Case study on Snow Water Equivalent H SAF SWE-H (H65) product in December 2023, Germany

Case Studies

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Sommario

1 Short Introduction/Abstract

End of November and at the beginning of December 2023, Germany was faced with wide-spread and intense snowfall, leading to an elevated risk of flooding when snow started to melt. The present case study assesses the quality of HSAF SWE-H (in the following referred to as H65) data, compared to other data products for daily estimates of snow-water equivalent (SWE) on point-scale and catchment scale (1,000 to 10,000 km^2).

2 Summary

Date & Time	25 November 2023 00:00 UTC – 15 December 2023 23:59 UTC
Region	Germany
HSAF Products	SN-SWE-H (H65)
Satellites	DMSP F18
Instruments	SSMIS
Latitude/Longitude	45°-55°N, 5°-17°E

In November/December 2023, Germany was faced with intense snowfall. While first occurring only locally at high altitudes, a drop in temperatures coinciding with intense snowfall led to a wide-spread snow cover down to low altitudes from 29th November until 8th December.

The subsequent melting of locally high snow depths coupled with high rainfall rates caused the swelling of creeks and rivers so that, especially in south-eastern Germany and the low mountain ranges the risk of flooding rose.

To enable a real-time, spatially disaggregated estimate of the snow-water equivalent (SWE), the present case study has assessed the quality of HSAF H65 data (EUMETSAT, 2023) at point and catchment-scale (1,000 – 100,000 km^2) compared to in situ measurements at weather stations operated by Deutscher Wetterdienst (DWD) and SWE estimates by water balance model LARSIM-ME (BfG, 2023).

For widespread snow cover, H65 shows high capability in estimating extent, hotspots and magnitude of SWE, both, compared to point measurements and when aggregated to catchment scale. It therefore provides high value in complementing other data sources to assess SWE for widespread, intense snowfall in the lowlands and low mountain ranges of Germany.

More local snow occurrence is difficult to detect correctly, as is the quantification of SWE on wet, aging snow, as product H65 is only able to correctly detect SWE under dry snow conditions. Therefore, onset of the event and melting process are less accurately quantified/missed. In addition, on catchments with alpine influence, the model systematically underestimates SWE because the product is most suitable for snow depth under ca. 100 cm and SWE lower than 100 mm. These are the two major limitations of product SWE-H in detecting snow in regions where the climate is more oceanic, wet and mild, compared to the northern polar Regions.

3 Description

3.1 Weather condition

After a relatively dry year, November and December 2023 saw large amounts of precipitation. Coupled with dropping temperatures, this resulted in widespread snow coverage from end of November till the first December decade. Figure 2 displays daily surface weather maps for the time period from 25th November until 15th December.

On 25th November, a small-scale low-pressure system brought showery precipitation, with the snow line between 400 and 600 meters in the North-West and West of Germany. In the East and South it snowed down to lower altitudes. The northerly current led to an orographic lift in the Alps resulting in snowfall all day in this region (DWD, 2023a). The following days brought mostly rain and snow mixed with rain (DWD, 2023b).

However, large-scale precipitation and the occlusion of a frontal system along with the subsequent inflow of polar air, as it moved to the Czech Republic, led to a rapid drop in temperature on 27th and 28th November (see Figure 1). This was sufficient to cause snowfall down to the lowest altitudes. The federal states of Germany North-Rhine Westphalia, Thuringia, Saxony, Saxony-Anhalt, southern Brandenburg and the north and east of Bavaria saw a lot of snowfall and a consequent snow cover in many places. Fresh snow locally accumulated to 10 to 15 cm at 300 to 400 m a.s.l. and to 20 cm above 500 m a.s.l. A particular hotspot was the federal state Hesse and the north-east of Rhineland-Palatinate (central western part of Germany). The orographic lift at the low mountain ranges Westerwald and Taunus led to long-lasting and strong snowfall (approx. 18 hours) with a related snow depth of 10 to 20 cm, down to 200m a.s.l. (DWD, 2023c).

On 29th November, the approaching low-pressure system brought snow for northern and north-eastern Germany over the following days, caused by the Lake Effect Snow phenomenon. Cold air flowing over large, relatively warm water bodies destabilizes the stratification of the atmosphere. Heat- and moisture enriched air already cools down and condenses in the lower layers of the atmosphere, potentially leading to spatially delimited, heavy snowfall (DWD, 2023d).

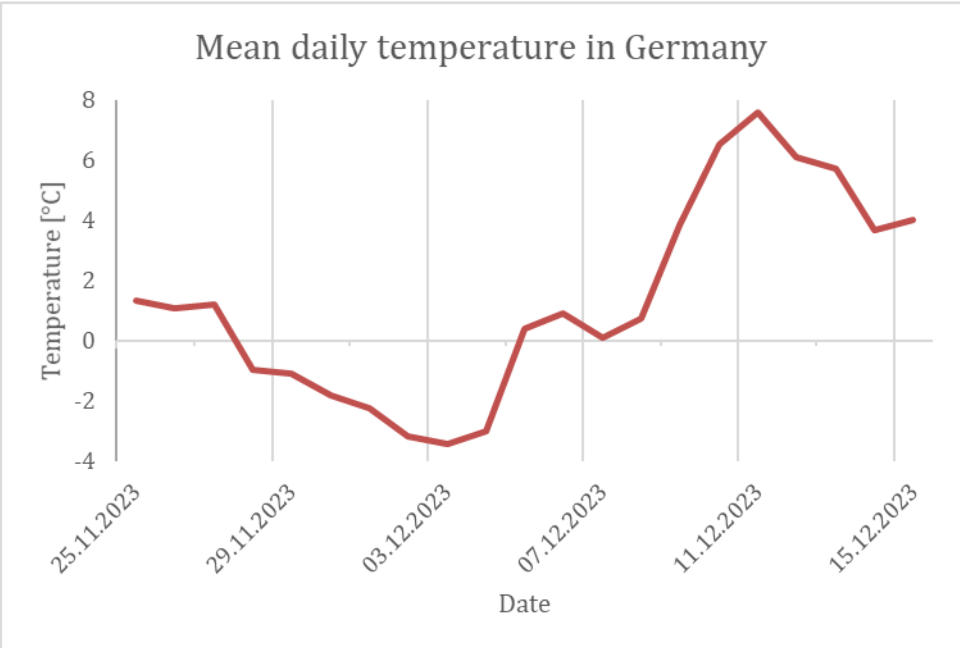

Figure 1: Spatially averaged daily mean air temperature in Germany from 25th November - 15th December 2023 (data source: DWD (2023), adapted by: BfG (2023))

25.11. 26.11. 27.11.

