2. Climate Applications

2.1 Energy and water closure

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2.1.1 Introduction

The water cycle of the Earth distributes water mass through the various water storage reservoirs of the planet. The water cycle is tightly related to the energy cycle of the Earth through diabatic heating in the atmosphere when water changes its phase (Stephens et al., 2012). The energy cycle of the Earth is represented by the flux of solar and terrestrial radiation, turbulent fluxes and moist static energy divergence within the Earth climate system. One notorious example of the coupling between the water and energy cycle in the climate system is manifested in the water vapor feedback process (Ramanathan, 1981). When radiative forcing is imposed by increasing the concentration of CO_2 in the atmosphere, the direct radiative effect is to warm the surface and the lower troposphere and cool the stratosphere. As surface temperature increases, evaporation also increases, allowing further increase in water vapor concentration in the warmer atmosphere. The increase of water vapor concentration is roughly 7% for each 1 K increase in temperature, following the Clausius-Clapeyron equation (Held and Soden, 2006). Water vapor itself is a strong greenhouse gas. It reinforces the initial warming, which induces a positive feedback on the climate system. Increased evaporation from the surface and a larger water vapor concentration in the atmosphere also imply an enhanced precipitation rate that also contributes to the warming of the atmosphere. More precisely, the increase in global precipitation rate in response to global warming is driven by the atmospheric radiative cooling rate, and is currently estimated to be around 2–3% for each 1 K increase in temperature (Stephens and Ellis, 2008). The slower increase in the precipitation rate than the increase in water vapor concentration is clear evidence of a tight relationship between the energy and water cycles. This coupling is an important aspect that has profound ramifications up to the climate sensitivity estimate because it is strongly related to hydrological sensitivity (Mauritsen and Stevens, 2015; Watanabe et al., 2018).

This prompted earlier investigators to explore the consistency among water and energy cycle elements and assess the closure of the water-energy budget observational capabilities. Budget assessments from observations of the water cycle only (Sheffield et al., 2009) or of both water and energy cycles (Stephens et al., 2012) further identified some significant deficits of closure in the observational portfolio. These studies lead to the conclusion that there is a need to adjust some fluxes to tend towards closure (Meyssignac et al., 2019). Significant progress in Earth observations of the water cycle prompt further assessment of the state of the art in our observational capabilities (Stephens et al., 2020).

Recently, optimal techniques that perform the adjustments objectively have been brought forward (L'Ecuyer et al., 2015; Rodell et al., 2015). These optimization techniques rely on enforcing global conservation laws playing with the uncertainty information that comes along with the data products. Modifications to the original datasets when closure is enforced are performed assuming changes lay within the stated uncertainty of each data product. This

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approach allows the assessment of whether the various fluxes are consistent (or not) among each other. In this approach, the closure of the water and energy cycles is enforced objectively and the consistency of the different fluxes is assessed. The paradigm of assessing the closure is shifted to the new paradigm: “enforcing the closure to assess consistency”.

We assess here both aspects; that is, how global and regional precipitation observations are closing budgets, and when closure is enforced, how consistent the precipitation estimates are. It is interesting to note that water and energy closure studies are a good complement to more classic evaluations of the gridded products using ground reference observations, particularly in data-scarce regions.

2.1.2. Water-only budget

At continental scales, the terrestrial water balance equation links precipitation (P) with river runoff (R), evapotranspiration (E) and water storage (S) as

$$P-E-R=dS/dt$$

Closure estimates rely to some extent on precipitation, but also on the other terms and their consistency, providing an integrated way to assess the performance of the precipitation. Note that bias in P and E can compensate easily in the water closure. The usually less-accurate evapotranspiration and runoff products may also not provide a strong constraint on precipitation.

2.1.2.1. Global land and globally-distributed basins studies

Munier and Aires (2018) explore the water budget closure framework over global land areas and perform optimization for 1°x1°grid boxes at a monthly scale. They use four satellite precipitation products (3B42v7, GPCP v2.2, CMORPH v1 uncorrected and PERSIANN-CDR v1).

The optimization using the closure only improves the original product’s scores for 60% of the stations (Figure 2.1.1). There, the improvements in RMS remains moderate, around 19%. This suggests that the original multi-product average is already close to reference ground-based observations and that other elements of the budget can only slightly improve the situation overall in this framework. Most of the evaluation is performed over the U.S. and Europe, which prevents drawing conclusions over the tropical regions.

