A Comparison between the GPM Dual-Frequency Precipitation Radar and Ground-Based Radar Precipitation Rate Estimates in the Swiss Alps and Plateau

PETER SPEIRS
Environmental Remote Sensing Laboratory, School of Architecture, Civil and Environmental Engineering, École polytechnique fédérale de Lausanne, Lausanne, Switzerland

MARCO GABELLA
MeteoSwiss, Locarno-Monti, Switzerland

ALEXIS BERNE
Environmental Remote Sensing Laboratory, School of Architecture, Civil and Environmental Engineering, École polytechnique fédérale de Lausanne, Lausanne, Switzerland

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ABSTRACT

The Global Precipitation Measurement (GPM) mission Dual-Frequency Precipitation Radar (DPR) provides a unique set of three-dimensional radar precipitation estimates across much of the globe. Both terrain and climatic conditions can have a strong influence on the reliability of these estimates. Switzerland provides an ideal testbed to evaluate the performance of the DPR in complex terrain: it consists of a mixture of very complex terrain (the Alps) and the far flatter Swiss Plateau. It is also well instrumented, covered with a dense gauge network as well as a network of four dual-polarization C-band weather radars, with the same instrument network used in both the Plateau and the Alps. Here an evaluation of the GPM DPR rainfall rate products against the MeteoSwiss radar rainfall rate product for the first two years of the GPM DPR’s operation is presented. Errors in both detection and estimation are considered, broken down by terrain complexity, season, precipitation phase, precipitation type, and precipitation rate. Errors are considered both integrated across the entire domain and spatially, and consistent underestimation of precipitation by GPM is found. This rises to $-25\%$ in complex terrain in the winter, primarily due to the predominance of DPR measurements wholly in the solid phase, where problems are caused by lower reflectivities. The smaller vertical extent of precipitation in winter is also likely a cause. Both detection and estimation performance are found to be significantly better in summer than in winter, in liquid than in solid precipitation, and in flatter terrain than in complex terrain.

1. Introduction

The Global Precipitation Measurement (GPM) mission Core Observatory satellite was launched on 27 February 2014 (Neeck et al. 2014). It carries two instruments: a passive microwave radiometer GMI (Draper et al. 2015) and the Dual-Frequency Precipitation Radar (DPR; Furukawa et al. 2015). The satellite is intended as a replacement to the Tropical Rainfall Measuring Mission (TRMM) satellite [for more information on TRMM, see Kummerow et al. (1998)]. The two major differences between the GPM satellite and its predecessor are that the new satellite has a significantly higher-angled orbit ($\pm 65^\circ$ instead of $\pm 35^\circ$) and that GPM carries a dual-frequency Ku- and Ka-band radar (the DPR) rather than the single-frequency Ku-band Precipitation Radar (PR) carried by TRMM.

Just as the TRMM PR was used previously, the GPM DPR is intended primarily to be used as the calibration basis for radiometer-derived global precipitation products (Neeck et al. 2014). As such, it is important that it provides a reliable reference in as many circumstances as possible. For this reason, NASA and JAXA are running a large-scale ground validation in
the United States (Schwaller and Morris 2011), as well as partnering with various other groups elsewhere in the world. Two very large ground validation campaigns in complex terrain are the 2014 Integrated Precipitation and Hydrology Experiment (IPHEX; Barros et al. 2014) and the NASA Olympic Mountains Ground Validation Experiment (OLYMPEx; Houze et al. 2015). IPHEX took place in the Southern Appalachian Mountains (United States), with an intense observation period running from May to July 2014. It involved multiple ground-based radars at S, X, Ku, and Ka bands; multiple Micro-Rain Radars (MRRs); disdrometer and rain gauge networks; and aircraft-based radiometer and X-, Ku-, Ka-, and W-band radar measurements. This experiment was intended to improve space-based estimations of orographic precipitation in complex terrain and to determine the usefulness of satellite precipitation estimates for hydrology. OLYMPEx ran from November 2015 to February 2016 in the Olympic Mountains in Washington State, United States. One of the key features of this campaign was the ability to make observations both over ocean at mid-latitudes and complex terrain. This campaign also involved a wide range of ground instruments, including rain gauges; disdrometers; remote cameras; multiple MRRs; and S-, X-, Ku-, and Ka-band radars as well as S-band radar data from the operational network. Multiple aircraft-based radar and radiometer measurements were also involved. The work presented here is more narrowly focused on the performance of the DPR precipitation rate products in complex terrain and across seasons. Additionally, the terrain in our study region, the Alps, is significantly more complex than that in either IPHEX or OLYMPEx, and exhibits a far greater vertical extent.

Precipitation in mountains is inherently complex because of interactions between the terrain and the atmosphere. The resultant effects have been (and are) the subject of extensive research (e.g., Houze 2012). Additionally, the higher altitudes (and hence lower temperatures) mean that a high proportion of the precipitation on mountains falls as snow, resulting in significant amounts of water being stored on mountains as snow and in the form of glaciers (Viviroli et al. 2007). This makes mountains a vital water source in many parts of the world.

The same terrain and cold conditions that make mountains an important water store also make the measurement of precipitation challenging: the terrain and low temperatures make access for installing instruments difficult, and the mountains cause occlusion and partial shielding for radars (e.g., Germann and Joss 2004), restricting measurements to above the mountains and in the valleys adjacent to the radars. Satellite-based radars have the potential to overcome these challenges: for a satellite the difficulty of installing ground instruments is irrelevant, and the near-nadir pointing nature of its measurements means that occlusion is not a significant issue. Having said that, the $5 \times 5 \text{km}^2$ footprint of GPM means that clutter contamination will typically limit GPM measurements to being above mountains, except in areas with very broad valleys. Nevertheless, the GPM DPR can add significant new coverage to mountainous areas, especially in poorly instrumented parts of the world.

Switzerland makes an ideal testbed for mountainous precipitation comparisons, as it consists of a mixture of very mountainous terrain (the Alps), more gentle mountainous terrain (the Jura Mountains), and a flatter plateau, all covered by the same instrument network. The small size of the country (approximately $41,000 \text{km}^2$) means that it all tends to be exposed to similar weather systems, albeit strongly influenced by topography (which is the focus of this study), and with the exception of the very far south of the country (Ticino), which is separated from the rest of the country by the Alps. The country is also well instrumented: for almost all of the period of this study, it was covered by a network of four dual-polarization C-band weather radars (Germann et al. 2015), as well as a network of around 190 weighing gauges (increasing over the course of the study).

Previous studies have investigated various aspects of the GPM DPR’s performance. For example, in simulations Kubota et al. (2014) found that, with the codes intended for use at launch, an underestimation of precipitation was expected from the Ka-band radar, but not from the Ku-band radar and dual-frequency product. Toyoshima et al. (2015) evaluated the estimation of the storm-top height by GPM and suggested that the benefits of the Ka-band radar for such measurements may not be as significant as expected.