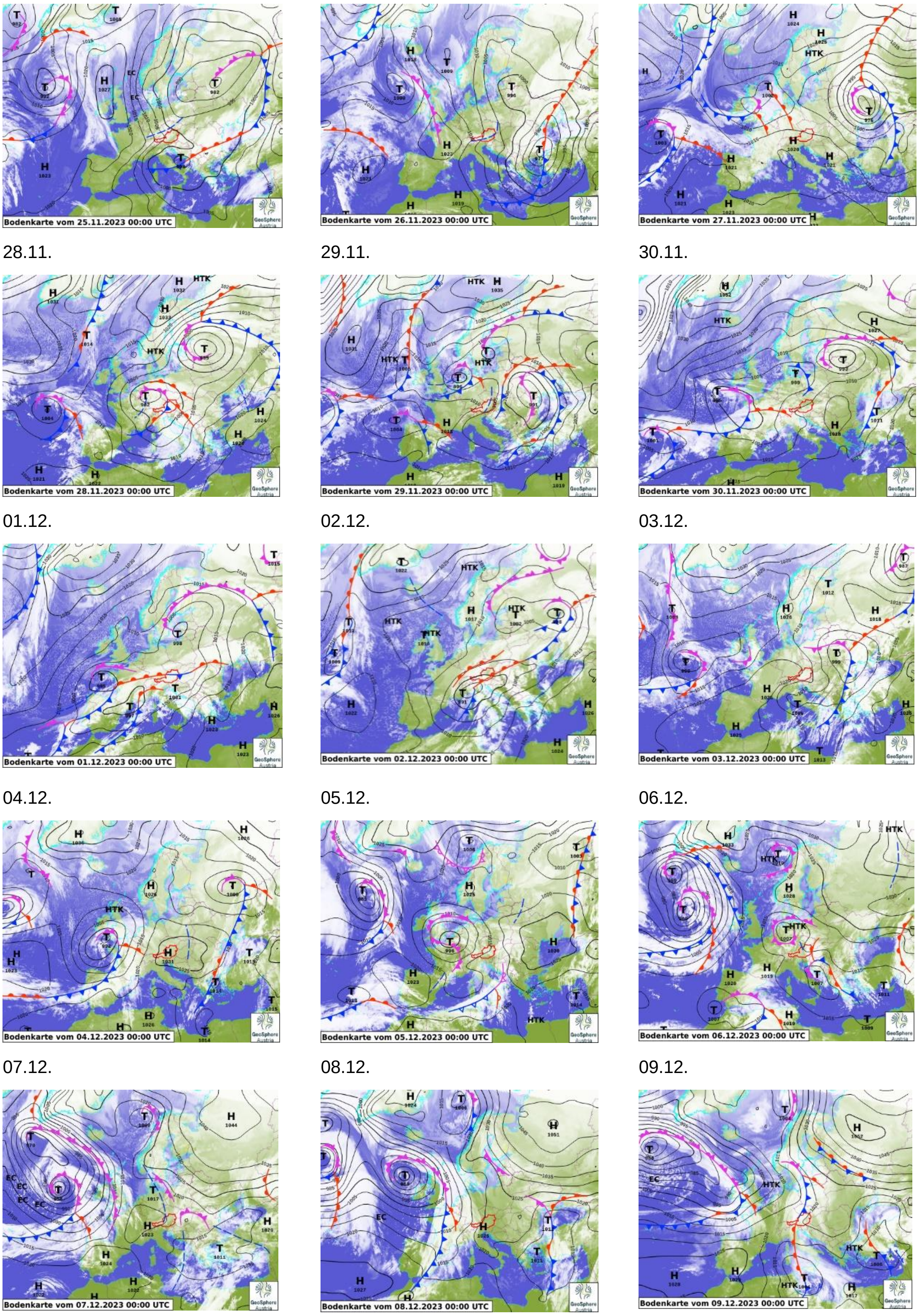

Figure 2: Daily surface weather analysis (25th November - 9th December) (GeoSphere Austria, 2023)

On 1st and 2nd December a low-pressure system arriving from Italy resulted in heavy snow fall in South-Eastern Germany. The subsequent high-pressure system led to clear skies and a stable snow layer. In South East Germany the temperature dropped to -12 and -19 °C (DWD, 2023e).

However, the approaching low-pressure system from south-west announced the melting phase with sleet and black ice. On 5th December new snow only still fell at higher altitudes while at lower altitudes positive temperatures of up to 5°C were reached. Only in north-east and the very north and south-east of Germany snow still fell down to the lowest altitudes (DWD, 2023e).

As mild sea air, approaching from the British Islands, prevailed over frosty air from northern and eastern Europe, temperatures increased to 5 to 10°C, resulting in rainfall in western Germany on 8th December, reaching the east in the night of 9th December. Wind, rain and positive temperatures let the snow cover melt up to higher altitudes. In the following days the snow line rose to 1,000 m, in the alps even to 2,000 m a.s.l. (DWD, 2023f).

The rain combined with snow melt, resulted in a strong swelling of creeks and rivers. Especially in southern Germany and the lower mountain ranges, where the snow depth was still high, the danger of floods rose (DWD, 2023f; DWD, 2023g).

Figure 3 and Figure 4 illustrate the simulated discharge, aggregated precipitation and mean SWE, derived from the LARSIM-ME hydrological model, for six sub-catchments of the rivers Rhine, Danube and Elbe – all located in the low mountain ranges in eastern Germany (see Figure 5). The building up of snow, starting from 23rd November with an SWE of up to 60 mm, and the subsequent melting process as off 9th December were followed in all sub-catchments by large discharge peaks.

To foresee such high discharge peaks, it would be of interest to have accurate, spatially disaggregated, near-real time information on SWE. In the following the HSAF H65 data product on SWE is therefore assessed in terms of its value to complement other data sources.

A comparison to in situ measurements at German weather stations and to modelled SWE at the catchment-scale (1,000-100,000 km^2) is conducted to assess the accuracy of H65 data at different scales.

Heitzenhofen (Naab; Danube)

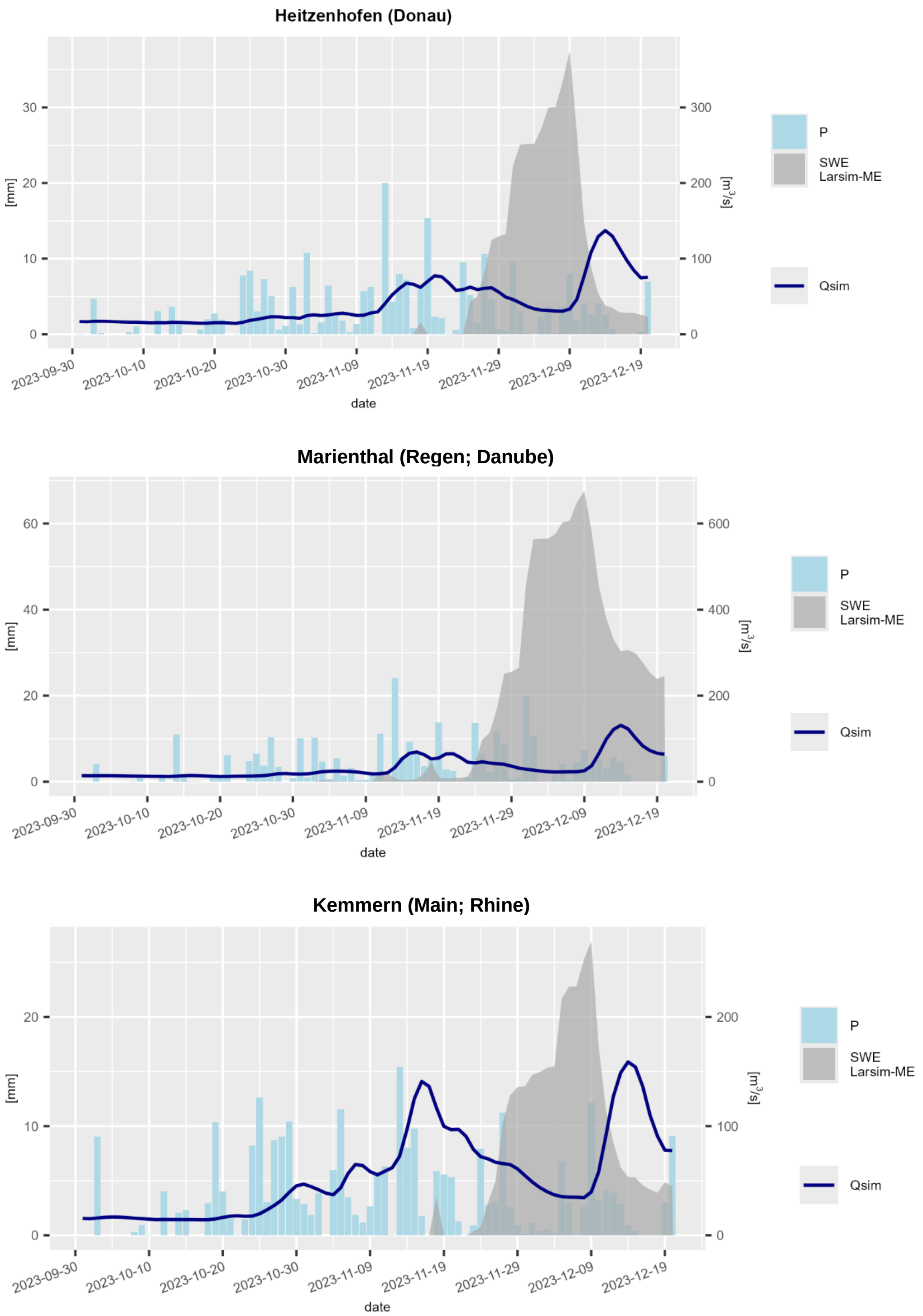

Figure 3: Daily discharge [m³/s], spatially aggregated precipitation [mm] and mean SWE [mm] for different sub-basins of Rhine and Danube for 1st October to 20th December 2023. SWE derived from LARSIM-ME model (BfG, 2023).

