3.3. Emerging techniques for precipitation assessment and consistency studies

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3.3.1. Introduction

Accurate precipitation estimation is critical to study the Earth and advance science and applications. Towards this goal, observations from satellite, ground radar and in situ instruments are used, either individually or in combination, to better capture spatiotemporal sampling and accuracy of precipitation. Despite their overall merits, ground radars and in situ observations provide limited coverage for global precipitation estimation. In certain conditions, in situ data also face major uncertainties (for example, to measure snowfall due to gauge undercatch problems) (Yang et al., 2005; Behrangi et al., 2018). Recognizing their spatiotemporal coverage, various space-borne sensors and missions have been utilized for precipitation retrieval. Some of them have precipitation studies and estimation as their main objective (for example, the TRMM and GPM missions) and several others are used because they are capable of providing the information needed for precipitation retrieval. Besides adding to precipitation sampling, the new sensors often contribute by filling remaining gaps in one or more areas. For example, with TRMM, major advancement in estimating near-surface and profile of moderate and intense precipitation was obtained over the tropics (~ 35°S/N); CloudSat enabled detection and estimation of snowfall and light rain with unprecedented sensitivity (~ –28 dBZ using the 94 GHz Cloud Profiling Radar observations) within ~ 81°S/N; and GPM extended TRMM capabilities and offered potentials for snowfall retrievals within ~ 65°S/N using its dual-polarization radar and passive microwave measurements at higher frequencies. Combination of such complementary datasets has made it possible to make new estimates for precipitation amount and distribution that can be used to guide and assess other precipitation products (for examples, see Behrangi et al., 2014; Olson et al., 2018). Besides those sensors that provide valuable information with direct application in precipitation retrieval, new opportunities have also become available through other instruments developed to better monitor and study the Earth system. If independent from typical methods used for precipitation retrieval, they may provide unique information for a consistency check or independent assessment. An example is the use of the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004) to add insights on snowfall accumulation by monitoring mass variations. Here we discuss a few of such opportunities.

3.3.2. Mass change observations

In high latitudes and cold regions, satellite and ground measurements face large uncertainties. Unknown or variable surface emissivity over snow and ice surfaces and the dominance of light rain and snowfall in high latitudes and cold regions have made it difficult for both microwave and infrared techniques to retrieve snowfall. Rain gauges also face large snowfall undercatch that might exceed 100%, making it difficult to estimate snowfall and quantify its accumulation. It has been shown that using a completely independent observational technique (that is, gravimetry versus radiometry), it is possible to estimate snowfall accumulation by monitoring mass variations over sufficiently large areas. Using ten years of GRACE observations and through the mass balance method, where and when no surface melting occurs for at least a month, Behrangi et al. (2018) calculated monthly and seasonal snowfall accumulation and utilized them to assess other precipitation products (that is, GPCC and GPCP) as well as two common gauge-undercatch correction factors (CFs). In their study, evapotranspiration and

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sublimation were quantified from reanalysis, but it was found that they only slightly contribute to the mass balance equation. The study was limited to grids with near surface temperature below 1°C for at least a month, so runoff could be negligible within the mass balance equation. GRACE and evapotranspiration observations were also used in large endorheic basins in High Mountain Asia to estimate monthly accumulated precipitation (Behrangi et al., 2017). An endorheic system is a closed drainage system that retains water and allows no outflow to other external bodies of water; therefore there is no need for streamflow observations to close the mass budget equation. The results were compared with satellite and in situ-based precipitation products, and it was found that most of the products agree well with each other and GRACE analysis in summer, but capture about or less than 50% of the total precipitation estimated using GRACE in winter. Similarly, GRACE observations were used to study the recent increase in lake volumes of the Tibetan Plateau's endorheic basins, and it was found that increased net precipitation contributes the majority of water supply for the lake volume increase (Zhang et al., 2017).

3.3.3. Mass change and streamflow observations

With streamflow observations at basins outlets, there is no need to limit the mass balance analysis to endorheic basins or grids that are cold enough to not generate runoff from snowmelt. Studies using streamflow and GRACE observations have shown great applications for precipitation assessment over the arctic basins. In a recent study, observations of streamflow and storage (mass) change from GRACE, together with estimates of evapotranspiration and sublimation, were used to close the mass budget equation over six arctic basins and investigate monthly time series and multiyear precipitation rates over the studied basins (Behrangi et al., 2019). These analyses were then used to assess two popular CFs: the Legates climatology (CF-L) utilized in GPCP and the Fuchs dynamic correction model (CF-F) used in GPCC monitoring product. The results over the study basins suggested that, based on GRACE and streamflow observations, the CF-F is preferred. GPCP uses CF-L to correct GPCC before merging with satellite data. This study suggests that more efforts are needed to assess which CF method (or combination of methods) should be used for global implementation in GPCP. In lack of other in situ observations, the use of mass change observations seems to provide valuable insights, even at coarse spatial resolution.

