A new estimate for oceanic precipitation amount and distribution using complementary precipitation observations from space and comparison with GPCP

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Abstract
This study produces near global (81°S/N) spatial and seasonal maps of oceanic precipitation rate using complementary information from advanced precipitation measuring sensors and provides an independent reference that can be used to assess current precipitation products. The Merged CloudSat, Tropical Rainfall Measuring Mission (TRMM), and Global Precipitation Measurement (GPM) (MCTG) estimate uses light rainfall and snowfall estimates from CloudSat and merges them with the combined radar-radiometer products available from the TRMM and the GPM mission. The merging process is performed at grid level and for each season, so maps of the merged products can be constructed. MCTG was then compared with the most recent Global Precipitation Climatology Project (GPCP) product (V2.3) to identify regional, seasonal, and annual differences between the two products. Several areas of major differences were highlighted, among those are regions near 5°N/S, 20°N/S, 40°N/S and 60°N/S. These regions also show seasonal variations in the magnitude and exact location of the differences. The largest differences between GPCP and MCTG occur around 40°S and 60°S, showing an under- and overestimation of MCTG, respectively. Overall, MCTG suggests that GPCP underestimates the annual oceanic precipitation rate by 9.03%, while seasonal rates are underestimated by 7.14%, 9.71%, 9.96%, and 9.73% for winter, spring, summer, and fall, respectively. Such differences in global oceanic precipitation rates need to be considered in the future updates in water and energy budget calculations and in future updates of GPCP.

1. Introduction
Accurate knowledge of precipitation amount and distribution is important to improve our understanding of the current state of the Earth’s climate, the water and energy budgets, and hydrological cycle responds to the zonal energy imbalances that force climate change (Andrews et al 2009). It can also contribute to the improvement of regional and climate models.

Satellites provide the most important instrument to quantify precipitation amount and distribution over ocean that covers more than 70% of the Earth’s surface. Since the application of satellite for estimation of precipitation rate, more than four decades ago, major advances have been made in improving space borne sensors and retrieval methods (e.g. Skofronick-Jackson et al 2017, Levizzani and Cattani 2019, Randel et al 2020). The operation of Tropical Rainfall Measuring Mission (TRMM) in 1997, covering ~35°S/N, led to significant improvement in retrieval of moderate to intense precipitation over the tropics. The launch of CloudSat (Stephens et al 2008, 2010) with the 94 GHz (W band) cloud profiling radar (CPR) in 2006 enabled near global (~81°S/N) high-quality detection and estimation of snowfall, light rainfall, and drizzle (Haynes et al 2009). The recent launch of the Global Precipitation Measurement (GPM) Mission in 2014 with GPM core instruments, the dual-frequency precipitation radar (DPR) and GPM microwave imager (GMI), enabled
to extend the capability of capturing moderate and intense precipitation to $\sim 65^\circ S/N$. It also offered higher sensitivity (than TRMM but not CloudSat) to retrieve snowfall and light rainfall. The above suite of advanced sensors, creates a great opportunity to refine our estimates of the amount and distribution of global precipitation, which in turn is critical to improve understanding of water and energy balance of the planet (Stephens et al. 2012, Rodell et al. 2015, L’Ecuyer et al. 2015).

Recognizing the complementary information provided by CloudSat and TRMM radars (Berg et al. 2010), Behrangi et al. (2014) combined precipitation distributions from CloudSat, TRMM, and Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) to calculate zonal distribution of annual precipitation intensity within $81^\circ S/N$ and compared it with Global Precipitation Climatology Project (GPCP) V2.2 to highlight regions of main difference between the two products. They showed that GPCP precipitation estimate is likely low by about 5% over global ocean, but that was prior to increase in TRMM precipitation and without considering recent insights gained by GPM. The potential for underestimation of GPCP has also been noted by other studies for example Yin et al. (2004) showed that GPCP can be about 10%–15% smaller than the Climate Prediction Center Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1997) product over tropical oceans. Adler et al also showed that GPCP can be biased low by 16% at small tropical atolls.