To the best of the authors’ knowledge, there is no existing published work looking at GPM DPR precipitation estimates in complex terrain. However, there is a body of work on the performance of the TRMM PR in mountainous terrain. For example, Duan et al. (2015) reported on a 5-yr comparison between the TRMM PR and gauge precipitation measurements in the Appalachian Mountains in the United States. They found broadly reasonable agreement, better than that from distant ground-based radars. They also found that rain classified as stratiform produced higher false alarm rates than other rain types, missed detections were far more common in winter than summer, and very heavy rainfall was severely underestimated (which they associate with possible nonuniform beamfilling). Other works in the area include that of Barros et al. (2000), which found better TRMM PR performance at low elevations than at high elevations based on gauge comparisons in Nepal.
TRMM PR data have also found use in precipitation studies in mountainous areas [e.g., Romatschke et al. (2010), who used TRMM PR data to study extreme convection in Southeast Asia, and Gabella et al. (2011), who used the data to evaluate ground-based radar range degradation in the Mediterranean area]. While not evaluations of the TRMM PR in mountainous regions per se, such studies do demonstrate the scientific utility of the stand-alone PR (and hence DPR) products, and therefore the need for an understanding of the limitations of their performance in mountainous regions.

There are some studies comparing the TRMM rain product against that of ground-based radar networks over larger areas, albeit not specifically over complex terrain, such as that of Chen et al. (2013), which used a methodology somewhat similar to that used here.

The 3B42 satellite product has also been found to have issues in complex terrain. This is a combined radar and radiometer product produced at 3-hourly intervals, covering much of the globe on a 0.25° × 0.25° grid. Examples of studies that cover complex terrain include Condom et al. (2011), Mourre et al. (2016), and Nastos et al. (2016). Nastos et al. (2016) in particular found more pronounced underestimation over mountainous regions than in lower-lying regions. However, since these evaluations were of accumulation over longer time periods rather than snapshot measurements, and were based largely on radiometer measurements, the results are not directly comparable to the work presented here.

A smaller number of studies have looked at the 3A25 product. This is the monthly precipitation product based on radar data only covering much of the globe on a 5° × 5° or 0.5° × 0.5° grid. Some examples include Gabella et al. (2006b) and Prasetia et al. (2013), although to the best of the authors’ knowledge, no such studies have looked specifically at the performance of this product in complex terrain.

GPM’s stand-alone level 2 DPR product is unlikely to be as broadly used as ground-based measurements or level 3 satellite products (such as the 3B42 product described above): it provides only occasional snapshot coverage of particular points of the globe (e.g., there are approximately two overpasses that at least partially cover Switzerland every 3 days). However, it will be vitally important to the generation of the level 3 products. It will also find considerable use in studies where snapshot measurements are useful or where information on vertical structure is required (information not provided by radiometer products), as TRMM’s PR did (e.g., Romatschke et al. 2010; Houze et al. 2011). In areas with poor ground instrumentation, it will provide information that would be otherwise unavailable. It is also likely to be used to facilitate comparisons between radar systems whose coverage areas do not overlap. Additionally, it will be possible to use the DPR to evaluate attenuation/range corrections applied to individual radars, as was done with the TRMM PR in Gabella et al. (2006a, 2011).

In this paper, an evaluation is made of the GPM DPR level 2 estimated surface precipitation products against equivalent estimates from the MeteoSwiss radar product, across a range of different terrain types from 9 March 2014 (when the first DPR rainfall data are available over Switzerland) to 29 February 2016. We begin by providing a brief description of the products in section 2, along with the preparation of the MeteoSwiss data to match those from GPM, and the terrain classification method used. The comparison metrics used are defined in section 3. In section 4 we provide a comparison between the MeteoSwiss radar product and gauge-measured accumulations. A comparison of the DPR’s performance against the MeteoSwiss product broken down by season, precipitation type, precipitation phase, and terrain classification is given in section 5a. A consideration of the spatial distribution of the errors is presented in section 5b.

2. Data and methods

a. GPM data

The GPM DPR consists essentially of two radars operated in tandem. The low-frequency Ku-band radar is very similar to that found on TRMM and scans a swath approximately 245 km wide across the satellite track, measuring some 49 footprints approximately 5 km in width and with 250-m vertical resolution. The Ka-band radar matches the scan of the Ku-band radar across the central 125 km of its swath, allowing for the application of dual-frequency algorithms to the data collected in the central swath. In addition, the Ka-band radar is used to make 24 high-sensitivity (thanks to a doubled range-bin size) measurements interleaved with the dual-frequency measurements across the narrower swath.

The GPM data used in this study are the GPM level 2 DPR data, version V04A. These data include many variables [see, e.g., the NASA/JAXA (2015) file specification], but the key variable evaluated in this work is the estimated surface precipitation rate (precipRateESurface—although in practice there is little difference between this variable and the precipRateNearSurface variable).

b. MeteoSwiss data

The GPM data are compared against a MeteoSwiss radar-derived precipitation mosaic. This mosaic is generated from the MeteoSwiss fourth-generation weather
radar network (Germann et al. 2015), which consists of five dual-polarization, full Doppler C-band radars. Three of these radars are located near the political boundaries of Switzerland to detect fronts and perturbations at as great a distance as possible, and two are located at high altitudes (3000 m) in the Alps. The radar locations and altitudes are given in Table 1 and are shown in Fig. 1 (top).

During the period covered by this study, the fourth generation was still being installed: Albis, La Dôle, and Monte Lema were installed and operational throughout, but Pointe de la Plaine Morte was merged into the mosaic approximately 2 months into the study, and Weissfluhgipfel was merged into the mosaic 2 months before the end of the study. Neither of the two newest radars add new pixels to the mosaic within Switzerland (but rather improve the quality of the rainfall rate estimates in the existing pixels). Because of this, no correction is made for the addition of the new radars. For the measurement height analysis, we make the simplification that Pointe de la Plaine Morte was present throughout the study and that Weissfluhgipfel was never present.

1) CALIBRATION AND ADJUSTMENT

Radar hardware calibration is performed periodically during preventative maintenance using a noise source, an internal test signal generator, and the sun. At other times, some 350 parameters are reported centrally 20 times every 5 min and automatically checked for anomalies. Additionally, every 5 min the noise source is injected into the reference signal input of the low noise amplifier and used to continuously calibrate the radar [more details in Vollbracht et al. (2014)], and daily monitoring of sun hits is used (Gabella 2015).

Quantitative precipitation estimation (QPE) adjustment is carried out on a long-term basis, rather than continuously for the product used here. For each radar, a mean field bias (MFB) is derived using a subset of good rain gauges. Here, “good” means better than average in terms of site characteristics, distance, and visibility from the radar site and agreement with hourly/daily radar estimates of the previous years. Typically, 6–10 close and “highly visible” rain gauges are used for each radar. The MFB is evaluated over a period of 1 year. At the time of the launch of the GPM satellite, three radars (Albis, La Dôle, and Monte Lema) were already MFB adjusted. The MFB of Pointe de la Plaine Morte was not completed until the end of June 2015, but a back correction has been applied to the data from before this time for this study. The number of gauges used in the vicinity of these four radars is currently 33.