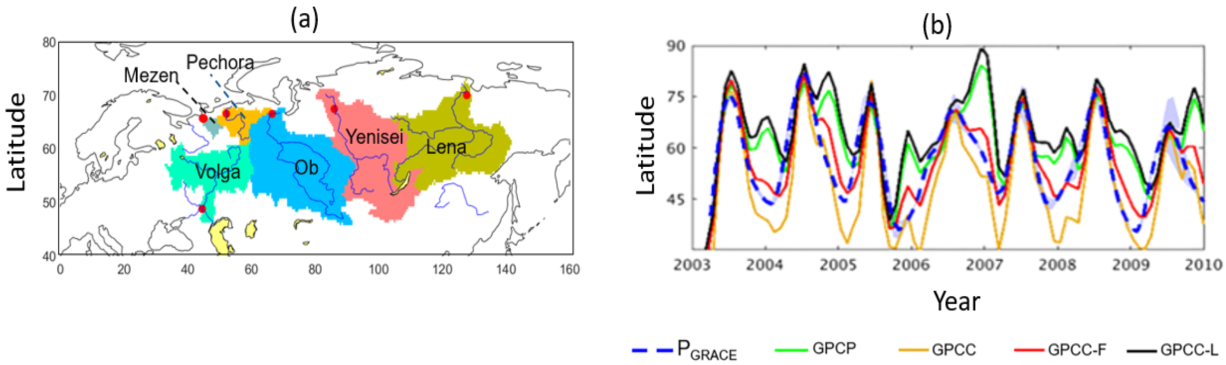

Figure 3.3.1. Times series of monthly mean precipitation rates from GPCC, GPCP, GPCC-L, GPCC-F, and GRACE over the Volga basin. Figures from Behrangi et al. (2019), with modifications. The red dots in panel (a) show the location of the outlet of the basins.

3.3.4. Mass change and ice discharge observations

Precipitation estimation over ice sheets (for example, Antarctica) is challenging because in addition to difficulties that snow and ice surface bring to precipitation estimation from radiometers, estimating snowfall accumulation over Antarctic ice sheets is complicated by ice divergence, the continual export of mass from the interior to the oceans via ice flow (Rignot et al., 2011). In other words, it is not possible to perform mass balance analysis (for example, using GRACE) over Antarctic grids or basins without accounting for ice discharge that can be as much as 2000 Gt per year (Gardner et al., 2018). However, efforts have made it possible to reconstruct ice discharge and changes in ice discharge over the Antarctic ice sheet by merging a comprehensive record of changes in Antarctic-wide ice flow, calculated by feature tracking of hundreds of thousands of Landsat image and mapping of surface velocity (Rignot et al., 2011; Gardner et al., 2018). Using mass change observations from GRACE and observational-based estimates of ice discharge values and their uncertainties over several Arctic basins, Behrangi et al. (2020) calculated annual snowfall accumulation over seven large Antarctic basins and compared the outcomes with several satellite and reanalysis products (Fig. 3.2.2). Their mass balance estimated snowfall accumulation using ice discharge and storage change observations were bounded by CloudSat snowfall estimates, presumably the most viable satellite-based snowfall product, with and without adjustment for the unmeasured near surface. Similar to Grazioli et al. (2017), the adjustment factor was calculated by dividing the cumulative precipitation at near-surface by precipitation accumulation at 1.2 km above the surface using the ECMWF Integrated Forecast System (ECMWF IFS). Such analyses provide an independent assessment of current satellite-based snowfall estimates over Antarctic and similar ice sheets (for example, part of Greenland where rainfall is not frequent), especially as GRACE-Follow On (GRACE-FO) continues to provide mass change observations.