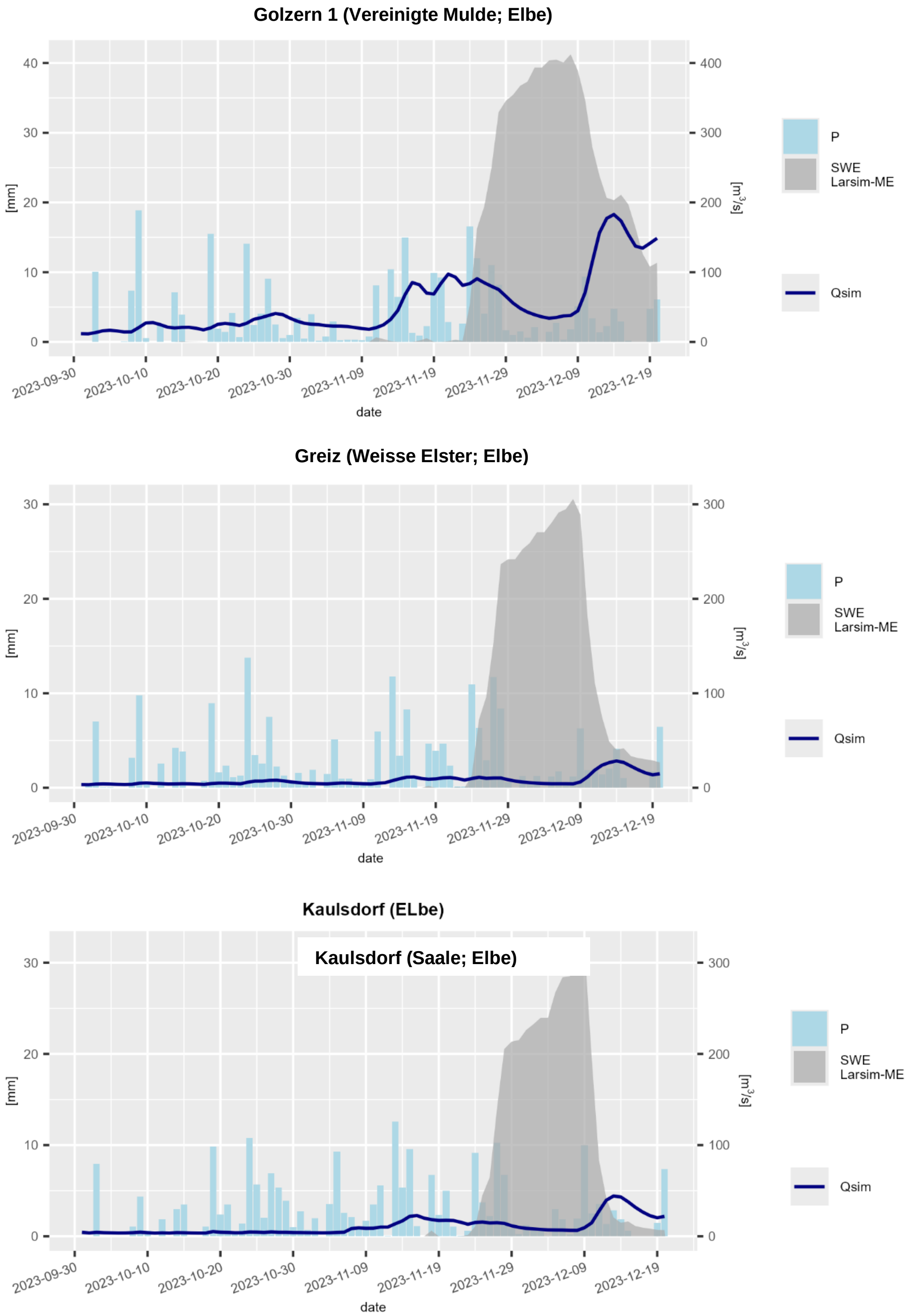

Figure 4: Daily discharge [m^3/s], spatially aggregated precipitation [mm] and mean SWE [mm] for different sub-basins of river Elbe for 1st October to 20th December 2023. Discharge and SWE derived from LARSIM-ME model (BfG, 2023).

3.2 Method

3.2.1 Scope of Analysis

The comparative analysis of H65 data to in situ measurements and modelled SWE was conducted on the scale of Germany major river basins (i.e. Rhine, Danube, Weser and Elbe) and on six smaller catchments of interest.

The parts of the major river basins analysed in the following are delineated on the left in Figure 5. The basins are further divided into sub-basins, in the following referred to Rhine 1, 2 and 3, Danube 1 and 2 and Elbe 1 and 2.

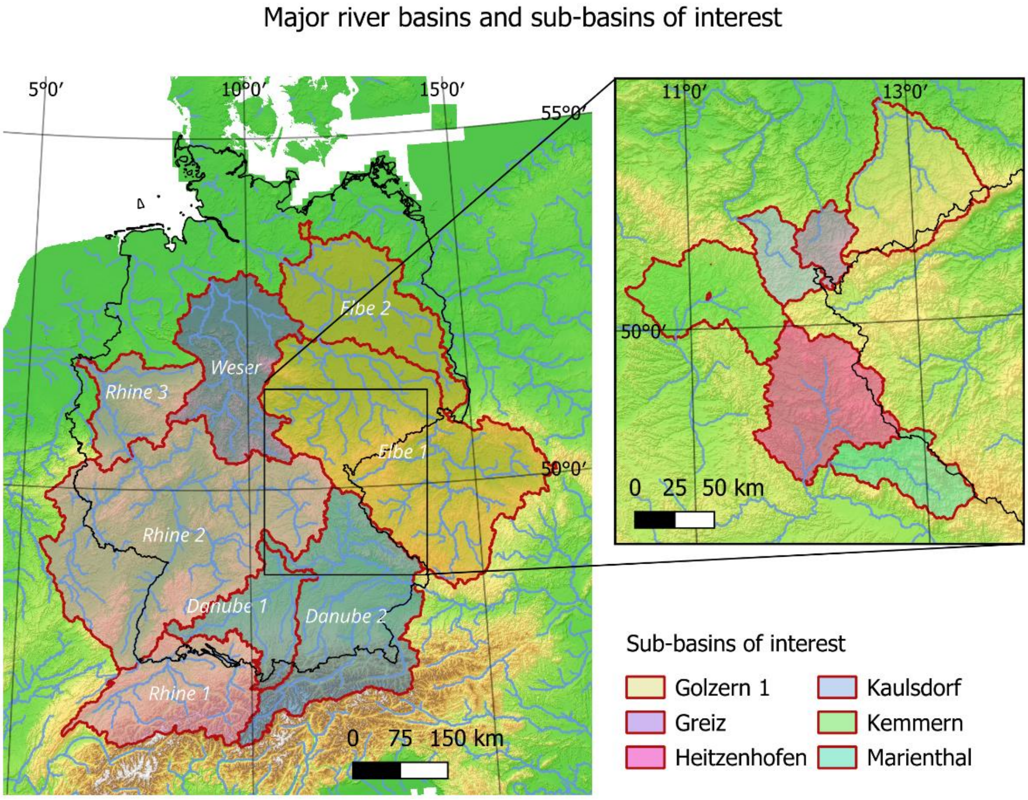

Figure 5: Major German river basins Rhine, Danube, Elbe and Weser further divided into sub-basins (left) and six sub-basins from water balance model LARSIM-ME (BfG, 2023) (right)

The location of the six smaller catchments, namely up to the discharge gauges Heitzenhofen and Mariental (Danube basin), Kemmern (Rhine basin), Golzern 1, Greiz and Kaulsdorf (Elbe basin), are illustrated on the right side. All catchments are located in eastern part of Germany in the low mountain ranges.