2) QUANTITATIVE PRECIPITATION ESTIMATION

Each MeteoSwiss radar performs plan position indicator (PPI) scans at 20 elevations from -0.2° to 40° every 5 min, but the scans are interleaved such that a representative subset of 10 PPI scans are performed every 2.5 min, allowing the precipitation mosaic to be updated at that time interval. Up to six 1° × 1° × 83 m clutter-free radar bins, corrected for partial shielding [as described in Germann et al. (2006)], are averaged in linear equivalent radar reflectivity factor Z to derive polar 1° × 1° × 500 m radar bins. The “best” estimate of precipitation at ground level is retrieved through a weighted average of multiradar observations aloft. The weighting function depends on the altitude above the ground (largest weights for 500 m resampled echoes
close to the ground) and the radar visibility (maximum weight for fully visible samples, reduced weight for partially shielded samples, and zero weight for fully shielded samples). Correction for the vertical profile of reflectivity (VPR) is done using an average profile based on space–time aggregation at the mesobeta scale (a period of a few hours and over the visible part of the area within 70 km of the radar). Figure 6 of Germann and Joss (2002) shows the orography-constrained shape of the cylinder used for deriving the “identified,” average mesobeta profile used in the operational compensation engine. VPR is dynamic and is calculated fully automatically with a vertical resolution up to 200 m (at ranges where that is possible). This is then converted to a 1-km square grid of the best estimate of precipitation rate at ground level. Additional information is available in Germann and Joss (2002) and Germann et al. (2006).

Further refinement is applied to the QPE grid based on annual accumulation bias [see Eq. (4)] comparisons against gauge measurements. Two such adjustments were made over the experimental period covered here, and these, and the MFB adjustment to the Pointe de la Plaine Morte radar, were compensated for by adjusting rainfall rates prior to the end of June 2015 by +0.3 dB and prior to the end of November 2014 by an additional +0.5 dB.

3) MEASUREMENT HEIGHTS

A potential factor affecting the comparison between the GPM and MeteoSwiss measurements is the differences between the heights at which their measurements are made. This information is provided as part of the GPM product, but it must be determined for the MeteoSwiss product. An estimate has been produced by using the VisHydro package (Pellarin et al. 2002) to estimate a visibility map for each elevation used with the four MeteoSwiss radars in operation for the bulk of this campaign. This has been done using the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM; Jarvis et al. 2008) downsampled to 200 m resolution. The visibility output was put on the same 1-km grid as the MeteoSwiss radar mosaic. All pixels with at least 75% visibility from a given radar and that are within range of that radar have been assumed to be measurable by that radar. The lowest elevation from each radar was then taken and converted to a height above mean sea level. Then, for each pixel the lowest height from each of the radars measuring that pixel was taken to be the lowest height measurement for that pixel, shown in Fig. 1 (bottom). The strong influence of terrain can be seen, as can the need for the Weissfluhgipfel radar to improve the quality of measurements in the far east of Switzerland.

4) CLIMATOLOGY

Also from MeteoSwiss are the gauge-derived annual precipitation amounts shown in Fig. 2. Here (by comparison with Fig. 3) it can clearly be seen that topography strongly affects precipitation across Switzerland. The dominant weather pattern across much of Switzerland is westerly/northwesterly wind bringing precipitation that falls primarily on the northwestern Alps, with a secondary area of higher precipitation in the smaller Jura Mountains in the northwest of Switzerland.
Much of the Plateau is comparatively drier, as is the far east of Switzerland. The very south of Switzerland (around Ticino) tends to get its precipitation from a different weather pattern (southerly wind from the Mediterranean), resulting in high amounts of precipitation on the mountains in that area.

c. Data preparation

A number of criteria were used to select the data to be analyzed. First, only GPM footprints that lay within or close to Swiss borders were kept. This was because the MeteoSwiss radar data bias corrections are computed from gauges located within the Swiss borders, and so the resultant correction applied is likely to be more valid within the borders than elsewhere. Additionally, only cases where topographic information exists in the Swiss Federal Office of Topography (SwissTopo) 25 m DEM dataset (Swiss Federal Office of Topography 2005) for at least 90% of the nominal area of the GPM DPR footprint were included in cases where any kind of terrain classification was made. The DEM is complete within Switzerland, but for footprints at least partly outside Switzerland’s political border SwissTopo DEM information is not always available.

The data were further restricted to overpasses from launch (first measurements over Switzerland on 9 March 2014) to the end of February 2016, and to cases where both ground-based radar data and at least one of the GPM DPR rain products were available. The total number of overpasses for each overpass type are given in Table 2.

Since the MeteoSwiss radar data are at a significantly higher spatial resolution than the GPM data, it is necessary to determine equivalent single rainfall rate values from the MeteoSwiss data to match each GPM rainfall rate. Many different approaches could be taken, but a reasonable expectation for an end user would be that the GPM-determined rainfall rate represents the average rainfall rate across its 5-km footprint. Therefore, the arithmetic mean of the relevant MeteoSwiss data square kilometer grid values is taken as the representative equivalent value. The relevant MeteoSwiss grid values are taken to be all of those whose grid-square center value lies within the measurement swath, and which

<table>
<thead>
<tr>
<th>All</th>
<th>With precipitation</th>
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<tbody>
<tr>
<td>Ku only</td>
<td>528</td>
</tr>
<tr>
<td>Ku and Ka</td>
<td>393</td>
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<tr>
<td>Ka only</td>
<td>392</td>
</tr>
<tr>
<td>Total unique</td>
<td>530</td>
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Table 2. Number of overpasses of Switzerland. Overpasses with precipitation are defined to be those that have at least one DPR footprint containing precipitation according to at least one of the DPR products and/or the MeteoSwiss radar product.
have the GPM footprint center as their nearest neighbor. The GPM footprint locations vary from overpass to overpass, so a different set of grid values are averaged for every footprint, with the number of points averaged per footprint varying from 23 to 29.

A similar approach is taken with the minimum MeteoSwiss measurement heights (Fig. 1, bottom) to compute a minimum MeteoSwiss measurement height in the GPM footprint: the mean of all the grid values whose centers meet the requirements outlined above is computed and taken to be representative of the MeteoSwiss minimum measurement height.

d. Terrain classification

Since the key objective of this study is to determine the relative performance of the GPM precipitation product in more and less complex terrain, it is necessary to define what constitutes complex terrain. In a location such as Switzerland with such a pronounced difference between the Alps and the Plateau, it is possible to make such a division by eye. Many less subjective techniques exist for doing this (see, e.g., Huaxing 2008), but there is no need for such complexity in this case: rather, the standard deviation of the DEM of the terrain within a 2.5-km radius of the center point of each DPR measurement grid point (i.e., approximately the area of the GPM footprint) is used as a discriminant. This has been computed from the SwissTopo 25 m DEM. Figure 3 shows Switzerland’s topography (from the SRTM DEM to allow for the inclusion of topography beyond Switzerland’s borders), the standard deviation for the overpass footprints averaged on a 5-km grid from all overpasses considered, and a histogram of the footprint standard deviation values. The standard deviation values were found to have a clear bimodal distribution, and it was decided to use the approximate minimum between these modes (160 m) as the threshold for distinguishing between complex and noncomplex terrain.

Figure 3 also shows the fraction of cases above this threshold on the same 5-km grid: it can be seen that this reasonably distinguishes the Alps in southern and eastern Switzerland and the Jura Mountains in northwestern Switzerland from the remaining flatter Plateau. Note also that similar analyses to those presented in this paper have been performed using a purely visual divide between complex and noncomplex terrain, with very similar results.

All of this combined gives two years of rainfall rate value pairs, from the ground-based radar network and the GPM DPR, which can be associated with complex or flat terrain, to a precipitation type (where the DPR algorithm identifies one) and to a particular time.