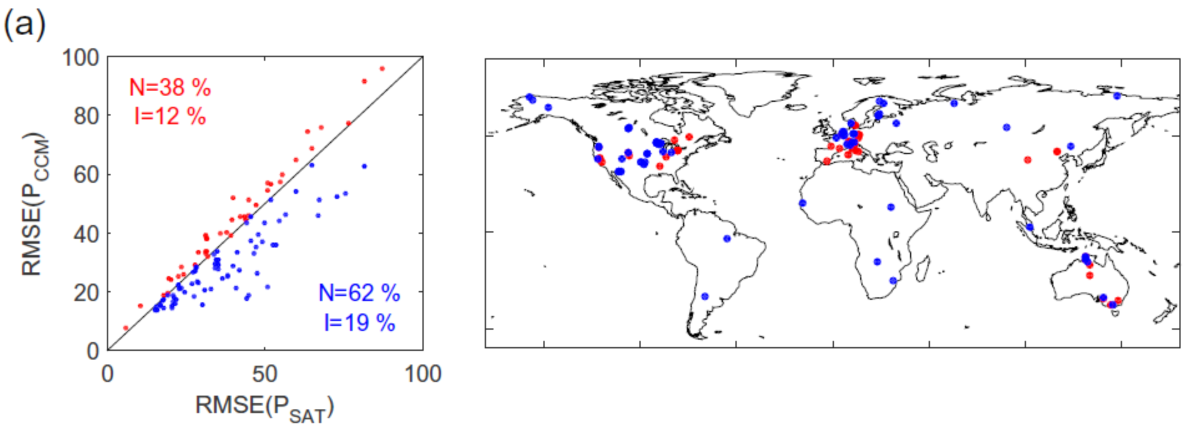

Figure 2.1.1. Comparison of corrected precipitation using CCM+CIC with FLUXNET observations. Left: scatter plot of RMSE of original satellite datasets and CCM corrected dataset (N is the percentage of stations where CCM improves P, I is the average relative improvement). Right: location of stations where the CCM improves (blue) or degrades (red) P. Adapted from Munier and Aires, 2018

Focusing on 96 globally-distributed catchments of various size and under various climates, Lorenz et al. (2014) explore the water closure of different datasets, including for ground-based precipitation products [GPCC data, National Weather Service Climate Prediction Center retrospective analysis (CPC), The University of East Anglia's Climatic Research Unit's global climate dataset (CRU) and data from Willmott, Matsuura and collaborators at the University of Delaware (UDEL)] and one satellite product (GPCP). Water budget closure is reasonably achieved only in a few cases with a given combination of datasets. In most catchments, the major characteristic is a significant imbalance. Precipitation strongly influences the budget in the tropics; the GPCC and GPCP products show best scores. In the Arctic, GPCP provides the best results, probably owing to the undercatch correction. The study emphasizes that performance over an individual catchment does not hold for the other regions.

2.1.2.2. Regional land studies

While a systematic exploration of all the ongoing regional studies about precipitation and closure is out of the scope of the present chapter, we have selected a few references that convey the main messages.

2.1.2.2.1. *High Mountain Asia*

Yoon et al. (2019) explore the regional water closure using a water balance model and ten gridded precipitation datasets over 17 years. It includes in situ, reanalysis and satellite-based products. The products that incorporate rain gauges are shown to reach higher accuracy in the surface balance estimates. Satellite products exhibit systematic underestimation and low correlations over the Tibetan Plateau and high elevation areas. The spread in the precipitation estimates at the regional scale is significantly large than those from global studies. Generally, the in situ-based products outperform the other datasets.

2.1.2.2.2. *Mediterranean Area*

Pellet et al. (2019) estimate the closure of the water budget over Mediterranean catchments using a few observational precipitation products (the same as Munier and Aires, 2018) and various other fluxes estimates. The optimization method brings only a marginal improvement on the original multi product simple average with a 10–15% improvement on the RMS and no change on the correlation with the ENSEMBLES Observation EOBS reference dataset. This is indicative of the relative proper accuracy of the gauge corrected satellite products over this area at this scale.

2.1.2.2.3. *Mississippi Basin*

Munier et al. (2014) focus on this well-gauged basin to assess their methodology at the regional scale. The study is limited to a few sets of precipitation products [3B43 V7 CMORPH, V1.0, the NRL blended technique, and the Global Precipitation Climatology Project (GPCP, V2.2)]. It reveals a strong discrepancy between NRL and CMORPH and the gauge adjusted products. Yet enforcing the water budget closure at the catchment scale permits optimization of the products reaching very high R^2 scores (>0.85) for each of the 4 products at the monthly scales. The corrected product seems to be fit for future hydrological analysis.