The time period of analysis is restricted to the 25th November 2023, when first stations in the low mountain ranges in eastern Germany recorded snow, to 15th December 2023 as the last day when H65 observations mark larger areas as snow-covered.

3.2.2 Data

H65 data

For the present case study, HSAF H65 data on SWE was used to assess its value in complementing on-ground measurements. H65 data is available on NSIDC EASE-Grid 2.0 North at a spatial resolution of 25x25 km and daily timesteps.

Data was prepared by projecting the data to WGS84 and cropping it to the area of interest.

Station data

Daily in situ measurements on snow height and SWE were downloaded from the Climate Data Center by Deutscher Wetterdienst (DWD CDC) for the time period from 1st November until 31st December 2023 (DWD Climate Data Center, 2024). SWE measurements are only reported for times of snow occurrence for a total of 378 stations. Regular time series of records were produced, where missing days were filled with zero whenever the corresponding snow height record was zero. Out of the resulting daily records, 14.4% were non-zero SWE measurements.

LARSIM-ME data

As part of BfG's large scale water balance model, LARSIM-ME (BfG, 2023; LEG, 2024), daily simulations of SWE at a spatial resolution of 5x5 km² are provided and can be spatially aggregated to catchment level.

3.2.3 Analyses

Comparison of H65 SWE observations to in situ measurements

In a first step SWE observations from the H65 HSAF product were compared to in situ measurements in Germany on a daily basis. A visual comparison of station data to H65 data was conducted, followed by a quantitative analysis of H65's ability to (A) detect snow and (B) estimate the SWE.

For the quantitative analysis, cell values for the satellite product were assigned to the nearest snow station as long as this station was located no further than 15 km from the grid cell's center. To evaluate whether H65 detects existing snow cover, the pairs' values were transferred into binary *snow/no snow* values and the following metrics were computed:

1. Probability of detection (POD), as the probability that *snow* (in situ measurements of SWE or SH > 0) is detected as such.
2. False alarm rate (FAR), as the rate of *snow* detections within the H65 product which are not supported by on ground measurements (*no snow* at nearby station).

For those instances where both, H65 and in situ measurements, suggested snow, SWE observations were then compared in terms of their value. Only records were used where the measured snow height was between 20 and 100 cm. The following metrics were used to assess H65's ability to correctly estimate the SWE:

1. Root Mean Square Error (RMSE)
2. Mean Error (ME)

Sub-basin intercomparison of H65 to LARSIM-ME

Based on the sub-basin delimitations, H65 and LARSIM-ME data were spatially aggregated. The two products were then compared on a daily basis for each of the sub-basins. Metrics used for comparison were:

1. RMSE
2. ME
3. Correlation coefficient (CC)

4 Results

4.1 Spatio-temporal comparison of H65 data to in situ SWE measurements

Table 1: Binary and continuous statistics for the comparison of H65 SWE data (EUMETSAT, 2023) to in situ measurements (DWD Climate Data Center, 2024) in Germany from 25th November to 15th December

	Binary statistics		**Continuous statistics**	
Statistic	POD	FAR	RMSE	ME [mm]
25/11-15/12/23	0.75	0.30	39.7	-10.4

Table 1 displays the binary and continuous statistics for the comparison of H65 observations to in situ measurements for the entire time period of analysis. The POD is high with 75% of the snow records by stations being paired with snow observations from H65. However, this also comes at the cost of a FAR of almost 30%.

For pairs, where station and H65 records suggested snow and where the corresponding snow height measurement ranged between 20 and 100 cm, the RMSE was 39.7. There is a general notion of a slight underestimation by the H65 product by about 10 mm. However, a closer look at the evolution of error metrics over time reveals no systematic bias in H65 data compared to station data.

The spatio-temporal patterns of H65 observations and in situ data are displayed in daily maps in Figure 6 to Figure 9. Station locations are represented by circles, color-coded based on their respective daily SWE measurements. Hence, a straight-forward comparison between gridded H65 data and in situ measurements is possible.

The maps show that the on-set of snow at stations in central Germany was only detected several days later, with a wide-ranging detection of the snow only starting from 1st December 2023. In early December, both snow coverage and SWE values are captured well. High SWE measurements in South-Eastern Germany are matched with similarly high H65 observations. As of 10th December, there is a clear trend of less stations with snow observations which is only partially reproduced by H65. Especially, in Northern Germany and Eastern Germany high SWE observations from H65 data as off 10th December are not supported by in situ measurements. Snow is only still recorded very locally.

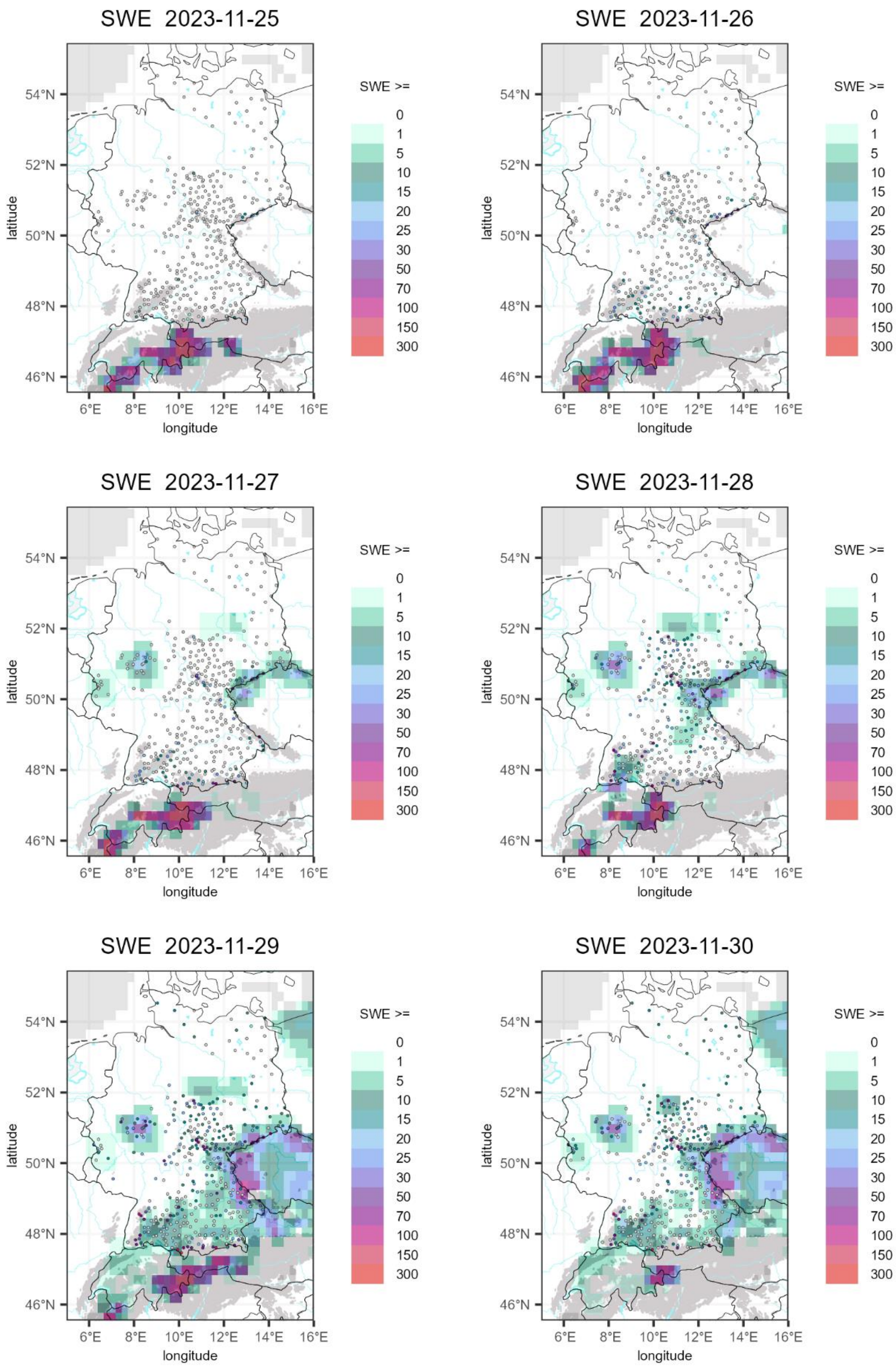

Figure 6: SWE estimates by HSAF H65 (EUMETSAT, 2023) and from in situ measurements at weather stations (DWD Climate Data Center, 2024) for 25th-30th November