3. Evaluation methods

a. Threshold selection

To evaluate detection it is necessary to set a detection threshold, the choice of which can have a significant effect on the metrics used to assess detection performance. The objective is to distinguish between precipitation and no-precipitation cases, so the threshold is set to be as low as can reasonably be detected by both instruments. Using the same threshold for each instrument makes the implicit assumption that the instruments are identically biased in their rainfall rate measurements, but any deviation from this risks unfairly penalizing one instrument for failing to detect something that it is not expected to be able to detect. The threshold has also been chosen to ensure that both instruments should be capable of detecting a beam-filling uniform rainfall rate precipitation event at that rate.

The lowest nonzero square kilometer grid rainfall rate reported in the MeteoSwiss mosaic is 0.1 mm h$^{-1}$. The MeteoSwiss GPM-grid rainfall rate is computed by averaging multiple kilometer grid values and so can drop far below this, but the requirement for the detection of a beam-filling uniform rainfall rate at the threshold rate means that the lowest possible threshold for the MeteoSwiss data must be 0.1 mm h$^{-1}$. The smallest nonzero rainfall rate in the considered GPM data for both Ku-only and dual-frequency cases is 0.0249 mm h$^{-1}$, and for the high-sensitivity Ka-only data is 0.1199 mm h$^{-1}$.

The Ka-only data therefore require a threshold of at least 0.1199 mm h$^{-1}$. However, the MeteoSwiss mosaic granularity and the uniform beam-filling requirement mean that a threshold of 0.15 mm h$^{-1}$ (the lowest reported rainfall rate in the mosaic above 0.1199 mm h$^{-1}$) must be used instead. Similarly, the Ku-only and dual-frequency data require a threshold of at least 0.1 mm h$^{-1}$. However, the practical difference between using this threshold and a 0.15 mm h$^{-1}$ threshold is small: for the Ku-only data, 99.84% of all nonzero values are above 0.1 mm h$^{-1}$ and 99.62% above 0.15 mm h$^{-1}$, and similar results are obtained for the dual-frequency data. For consistency, we opt to use the same 0.15 mm h$^{-1}$ threshold for all three DPR products.

These are far lower thresholds than the nominal minimum rainfall rates detectable by GPM, which are 0.5 mm h$^{-1}$ for the Ku-only and dual-frequency products and 0.2 mm h$^{-1}$ for the Ka-only product (Iguchi et al. 2015). However, in practice the difference in the results with the two thresholds was found to be reasonably small, and so the lower thresholds are used. Additionally, using such thresholds would involve excluding a large fraction of the nonzero rainfall rate
values for the Ku-only and dual-frequency products: 31.9% and 36.2%, respectively. Since the nominal and lower thresholds for the Ka-only product are so much closer, less difference is seen with this product. A small sample of results with the nominal threshold is given in the results section.

Histograms of the measured rainfall rate values measured by both the MeteoSwiss radars and the GPM DPR are shown in Fig. 4. It can be seen that the MeteoSwiss product reports many events with rainfall rates below the DPR detection threshold, and that in almost all the rainfall rate bins shown, GPM reports fewer events than the MeteoSwiss product.

**b. Detection metrics**

The metrics used to evaluate the detection performance are quite standard, so here only a brief summary is given. More details can be found in, for example, Schaefer (1990). In all GPM–MeteoSwiss comparison cases, the MeteoSwiss data are the reference and the GPM data are tested against it, whereas in the gauge–MeteoSwiss radar comparison, the gauge data are the reference. Determinations are considered to be true where the test determination agrees with the reference determination, and false otherwise.

Positive detections are where the test product determines that there is precipitation and negative detections where the test product determines that there is no precipitation.

Therefore, true positive (TP) is used to denote cases where both the reference and test detect precipitation, false positive (FP) is used to denote cases where the test detects precipitation but the reference does not, false negative (FN) is used to denote cases where the reference detects precipitation but the test does not, and true negative (TN) is used to denote cases where the test and reference measurements agree that there is no precipitation.

Using the number of cases in each category, the probability of detection (POD) can then be written as

\[
\text{POD} = \frac{TP}{TP + FN},
\]

since \(TP + FN\) gives the total number of cases where there was precipitation. The false alarm rate (FAR) can similarly be written as

\[
\text{FAR} = \frac{FP}{TP + FP},
\]

since \(TP + FP\) gives the total number of cases where the test product reported precipitation.

Combining all four elements of the contingency matrix into a single metric, the Heidke skill score (HSS; also known as Cohen’s kappa) is given by

\[
\text{HSS} = \frac{2[TP(TN) - FP(FN)]}{(TP + FN)(FN + TN) + (TP + FP)(FP + TN)}.
\]

This compares the performance of the method/measurements to that of random guessing (with the choices made in proportion to that actually determined by the method/measurements used). This will be 1 for a perfect method/measurement, 0 for a method/measurement with performance equal to random guessing, and negative for a method/measurement that performs less well than random guessing. The HSS is commonly used in the evaluation of numerical weather prediction models (see, e.g., Doswell et al. 1990).

**c. Estimation metrics**

A huge number of different possible measures of the performance of measurements exist, far too many to be included here. Instead, a small subset of the possible measures is included to encapsulate the key properties of the
relationship: the correlation, a measure of the offset of the test measurements from the reference measurements, and a measure of the spread of the test measurements around the reference measurements. In all cases (except as outlined in section 3d), we compute all the estimation metrics only where both products report rain above the threshold (TP cases). For correlation, the standard Pearson correlation coefficient $r$ is used, applied to the log of the rainfall rates (to minimize the influence of the asymmetry of the rainfall rate distribution). The overall bias is used as a measure of the offset and is computed from (Sideris et al. 2014)

$$\text{bias} = 10 \log_{10} \left( \frac{\sum_i R_{\text{test},i}}{\sum_i R_{\text{ref},i}} \right),$$

where $R_{\text{test},i}$ is the rainfall rate (mm h$^{-1}$) reported by the product under test for the $i$th footprint and $R_{\text{ref},i}$ is the rainfall rate reported by the reference product with that footprint. Finally, the median absolute deviation from the median (MADM) is used as a measure of the spread around the MeteoSwiss measurements and is given by

$$\text{MADM} = \text{median}(|x - \text{median}(x)|),$$

where

$$x = 10 \log_{10} \left( \frac{R_{\text{test}}}{R_{\text{ref}}} \right).$$

In cases where the probability density function (PDF) of $x$ is symmetric, the MADM is half of the widely used interquartile range.

d. Error breakdown classes

It is also useful to be able to break down errors in the precipitation estimates by type. This is done here in the style of Tian et al. (2009). The error for each GPM DPR footprint measured is determined to be the difference between the rainfall rate reported by GPM and the rainfall rate calculated from the MeteoSwiss radar mosaic. This means that GPM overestimations result in a positive value, while GPM underestimations result in a negative value. These errors are then masked according to four different criteria: the total error includes every point, irrespective of other criteria; the hit error is calculated on TP cases, that is, where both the GPM-measured rainfall rate $R_{\text{GPM}}$ and the MeteoSwiss-measured rainfall rate $R_{\text{MS}}$ are above the threshold; missed precipitation on FN cases, where $R_{\text{MS}}$ is above the threshold but $R_{\text{GPM}}$ is not; and false precipitation on FP cases, where $R_{\text{GPM}}$ is above the threshold but $R_{\text{MS}}$ is not. In TN cases the error is zero by definition.

