 cycle and the sea level change will then also be obtained.

Taking a step-wise approach the following urgent actions might be given high priorities:

- Improved and sustained observations of precipitation (both over ocean and land) as the basic driver both for numerical weather prediction and hydrological land surface models to quantify global and regional trends in the water cycle;
- Improved and sustained observations of snow water equivalent (SWE), soil moisture, and land cover change and their assimilation into dedicated high spatial resolution hydrological land surface models to better quantify stream flow, soil moisture and evapotranspiration and the carbon cycle;
- Enhanced ground water monitoring from satellite gravity observations;
- Improved inputs from higher resolution space data for snow- and ice inventories as important water storage and frozen soil/permafrost monitoring;
- Inventories of data needed to do broad assessments of socio-economic trends of water use (e.g., agricultural water demands, water quality demands);
- Improved assessment of the insights offered by the recent satellite monitoring of sea surface salinity regarding the oceanic branch of the hydrological cycle;
- Improved quantitative observation of river discharges;
- Enhanced monitoring of the surface albedo (e.g. from changes in snow cover and composition, sea ice extent, glacier and ice sheet extent) and its influence on evaporation, cloud formation and precipitation.

Increased international collaboration and the use of observations from many satellites and/or satellite constellations together with dedicated in-situ observation networks will constitute important assets.

5.3 Next steps:

5.3.1 Recommend analyses or intercomparisons (engaging WCRP, etc)

Key elements of the water cycle, such as the atmospheric vapor transport, the evaporation minus precipitation over the ocean, and the surface salinity, show significant changes over the coming century in response to enhanced greenhouse gas emissions and global warming. The spatial response of SSS and E – P to warming in CMIP5 is, for instance, far from identical as demonstrated by Levang and Schmitt, 2015. The results suggest that if the salinity field is to be used as a global “rain gauge” for Earth’s water cycle, the effects of ocean mixing and advection and large-scale interbasin patterns of moisture convergence must be considered in addition to the predicted amplification of the local surface forcing.

5.3.2 Opportunities (e.g new technologies, process studies (engaging WCRP, etc)

The four WCRP core projects are: Climate and Cryosphere (CLiC), Climate and Ocean Variability, Predictability and Change (CLIVAR), GEWEX and the Stratospheric-tropospheric Processes And their Role in Climate (SPARC). A series of grand challenges, all with direct or partly connection to the water cycle, are targeted by these core projects including:

- Melting Ice and Global Consequences
- Clouds, Circulation and Climate Sensitivity
- Carbon Feedbacks in the Climate System
- Weather and Climate Extremes
- Water for the Food Baskets of the World
- Regional Sea-Level Change and Coastal Impacts
- Near-term Climate Prediction

These challenges are promoted through community-organized workshops, conferences and strategic planning meetings to identify exciting and high-priority research that requires international partnership and coordination, and that yields "actionable information" for decision makers. The grand challenges are both highly specific and highly focused, with particular aim to:

- identify barrier preventing progress in a critical area of climate science;
- enable the development of targeted research efforts with the likelihood of significant progress over 5-10 years, even if their ultimate success is uncertain;
- enable the implementation of effective and measurable performance metrics.

5.3.3 Next steps. (e.g. workshops, task team).

The planned GCOS joint panel meeting in Marrakesh, Morocco from 18-22 March 2019 will have participants from the 3 WMO-IOC sponsored panels (AOPC, OOPC and TOPC) together with invited experts from WCRP/WDAC and the joint CEOS-CGMS Working Group on Climate. It is timely and as the draft agenda indicate the meeting aims to discuss the status of the carbon, water and energy cycles in both plenary and break-out sessions. The intention of this note is to provide an upfront draft view of the status on the quantitative understanding of the water cycle. As an outcome of the meeting the aim is to deliver an updated refined version of the note that identify where future priority work is needed. In so doing it should be consistent with the present version of the performance metrics provided under the grand challenges within WCRP.

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Annex: ECV product requirement tables

The ECV products requirements in this Annex should be considered target requirements, i.e. requirements that data providers should aim to achieve over the next 10 years. Annex B provides an explanation of some of the terms used in this annex.

NOTES:

(a) The required measurement uncertainties are presented as 95% confidence intervals (approximately two standard deviations);

(b) Stability is quoted per decade, unless otherwise indicated;

(c) Resolution is horizontal resolution where one value is quoted.

Main Water Cycle related ECV product requirements.