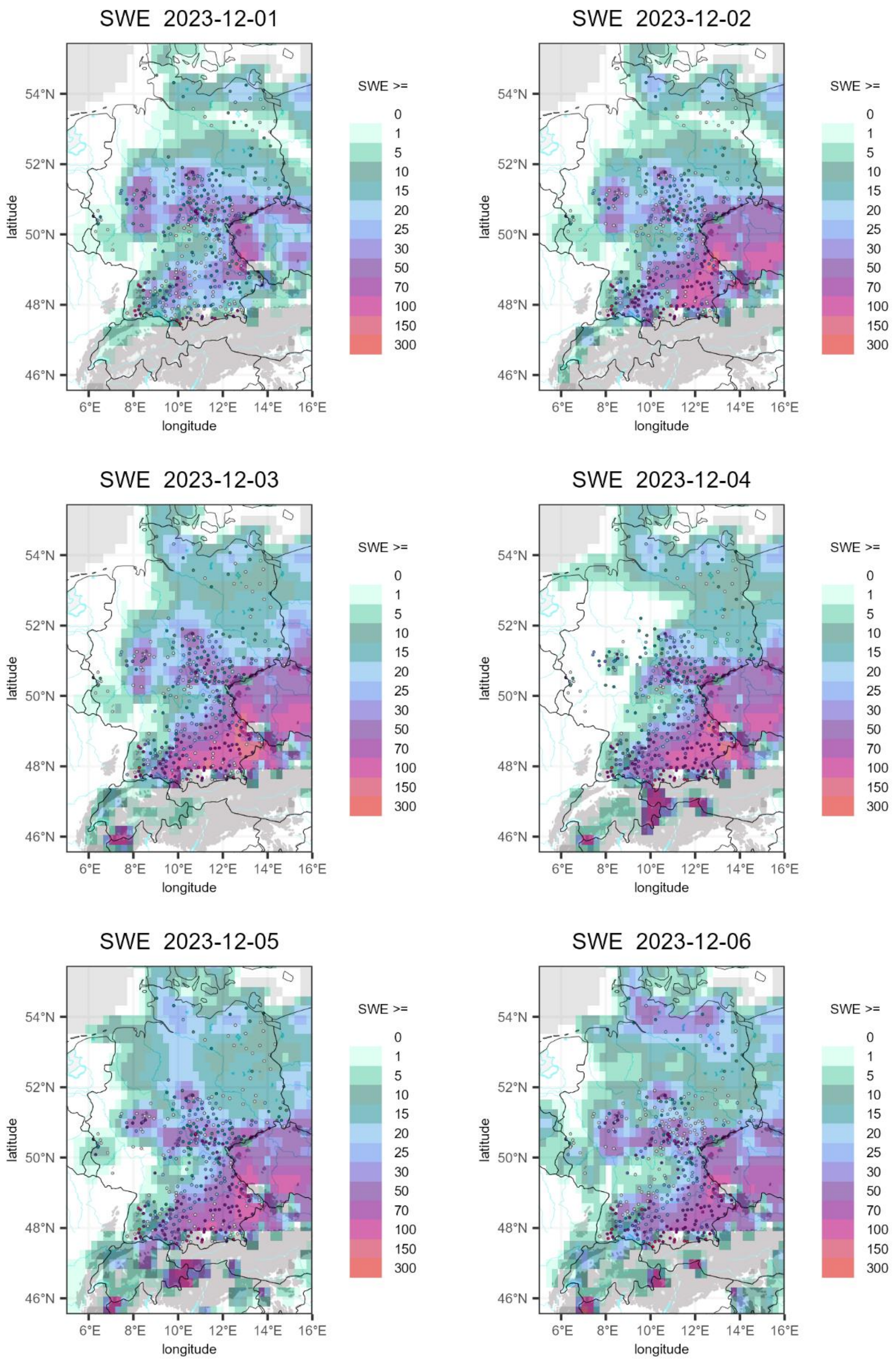

Figure 7: SWE estimates by HSAF H65 (EUMETSAT, 2023) and from in situ measurements at weather stations (DWD Climate Data Center, 2024) for 1st-6th December

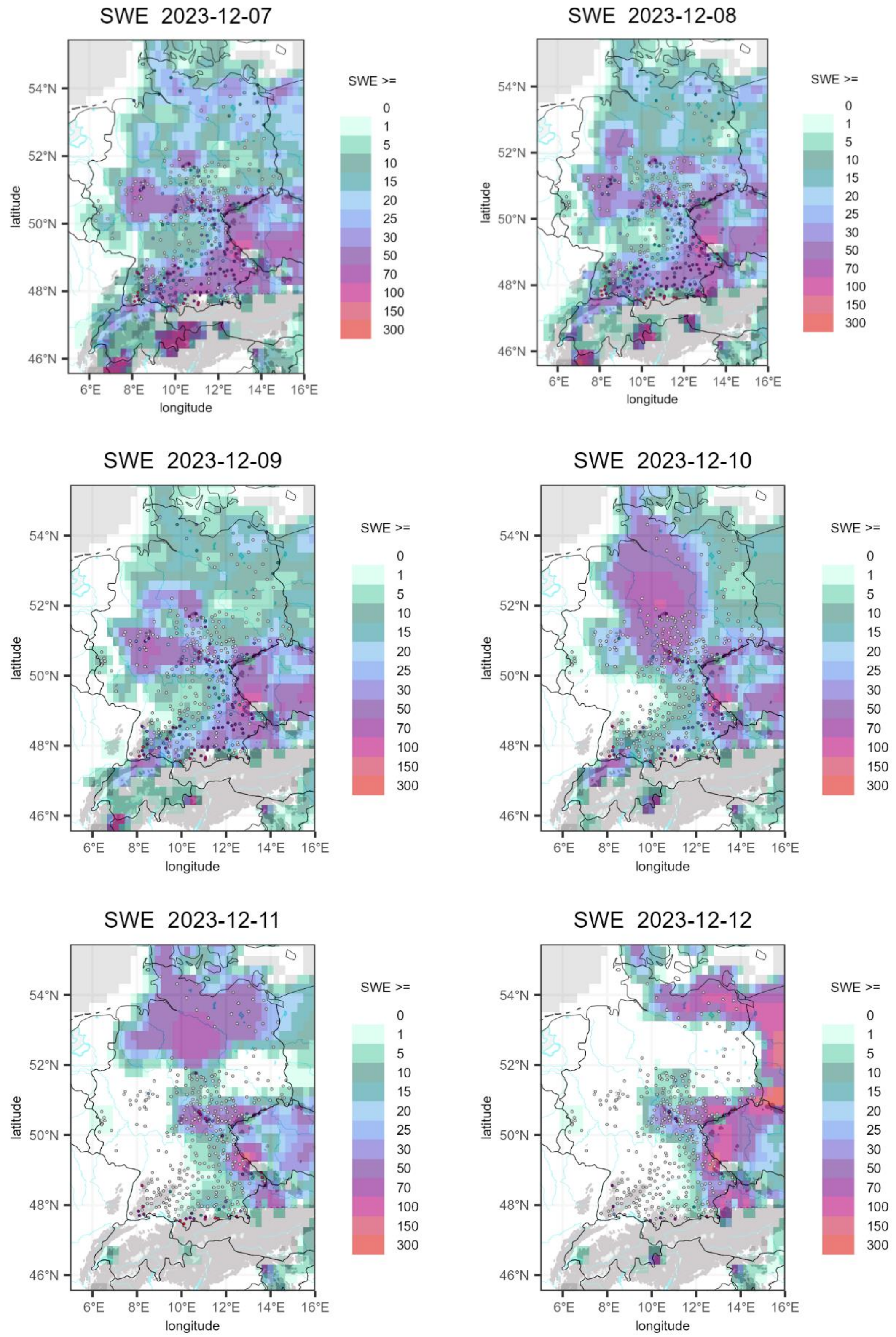

Figure 8: SWE estimates by HSAF H65 (EUMETSAT, 2023) and from in situ measurements at weather stations (DWD Climate Data Center, 2024) for 7th-12th December