These individual error values are then grouped on a $5 \times 5$ km$^2$ grid by nearest neighbor and the mean value computed for all the overpasses grouped at each grid point, allowing an evaluation of the spatial distribution of the errors.

4. Ground radar performance

Since the MeteoSwiss ground radar product is to be used as a reference, and there is as yet no work in the literature comprehensively detailing its performance, a brief evaluation of the relevant performance parameters is presented here to aid interpretation of the results of the GPM comparison. Since the primary interest of this paper is the effects of terrain and season on the GPM DPR measurements, a comparison against gauges over the summers and winters during the first 2 years of GPM are used, additionally split by terrain classification. The terrain classification is carried out in the same manner as for the GPM DPR footprints detailed earlier, applied to the 25-m SwissTopo DEM in a 5-km diameter circle around each gauge, with the same threshold of a standard deviation of 160 m used.

Since the gauge data are recorded in 10-min increments, and with a 0.1-mm resolution, they provide a poor instantaneous measurement of rainfall rate. Instead, the comparison is made between hourly gauge accumulations and hourly radar accumulations. A threshold of 0.3 mm h$^{-1}$ is used because it is large enough to avoid one or two erroneous counts of the gauges during clear sky and is small enough to detect a drizzle event lasting at least 30 min. The MeteoSwiss gauge network

| Table 3. Hourly comparison between the MeteoSwiss ground-based radar product and gauge measurements. |
|----------------------------------|----------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Mean gauge $R$ (mm h$^{-1}$)     | Max gauge $R$ (mm h$^{-1}$)      | POD            | $r$            | Bias (dB)      | MADM (dB)      | Hours with precipitation |
| JJA                              | 1.75                            | 67.2           | 0.76           | 0.63           | 0.39           | 2.10            | 77 448         |
| DJF                              | 1.01                            | 18.8           | 0.59           | 0.44           | -0.78          | 2.13            | 86 171         |
| Complex JJA                      | 1.69                            | 64.4           | 0.73           | 0.58           | 0.45           | 2.26            | 50 007         |
| Complex DJF                      | 1.03                            | 18.8           | 0.55           | 0.43           | -0.86          | 2.15            | 52 804         |
| Flat JJA                         | 1.85                            | 67.2           | 0.83           | 0.70           | 0.30           | 1.89            | 27 441         |
| Flat DJF                         | 0.99                            | 8.7            | 0.65           | 0.46           | -0.66          | 2.12            | 33 367         |
FIG. 5. The performance metrics for hourly MeteoSwiss radar product measurements compared against the equivalent gauge accumulations, on a gauge-by-gauge basis.
has been increasing in size over the course of this study, but here we opt to limit the gauges to the 190 present in every season of the study.

The results of this comparison are shown in Table 3. Precipitation rates can be seen to be higher in summer than in winter. The radar performance is better in terms of both detection and estimation in summer than in winter and in flat terrain than in complex terrain. The product also somewhat overestimates precipitation amounts in the summers considered (bias of 0.39 dB, or 9.4%) and somewhat underestimates in winter (bias of −0.78 dB, or −16.4%). The under- and overestimations are more pronounced in complex terrain than in flat terrain, but the trend remains the same.

The parameters on a per-gauge basis for winter and summer are shown in Fig. 5, illustrating the spatial variability of the performance. In the areas with more complex terrain (see Fig. 3), performance is poorer than in flatter terrain. There is a notable drop-off in performance in the far east of Switzerland, where the radar coverage is poorest.

Overall, it appears that the MeteoSwiss radar mosaic can be used as a reference to assess the quality of the GPM DPR precipitation estimates over Switzerland, provided its limitations are borne in mind, in particular its limited performance in the far east of Switzerland.

5. Results

The total rainfall accumulation (assuming a constant rainfall rate for 5 min) as measured by both the DPR measurements and the MeteoSwiss radar network, together with the total number of nonzero precipitation cases, binned on a 5-km grid, is shown in Fig. 6. Clear differences exist between both the total measured accumulation and the total number of footprints with precipitation measured with GPM and with the MeteoSwiss radars. GPM significantly underestimates the total accumulation.

A potential benefit of using space-based radars to measure in complex terrain is the lack of occlusion allowing for measurements to conform more closely to the terrain than their ground-based counterparts. However, Fig. 7 shows that, while this is sometimes the case over Switzerland, more of the time the ground-based radar measurements are as close or closer to the ground than GPM, and almost all of the time in flat terrain. Also notable in this figure are the large spikes in the MeteoSwiss heights above sea level: these result from the low-elevation (near 0°) PPIs from the radars. There is considerable spread in the height of the GPMs above the ground, even in flat terrain. The clutter-free bottom height above terrain in the Plateau gets higher with increasing angle of incidence, going from an average.
of 900 m at 0° to an average of 2 km at 18° (for the Ku-only product). This indicates that the spread in ranges with which the beam intercepts the ground at least partly causes the change in minimum measurable height.

a. Integrated analysis

For clarity, the discussion here is restricted to the performance of the dual-frequency Ku and Ka product, which generally outperforms both the Ku-only and the high-sensitivity Ka-only product. Some brief comparisons with the other products are provided where appropriate here, and more details on the other products are available in the appendix.

1) DETECTION

Figure 8 shows the POD and HSS for the dual-frequency product, for both the preferred lower thresholds and the nominal GPM DPR thresholds, as a function of terrain type, season, and precipitation rate. The differences between the results with the two thresholds are small and the broad trends are the same, so it is reasonable to consider only the lower threshold results.

Detection performance across all of Switzerland is reasonable, with an HSS of 0.7. However, the POD of 0.567 is lower than is desirable for many applications, and, given the hourly MeteoSwiss POD is 0.76 in summer, the true POD is likely to be even lower. The very low false alarm rate means that GPM detecting precipitation missed by MeteoSwiss cannot be more than negligible: for all of Switzerland with the dual-frequency product, there are 12,325 cases where GPM detects precipitation classified as TP, and only 368 FP cases. Even if all the FP cases were attributed to precipitation erroneously missed by MeteoSwiss, the POD would only increase to 0.574. It is notable that, contrary to what may be expected, the POD does not improve significantly if the threshold is increased from the lower threshold to the nominal threshold. This may partly be explained by measurement bias: where the analysis is restricted only to cases where the reference (MeteoSwiss) rainfall rate is greater than 1, 3, or 6 mm h\(^{-1}\) but the standard threshold is applied to GPM, the POD increases significantly, reaching 0.954 for \(R > 6\text{ mm h}^{-1}\). The generally good HSS results across the board result in larger part from the excellent FAR results.

2) ESTIMATION

Figure 9 shows the correlation, bias, and MADM for the dual-frequency product. Some example scatter diagrams are shown in Fig. 10. It can be seen that, across Switzerland, there is reasonable correlation, albeit with quite a large spread (MADM) and a negative bias...
Correlation gets significantly worse as the minimum rainfall rate increases, but since it is a log correlation, this is partly due to the substantial compression of the axes ranges as lower rainfall rates are excluded.

