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How Does Ground Clutter Affect CloudSat Snowfall Retrievals Over Ice Sheets?

Cyril Palerme, Chantal Claud, Norman B. Wood, Tristan L'Ecuyer, and Christophe Genthon

***Abstract*— CloudSat has provided the first spaceborne snowfall observations in polar regions. Nevertheless, CloudSat retrievals may be affected by ground clutter even if the snowfall rate at the surface is estimated from the reflectivity measured at about 1200 m above land/ice surface. In this study, the impact of ground clutter contamination on CloudSat snowfall retrievals over the Antarctic and Greenland ice sheets is investigated. Our results suggest that ground clutter affects CloudSat snowfall observations over some areas, particularly over complex terrain such as mountain ranges and fjords. Over these areas, the snowfall rates deduced from CloudSat observations can be, therefore, significantly overestimated. This has implications when developing snowfall climatologies from CloudSat products.**

***Index Terms*— CloudSat, ground clutter, snowfall.**

I. INTRODUCTION

CloudSat has provided unprecedented data sets for the study of clouds and precipitation in polar regions, thanks to its cloud profiling radar (CPR) that allows to observe the vertical distribution of hydrometeors up to 82° of latitude. The high frequency of the CPR (94 GHz) is particularly suitable for observing light snowfall [1], [2], and is, therefore, very relevant for high-latitude precipitation. That is why several studies used CloudSat products for precipitation studies over the Arctic and Antarctic regions [3]–[5]. Nevertheless, the reliability of CloudSat snowfall retrievals is difficult to assess in some remote areas where no *in situ* precipitation observations are available.

CloudSat observations are affected by ground clutter contamination [6], which prevents to detect precipitation close to the surface. The magnitude and vertical extent of the reflectivity enhancement caused by ground clutter vary depending on surface characteristics such as topography, roughness, and material [7], [8]. In order to avoid ground clutter contamination, the snowfall rate at the surface in the CloudSat precipitation algorithms [7], [9], [10] is estimated from the reflectivity measured in the first vertical bin which is expected not contaminated by ground clutter (called the near-surface bin). However, if the near-surface bin is contaminated by ground clutter, it would increase the reflectivity, and the algorithm would, therefore, produce a spuriously high snowfall rate [7].

In this study, the impact of ground clutter contamination on the CloudSat snowfall retrievals over the ice sheets is investigated. Particular attention is given to areas with a complex topography, where ground clutter is expected to be strong [7], [8]. This study should help to sort CloudSat observations in order to improve snowfall climatologies from CloudSat products. The data sets and the methods used in this study are described in Section II. In Section III, the locations and the precipitation rates of CloudSat snowfall retrievals are analyzed in order to assess the impact of ground clutter contamination. The discussion and conclusion of this study are then presented in Section IV.

II. DATA AND METHODS

The CloudSat CPR, launched in April 2006, has been the first spaceborne weather radar with a spatial coverage including the polar regions (up to 82° of latitude). The CPR is a W-band radar (94 GHz) which provides reflectivity profiles at a vertical resolution of 240 m over a 1.4 km × 1.7 km footprint. In this study, the performance of the CloudSat 2C-SNOW-PROFILE product (R04 version) [10] is evaluated. This product provides estimates of vertical profiles of snowfall rate if the assessed melted fraction of precipitation is lower than 10% [10]. The melted fraction is estimated using the air temperature analyzed by the European Centre for Medium-Range Weather Forecasts operational analysis, and a model of melting layer [11]. In the 2C-SNOW-PROFILE product, the snowfall rate is available at every vertical bin over the height potentially contaminated by ground clutter (the blind zone). The blind zone is defined as the two bins above the bin containing the surface over the oceans, and as the four bins above the bin containing the surface over land [10]. The snowfall rate at the surface is then deduced from the reflectivity measured in the bin immediately above the blind zone. It is assumed in this algorithm that the snowfall rate at the surface is the same as the snowfall rate in the near-surface bin. Therefore, this algorithm does not take into account the processes that can influence the snowfall rate in the blind zone such as shallow precipitation or evaporation.