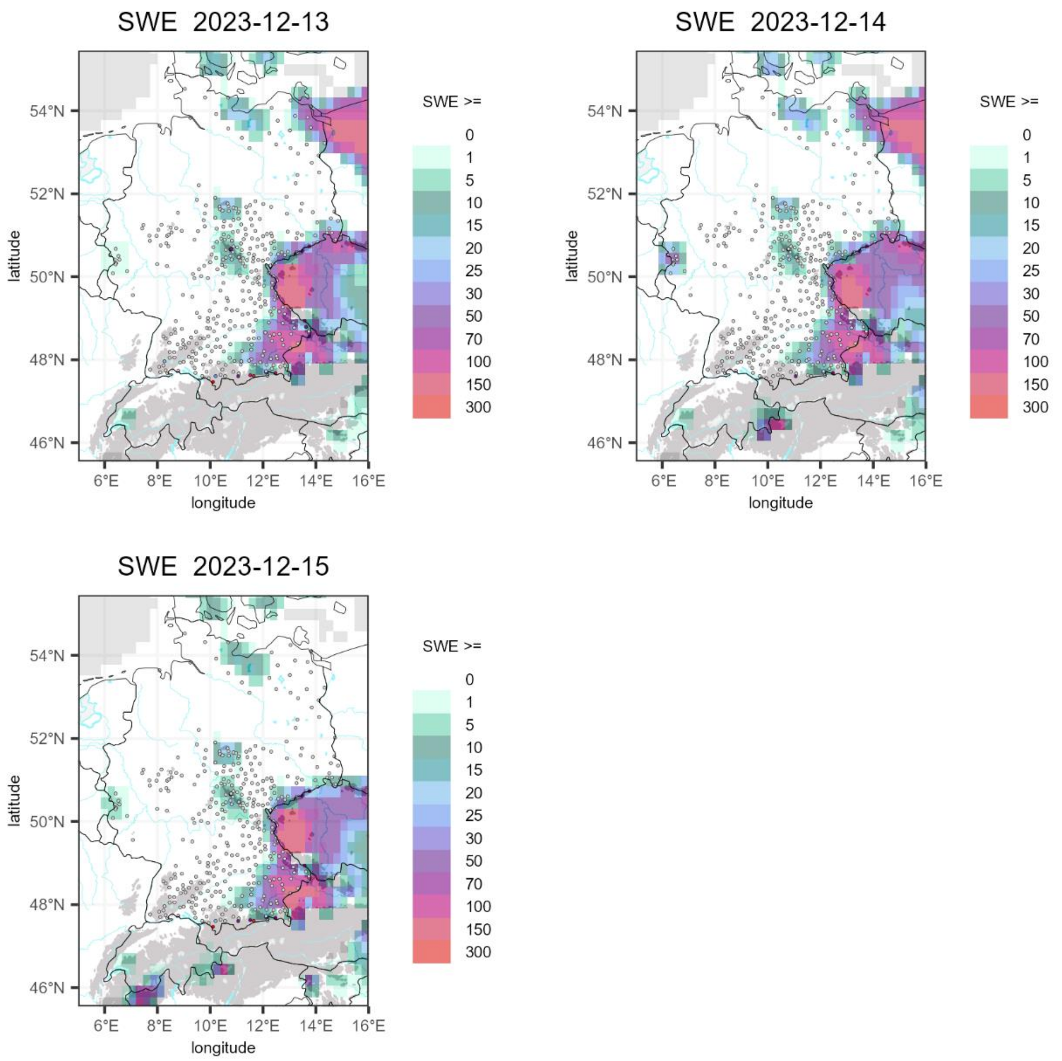

Figure 9: SWE estimates by HSAF H65 (EUMETSAT, 2023) and from in situ measurements at weather stations (DWD Climate Data Center, 2024) for 13th-15th December

The temporally variable relationship between H65 and in situ measurements also shows in Figure 10.

The upper graph illustrates POD and FAR over time along with a gradient illustrating the aging process of the snow. Especially at the beginning of the time period, the fraction of snow which was detected as such was comparably low, with a POD below or close to 0.5 until 30th November. A very high POD close to 1 is observable for the time period from 1st to 10th December, followed by a decrease in the following days. The FAR is high at the beginning and the end of the time period but falls below 0.25 from 28th November until 7th December.

These results illustrate the difficulty of detecting local snow, especially when on mountain ranges. On the other hand, they show the over-sensitivity to local snow, where often H65 SWE *snow* records cover a wider area than suggested by local measurements. When there is wide-spread snow coverage, on the other hand, H65 performs well: not only detecting snow accurately (high POD and low FAR), but also identifying “hotspots” and matching SWE measurements from stations well.

This also becomes apparent when inspecting the lower graph in Figure 10. The ME shows a high variability with a mean deviation of H65 observations from station measurements ranging between -63 mm and +13 mm. Deviations are within the range of +-25mm from 1st until 7th December. However, at the beginning of the time period and especially towards the end there is a tendency by H65 to underestimate SWE. This suggests that, especially for low snow depths and for aging snow, SWE is underestimated by H65.