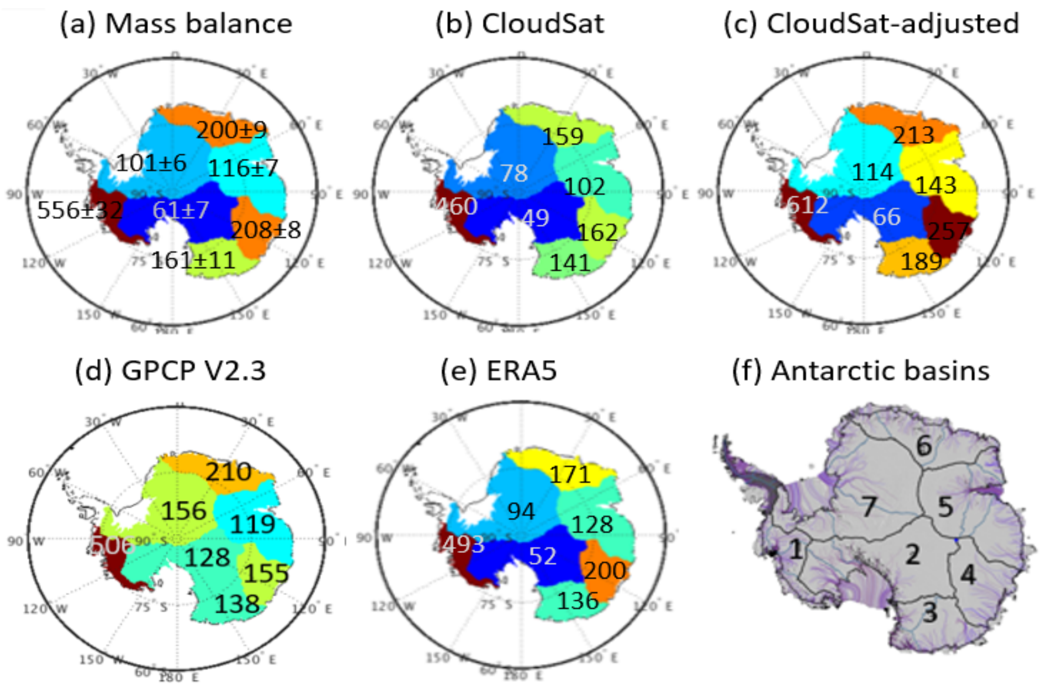

Figure 3.3.2. Annual snowfall rate estimated from various products for each of the seven basins [shown in panel (f)]. The errors shown for mass budget estimates represent combined errors from GRACE, ice discharge and basal melt estimates with details discussed in Gardner et al. (2018). The figure is based on Behrangi et al. (2020) with some modifications.

3.3.5. Snow depth observations

Observation of snow depth can provide an estimate of the net precipitation accumulation after accounting for snow density, sublimation, redistribution due to wind and melt losses between the two survey dates. By calculating snow water equivalent (SWE) from snow depth observations, it is possible to directly compare snowfall accumulation with changes in SWE.

Through the selection of a major snowfall event with a large accumulation signal, one can also maximize the snowfall accumulation signal and minimize the losses during the short period. Using spatially-complete SWE products from the Airborne Snow Observatory (ASO, Painter et al., 2016), Behrangi et al. (2018) used changes in SWE observations to quantify snow accumulation in cold mountain environments in the western U.S. and compared the outcomes to six satellite-based precipitation products, a ground-based radar, and three in situ snow pillows. They also assessed the bias-scaling relationship (that is, point versus areal estimates) that is often not considered when point measurements are used in evaluating gridded products. By focusing on snowfall over snow accumulation period in CONUS, Panahi and Behrangi (2020) used changes in SWE based on a gridded in situ observation product (University of Arizona snow water estimate, UA-SWE) together with mass change observations from GRACE to assess snowfall estimates of several precipitation products as well as to investigate the gauge undercatch correction methods. While expanding such analysis to other regions using satellite-based SWE observation is possible (for example, Tian et al., 2014), the quality of SWE products determines the extent of these assessment methods.

Snow depth observations are also available over sea ice and can be used for an independent assessment of snowfall accumulation. Almost no reference precipitation data sets exists over sea ice and the current precipitation products are highly uncertain. Studies have shown that using an ultra-wideband radar system on NASA's Operation IceBridge (OIB) airplane, snow depth on sea ice can be measured and used to determine uncertainties in other satellite-derived snow depth products (Brucker and Markus, 2013). By using a proper snow density value, snow depth measurements on sea ice have been used to assess snowfall accumulation from satellite (Song et al., 2020) or reanalysis (Boisvert et al., 2018; Blanchard-Wrigglesworth et al., 2018) products over sea ice. Efforts are underway to use satellite altimetry to produce spatially and temporally more-complete observations of snow depth on sea ice than that offered by OIB. Launched in September 2018, the Ice, Cloud and land Elevation Satellite (ICESat-2) together with CryoSat-2 should enable extending snow depth estimations over the entire arctic sea ice using differences in freeboard heights observed by the two instruments (e.g., Kwok et al., 2020). Upon retrieving quality snow depth estimates, the outcomes can potentially provide unique opportunities for the assessment of precipitation products over sea ice.