Here, by building on the strengths that each sensor offers, we extend the previous studies and utilize a combination of observations from CloudSat, TRMM, and GPM to construct seasonal and spatial maps of precipitation. The outcomes are then compared with GPCP V2.3 to identify regions of main difference between the annual and seasonal precipitation values and distributions. GPCP is commonly used for global water budget analysis (e.g. Rodell et al. 2015) and bias adjustment of other precipitation products. For example GPCP is used at monthly scale to bias adjust PERSIANN-CDR (Ashouri et al. 2015) within $60^\circ S/N$ and also to bias adjust the Integrated Multi-satellitE Retrievals for GPM (IMERG) (Huffman et al. 

Figure 1. (a) Zonal distributions of mean precipitation rates from MCTG, GPM_2BCMB_TRMM, and GPCP V2.3 for 2007–2010, and GPM_2BCMB for 2014–2017. The size of zonal bins in X axis is consistent with GPCP V2.3 resolution ($2.5^\circ$), (b) zonal mean precipitation of MCTG minus GPCP, and (c) percent relative difference between MCTG and GPCP calculated by dividing the zonal mean precipitation of MCTG minus GPCP by that of GPCP multiplied by 100.
2019) over global land and high latitude oceans up to the poles. Our comparison can add insights on potential regional and seasonal biases that GPCP might have over ocean, where in situ observations are limited and large uncertainties are expected (e.g. Adler et al 2012). The present work differs from the work by Behrangi et al (2014) mainly because (1) it utilizes GPM and a new version of TRMM combined product in light of GPM observations, in addition to the precipitation estimates from CloudSat, and (2) it produces maps of seasonal and annual merged precipitation products with a nearly complete coverage (i.e. 81°S/N) over the global ocean, instead of only zonal estimate of annual precipitation rate developed in Behrangi et al (2014).

2. Data set and method

2.1. Data set
Table 1 summarizes the data sets used in the present work. CloudSat and GPM products were used to develop the merged precipitation product that was then compared with GPCP. A brief description of each product is also provided below.

- CloudSat products
  We used the latest CloudSat 2C-SNOW-PROFILEP1-R05 (Wood Norman et al 2014) for snowfall rate, and 2C-RAIN-PROFILE (Lebsock Matthew and L’Ecyer Tristan 2011) for rainfall rate. In rare situation (e.g. less than 0.2%) poleward of 65°S/N, where CloudSat may face signal saturation precipitation rate was obtained from the AMSR-E rain rate (GPM_2AGPROFAQUAAMSRE_CLIM) collocated to CloudSat footprints. With the minimum detectable signal of $\sim -28$ dBZ (e.g. 0.02 mm h$^{-1}$ precipitation rate; Stephens et al 2010), CloudSat is one of the best sensors to detect and estimate snowfall and light rainfall.

- GPM_2BCMB V06
  TRMM Combined Precipitation (TRMM Ku radar and microwave radiometer/imager), first released with the ‘V8’ TRMM reprocessing. This is the new (GPM-formatted) TRMM product. It replaces the older TRMM_2B31. In principle, this combination should provide the most accurate, high resolution estimates of surface rainfall from TRMM platform and consistent with the GPM_2BCMB NS.

- GPCP V2.3
  The latest monthly GPCP product (V2.3) (Adler et al 2018) is used here for comparison. GPCP was formed as a community-based analysis of global precipitation under the support of the World Climate Research Program (WCRP) and the product has been widely used by the research community. GPCP improvements have been made at various intervals over the past several years (Adler et al 2003, Huffman et al 2009) and is one of the few state-of-the-art ‘global’ long-term precipitation products (since 1979) that is well maintained and is widely used as an observational reference by international communities. GPCP products are computed through merging of various observational data sets (satellite and gauge) in both space and time. The satellite component includes precipitation estimates from passive microwave and infrared estimates and precipitation gauge data are assembled and analyzed by the Global Precipitation Climatology Centre (GPCC) (Schneider et al 2017; Becker et al 2013).

One of the important challenges that GPCP faces is precipitation retrieval in high latitudes, as the current retrieval algorithms and microwave and infrared sensors do not provide accurate rain and snowfall estimates (Liu 2008; Behrangi et al 2012a). GPCP estimates high latitude precipitation rate using a regression relationship between collocated rain gauge measurements and a few cloud-related parameters (e.g. cloud-top pressure, fractional cloud cover, and cloud-layer relative humidity) calculated from Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) and the Atmospheric Infrared Sounder (AIRS) data (Susskind et al 1997, Adler et al 2003, Huffman et al 2009). Previous studies have shown that just having the gauge climatology is an important asset to improve GPCP (e.g. Bolvin et al 2009) over land. In some cases the empirical estimating techniques developed with coastal and island gauges are then applied over the ocean. Clearly, challenges are larger over ocean, where there is almost no surface observation to bias adjust or assess the performance of the product.