3) TERRAIN

There is a very strong difference between the performance in complex and noncomplex terrain, as seen across all of the metrics (with a small number of minor exceptions). It is particularly noticeable that the bias in flat terrain is $-1.48 \text{ dB} (-29\%)$: far better than the $-2.7 \text{ dB} (-49\%)$ for complex terrain.

One possible source of the difficulties for the DPR in complex terrain is reduced performance of the surface reference technique. However, we find that in practice there is only a small change in the proportion of cases where the surface reference technique is reported as unreliable in the DPR product when moving from flat to complex terrain, from 44% to 47%. There is also a slight shift in the proportion of the remaining footprints from reliable to marginal: 55.5% of the remainder in flat are marginal, but 56.1% of the remainder in complex terrain. This is not sufficient to account for the large differences in performance with terrain type.

4) SEASON

It is also clear that season is very important for DPR performance. For detection, far better performance is found in the summer than in the winter across all three products. This is not surprising, since the proportion of solid precipitation measured will be higher in winter: Fig. 11 shows histograms of the average minimum measurement heights for both the MeteoSwiss radars and the GPM DPR above the 0°C level reported in the
GPM DPR data as a function of season and terrain type. It can clearly be seen that in winter the bulk of the measurements made are higher than the 0°C level, and so likely in the solid phase. Another factor influencing the poorer winter measurements may be the smaller vertical extent of precipitating systems in Switzerland in winter: this can be seen from the GPM DPR storm-top product, shown in Fig. 12. The smaller vertical extent will mean that the measurement height will often be closer to storm top, making the extrapolation to the ground-level precipitation rate more challenging.

When the seasonal analysis is broken down by terrain type, the biggest difference in terms of detection between summer and winter is seen in complex terrain. This is to be expected, in part since the complex terrain is also generally the terrain at higher elevations and so the precipitation within the volumes being measured by the GPM DPR will be almost exclusively solid precipitation in winter (Fig. 11). In the flatter terrain, the difference between summer and winter detection is less pronounced.

In terms of estimation, the picture is a little more complicated. Performance is always better in summer than in winter, but there is a more marked difference between summer and winter in flat terrain than in complex terrain for both correlation and bias. At least in part, this is because the performance in summer in flat terrain is very good: the summer bias obtained is only −0.68 dB (~14%) (although note that the MeteoSwiss radars exhibit a slightly positive bias in flat summer terrain and a slight negative bias in flat winter terrain, reducing the difference between summer and winter in these measurements). Under near-ideal conditions, the GPM DPR dual-frequency product performs well.

5) PRECIPITATION PHASE

It is also possible to explore the precipitation phase and the relative effect this has on the measurements more directly, removing season and terrain classification as explicit classes. This is done by considering possible combinations of the GPM DPR clutter-free bottom being above or below the melting layer and the mean minimum MeteoSwiss measurement height in the footprint being above or below the melting layer. Here, above the melting layer is taken to be 100 m or more higher than the 0°C level (reported in the GPM DPR product) and below is taken to be 800 m or more lower than the 0°C level. This range is chosen based on the report in Iguchi et al. (2015) that the melting layer is typically found around 500 m below the reported 0°C level, the melting layer thicknesses of around 200–600 m measured by Wolfensberger et al. (2016), and to allow for some variation between the true 0°C level and the value reported in the GPM DPR data files (such variation is inevitable given that the 0°C level reported is not directly measured). This is somewhat crude, but it will nevertheless serve to separate the hydrometeor phase into predominantly solid above and predominantly liquid below (indeed, it has been found in practice that using lower thresholds of 500 or 300 m below the 0°C level instead increases...
the number of below samples, but does not substantially alter the results).

Applying these thresholds across all Switzerland yields the performance metrics shown in Table 4. The removal of all points that lie between 100 m above and 800 m below the 0°C level reduces the total number of samples by 28.6%. Of the samples left, 98.9% are cases where the both measurements are above the melting layer, or both below. Of the remainder, the MeteoSwiss measurements above the melting layer with the DPR measurements below form slightly over half of the samples, but less than a quarter of those with precipitation. Almost all of these samples are in the far east of Switzerland, in the area with the poorest ground radar coverage, and also one of the driest parts of the country. The quality of the MeteoSwiss above/DPR below sample is too poor to be representative, but the values are included in the table for completeness.

The MeteoSwiss below/DPR above dataset is also small, but the distribution of points around the country is more representative, generally clustered around the Albis and Monte Lema radars, with a smaller (and drier) number around the Pointe de la Plaine Morte radar. These are all in areas where higher-quality measurements are expected, and therefore, while the dataset is small, it is of sufficient quality to allow the evaluation of the DPR’s performance above the melting layer.

Restricting the comparison to cases where the MeteoSwiss measurements are below the melting layer, it can be seen that there is a notable difference in the performance depending on whether the DPR measurements are made above or below the melting layer. The POD drops from 0.784 to 0.633 when measuring in the solid phase, correlation drops from 0.796 to 0.75, and, perhaps most significantly, the bias increases from 0.733 to 2.43 dB (from 15.5% to 42.9%). The FAR appears better with MeteoSwiss below and GPM above, but note that if the FAR remained the same between the below/below and below/above cases, only 2 of the 780 samples in the below/above cases would be false alarms: this sample set is not large enough to make a strong statement about the change in the false alarm rate with GPM DPR measurement phase.

The lower probability of detection for GPM in the solid phase can largely be explained by the lower reflectivity of the equivalent rainfall rate in the solid phase than in the liquid phase. The mean GPM DPR measured reflectivity for all positive MeteoSwiss measurements below the melting layer with GPM above is 23.4 dBZ (corresponding to a mean rainfall rate of 3.47 mm h⁻¹, median 2.58 mm h⁻¹) for successful DPR detections and 15.7 dBZ (mean rainfall rate 1.05 mm h⁻¹, median 0.64 mm h⁻¹) for missed detections. For GPM

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**FIG. 10.** Example correlation plots for the dual-frequency Ku and Ka product. The color bars indicate the number of samples lying within each grid area, with no color indicating no data points in that grid area. The red line is the 1:1 line, and the green line is a straight line fit to the log–log data.
below, the equivalent numbers are 24.23 dBZ (mean rainfall rate 1.96 mm h\(^{-1}\), median 1.14 mm h\(^{-1}\)) for successful detections and 14.72 dBZ (mean rainfall rate 0.86 mm h\(^{-1}\), median 0.27 mm h\(^{-1}\)) for missed detections. In other words, the reflectivities of missed detections are similar irrespective of phase, but these correspond to very different rainfall rates.

However, it is not sufficient to say that there is some reflectivity threshold that defines the DPR detection limit. The 5th percentile of the measured reflectivity at the clutter-free bottom for the successful detections with the MeteoSwiss measurement below the melting layer and the GPM above (i.e., where attenuation should be less significant for GPM) is 15.2 dBZ, and the 95th percentile for the missed detections is 19.7 dBZ. Reflectivity is significant, but it does not entirely explain the detection performance.

The bias is calculated only on true positive detections, so lower reflectivity values alone are not sufficient to explain the poorer performance from the DPR above the melting layer. This appears instead to arise from a systematic underestimation of rainfall rates from measurements in the solid phase, at least over Switzerland.