In addition to the snowfall rate, the 2C-SNOW-PROFILE product also provides an estimation of the snowfall rate

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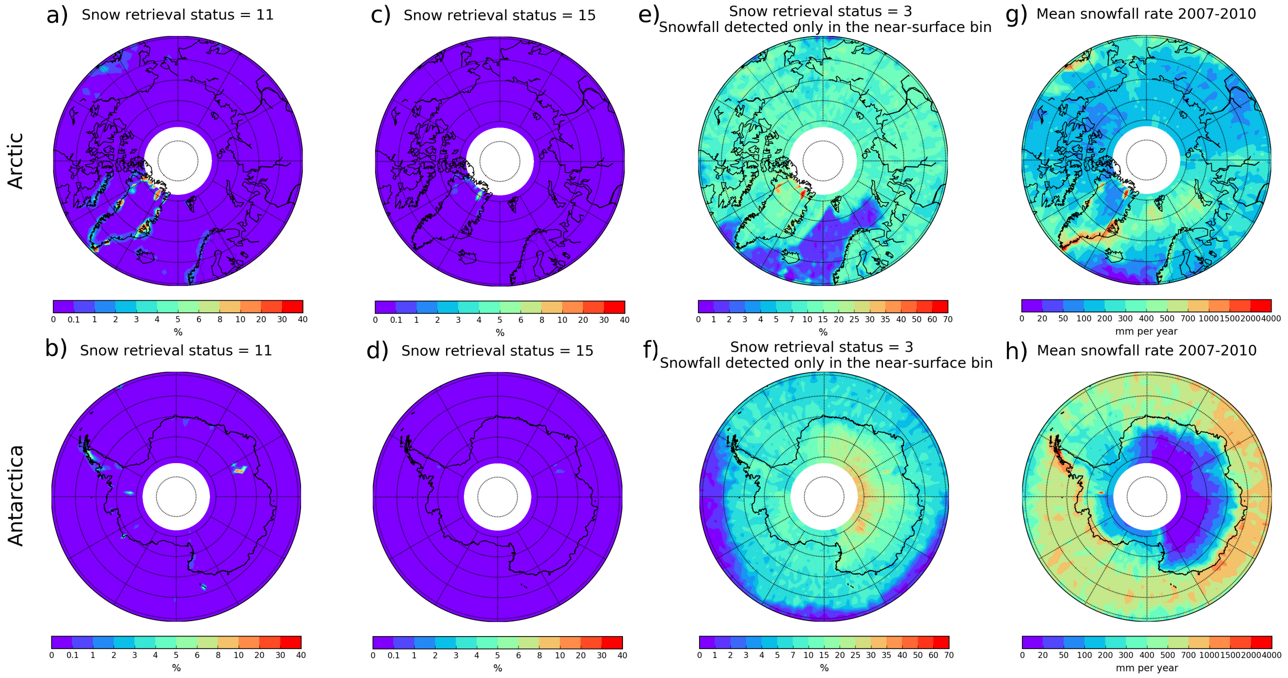

Fig. 1. Occurrence frequency (%) of CloudSat observations with a snow retrieval status equal to 11 (a) and (b) and equal to 15 (c) and (d) compared to the total number of observations in which snowfall is detected at the surface (the colorscale is not linear). Occurrence frequency (%) of CloudSat observations with a snow retrieval status of 3 in which snowfall is only detected in the near-surface bin (e) and (f) compared to the total number of observations with a snow retrieval status of 3 [the colorscale is different of the colorscales used in (a)–(d)]. Mean snowfall rate (mm per year) when the observations with a snow retrieval status higher than 3 are excluded (g) and (h).

uncertainty, and a number of information such as a level of confidence, and a flag indicating if some errors occur in the retrieval process. In this study, the variable "snow_retrieval_status" (SRS) is used to sort the CloudSat observations. This variable is represented by an 8-bit field [10]. Only the first four bits are used here. Bit 0 is activated if a snow layer is detected in the profile, and bit 1 is turned on if the algorithm indicates snowfall at the surface. Therefore, when snowfall is detected in the near-surface bin, the SRS is usually equal to 3 (bits 0 and 1 turned on). When the SRS is higher than 3, it means that something special has been detected by the algorithm. If bit 2 is activated, it means that a retrieval was performed but produced large chi-square values. It may be an indication that the algorithm has converged to a state that is not consistent with the observations. Bit 3 is turned on if the snowfall rate in the near-surface bin is much larger than the snowfall rate in the bin immediately above. It can indicate the presence of shallow precipitation, ground clutter contamination, or partial melting of the snow (due to the stronger reflectivity of liquid water compared to snow).