2.2. Method
The approach for merging the TRMM and GPM products with CloudSat estimates is similar to that described in Behrangi et al (2012a, 2014) using TRMM PR and CloudSat to produce a zonally merged product at each latitude, but here we applied the method to every 2.5° × 2.5° grids for each season. GPM_2BCMB_TRMM product was used within 36°S/N and GPM_2BCMB product was used between 36°S/N and 65°S/N where TRMM is not available. In some cases the empirical estimating techniques developed with coastal and island gauges are then applied over the ocean. Clearly, challenges are larger over ocean, where there is almost no surface observation to bias adjust or assess the performance of the product.
for the combined products and CloudSat using 60 log-scaled precipitation rate bins ranging from 0.01 to maximum observed precipitation in the grid of calculation and its surrounding grids, (2) determining a bin of precipitation rate, before which CloudSat shows higher precipitation fraction and after which the combined product shows higher fraction of precipitation occurrence (3) trusting CloudSat precipitation rates before the precipitation rate identified in step 2 and using the combined product after that to construct the full volume distribution of precipitation that can be used to estimate the total precipitation amount from the combination of the two sensors (see Behrangi et al. 2012a for more details). To account for differences in spatial resolution between the two products, precipitation rates from five successive CPR estimates were averaged within the ∼5 km resolution of the combined product, similar to that suggested by Behrangi et al (2012a). It has been shown that the use of day-time only CloudSat observations can cause bias (Behrangi et al. 2014, Milani and Wood 2019), thus in this study we used CloudSat data for 2007–2010, when full day- and night-time observations are available. Accordingly, we used 2007–2010 estimates from GPM_2BCMB_TRMM within 35°S/N, but used 3 years (April 2014–March 2017) estimates from GPM_2BCMB for extra tropics between 35°S/N and 65°S/N, where GPM_2BCMB_TRMM is not available. Note that the number of samples obtained from GPM_2BCMB_TRMM is larger than the number of samples obtained from GPM_2BCMB over the tropics, especially near the edges of TRMM coverage around 35°S/N. Comparison of the zonal and geographical maps of mean precipitation rates from GPM_2BCMB_TRMM products (with original TRMM samples and with a subset of samples equivalent to GPM sample count) showed no noticeable differences in the mean precipitation rates due to the sampling differences (supplementary figures S1 and S2 (available online at stacks.iop.org/ERL/15/124042/mmedia)). Figures S1 and S2 also show that the GPM_2BCMB_TRMM V06 and GPM_2BCMB V06 products produce similar zonal and geographical mean precipitation rates for the period that the two products overlap in time (April 2014–March 2015). This is because efforts have been made to make the GPM_2BCMB_TRMM V06 product as consistent as possible with the GPM_2BCMB V06, so a single common reference dataset can be utilized to ‘cross-calibrate’ precipitation rates from all of the passive microwave radiometers in the TRMM and GPM constellations (Osland 2018). Climatology of mean precipitation rate for the two periods (2007–2010 and April 2014–March 2017) were also compared using GPCP V2.3, providing a consistent and continuous precipitation rate across the two periods. Slight changes were found between the two periods over the tropics (e.g. within 35°S/N), but the changes were found fairly negligible (less than 1%) over the extra tropics (see figure S3). This supports the use of GPM_2BCMB_TRMM V06 (instead of GPM_2BCMB V06) for merging with CloudSat data over the tropics, as TRMM and CloudSat overlap in time for the 2007–2010 period.

For regions poleward of 65°S/N, precipitation is mainly from CloudSat. CloudSat may face signal saturation under intense precipitation, although this is rarely poleward of 65°S/N (see Behrangi et al 2012a). In such cases precipitation intensity from AMSR-E was used if AMSR-E precipitation rate exceeds CloudSat precipitation rate. The approach is thus produces a Merged CloudSat, TRMM, and GPM estimate, hereafter referred to as MCTG. MCTG provides a new estimate of ocean precipitation rate and its spatial distribution within 81°S/N (i.e. CloudSat coverage) that could be used to guide models and future development of global precipitation products.