2.1.3. Regional atmospheric budget over ocean

The vertically-integrated atmospheric water budget links precipitation (P), evaporation (E) and the convergence of water vapor in the atmosphere (▽Q) after neglecting the storage term

$$E - P = \nabla Q$$

∇Q is nominally obtained from atmospheric reanalysis and as with the previous hydrologic budget equation, it allows the assessment of the consistency of the precipitation products with the other data sources, but compensating errors will not be revealed.

Brown and Kummerow (2014) perform such budget calculations over various tropical oceanic basins using the precipitation from GPCP. Figure 2.1.2 indicates a remarkably good ability to close the budget at these scales over this 10-year period.

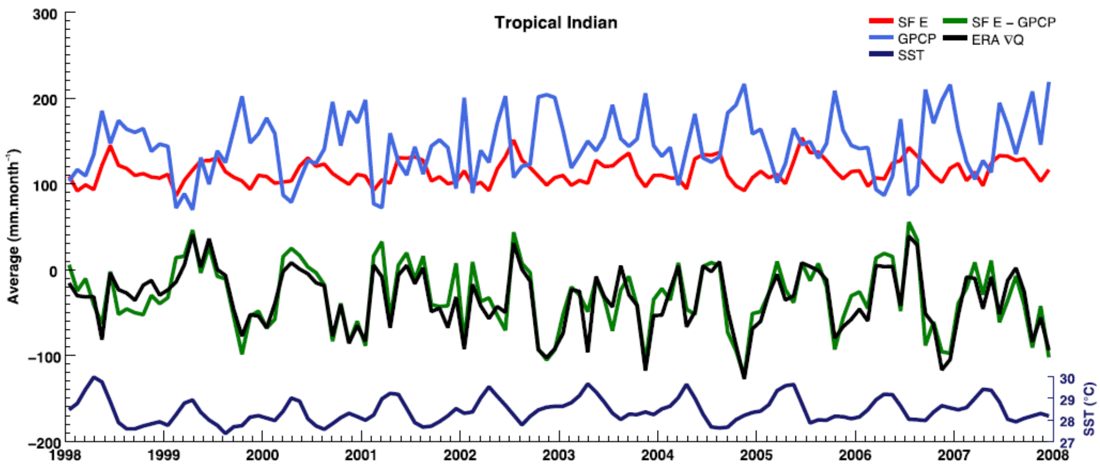

Figure 2.1.2. Monthly average time series of SeaFlux evaporation (SF E) and GPCP precipitation over the Tropical Indian Ocean region. Observation-based freshwater flux (E-P), European Centre for Medium-Range Weather Forecasts Re-Analysis dataset (ERA-Interim) atmospheric moisture divergence (∇Q) and sea surface temperature (SST) are also shown.

The accuracy of the GPCP estimate hence revealed is of similar magnitude over the other basin with some slight changes in the Pacific Ocean along the time yet to be fully understood. Since a number of satellite products eventually adjust onto GPCP monthly over the ocean (CMORPH, PERSIANN-CDR), this good behavior is likely to hold for these products as well. The E-P ocean freshwater budget is linked to the salinity of the ocean. Recent measurements of surface salinity could contribute to further constrain E-P estimates over the world's oceans. The relationship between E-P and salinity is governed by upper ocean dynamics, ice sheets melting, and other phenomenon, making it somewhat difficult to infer from salinity observations. Salinity could nevertheless bring additional consistency constraints that could eventually help to assess E-P over the ocean (Yu et al., 2020).

2.1.4. Water and energy budget

The water and energy cycles follow water mass and energy conservation laws respectively. The conservation of water mass and energy at the surface are coupled through evaporation (see also Kato et al., 2016). The water mass balance for a regional land surface is

$$dS/dt_i = P-E-R$$

where S is the land water storage, P and E are precipitation and evaporation rate, and R is runoff. At an annual global scale, the evaporation rate at the surface balances with the precipitation rate. The energy balance at the surface is

$$NET = DLW+DSW-ULW-USW-SH-L_eE$$

NET is the surface net energy, DLW (DSW) the downward longwave (shortwave) radiation, ULW (USW) is the upward longwave (shortwave) surface radiation, SH is the sensible heat flux, and L_eE is evaporation rate multiplied by the enthalpy of vaporization. Note that bias in P and E can compensate easily in the water closure and less so in the water and energy closure owing to the radiation constraint. The usually more-accurate radiation estimates can also provide a stronger constraint on the precipitation.