In this study, the CloudSat 2C-SNOW-PROFILE product has been processed over a grid of 1° (latitude) × 2° (longitude) over the polar regions. It has recently been shown that the CloudSat snowfall climatology derived at this spatial resolution agrees well with ground-based radar observations at three Antarctic stations [12]. The period 2007–2010 is used here to take into account all the full years of day and night observations available in the CloudSat 2C-SNOW-PROFILE product. Furthermore, the mean snowfall rates are assessed over the grounded ice sheets in this study.

III. RESULTS

A. *CloudSat Observations With a Snow Retrieval Status Equal to 11 or Equal to 15*

Fig. 1 shows the spatial distribution of CloudSat observations with an SRS equal to 11 (meaning that the snowfall rate in the near-surface bin is much larger than in the bin immediately above) and equal to 15 (meaning that the algorithm has produced large chi-square values in addition to a strong vertical gradient in snowfall rate between the near-surface bin and the bin immediately above). This large difference in the snowfall rate between the two bins immediately above the blind zone can be the result of shallow precipitation, partial melting of the snow, or ground clutter contamination [10]. If mixed precipitation has an influence on these observations, there should be a seasonal variability in the occurrence of these CloudSat snowfall retrievals. In Greenland and in Antarctica, there is no clear seasonal cycle in the occurrence of CloudSat observations with an SRS equal to 11 and equal to 15 (Figs. S1 and S2 of the Supplementary Material), which means that these observations are not significantly influenced by partial melting of the snow.

The occurrence frequencies of CloudSat observations with an SRS equal to 11 and equal to 15 are particularly high over Greenland compared to the rest of the Arctic region (Fig. 1). These observations occur mainly in northern Greenland and over a few locations on the coast of the ice sheet. The maximum frequency of observations with an SRS equal to 11 is observed in southern Greenland, where it reaches almost 29% of the snowfall events observed with CloudSat. In Antarctica, the observations with an SRS equal to 11 and equal

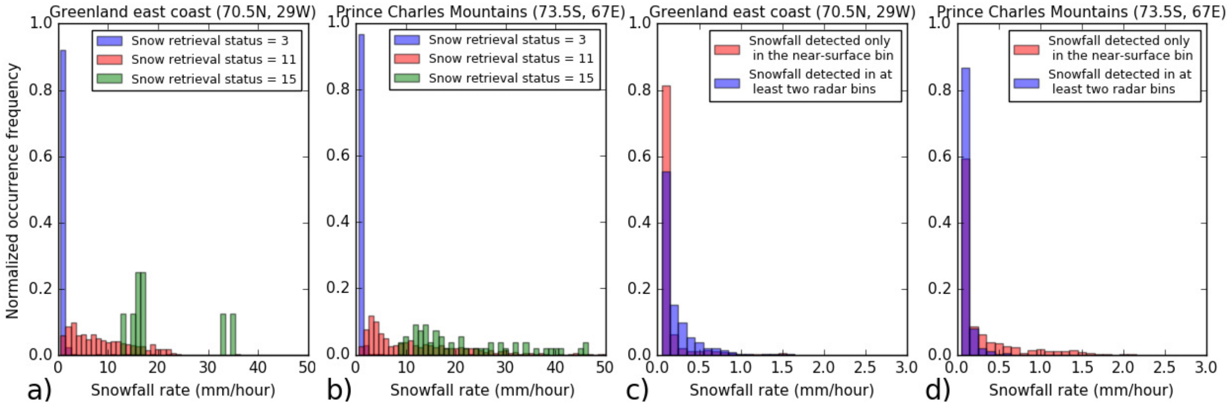

Fig. 2. (a) and (b) Occurrence frequency histograms of CloudSat observations with a snow retrieval status equal to 3, 11, and 15 over the Greenland east coast and over the Prince Charles Mountains. Each histogram is independent; therefore, the sum of occurrence frequencies of observations with a snow retrieval status equal to 3 (or 11 or 15) is equal to 1. (c) and (d) Occurrence frequency histograms of CloudSat observations with a snow retrieval status equal to 3 in which snowfall is only detected in the near-surface bin and in more than one bin over the Greenland east coast and over the Prince Charles Mountains. Each histogram is independent; therefore, the sum of occurrence frequencies of observations with snowfall detected only in the near-surface bin (or in more than one bin) is equal to 1.