It is interesting to note that for the above/above case, the DPR probability of detection is significantly worse than the below/below or below/above cases. The GPM bias is also significantly more negative, which is surprising given the expectation from the radar–gauge comparison (section 4) that the MeteoSwiss product would tend to underestimate in winter and hence in the solid phase, making the overall underestimation even smaller. This suggests that there is a larger problem with the DPR measurement in the above/above cases than in the DPR above, MeteoSwiss below cases. There are several possible reasons for this: the terrain complexity for above/above cases is higher than for GPM above, MeteoSwiss below, the average separation between the GPM clutter-free bottom and the terrain is larger, and the separation between the storm-top height and the GPM clutter-free bottom is smaller.

Since these above/below category pairs somewhat correlate with terrain complexity (and therefore lowest
measurement height), it is helpful to try to separate the effect of terrain complexity from the effect of phase. Tables 5 and 6 show the same categories but for complex terrain only and flat terrain only, respectively. The same patterns hold for both cases as for all Switzerland (ignoring the GPM below/MeteoSwiss above category, which, for the same reasons as for the all of Switzerland case, are not reliable, but shown for completeness). However, the bias in the below/below case is notably worse in complex terrain than in flat terrain, while the reverse is true for solid precipitation. Other than bias, the below/below cases are generally very similar in both complex terrain and in flat terrain.

The details as to why the GPM DPR product performs more poorly in the solid phase than in the liquid phase, in terms of estimation particularly, are not clear from this work, but it can be said that this is a significant contributing factor to the poorer performance found in complex terrain.

6) PRECIPITATION TYPE

Using the GPM-identified precipitation classes, better performance is seen in convective than stratiform rain across all three products (this holds even if the nominal thresholds are used). This is in agreement with the results found by Duan et al. (2015) for the TRMM PR, who reported a higher FAR in stratiform rain.

7) OTHER GPM DPR PRODUCTS

The preceding analysis has been primarily for the dual-frequency Ku and Ka product. Similar analyses have also been applied to the Ku-only product and the high-sensitivity Ka-only product. In both cases it was found that the broad patterns in relative performance held across all three products. The Ka-only product performed significantly more poorly than either of the other products in terms of bias, but the performance is otherwise broadly comparable (notably with a slightly better HSS, resulting from a better POD and a better FAR). The Ku-only product performed slightly less well than the dual-frequency product by most metrics. The differences were small, and it may be that for some users the advantage of the wider coverage outweighs the slight performance impairment. Interested readers are directed to the tables in the appendix, where full results are given for the three products.

b. Spatial analysis

Results for the geographic distributions of errors are shown in Fig. 13 for the dual-frequency product. First, it
should be noted that precipitation is not uniform across Switzerland. The subsample of precipitation during overpasses is not quite sufficient to draw out the full climatological picture (compare with Fig. 2), but there is a fairly uniform number of cases with precipitation across much of Switzerland, with far more precipitation found over the northeastern Alps and comparatively less precipitation in the far east of Switzerland, as well as around Geneva in the far west. The lower precipitation in the east of Switzerland is a real effect, but the radar coverage in this region was poorer than in the rest of the country, so it is possible that the reference measurements underreport the total precipitation. This coverage issue has been improved as of January 2016 by the addition of a new radar at Weissfluhgipfel, but this was after the bulk of the period studied here.

From the total errors, it is quite clear that errors over the Alps dominate, with a secondary set of slightly smaller errors over the Jura Mountains in the northwest. Over the flatter Swiss Plateau errors are small, and, particularly in summer, it is notable that where there are more significant errors these are sometimes positive (i.e., GPM overestimation) as opposed to the near-uniform underestimation everywhere else. GPM is closer to unbiased relative to the MeteoSwiss product here.

Hit errors make up almost all of the errors in all cases and are concentrated primarily in the Alps. Most of the rest of the errors are missed precipitation, which again occurs primarily in the Alps and the Jura Mountains, although there is also a reasonably strong contribution from the center of the Plateau. Also note that the contribution from the Alps to the missed precipitation is stronger in winter than in summer, as would be expected given the predominantly solid precipitation and the higher limit to the lowest elevation measurable by GPM. In the terrain classified as complex in this work, the average clutter-free bottom height is 3.3 km, as opposed to 1.7 km for the terrain classified as flat. Since the complex classification includes parts of the Jura Mountains as well as the Alps, the figure will be even higher over the Alps.

Finally, false precipitation makes up a comparatively small proportion of the overall error, and the only strong values occur over the Alps. There are a comparatively large number of points in the far east of Switzerland, especially given the relatively low number of rainfall events recorded here. Some of these values are likely real, but the poorer ground radar coverage here means that it may be that not all of these measurements are false.

This analysis was also applied to the Ku-only and the high-sensitivity Ka-only products, and a similar spatial distribution of errors was found, with the exception of almost no false precipitation in the Ka-only data. For the Ka-only data, while the error spatial distribution was similar, the magnitudes of the errors were significantly larger.

### 6. Conclusions

This paper has evaluated the version 04A estimated surface precipitation products from the GPM DPR over the complex terrain over Switzerland against measurements from the MeteoSwiss C-band operational network over a period of approximately 2 years.

The acceptable level of performance is application dependent. However, it is clear that in summer (and hence primarily in rain) and in flatter terrain the DPR Ku-only and dual-frequency products are reliable, exhibiting only a small negative bias of around \(-0.58 \text{ dB} (-13\%), \text{ Ku only}\) or \(-0.68 \text{ dB} (-14\%, \text{ dual frequency})\). Given that the MeteoSwiss product exhibits a small positive bias (0.39 dB) in summer relative to hourly gauge accumulations, the actual DPR bias values are likely closer to unbiased than shown here. One possible issue

### Table 5. As in Table 4, but for complex terrain only.

<table>
<thead>
<tr>
<th>MS</th>
<th>GPM</th>
<th>POD</th>
<th>FAR</th>
<th>HSS</th>
<th>$r$</th>
<th>Bias (dB)</th>
<th>MADM (dB)</th>
<th>Samples</th>
<th>With precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above</td>
<td>Above</td>
<td>0.366</td>
<td>0.0394</td>
<td>0.505</td>
<td>0.521</td>
<td>-4.1</td>
<td>1.64</td>
<td>81423</td>
<td>7536</td>
</tr>
<tr>
<td>Above</td>
<td>Below</td>
<td>0.227</td>
<td>0.167</td>
<td>0.35</td>
<td>-0.38</td>
<td>-2.89</td>
<td>1.8</td>
<td>876</td>
<td>22</td>
</tr>
<tr>
<td>Below</td>
<td>Above</td>
<td>0.649</td>
<td>0.737</td>
<td>0.757</td>
<td>-2.32</td>
<td>-1.28</td>
<td>1.93</td>
<td>9245</td>
<td>682</td>
</tr>
<tr>
<td>Below</td>
<td>Below</td>
<td>0.779</td>
<td>0.0568</td>
<td>0.843</td>
<td>0.799</td>
<td>-2.4</td>
<td>1.64</td>
<td>81423</td>
<td>7536</td>
</tr>
</tbody>
</table>