### Table 1. Data sets used in this study.

| Data/period                  | Coverage/resolution       | Source                                      |
|------------------------------|---------------------------|---------------------------------------------|
| GPCP V2.3                    | Gridded, 2.5° × 2.5°, monthly | http://gpcp.umd.edu/ (Adler et al 2018)     |
| CloudSat rain and snowfall over ocean, 2006–2010 | Orbital (~1.4 × 1.7 km) 81°S–81°N | 2C-SNOW-PROFILE V5 (Wood Norman et al 2014) and 2C-RAIN-PROFILE V4 (Lebsock Matthew and L’Ecuyer Tristan 2011), http://cloudsat.atmos.colostate.edu. |
| GPM_2BCMB V06                | Orbital (5 × 5 km); 67°S–67°N | GES DISC (Olson et al 2018a)               |
| GPM_2BCMB_TRMM V06           | Orbital (5 × 5 km); 36°S–36°N | GES DISC (Olson et al 2018a)               |
| GPM_2 AGPROFAQUAMSRE _CLIM-V05 | 10 km × 10 km orbital | GES DISC (GPM Science Team 2018)           |

3. Results

Figure 1(a) shows the Zonal distributions of mean precipitation rates from MCTG,
GPM_2BCMB_TRMM, and GPCP V2.3 for 2007–2010, and GPM_2BCMB for April 2014–March 2017. The increase of precipitation rate relative to GPCP at precipitation peak around 5°N is mainly driven by the GPM_2BCMB_TRMM product and could be related to an increase in the radar reflectivity factor as a result of new calibrations (Iguchi et al. 2018). Moving towards higher latitudes, precipitation difference between MCTG and GPM_2BCMB_TRMM increases, regions with frequent stratocumulus clouds (shown in figure 2(a) with crosses) often show frequent light precipitation that might be captured by CloudSat but not with other instruments (Behrangi et al. 2012a, 2012b). This partly contributes to the differences observed around 20°S/N. Around 36°S/N at the edges of TRMM coverage, GPM_2BCMB_TRMM and GPM_2BCMB are fairly consistent with each other and both show slightly lower precipitation rates than MCTG. Starting from ~40°S/N and towards higher latitudes GPM_2BCMB mean precipitation rate falls off quickly compared to both MCTG and GPCP. The difference between MCTG and GPM_2BCMB reaches its maximum in higher latitudes and could be as large as ~2 mm d^{-1} around 65°N, as can be seen in figure 1(a). The largest differences between GPCP and MCTG occur around 40°S and 60°S. GPCP underestimates MCTG around 40°S by ~0.8 mm d^{-1} (figure 1(b)), or more than 25% relative difference compared to GPCP (figure 1(c)). However, at around 60°S GPCP overestimates MCTG by ~0.6 mm d^{-1} (figure 1(b)), or ~25% relative difference compared to GPCP (figure 1(c)). The increase of precipitation rate around 40°S/N is mainly due to contribution of CloudSat rain to the merged products. The GPCP’s local maximum around 60°S is likely unrealistic. It is likely that the absolute calibration of GPCP TOVS/AIRS precipitation over these remote ocean locations is problematic (personal communication with Dr. George Huffman and Robert Adler, lead developers of GPCP). The zonal percent difference shown in figure 1(c) is calculated by subtracting the zonal mean precipitation rate of GPCP from MCTG and dividing the difference by the GPCP value. The large relative differences in very high latitudes (e.g. around 80°S and 70°N) are mainly caused by the small precipitation rates at the denominator.