2.1.4.1. Global

Previous studies have demonstrated that, in the current climate, variability in atmospheric energy balance, ∆NETATM, is primarily governed by changes in longwave radiation (ULW - DLW) and precipitation (P) (Allen and Ingram, 2002; Held and Soden, 2006). As a result, atmospheric longwave cooling exerts a robust control on global precipitation in the equilibrium climate as demonstrated by Stephens and Ellis (2008). The implications of this link between the energy and water cycle are readily evident in recent reconstructions of Earth's energy budget. When energy and water cycle fluxes from state-of-the-art satellite observations or reanalysis are combined to reconstruct the global atmospheric and oceanic energy budgets, large residuals emerge that exceed in situ estimates of atmospheric and ocean heat uptake by an order of magnitude. One or more fluxes must be adjusted to resolve these imbalances. Two approaches emerged for reconciling the implied energy imbalances with in situ observations. Trenberth et al. (2009) chose to reduce the downwelling radiation (primarily DLW) into the surface while Stephens et al. (2012) argued that global precipitation estimates should be increased, sparking intense debate as to which flux datasets were more accurate. While subjective arguments could be made for adjusting either precipitation or DLW, the discrepancies in the resulting global, annual-mean precipitation estimates exceeded 10%.

The debate fueled by these competing energy budget reconstructions led a large group of investigators in NASA's Energy and Water cycle Study (NEWS) to develop an objective approach to imposing energy and water cycle closure constraints. By adjusting fluxes using a 1D-VAR framework that explicitly accounted for uncertainties in component fluxes, L'Ecuyer et al. (2015) and Rodell et al. (2015) generated closed energy and water budgets on global and continental scales. This work suggests that current satellite-based estimates of global precipitation need to be increased by 4%, an adjustment that falls within existing error bars, to properly balance global evaporation and close the atmospheric and surface energy budgets (Rodell et al., 2015).

2.1.4.1.1. *Towards assessing multiple precipitation products water and energy closure*

As a preliminary step towards assessing the various precipitation products' consistency within the optimized framework, a first comparison of the global diabatic heating variability is needed. Indeed, on the global and annual scale, net atmospheric irradiance divergence must be balanced by surface sensible heating and diabatic heating rate by precipitation (Stephens and Ellis, 2008). The net atmospheric radiation divergence is derived from Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) edition 4 and the global latent heat value is derived from a subset of global precipitation products from Frequent Rainfall Observations on GridS (FROGS: Roca et al., 2019). The quasi-global satellite products have been completed poleward using the GPCP "truly" global product data, forming a larger ensemble of products to assess. In complement to satellite-based estimates, a handful of reanalysis products is also included in the study.

The variability of monthly anomalies is +-1 Wm-2 (Figure 2.1.3). The results indicate a strong lack of consistency of the precipitation products with the exception the GPCP estimates and that of European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5), especially after 2007. The PERSIANN and the CMORPH products also seem to track the net atmospheric irradiance well, which is not surprising since the products are scaled on GPCP at monthly scale (only over ocean for CMORPH). Most of the precipitation products overestimate the diabatic heating variability and some show substantial trends with no equivalent in the radiation-derived budget.