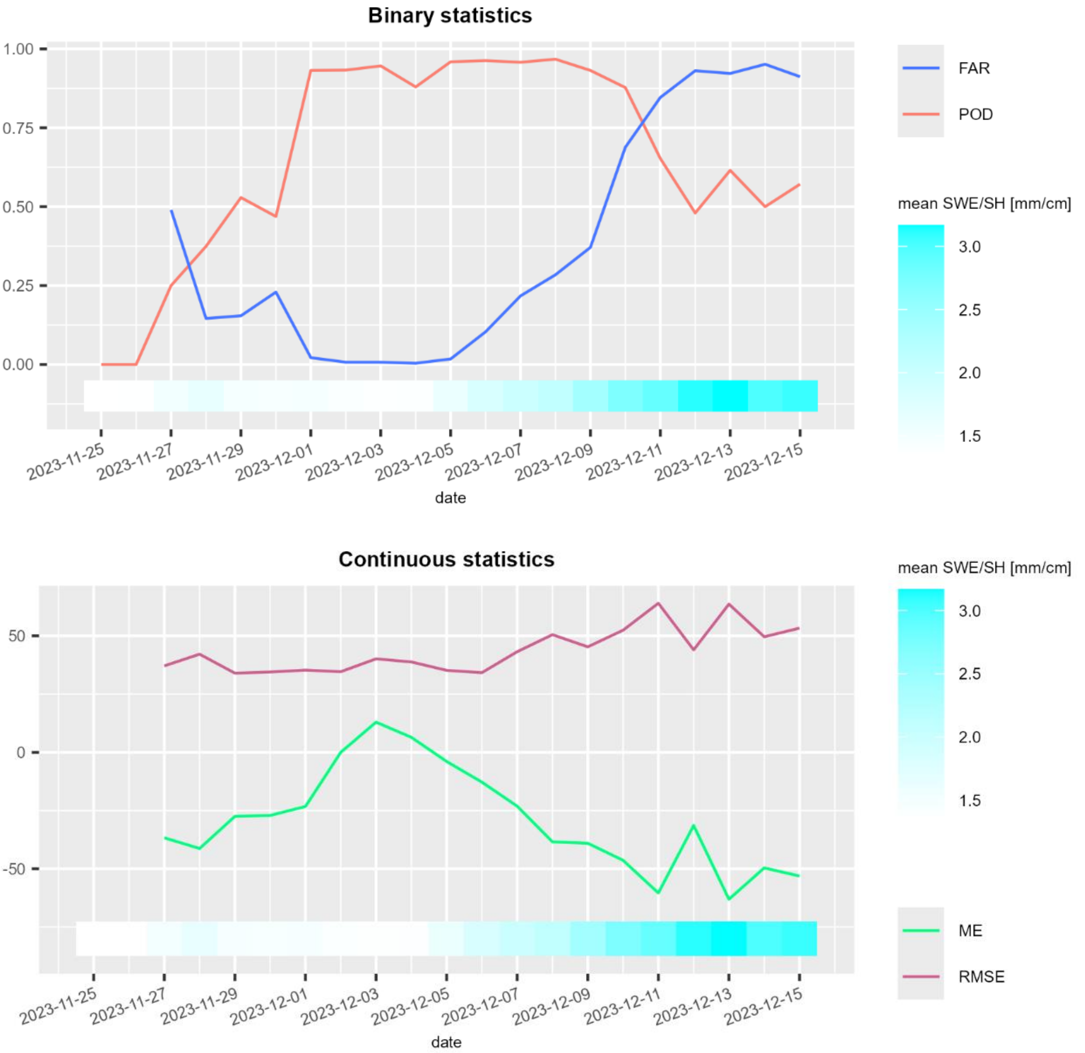

Figure 10: POD [-], FAR [-], ME [mm] and RMSE [mm] over time (25th November-15th December 2023) for H65-station-intercomparison (DWD Climate Data Center, 2024; EUMETSAT, 2023) in Germany. Continuous statistics are only computed on the fraction of data where both, H65 and in situ measurements, suggested snow and the snow height measured was between 20 and 100 cm.

4.2 Basin-scale comparison of mean SWE from H65 observations and LARSIM-ME modelling results

4.2.1 Comparison for major German sub-basins

Figure 11 and Figure 12 illustrate the temporal evolution of mean SWE for the eight sub-basins of the major river basins in Germany. There is significant variability in the quality of H65 observations compared to LARSIM-ME SWE estimates.

A strong underestimation of mean SWE by H65 is visible for Rhine 1, Danube 1 and Danube 2 with an ME ranging between -45 mm and -95 mm (see Table 2). The underestimation can be ascribed to the partially alpine basins where the steep slopes render the detection of snow more difficult.

All other catchments show a good comparability of H65 to LARSIM-ME for the time period from 1st until 9th December. Especially, sub-basins Rhine 2 and Elbe 1 (river basins dominated by low mountain ranges) suggest high similarity between satellite products and LARSIM-ME with CCs of 0.7 and 0.67 respectively and a small average deviation of +-3 mm. However, the missed snow onset by H65 becomes visible on all of these catchments. In addition, the wide-spread snow coverage recorded by H65 in Northern and Eastern Germany as off 10th December also shows in the Northern and Eastern Sub-basins (Rhine 3, Weser, Elbe 1 and Elbe 2) as peaks in SWE, unmatched by LARSIM-ME.

Table 2: Quality metrics for mean SWE comparison of H65 (EUMETSAT, 2023) to LARSIM-ME on sub-basins of the major river basins in Germany (25th November-15th Decemer 2023)

	Rhine 1	Rhine 2	Rhine 3	Weser	Elbe 1	Elbe 2	Danube 1	Danube 2
Area [km^2]	35,897	103,652	20,347	37,718	94,060	37,890	56,401	20,252
N_{obs}	21	21	21	21	21	21	21	21
Mean SWE (LARSIM-ME) [mm]	102	7.4	4.9	7.7	19	2.9	56	95
RMSE [mm]	99	4.8	4.9	13	8.8	7.9	47	75
ME [mm]	-94	-3.1	0.61	3.6	2.0	3.8	-45	-73
CC	-0.39	0.70	0.49	0.25	0.68	0.16	0.79	0.72

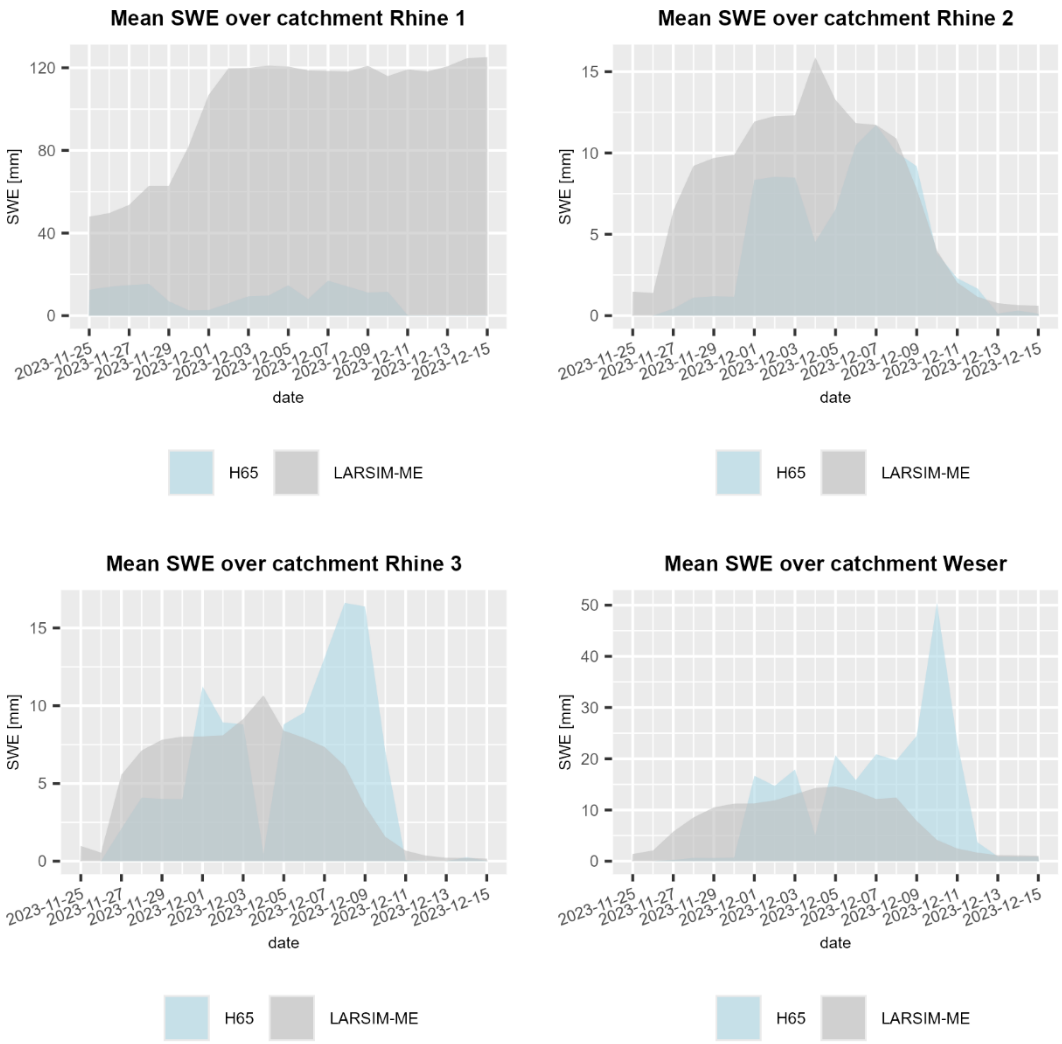

Figure 11: Basin-scale comparison of H65 SWE data (EUMETSAT, 2023) to LARSIM-ME modelled SWE (BfG, 2023) for Rhine and Weser river sub-basins.