Figure 2 shows spatial maps of annual mean precipitation rate from MCTG, GPCP, and GPM_2BCMB-TRMM combined with GPM_2BCMB (figures 2(a), (c), and (e)) and their relative difference from MCTG (figures 2(b) and (d)). In figure 2(d), GPM_2BCMB-TRMM covers the tropics within 35°S/N and GPM_2BCMB covers extra tropics between 35°S/N and 65°S/N in both hemispheres. While the overall patterns of annual precipitation rate are similar among these products, the maps of differences suggest that the combined radar-radiometer products largely underestimate precipitation in higher latitudes and over the dominant stratocumulus regions (figure 2(d)). GPCP shows a mix of overestimation and underestimation compared to MCTG (figure 2(b)). The GPCP’s underestimation around 40°S and overestimation around 60°S appear across the entire longitudes, while in the northern hemisphere patterns are less uniform and vary regionally. This might be due to the hemispheric differences in the land distribution.

Figures 3 and 4 show zonal distribution and geographical maps of mean precipitation rates from MCTG and GPCP for different seasons. Figure 3 displays that at seasonal scales, the zonal distribution of precipitation means are less symmetric than that observed in the annual plot (figure 1(a)) and the differences between GPCP and MCTG can change seasonally. In all four seasons there are fairly large differences between MCTG and GPCP near the peak of the distribution at ~5°N, mainly related to the contribution of the combined product. Near 40°N, GPCP shows a much lower zonal mean precipitation rate than MCTG in winter and fall (figures 3(a) and (d)). As can be seen in figure 4, MCTG shows higher precipitation rates than GPCP for storm tracks in northern Atlantic and Pacific Oceans, especially near 40°N in winter and fall that could be a reason for the observed difference. This is also the case near 40°S, where GPCP shows a considerably lower mean precipitation rate than MCTG in spring and summer that can also be linked to location of storm tracks (figure 4). Near 60°S, GPCP shows larger mean precipitation rate than MCTG across all seasons. This difference is largest in winter (figure 3(a)) and spring (figure 3(b)) and can also be seen in the spatial maps as a relatively uniform feature across all longitudes (figures 4(c) and (f)). For this region, GPCP shows a relatively uniform precipitation with little longitudinal variation, that is not supported by MCTG (figure 4) and reanalysis products (Behrangi et al. 2016; figure 14). This could be related to lack of sufficient signals in the infrared-based precipitation estimates (i.e. from AIRS) (Susskind et al. 1997) used in GPCP in this latitude.

The geographical maps of MCTG (figure 4; left-side column) and GPCP (figure 4; the middle column) seasonal mean precipitation rates and their differences (figure 4; right-side column) can provide additional insights on the discrepancies between the two products. For example, in winter, spring, and fall MCTG shows higher precipitation rates than GPCP poleward of 60°N across most longitudes except over parts of Atlantic oceans. This pattern changes in summer, when GPCP shows larger precipitation rate than MCTG in most regions poleward of 60°N. Behrangi et al. (2016) showed that unlike few other products, GPCP V2.2 does not display a noticeable precipitation gradient around 70°N over the Atlantic Ocean (i.e. GPCP shows similar precipitation rates north and south of 70°N). This feature is also noticeable in
Figure 2. Spatial maps of annual mean precipitation rate from (a) MCTG, (c) GPCP, and (e) GPM_2BCMB-TRMM combined with GPM_2BCMB and the relative difference between (b) MCTG and GPCP, and (d) MCTG and the combined products shown in (e). Spatial resolution of the maps is consistent with GPCP V2.3 and is at 2.5° × 2.5°.

Figure 3. Zonal distribution of mean precipitation rates from MCTG and GPCP for (a) winter, (b) spring, (c) summer and (d) fall. The size of zonal bins in X axis is consistent with GPCP V2.3 resolution (2.5°).

GPCP V2.3, in which the gradient is still small, especially compared to MCTG in fall and summer (figures 4(g), (h), (j), and (k)). The relative difference maps shown in the right column of figure 4 also highlight regions of main relative difference between GPCP and MCTG. The underestimation of GPCP
compared to MCTG is clearly noticeable over the dominant stratocumulus regions. These areas, appear as red in figures 4(c), (f), (i), and (l), also show large regional and seasonal variations. The differences are noticeable in terms of magnitude, location, and pattern across different seasons as can be seen in figure 4. The overall impact of the GPCP underestimation over these regions can be seen in the zonal pots shown in figure 3, where a relatively large difference between MCTG and GPCP is seen in regions between 15°S/N and 25°S/N, often near the local minima in the zonal plot that varies with seasons. Note that the upper bound of the dominant stratocumulus region is wide near 5°S. This can also explain the large difference between GPCP and MCTG in this region.