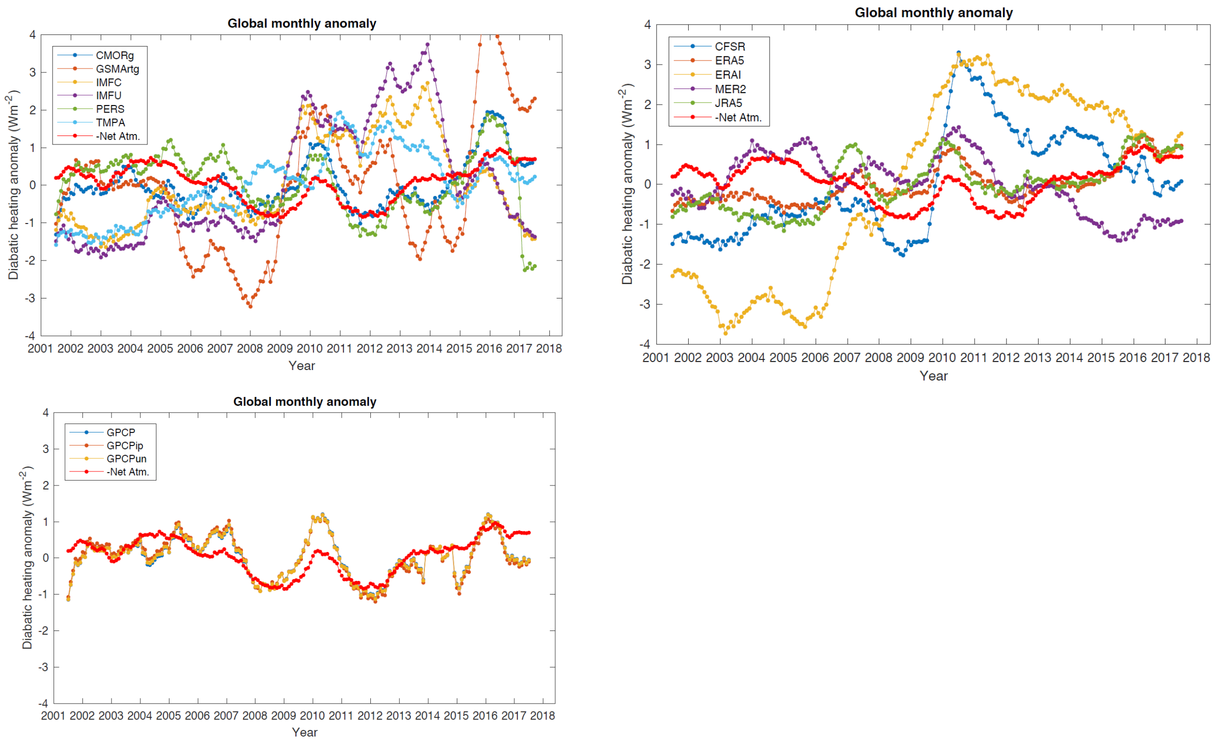

Figure 2.1.3. Time series of the deseasonalized monthly anomaly of global diabatic heating for various filled satellite (top left) and reanalysis (top right) and truly global satellite (bottom left) products. In both panels, anomalies of net atmospheric irradiance are shown by the red line.

2.1.4.1.2. *Multiple precipitation products using water budget only closure*

Hobeichi et al. (2020a) investigate five global products, two from satellite (IMERG, GPCP), two ground-based [GPCC, Rainfall Estimates on a Gridded Network (REGEN)] and one reanalysis, the second Modern-Era Retrospective analysis for Research and Applications (MERRA-2). The assimilation-based method of Hobeichi et al. (2020b) is used. It is implemented globally at the resolution of half a degree and at monthly time scales and performs a simultaneous enforcement of the closure of the surface water and energy budgets. Using various metrics, the analysis shows that GPCC best closes the budget of the high latitudes while GPCP leads in the tropics. The REGEN data test seems to best perform over semi-arid regions of northern Africa and the Middle East and in the moist Southeast Asia. IMERG outperforms the other products only over Australia.

Figure 2.1.4 indicates that despite having a significantly lesser performance, the MERRA-2 uncertainty characterization is relevant as the adjustments due to the closure remain bounded by the uncertainty. Unlike MERRA-2, the satellite and ground-based products' uncertainty appears not to be adequate in most of the regions, suggesting a deeper elaboration on uncertainty for these products.