to 15 occur over the mountainous areas (the Prince Charles Mountains, the Vinson Massif, the Antarctic Peninsula, and the Transantarctic Mountains). The occurrence frequency of the observations with an SRS of 11 is maximum over the Prince Charles Mountains, where these observations represent about 20% of the snowfall events observed with CloudSat (Fig. 1). While the observations with an SRS of 15 are negligible in terms of the mean snowfall rate over Antarctica (about 0.3%), they represent about 23% of the Greenland mean snowfall rate. The observations with an SRS of 11 account for about 35% and 7% of the mean snowfall rates of the Greenland and Antarctic ice sheets, respectively.

The snowfall rate at the surface in the CloudSat observations with an SRS of 11 is, on average, much larger than in the observations with an SRS of 3 (Fig. 2). It is even higher in the observations with an SRS of 15, with sometimes values which seem unrealistic for the regions analyzed (Fig. 2). Similar results have been found in other areas (Fig. S3 of the Supplementary Material).

In Fig. 3, the locations of CloudSat observations with an SRS equal to 3 and equal to 11 are shown over the east coast of Greenland (about 70.5°N, 29°W) and over the Prince Charles Mountains (about 73.5°S, 67°E). The observations with an SRS of 11 occur mainly on the edges of the fjords over the east coast of Greenland and on the peaks of the Prince Charles Mountains. Ground clutter is expected to be strong over these areas of complex topography, but orographic precipitation could also occur and produce large snowfall gradients between the near-surface bin and the bin immediately above. However, in the case of orographic precipitation, these observations should also occur a few kilometers next to the fjord edges or next to the mountains. Moreover, the observations with an SRS of 11 are sparsely located along the ridges and the coasts, while we could expect that orographic precipitation occurs all along the ridges and the coasts (Figs. 3 and S4). Due to the spatial distribution of the observations with an SRS of 11 and the particularly high snowfall rates of these retrievals (Fig. 2), we consider that these observations are very likely contaminated by ground clutter. However, in northern Greenland, a large number of observations with a snow retrieval status equal to 11 and 15 occur in areas without complex terrain. This is likely due to inaccuracies in the digital elevation model used in the product [7], [13] (Fig. S5 of the Supplementary Material). Nevertheless, the 2C-SNOW-PROFILE product has recently been updated using a more accurate digital elevation model, and the number of CloudSat observations with an SRS of 11 and 15 is much lower in northern Greenland in the new version (R05).

B. CloudSat Observations With Snowfall Observed Only in the Near-Surface Bin

When snowfall is only detected in the near-surface bin and not in the radar bins above, the retrievals could also be affected by ground clutter. Fig. 1 shows the occurrence frequency of the observations with snowfall detected only in the near-surface bin when the SRS is equal to 3 (meaning that snowfall is observed at the surface). While these observations occur over the whole surface of the ice sheets, a high frequency of these events is observed in northern Greenland, where a large number of observations with an SRS of 11 and 15 also occur. The spatial distribution of these events is fairly close to the spatial pattern of the observations with an SRS equal to 11 (Fig. 3), although the CloudSat retrievals with snowfall detected only in the near-surface bin do not only occur on the fjord edges and on the peaks. The snowfall rates at the surface in these observations are usually weak (Fig. 2) and do not significantly impact the mean snowfall rate over Antarctica (about 0.5%). However, the mean snowfall rate over Greenland is 9% lower without these observations. The snowfall rate from the CloudSat retrievals with snowfall detected only in the near-surface bin is, on average, stronger than the snowfall rate from the observations with snowfall detected in at least two radar bins over the Prince Charles Mountains (Fig. 2). Nevertheless, it is the contrary over the Greenland east coast, and it is difficult to conclude whether these observations are affected by ground clutter.