3.3.6. Complementary radar observations

Over ocean where in situ observations are generally lacking and precipitation products have large spread (Adler et al. 2012), using complementary observations from the best-known satellite products could provide a reference to assess other satellite products. Recognizing the complementary observations from CloudSat (for example, for drizzle, light precipitation and snowfall estimation) and TRMM (for moderate and intense precipitation), Behrangi et al. (2014; 2012) developed a Merged CloudSat, TRMM and Advanced Microwave Scanning Radiometer (AMSR) (MCTA) product and used that to determine the zonal distribution of precipitation over the ocean. AMSR coincides with CloudSat, and is used where and when CloudSat faces signal saturation problems under intense precipitation events. A comparison of MCTA with GPCP V2.2 showed that GPCP may underestimate oceanic precipitation by about 5%. This number agreed well with what Rodell et al. (2015) found through water budget analysis. The launch and operation of GPM enables us to extend the estimate of moderate and intense precipitation from the tropics to the extratropics (that is, from 35°S/N to 65°S/N). Accordingly, a new product was developed by Behrangi and Song (2020) that provides seasonal maps of the Merged CloudSat, TRMM, and GPM (MCTG) precipitation rates. MCTG provides additional insights on zonal and regional magnitude and distribution of precipitation rate over the ocean, and it was recently used to assess and revise GPCP over the oceans together with the Tropical Composite Climatology (TCC) (Adler et al., 2009; Wang et al., 2014). The revised GPCP product (V3.1)

(Huffman et al., 2020) shows major differences compared to its previous version (V2.3), especially over the Southern Oceans (Fig. 3.3.3), and suggests an increase of about 6% in global oceanic precipitation. This is another example of how recent sensors can be used to guide precipitation assessments where and when accurate or sufficient in situ data are generally lacking.

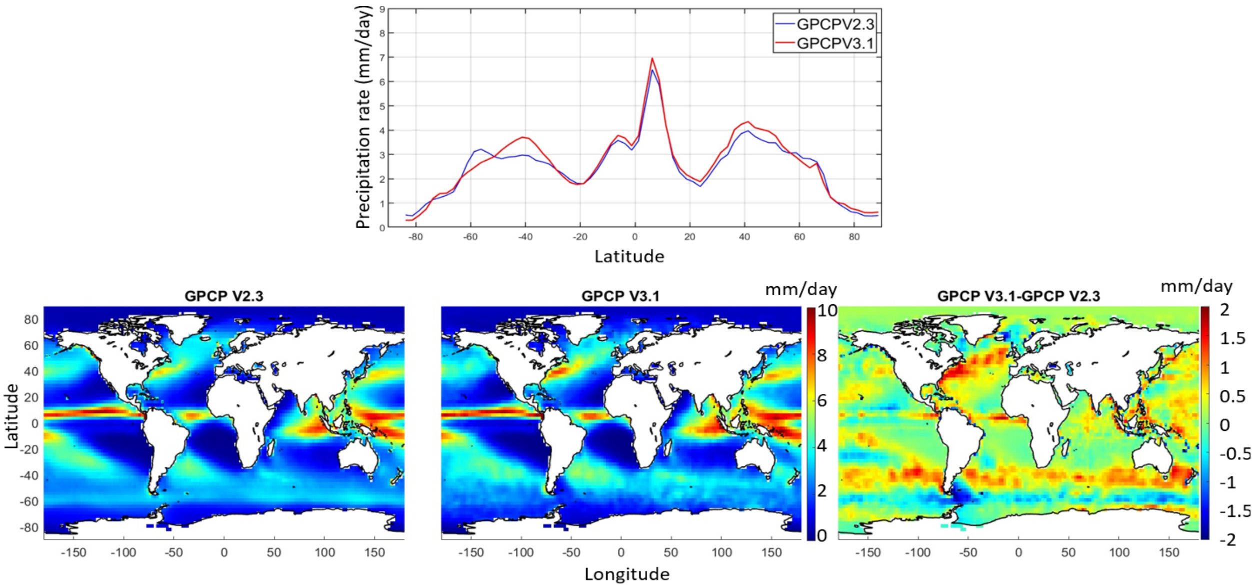

Figure 3.3.3. (Top row) Comparison of the zonal distribution of precipitation from GPCP V2.3 and GPCP V3.1. Annual maps of mean precipitation from of GPCP V2.3, GPCP V3.1, and their difference (GPCP V3.1 minus GPCP V2.3) are shown in the bottom left panel, the bottom middle panel and the bottom right panel, respectively. The plots are constructed based on average precipitation calculated from 36 years (1983–2018) of data.

3.3.7. Concluding remarks

Here we provided examples of a few opportunities that can add insights to precipitation assessment, especially over regions and periods where current precipitation products face large uncertainties. These were mainly based on observation of some properties of precipitation (that is, mass change from GRACE and GRACE-FO, SWE from ASO, snow depth from OIB, etc.) together with other types of observations such as streamflow and ice discharge. The value of complementary observations from radars over the ocean was also discussed.

The use of complementary or independent observations to assess precipitation products seems valuable and is likely not limited to those presented here. With the emergence of new generation of sensors to better study the Earth system, it is important to keep an eye on their potential for guiding current precipitation products and consistency checks across the variables of the water cycle. Nonetheless, the extent that such observations can be useful depends on how they might contribute to filling existing gaps, their quality and associated uncertainties.

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