Figure 12: Basin-scale comparison of H65 SWE data (EUMETSAT, 2023) to LARSIM-ME modelled SWE (BfG, 2023) for Elbe and Danube river sub-basins.

4.2.2 Comparison for catchments in Eastern part of Germany

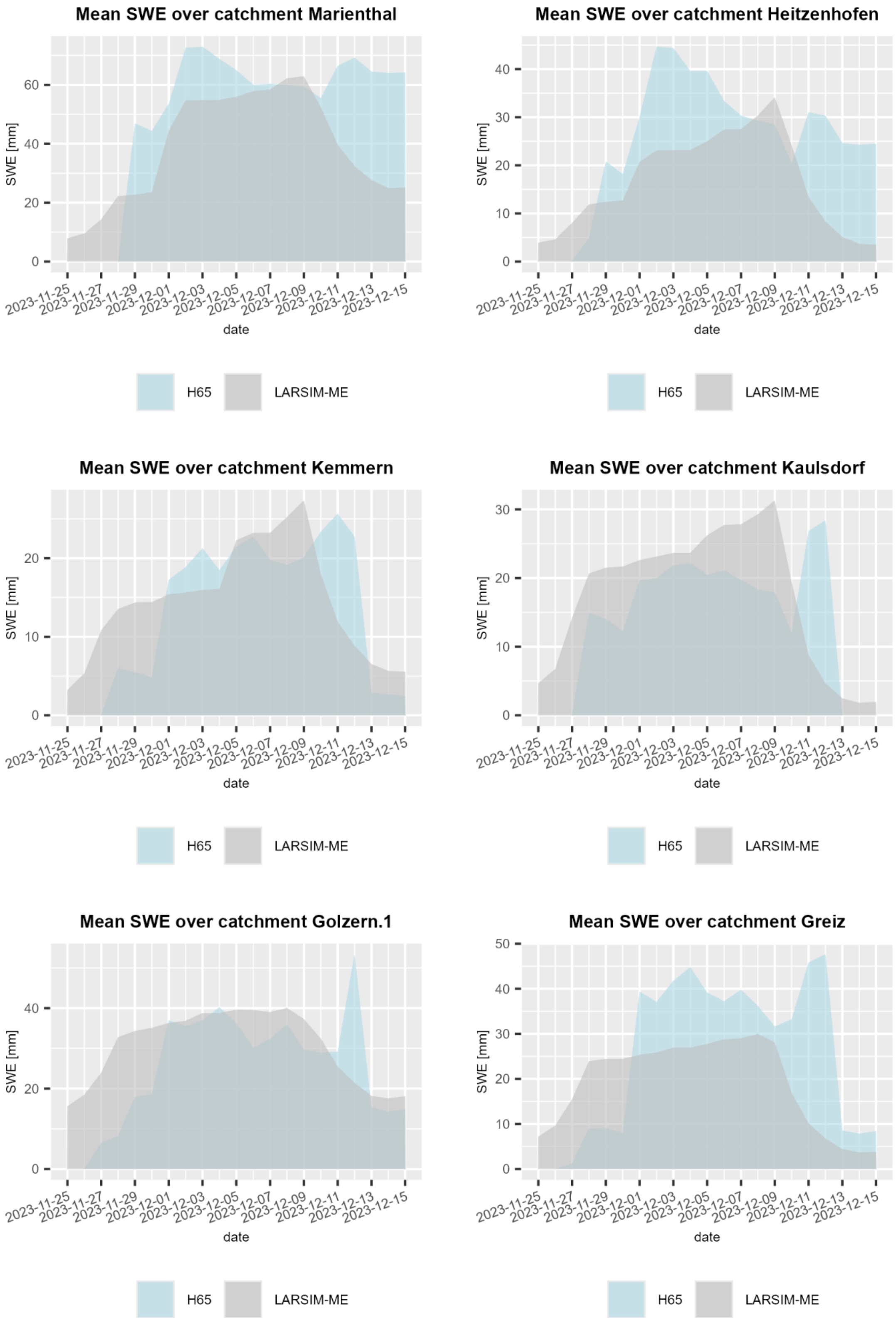

Figure 13: Catchment-scale comparison of H65 SWE data (EUMETSAT, 2023) to LARSIM-ME modelled SWE (BfG, 2023)

Table 3: Quality metrics for mean SWE comparison of H65 (EUMETSAT, 2023) to LARSIM-ME (BfG, 2023) on six catchments in Eastern Germany (25th November-15th Decemer 2023)

	Marienthal	Heitzenhofen	Kemmern	Kaulsdorf	Golzern 1	Greiz
Area [km²]	2,590	5,432	4,251	1,665	5,422	1,255
N_{obs}	21	21	21	21	21	21
Mean SWE (LARSIM-ME) [mm]	38	16	14	17	30	19
RMSE [mm]	21	14	6.8	9.5	12	16
ME [mm]	11	8.2	-1.3	-3.6	-5.7	6.0
CC	0.71	0.60	0.69	0.59	0.59	0.48

Figure 13 depicts the temporal evolution of mean SWE for the six catchments in Eastern Germany. For all catchments there is a reasonable similarity between LARSIM-ME estimates and H65 data. CCs range between 0.48 and 0.71 and MEs are no larger than 11.42 mm (see Table 3).

Again, the snow onset is delayed on all catchments and the melting process is not correctly captured. Rather, there is another peak in SWE from H65 on 10th-12th December, not supported by LARSIM-ME data. In addition, during the main snow days, SWE is overestimated in catchments Marienthal, Heitzenhofen and Greiz.

5 Conclusion

The present case study has assessed the quality of H65 data compared to in situ measurements at weather stations operated by Deutscher Wetterdienst and model estimates by water balance model LARSIM-ME on snow water equivalent SWE. Time period 25th November to 15th December 2023 was picked as the period of interest for this in-depth analysis of H65 data for the strong impact that snow melting at the end had on discharges at many stream gauges in Germany.

The results reveal a good match between H65 data and in situ measurements, in terms of spatial extent and magnitude, for the time period of 1st-10th December. More local snow phenomena and thinner snow layers, on the other hand, seem to be more challenging to quantify. Hence, the snow onset is delayed, as is the melting process. Contrary to in situ data, H65 seems to suggest wide-spread snow coverage in Northern and Eastern Germany, well beyond the 10th December.

In a second step, the quality of H65 data was held against SWE estimates by LARSIM-ME. The LARSIM-ME model is an operational hydrological model at BfG and therefore not primarily dedicated to SWE prediction, nor are internal SWE estimates validated with ground data. Therefore, results by this model need to be interpreted with caution. However, qualitative results obtained from the comparison of SWE from H SAF H65 to LARSIM-ME are consistent with prior findings.

The missed snow onset leads to an early accumulation of snow in LARSIM-ME unmatched by H65. On the other hand, peaks in SWE after 10th December only appear in the spatially averaged H65 data while according to LARSIM-ME SWE in all catchments has started to decline by 9th December.

For the time period of intense and wide-spread snow occurrence, spatially averaged H65 observations compare reasonably well to LARSIM-ME estimates at catchment scales of 1,000 to 100,000 km^2. Only for those sub-basins with alpine influence, the insuitability of H65 for snow depths > 1m and SWE > 100 mm leads to a consistent underestimation of SWE by H65.

As mentioned above, the two data sources within the present case study have their individual sources of uncertainty:

1. In the case of in situ data, measurement errors, the handling of missing values and the very limited spatial representativity of measurements may affect the quantitative outcomes of the present analysis.
2. LARSIM-ME provides modelled SWE data and there is no direct way of assessing the quality of these estimates as reference data for the present case study.

However, qualitative results generalize well among the two data sources. Therefore, the dual approach could be considered a good way to counteract the individual uncertainties of the two data sources.

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