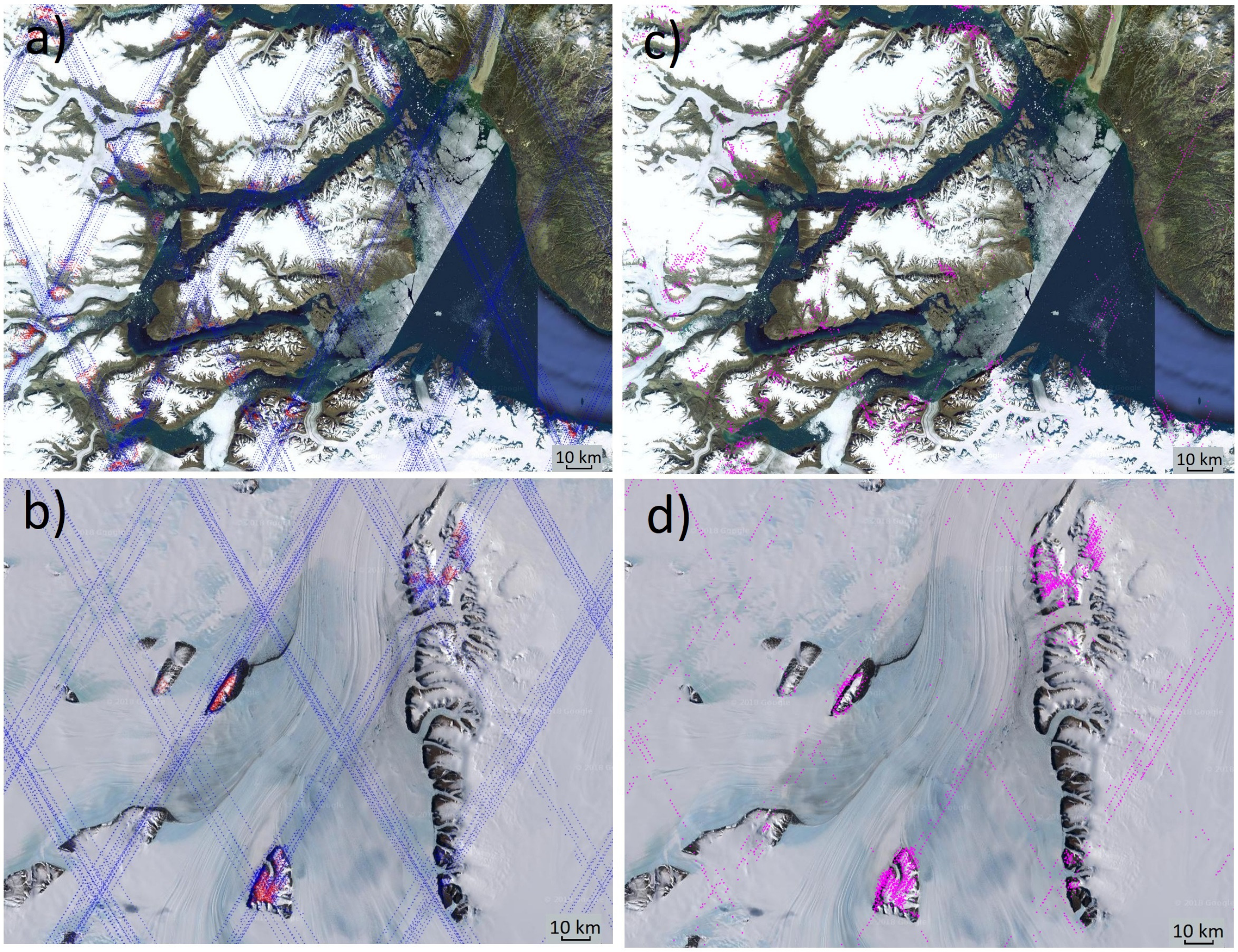

Fig. 3. Locations of CloudSat snowfall observations with a snow retrieval status equal to 3 (blue dots) and equal to 11 (red dots) on the (a) Greenland east coast, about 70.5°N, 29°W, and (b) on the Prince Charles Mountains in Antarctica, about 73.5°S, 67°E. (c) and (d) Locations of CloudSat observations with a snow retrieval status equal to 3 in which snowfall is only detected in the near-surface bin (pink dots). The scale is shown in the lower right corner of the pictures.