### Table 6. As in Table 4, but for flat terrain only.

<table>
<thead>
<tr>
<th>MS</th>
<th>GPM</th>
<th>POD</th>
<th>FAR</th>
<th>HSS</th>
<th>$r$</th>
<th>Bias (dB)</th>
<th>MADM (dB)</th>
<th>Samples</th>
<th>With precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above</td>
<td>Above</td>
<td>0.685</td>
<td>0.0113</td>
<td>0.77</td>
<td>0.556</td>
<td>-2.56</td>
<td>1.63</td>
<td>19474</td>
<td>4070</td>
</tr>
<tr>
<td>Above</td>
<td>Below</td>
<td>0.714</td>
<td>0.0625</td>
<td>0.791</td>
<td>0.456</td>
<td>-0.161</td>
<td>1.16</td>
<td>195</td>
<td>21</td>
</tr>
<tr>
<td>Below</td>
<td>Above</td>
<td>0.614</td>
<td>0.66</td>
<td>0.687</td>
<td>-2.86</td>
<td>1.28</td>
<td>146</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Below</td>
<td>Below</td>
<td>0.783</td>
<td>0.0411</td>
<td>0.854</td>
<td>0.791</td>
<td>-0.363</td>
<td>1.43</td>
<td>48792</td>
<td>3154</td>
</tr>
</tbody>
</table>
FIG. 13. Spatial distribution of errors from the dual-frequency measurements. From top to bottom, this shows the total number of GPM DPR measurements of each 5-km grid area, the number of GPM DPR measurements where a rainfall rate is greater than the threshold value (as determined by the MeteoSwiss network), the total error, hit error, missed precipitation (note that this is actually the absolute value of the missed precipitation, to allow it to be plotted on a log scale), and the false precipitation for (left) the entire measurement period, (center) JJA, and (right) DJF. These figures should be compared with Fig. 3 for the underlying topography.
for some applications is the POD of 0.757 for the dual-frequency product (i.e., the DPR misses 24% of all precipitation events). Since the MeteoSwiss product also misses some precipitation, the actual POD is likely to be lower. However, the POD quickly increases if the reference threshold is raised. For example, if reference to be lower. However, the POD quickly increases if the reference threshold is raised. For example, if reference rainfall rates greater than 1 mm h\(^{-1}\) are of interest (but the DPR threshold is left at 0.15 mm h\(^{-1}\)), then a POD of 0.967 is achieved. This results from a mixture of underestimation by GPM (as seen in the bias results) and a higher miss rate for GPM at lower rainfall rates.

Performance in complex terrain, and most especially winter in complex terrain, was found to be significantly worse than performance in summer and flatter terrain. The bias is large (−3.11 dB for the dual-frequency product, that is, it measures only 49% of the total rainfall accumulation in complex terrain in winter) and the detection metrics comparatively low (HSS of 0.424 for complex terrain in winter). Given that the MeteoSwiss product is somewhat negatively biased relative to gauges in winter and also misses more precipitation in winter than in summer, the true GPM bias and HSS in winter are likely worse than reported here. Nevertheless, in some circumstances it will provide data in regions where little else is available, and it may well be sufficient in such cases.

The high-sensitivity Ka-only product was found to perform well in terms of detection when compared with the other products, but significantly less well than the other products considered in terms of bias (see the appendix for more details).

The GPM DPR was found to consistently underestimate rainfall rates across all data subsets considered (with the exception of convective precipitation in flat terrain, and there are individual cases of overestimation elsewhere). This bias is especially pronounced in complex terrain and in winter. The main determining factor of GPM’s performance is whether or not its measurements take place entirely in the solid phase. However, specifically in less complex terrain and in the summer, the bias values were found to be around −0.6 dB (−14.8%) for the Ku and dual-frequency products. Under ideal conditions, the GPM DPR compares very well with the ground-based radar measurements used here.

It was also found that the nominal thresholds for GPM’s sensitivity are quite conservative, at least in the context of precipitation over Switzerland. The difference in performance between the low threshold used here (0.15 mm h\(^{-1}\)) and the nominal thresholds (0.5 and 0.2 mm h\(^{-1}\)) is quite limited.

The strong differences found between the two summers and the two winters considered (see appendix) suggest that longer-term studies may be necessary for this comparison. The random sampling nature of the GPM DPR’s measurements means that a representative set of events is not necessarily obtained from one or two years alone. More measurements (and hence more time) will improve the robustness of these estimates.

The rainfall rate product is only a very small part of what GPM can provide, and there is a lot of scope for other data being useful in an Alpine context. In the future we will be looking at comparisons of reflectivities, both on a very local scale as well as across
Switzerland. We will also be assessing the DPR bright-band estimates and the extent to which they can be useful in complex terrain.

Acknowledgments. We thank MeteoSwiss for the provision of the ground-based radar mosaic data, and for the permission to use it in this work. The MeteoSwiss radar mosaics associated with the overpasses are available on request from the author. We also thank the NASA/JAXA GPM DPR team for making available the necessary GPM precipitation data. These data are freely available from http://pmm.nasa.gov/data-access/downloads/gpm.

APPENDIX

Detection and Estimation Metrics Tables

The values computed for the various categories used are presented in Table A1 for the Ku-only data, Table A2 for the dual-frequency data, and Table A3 for the Ka-only data.

<table>
<thead>
<tr>
<th>TABLE A1. Ku performance.</th>
<th>POD</th>
<th>FAR</th>
<th>HSS</th>
<th>r</th>
<th>Bias (dB)</th>
<th>MADM (dB)</th>
<th>Samples</th>
<th>With precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Switzerland 0.567</td>
<td>0.029</td>
<td>0.695</td>
<td>0.643</td>
<td>-2.15</td>
<td>1.94</td>
<td>233 533</td>
<td>21 749</td>
<td></td>
</tr>
<tr>
<td>Complex 0.438</td>
<td>0.0364</td>
<td>0.58</td>
<td>0.628</td>
<td>-2.93</td>
<td>1.89</td>
<td>128 778</td>
<td>11 118</td>
<td></td>
</tr>
<tr>
<td>Flat 0.708</td>
<td>0.0231</td>
<td>0.804</td>
<td>0.676</td>
<td>-1.48</td>
<td>1.76</td>
<td>97 500</td>
<td>10 093</td>
<td></td>
</tr>
<tr>
<td>JJA 2014 0.633</td>
<td>0.0459</td>
<td>0.74</td>
<td>0.655</td>
<td>-1.37</td>
<td>2.09</td>
<td>30 797</td>
<td>30 56</td>
<td></td>
</tr>
<tr>
<td>JJA 2015 0.632</td>
<td>0.0519</td>
<td>0.74</td>
<td>0.658</td>
<td>-2.51</td>
<td>2.17</td>
<td>31 516</td>
<td>28 04</td>
<td></td>
</tr>
<tr>
<td>DJF 2014/15 0.489</td>
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for the high-sensitivity Ka data. These give the various performance metrics for the entire measurement period, as well as for smaller subsets of those data. In particular, the data are divided into complex and flatter terrain. Metrics are given by season, with June–August (JJA) representing summer and December–February (DJF) representing winter. Note that the stratiform and convective rain classifications are the GPM DPR classifications, meaning that they are only valid where GPM reports rain and so only TP and FN values are meaningful. This means that most detection metrics cannot be reported. Similarly, the MeteoSwiss rainfall rate is used to define the rainfall rate for the higher rainfall rate categories; therefore, only TP and FN values are meaningful and so again most detection metrics cannot be reported.

REFERENCES