For a quantitative summary, table 2 compares mean oceanic precipitation rates from GPCP and MCTG using annual and seasonal averages calculated for 2007–2010 and within 81°S–81°N. MCTG suggests that annual precipitation rate of GPCP should increase by 9.03%, while seasonal rates should increase by 7.14%, 9.71%, 9.96%, and 9.73% for winter, spring, summer, and fall, respectively. The annual increase of 9.03% is about 4.86% more than the 4.17% increase suggested by Behrangi et al. (2014) using combination of CloudSat and pre-GPM TRMM radar precipitation estimate. The observed increase in precipitation rate can be to a large extend related to the increase in precipitation rate by GPM_2BCMB-TRMM due to the new radar calibration (Iguchi et al. 2018) and retrieval methods in light of GPM observations. For example, only GPM_2BCMB-TRMM suggests 5.48% more precipitation than its corresponding GPCP V2.3 estimate when the two products are compared for 2007–2010 within 36°S/N.

3.1. Concluding remarks
In the present work we constructed seasonal maps of precipitation rates with near global coverage (i.e. 81°S/N) by merging precipitation products from CloudSat and combined radar-radiometer products

![Figure 4. Geographical maps of mean precipitation rates from MCTG (left column), GPCP (middle column), and their percent relative difference (right column) for different seasons shown in rows. The percent relative difference is calculated as MCTG minus GPCP divided by GPCP multiplied by 100.](image)
from TRMM and GPM, as these products can complement each other. The merged product, referred to as MCTG, is then compared with GPCP V2.3 to identify main difference between the annual and seasonal precipitation values and distributions. Several areas of major differences were highlighted, among those are regions near 5°N/S, 20°N/S, 40°N/S and 60°N/S where the magnitude and exact location of the differences vary with seasons. The largest differences between GPCP and MCTG occur around 40°S and 60°S. GPCP underestimates MCTG around 40°S by ~0.8 mm d\(^{-1}\) or more than 25% relative difference compared to GPCP. However, at around 60°S GPCP overestimates MCTG by ~0.6 mm d\(^{-1}\) or ~25% relative difference compared to GPCP.

Overall, MCTG suggests that annual precipitation rate of GPCP should increase by 9.03%, while seasonal rates should increase by 7.14%, 9.71%, 9.96%, and 9.73% for winter, spring, summer, and fall, respectively. This difference in global oceanic precipitation rate needs to be considered in the future updates in water and energy budget calculations (e.g. Trenberth et al. 2007; Stephens et al. 2012; Rodell et al. 2015; L’Ecuyer et al. 2015). The ~9% increase in global oceanic precipitation is still much smaller than ~15% increase in precipitation considered recently to bring the surface energy budget into a balance (Stephens et al. 2012), but it is also larger than ~5% increase in precipitation rate suggested by Rodell et al. (2015) over ocean through optimization of annual surface water budget. Knowing that GPCP might miss light rain and in view of the energy imbalance at the surface, Trenberth et al. (2009) somewhat arbitrarily increased the GPCP values by 5% with the hope that future analysis with sensors such as CloudSat can add more insights to the accurate numbers in future. The 5% increase in global precipitation is about 7% increase in precipitation over global ocean if precipitation estimates is considered unchanged over land.

Nonetheless, due to limited in situ observations over ocean, accurate estimation of precipitation over global ocean requires continuous improvement of precipitation retrieval methods and observing systems. CloudSat and GPM are among the two recent satellites that were utilized in our study. While CloudSat mission is ending, it is hoped that the near future EarthCARE mission (Illingworth et al. 2015) extend CloudSat-like observations for several years. Given the existing limitations, this study calls for more rigorous planning for future precipitation observing systems enabling higher accuracy and sufficient longevity to improve our quantitative understanding of global precipitation amount and distribution. Furthermore, systematic enhancement of in situ measurements over ocean seems to be another important effort that can help validate precipitation products and add insights into potential shortcomings in both observing instruments and retrieval methods. In fact, an extensive comparison of the outcomes of this study with collection of precipitation data from available atolls and ship measurements can be a subject of a future study to validate the outcome of this study. Such efforts together with systematic updates in global and regional water and energy budget calculations should enable us to better understand the state of the Earth’s climate and hydrological cycle responds to the energy imbalances that force climate change.