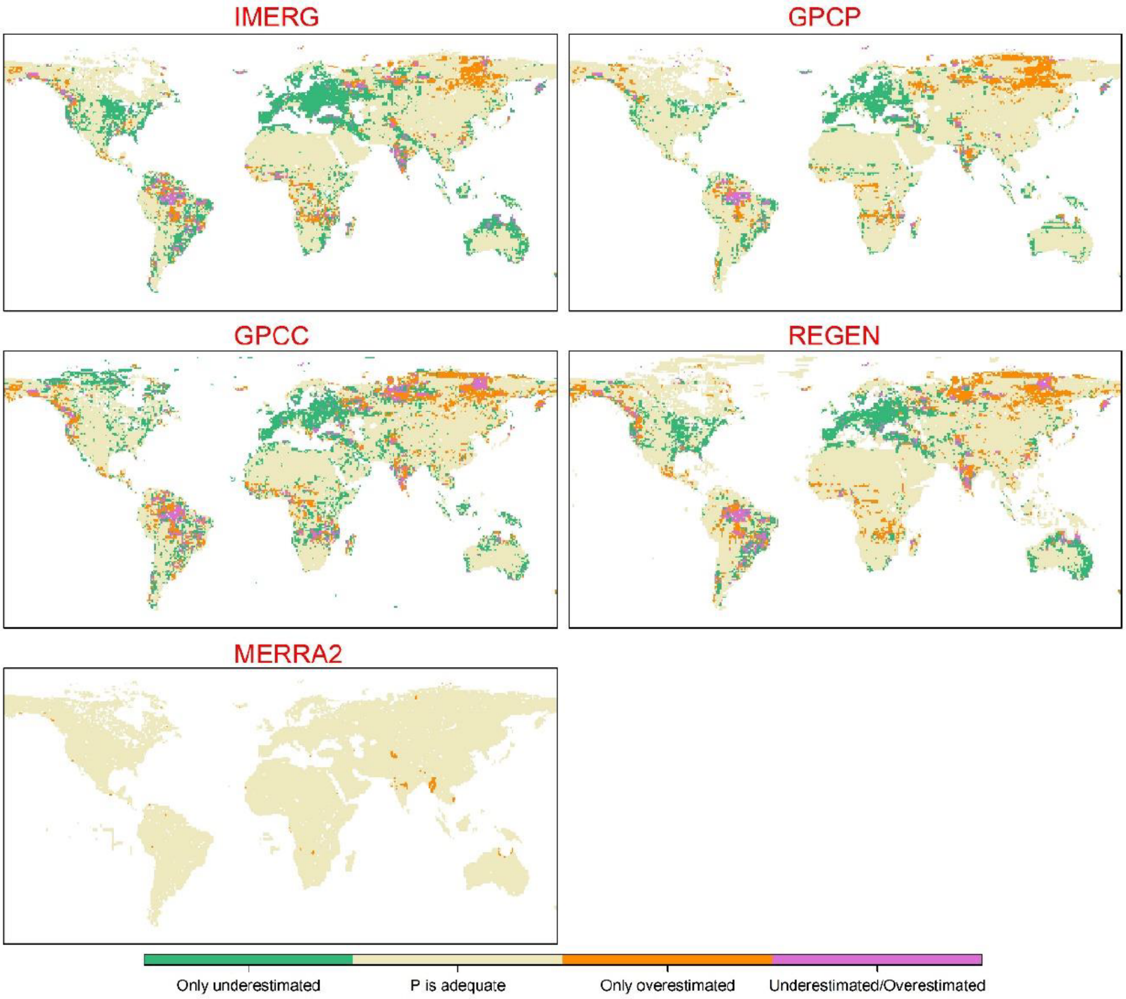

Figure 2.1.4. Regions where a P dataset had to undergo adjustments beyond its uncertainty bounds, indicating that it was originally underestimated or overestimated. Green grid cells are locations where P was found to be underestimated in at least one calendar month, but never overestimated. Orange grid cells refer to locations where P was found overestimated in at least one calendar month but never underestimated. Magenta grid cells show regions where P exhibited different behaviors (underestimated/overestimated) in difference calendar months. Beige grid cells are regions where changes applied to P do not exceed its uncertainty. From Hobeichi et al., 2020a

2.1.5. Summary

Optimization techniques have provided a useful way to assess the capability of the existing observations to close the water budget or the water and energy budget as well as the consistency of the estimated fluxes, once the closure is enforced. This leap forward enables the assessment of the new generation of products at the global scale as well as regionally, including the oceans, for which precipitation products' performances is usually poorly known. The emergence of new observational constraints on the surface freshwater budget via surface salinity measurements can further help with the consistency analysis over the ocean.

Water balance studies at a regional scale emphasize the better accuracy of the rain gauge-based products compared to the reanalysis and satellite datasets. Water budget only optimization yields only moderate changes and improvements of a few precipitation products, suggesting a relatively good consistency with evaporation and runoff. This status is of no use for global investigations and embodies the difficulty of benefiting from numerous regional land investigations from a global climate perspective.

Water and energy budget simultaneous closure optimization at global, multi-year scales shows that current global precipitation estimations need an adjustment that falls within existing error bars. Preliminary time series comparisons between energy and precipitation at the global scale, on the other hand, show large spread from the various precipitation products and significant unrealistic variability.

Systematic evaluation of the breadth of products available remains challenging, as most of the studies explore one or two products, making it difficult so far to reach a community-centric overview. Preliminary efforts using a dozen *global* datasets nevertheless reveal the large inconsistency between the precipitation and radiation budget, except for GPCP and ERA5.

2.1.6. Recommendations

Based on this first and partial attempt to assess the capability of precipitation products to contribute to water and energy cycle closure as well as their consistency with other fluxes, we are in a position to formulate some recommendations for the agencies and the community.