C. Snowfall Climatologies Over Greenland and Antarctica

When the bit 2 of the SRS is activated (SRS equal to 7 or 15), the snowfall rate at the surface is usually very high, and the vertical extent of the snowfall is usually very small (Figs. S7–S12 of the Supplementary Material). Due to these vertical profiles of the snowfall rate which seem unlikely and the uncertainties associated with these observations, we suggest to exclude the observations with an SRS equal to 7 and 15 when snowfall climatologies are produced. Fig. 1 shows the mean snowfall rate over the Arctic and over Antarctica when the observations with an SRS higher than 3 are excluded. With this criteria, the mean snowfall rate up to 82° of latitude is 321 mm per year and 159 mm per year over Greenland and Antarctica, respectively. Another possibility is to take into account the snowfall rate in the bin immediately above the near-surface bin when the SRS is equal to 11. If this criterion is used, the mean snowfall rate up to 82° of latitude is 320 mm per year over Greenland and 160 mm per year over Antarctica.

Furthermore, if the observations with an SRS higher than 3 are excluded and the observations with snowfall detected only in the near-surface bin are omitted, the mean snowfall rate is 292 mm per year over Greenland and 160 mm per year over Antarctica. The significantly lower mean snowfall rate in Greenland is mainly due to the high frequency of the observations with snowfall detected only in the near-surface bin in northern Greenland [Fig. 1(e)]. Interestingly, when the observations with snowfall detected only in the near-surface bin are excluded, the areas with a particularly high snowfall rate in the north of Greenland disappear (Fig. S13 of the Supplementary Material). This is consistent with a ground clutter contamination in the near-surface bin due to inaccuracies in the digital elevation model used in the CloudSat product.

IV. DISCUSSION AND CONCLUSION

The impact of ground clutter contamination on the CloudSat snowfall retrievals from the 2C-SNOW-PROFILE product has been investigated in this study. Most of the observations with a snow retrieval status of 11 or 15 are very likely contaminated by ground clutter over the Greenland and Antarctic ice sheets, and we recommend to exclude these observations when snowfall climatologies are produced. When the snow retrieval status is equal to 11, another possibility is to assess the snowfall rate at the surface from the snowfall rate in the bin immediately above the near-surface bin.

Furthermore, some observations with a snow retrieval status equal to 3 in which snowfall is only detected in the near-surface bin could also be contaminated by ground clutter. However, it is difficult to conclude whether these observations are affected by ground clutter because they occur everywhere over the ice sheets. A vertical continuity test such as the one developed by Kulie and Bennartz [7] could be used to remove the snowfall observations with a small vertical extent, which are potentially contaminated by ground clutter. According to Hiley *et al.* [8], a vertical continuity test contributes to remove ground clutter over land but is not useful over the oceans. Nevertheless, more shallow precipitation could be missed if a vertical continuity test is used. Milani *et al.* [14] have shown that the vertical continuity test developed by Kulie and Bennartz [7] significantly reduces the number of CloudSat snowfall observations with a snowfall rate higher than 1.5 mm per hour over the Antarctic ice sheet (using an algorithm developed by Kulie and Bennartz [7] and Hiley *et al.* [8]). The vertical continuity test has a weaker impact over the Southern Ocean where it does not significantly reduce the number of observations with a snowfall rate lower than 3.5 mm per hour [14].

Several studies have suggested that blowing snow particles could barely reach the height of the CloudSat near-surface bin [15]–[17]. However, these events are very rare, and due to the small size of blowing snow particles that could reach the near-surface bin, we consider that it is unlikely that blowing snow particles could be sufficiently reflective to be considered as precipitating snow in CloudSat observations [18].

A new version of the 2C-SNOW-PROFILE product has recently been released using a more accurate digital elevation model. The number of observations suspected to be contaminated by ground clutter has decreased in this version (particularly in northern Greenland), but the issues described in this letter remain significant in areas of complex terrain.

We consider that the Antarctic snowfall climatology presented here is an update of the climatology from Palerme *et al.* [4], and we recommend to use this new data set instead of the one from Palerme *et al.* [4]. This new climatology is made available to the general community (https://doi.pangaea.de/10.1594/PANGAEA.894946 [19]).

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