ECV	Product	Frequency	Resolution	Required measurement uncertainty	Stability (per decade)	Standards/ references
Precipitation	Estimates of liquid and solid precipitation	Monthly (resolving diurnal cycles and with statistics of three-hour values)	25 km/NA	0.5 mm/h	0.02 mm/decade	CMSAF requirements related to the HOAPS release 4.0 (CM-12611)
Evaporation from land	Latent heat flux Sensible heat flux	Sub-daily, latency of > 1 month	Threshold 25 km, goal 1 km	>10%	Better than 1%	
Ocean-surface heat flux	Latent heat flux	Hourly to monthly	1–25 km	10–15 Wm^2	1–2 Wm^2	
	Sensible heat flux	Hourly to monthly	1–25 km	10–15 Wm^2	1–2 Wm^2	
	Radiative heat flux	Hourly to monthly	1–25 km	10–15 Wm^2	1–2 Wm^2	
River discharge	River discharge	Daily	Per river	10 % (relative)		ISO/TC 113: WMO (2010) WMO (2008(a)) WMO (2009)
	Water Level	Daily	100 m	10 cm	1 cm/yr	
	Flow velocity	Few times per year for station calibration	Per river	10 % (relative)		
	Cross-section	Few times per year for station calibration	Per river	10 % (relative)		
Groundwater	Groundwater volume change	Monthly	100 km	10 cm	TBD	ISO/TC 147 ISO 5667-18:2001 part 18
	Groundwater level	Weekly	Per well	1 cm		
	Groundwater recharge	Weekly	Per well	10 % (relative)		
	Groundwater discharge	Weekly	Per well	10 % (relative)		
	Wellhead level	Weekly	Per well	1 cm		
	Water quality	Weekly	Per well	TBD		
Lakes	Lake water level	Daily	100 m	3 cm for large lakes, 10 cm for the remainder	1 cm/decade	WMO (2006, 2008(a)
	Water extent	Daily	20 m	10 % (relative) 5% (for 70 largest lakes)	5%/decade	
	Lake surface-water temperature	Weekly	300 m	1 K	0.1 K/decade	
	Lake-ice thickness	Monthly	100m	1–2 cm		
	Lake-ice cover	Daily	300 m	10 %	1 % /decade	
	Lake colour (Lake water-leaving reflectance)	Weekly	300 m	30 %	1 %/decade	
Soil moisture	Surface soil moisture	Daily	1–25 km	0.04 m^3/m^3	0.01 $m^3/m^3/year$	WMO (2008(b))

ECV	Product	Frequency	Resolution	Required measurement uncertainty	Stability (per decade)	Standards/ references
	Freeze/thaw	Daily	1–25 km	90 %	TBD	
	Surface inundation	Daily	1–25 km	90 %	TBD	
	Root-zone soil moisture	Daily	1–25 km	0.04 m^3/m^3	0.01 m^3/m^3/year	
Snow	Area covered by snow	Daily	1 km (100 m in complex terrain)	5% (maximum error of omission and commission in snow area); location accuracy better than 1/3 IFOV with target IFOV 100 m in areas of complex terrain, 1 km elsewhere	4% (maximum error of omission and commission in snow area); location accuracy better than 1/3 IFOV with target IFOV 100 m in areas of complex terrain, 1 km elsewhere	WMO (2008(c)), IGOS (2007), IACS/UNESCO(2009)
	Snow depth	Daily	1 km (100 m in complex terrain)	10 mm	10 mm	
	Snow-water equivalent	Daily	1 km	10mm	10 mm	
Glaciers	Glacier area	Annual (at end of ablation season)	Horizontal 15–30 m	5%		IGOS (2009), Paul et al. (2009), Zemp et al. (2013)
	Glacier elevation change	Decadal	Horizontal 30 m–100 m x vertical 1 m	2 m/decade	1 m/decade	
	Glacier mass change	Seasonal to annual (the latter at end of ablation period)	Vertical: 0.01 m or 10 kg/m^2 (at point location)	Better than 200 kg/m^2/year (glacier-wide)		
Ice sheets and ice shelves	Surface elevation cChange	30 days	Horizontal 100 m	0.1m/year	0.1m/year	
	Ice velocity	30 days	Horizontal 100 m	0.1m/year	0.1m/year	
	Ice mass change	30 days	Horizontal 50 km	10 km^3/year	10 km^3/year	
	Grounding line location and thickness	Yearly	Horizontal 100 m Vertical 10 m	1 m	10 m	
Water vapour (surface)		Hourly	Site	RH 1% DP 0.1 K	0.5%/decade 0.02 K/decade	Kate Willet
Water vapour	Total column water vapour	4 h	25 km/NA	2%	0.3%	
	Tropospheric and lower-stratospheric profiles of water vapour	4 h (troposphere), daily (stratosphere)	25 km/2 km 100–200 km/2 km	5%	0.3%	
	Upper tropospheric humidity	Hourly	25 km/NA	5%	0.3%	
	Stratospheric CH_4	Daily	100–200 km/2 km	5%	0.3%	

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