General recommendations:

- Validation/intercomparison/assessment studies should embrace the large breadth of existing products and not be restricted to one or two products
- Consolidate present findings; elaborate and refine the current set of diagnostics
- Improve the products, as the assessment has identified some non-robust features that deserve further attention. Provide feedback to the dataset providers on the details, perhaps with specific workshops.
- Fill the gaps in the assessment.
- Communicate the robust features of the datasets to support further research using the datasets.

2.1.6.1.1. *Specific recommendations*

- Better convey the optimization results at regional scales with ongoing field programs (for example, the GEWEX Hydroclimatology Panel)
- The documentation of the precipitation products' uncertainty should be advanced to fully benefit the optimization framework. This includes auto-correlation and structural error characterization at the monthly scale.
- Support the systematic use of the various precipitation products instead of the single product approach to help better identify the strengths and weaknesses of the products.

2.1.7. Acknowledgments

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2.1.8. References

Allen, M.R., and W.J. Ingram, 2002: Constraints on future changes in climate and the hydrologic cycle. *Nature*, 419, 224–232, https://doi.org/10.1038/nature01092.

Brown, P.J., and C.D. Kummerow, 2014: An assessment of atmospheric water budget components over tropical oceans. *Journal of Climate*, 27(5), 2054–2071, doi:10.1175/JCLI-D-13-00385.1.

Held, I.M., and B.J. Soden, 2006. Robust Responses of the Hydrological Cycle to Global Warming. *Journal of Climate*, 19, 21, 5686–5699, https://doi.org/10.1175/JCLI3990.1.

Hobeichi, S., G. Abramowitz, S. Contractor and J. Evans, 2020a: Evaluating precipitation datasets using surface water and energy budget closure. *Journal of Hydrometeorology*, 1–49, doi:10.1175/jhm-d-19-0255.1.

Hobeichi, S., G. Abramowitz and J. Evans, 2020b: Conserving Land–Atmosphere Synthesis Suite (CLASS). *Journal of Climate*, 33, 1821–1844, https://doi.org/10.1175/JCLI-D-19-0036.1.

Kato, S., K.M. Xu, T. Wong, N.G. Loeb, F.G. Rose, K.E. Trenberth and T.J. Thorsen, 2016: Investigation of the residual in column-integrated atmospheric energy balance using cloud objects. *Journal of Climate*, 29(20), 7435–7452, doi:10.1175/JCLI-D-15-0782.1.

L'Ecuyer, T., H.K. Beaudoing, M. Rodell, W. Olson, B. Lin, S. Kato, C.A. Clayson, E. Wood, J. Sheffield, R. Adler, G. Huffman, M. Bosilovich, G. Gu, F. Robertson, P.R. Houser, D. Chambers, J.S. Famiglietti, E. Fetzer, W.T. Liu, X. Gao, C.A. Schlosser, E. Clark, D.P. Lettenmaier and K. Hilburn, 2015: The Observed State of the Energy Budget in the Early Twenty-First Century. *Journal of Climate*, 28, 21, 8319–8346, https://doi.org/10.1175/JCLI-D-14-00556.1.

Lorenz, C., H. Kunstmann, B. Devaraju, M.J. Tourian, N. Sneeuw and J. Riegger, 2014: Large-scale runoff from landmasses: A global assessment of the closure of the hydrological and atmospheric water balances. *Journal of Hydrometeorology*, 15(6), 2111–2139, doi:10.1175/JHM-D-13-0157.1.

Mauritsen, T., and B. Stevens, 2015: Missing iris effect as a possible cause of muted hydrological change and high climate sensitivity in models. *Nature Geoscience*, 8, 346–351, http://dx.doi.org/10.1038/ngeo2414.

Meyssignac, B., T. Boyer, Z. Zhao, M.Z. Hakuba, F.W. Landerer, D. Stammer, A. Köhl, S. Kato, T. L'Ecuyer, M. Ablain, J.P. Abraham, A. Blazquez, A. Cazenave, J.A. Church, R. Cowley, L. Cheng, C.M. Domingues, D. Giglio, V. Gouretski, M. Ishii, G.C. Johnson, R.E. Killick, D. Legler, W. Llovel, J. Lyman, M.D. Palmer, S. Piotrowicz, S.G. Purkey, D. Roemmich, R. Roca, A. Savita, K. von Schuckmann, S. Speich, G. Stephens, G. Wang, S.E. Wijffels and N. Zilberman, 2019: Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance. *Frontiers in Marine Science*, 6, 1–31, doi:10.3389/fmars.2019.00432.