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### Data availability statement

No new data were created or analyzed in this study.

### References

Adler R F et al 2003 The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present) J. Hydrometeorol. 4 1147–67
Adler R F, Gu G and Huffman G J 2012 Estimating climatological bias errors for the Global Precipitation Climatology Project (GPCP) J. Appl. Meteo. Clima. 51 84–99
Adler R et al 2018 The Global Precipitation Climatology Project (GPCP) monthly analysis (new version 2.3) and a review of 2017 global precipitation Atmosphere 9 136
Andrews T, Forster P M and Gregory J M 2009 A surface energy perspective on climate change J. Climate 22 2557–70

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**Table 2.** Comparison of mean oceanic precipitation rate between GPCP V2.3 and MCTG calculated from 4 years (2007–2010) of data within 81°S–81°N.

|         | Annual | Winter | Spring | Summer | Fall |
|---------|--------|--------|--------|--------|------|
| GPCP (mm d\(^{-1}\)) | 2.88   | 2.94   | 2.78   | 2.81   | 2.98 |
| MCTG (mm d\(^{-1}\)) | 3.14   | 3.15   | 3.05   | 3.09   | 3.27 |
| Percent change compared to GPCP | 9.03   | 7.14   | 9.71   | 9.96   | 9.73 |
Ashouri H, Hsu K-L, Sorooshian S, Brödhaupt D K, Knapp K R, Cecil I D, Nelson B R and Pratt O P 2015 PERSIANN-CDR: daily precipitation climate data record from multisatellite observations for hydrological and climate studies Bull. Am. Meteorol. Soc. 96 69–83

Becker A, Finger P, Meyer-Christoffer A, Rudolf B, Schamm K, Schneider U and Ziese M 2013 A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. Earth Syst. Sci. Data 5 71–99

Behrangi A et al 2016 Status of high-latitude precipitation estimates from observations and reanalyses J. Geophys. Res.: Atmos. 121 4468–86

Behrangi A, Kubar T and Lambrigtsen B 2012b Phenomenological description of tropical clouds using cloudsat cloud classification Monthly Weather Rev. 140 3235–49

Behrangi A, Lebsock M, Wong S and Lambrigtsen B 2012a On the quantification of oceanic rainfall using spaceborne sensors J. Geophys. Res.: Atmos. 117 D20

Behrangi A, Stephens G, Adler R F, Huffman G J, Lambrigtsen B and Lebsock M 2014 An update on the oceanic precipitation rate and its zonal distribution in light of advanced observations from space J. Clim. 27 3937–65

Berg W, L’Ecuyer T and Haynes J M 2010 The distribution of warm rain from CloudSat J. Geophys. Res.: Atmos. 115 D24

Bolvin D T, Adler R F, Huffman G J, Nelkin E J and Potuizen J P 2009 Comparison of GPCP monthly and daily precipitation estimates with high-latitude gauge observations J. Appl. Meteorol. Climatol. 48 1843–57

GPM Science Team 2018 GPM AMSR-E on Aqua (GPROF) Climate-based Radiometer Precipitation Profiling L2 1.5 hours 5 km V05, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC) (https://doi.org/10.5067/GPM/AMSR/E/AQUA/GPROFCLIM/2A/05) (Accessed: March 2020)

Haynes J M, L’Ecuyer T S, Stephens G L, Miller S D, Mitrescu C, Wood N B and Tanelli S 2009 Rainfall retrieval over the ocean with spaceborne W-band radar J. Geophys. Res. 114 1–18

Huffman G J, Adler R F, Bolvin D T and Gu G 2009 Improving the global precipitation record: GPCP Version 2.1 Geophys Res. Lett. 36 17

Huffman G J, Adler R F, Bolvin D T, Hsu K, Kidd C, Nelkin E J, Tan J and Xie P 2019 Algorithm Theoretical Basis Document (ATBD) Version 06, NASA Global Precipitation Measurement (GPM)/Integrated Multi-satellite Retrievals for GPM (IMERG) (available at: https://gpm.nasa.gov/sites/default/files/document_files/IMERG_ATBD_V06.pdf)