Munier, S., F. Aires, S. Schlaffer, C. Prigent, F. Papa, P. Maisongrande and M. Pan, 2014: Combining data sets of satellite-retrieved products for basin-scale water balance study: 2. Evaluation on the Mississippi basin and closure correction model. *Journal of Geophysical Research*, 119(21), 12,100–12,116, doi:10.1002/2014JD021953.

Munier, S., and F. Aires, 2018: A new global method of satellite dataset merging and quality characterization constrained by the terrestrial water budget. *Remote Sensing of Environment*, 205, 119–130, https://doi.org/10.1016/j.rse.2017.11.008.

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

Ramanathan, V., 1981: The role of ocean-atmosphere interactions in the CO_2 climate problem. *Journal of the Atmospheric Sciences*, 38, 918–930.

Roca, R., L.V. Alexander, G. Potter, M. Bador, R. Jucá, S. Contractor, M.G. Bosilovich and S. Cloché, 2019: FROGS: a daily 1° × 1° gridded precipitation database of rain gauge, satellite and reanalysis products. *Earth System Science Data*, 11, 1017–1035, https://doi.org/10.5194/essd-11-1017-2019.

Rodell, M., H.K. Beaudoing, T.S. L'Ecuyer, W.S. Olson, J.S. Famiglietti, P.R. Houser, R. Adler, M.G. Bosilovich, C.A. Clayson, D. Chambers, E. Clark, E.J. Fetzer, X. Gao, G. Gu, K. Hilburn, G.J. Huffman, D.P. Lettenmaier, W.T. Liu, F.R. Robertson, C.A. Schlosser, J. Sheffield and E.F. Wood, 2015: The Observed State of the Water Cycle in the Early Twenty-First Century. *Journal of Climate*, 28.21, 8289–8318, https://doi.org/10.1175/JCLI-D-14-00555.1.

Sheffield, J., C.R. Ferguson, T.J. Troy, E.F. Wood and M.F. McCabe, 2009: Closing the terrestrial water budget from satellite remote sensing. *Geophysical Research Letters*, 36(7), doi:10.1029/2009GL037338.

Stephens, G.L., and T.D. Ellis, 2008: Controls of global-mean precipitation increases in global warming GCM experiments. *Journal of Climate*, 21, 6141–6155, doi:10.1175/2008JCLI2144.1.

Stephens, G.L., J. Li, M. Wild, C.A. Clayson, N. Loeb, S. Kato, T. L'Ecuyer, P.W. Stackhouse Jr., M. Lebsock and T. Andrews, 2012: An update on Earth's energy balance in light of the latest global observations. *Nature Geoscience*, 5, 691–696, http://dx.doi.org/10.1038/ngeo1580.

Stephens, G.L., J.M. Slingo, E. Rignot, J.T. Reager, M.Z. Hakuba, P.J. Durack, J. Worden and R. Rocca, 2020: Earth's water reservoirs in a changing climate. *The Royal Academy Proceedings: Mathematical, Physical and Engineering Sciences*, 476(2236), doi:10.1098/rspa.2019.0458, 2020.

Trenberth, K.E., J.T. Fasullo and J. Kiehl, 2009: Earth's global energy budget. *Bulletin of the American Meteorological Society*, 90, 311–323, https://doi.org/10.1175/2008BAMS2634.1.

Watanabe, M., Y. Kamae, H. Shiogama, A.M. DeAngelis and K. Suzuki, 2018: Low clouds link equilibrium climate sensitivity to hydrological sensitivity. *Nature Climate Change*, 8, 901–906, http://dx.doi.org/10.1038/s41558-018-0272-0.

Yoon, Y., S.V. Kumar, B.A. Forman, B.F. Zaitchik, Y. Kwon, Y. Qian, S. Rupper, V. Maggioni, P. Houser, D. Kirschbaum, A. Richey, A. Arendt, D. Mocko, J. Jacob, S. Bhanja and A. Mukherjee, 2019: Evaluating the Uncertainty of Terrestrial Water Budget Components Over High Mountain Asia. *Frontiers in Earth Science*, 7:120, doi: 10.3389/feart.2019.00120.

Yu, L., S.A. Josey, F.M. Bingham and T. Lee, 2020: Intensification of the global water cycle and evidence from ocean salinity: a synthesis review. *Annals of the New York Academy of Sciences*, 1–19, doi:10.1111/nyas.14354.