Iguchi T et al 2018 GPM/DPR level-2 algorithm theoretical basis document (https://pps.gsf.nasa.gov/Documents/ATBD_DPR_201811_with_Appendix3b.pdf)

Illingworth A J et al 2015 The EarthCARE Satellite: the next step forward in global measurements of clouds, aerosols, precipitation, and radiation Bull. Am. Meteorol. Soc. 96 1311–32

L’Ecuyer T S et al 2015 The observed state of the energy budget in the early twenty-first century J. Clim. 28 8319–46

Lebsock Matthew D and L’Ecuyer Tristan S 2011 The retrieval of warm rain from CloudSat J. Geophys. Res.: Atmos. 116 D20

Levizzani V and Cattani E 2019 Satellite remote sensing of precipitation and the terrestrial water cycle in a changing climate Remote Sens. 11 2301

Liu G 2008 Deriving snow cloud characteristics from CloudSat observations J. Geophys. Res. 113 D00A09

Milani L and Wood N 2019 CloudSat bias on falling snow estimates over the daylight only operational period (2012–2019): American Geophysical Union fall meeting 2019 (San Francisco, USA) (available at: https://onix.nasaa.gov/archive/naa/cast.nx.nasa.gov/2019034196.pdf)

Olson W S et al 2018a GPM Combined Radar–Radiometer Precipitation ATBD (Version 3), (available at: https://pps.gsf.nasa.gov/Documents/Combined_algorithm_ATBD.V05.pdf)

Olson W S 2018b GPM PR and TMI on TRMM Combined Precipitation L2B 1.5 hours 5 km V06, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC) (https://doi.org/10.5067/GPM/PR/TMI/TRMM/2B/06) (Accessed: 2/7/2020)

Randel D L, Kummerow C D and Ringerud S 2020 The Goddard Profiling (GPROF) Precipitation retrieval algorithm Satellite Precipitation Measurement. Advances in Global Change Research, Vol. 67 ed V Levizzani, C Kidd, D Kirschbaum, C Kummerow, N Nakamura and F Turk (Berlin: Springer) (https://doi.org/10.1007/978-3-030-24568-9_8)

Rodell M et al 2013 The observed state of the water cycle in the early twenty-first century J. Clim. 28 8289–318

Schneider T, Lan S, Stuart A and Teixeira J 2017 Earth System Modeling 2.0: A Blueprint for Models That Learn From Observations and Targeted High-Resolution Simulations Geophys. Res. Lett. 44

Skofronick-Jackson G et al 2017 The Global Precipitation Measurement (GPM) mission for science and society Bull. Am. Meteorol. Soc. 98 1679–95

Stephens G L et al 2008 CloudSat mission: performance and early science after the first year of operation J. Geophys. Res.: Atmos. 113 1–18

Stephens G L, L’Ecuyer T, Forbes R, Gettelman A, Golaz J-C, Bodas-Salcedo A, Suzuki K, Gabriel P and Haynes J 2010 Dreary state of precipitation in global models J. Geophys. Res. Atmos. 115 D24

Stephens G L, Li J, Wild M, Clayson C A, Loeb N, Kato S, L’Ecuyer T, Stackhouse P W, Lebsock M and Andrews T 2012 An update on Earth’s energy balance in light of the latest global observations Nat. Geosci. 5 691–6

Suskind J, Piraino P, Rokke L, Iredell L and Mehta A 1997 Characteristics of the TOVS Pathfinder path a dataset Bull. Am. Meteorol. Soc. 78 1449–72

Trenberth K E, Smith L, Qian T, Dai A and Fasullo J 2007 Estimates of the global water budget and its annual cycle using observational and model data J. Hydrometeor. 8 758–69

Wood Norman B, L’Ecuyer Tristan S, Heymsfield Andrew J, Stephens Graeme L, Hudak David R and Rodriguez P 2014 Estimating snow microphysical properties using colocated multisensor observations J. Geophys. Res.: Atmos. 119 8941–61

Xie P and Arkin P A 1997 Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs Bull. Amer. Meteor. Soc. 78 2539–58

Yin X, Gruber A and Arkin P 2004 Comparison of the GPCP and CMAP merged gauge–satellite monthly precipitation products for the period 1979–2001 J. Hydrometeorol. 5 1207–22