Response to the review of "Should radar precipitation depend on incident air temperature? A new estimation algorithm for cold climates."

RC1: Responses to S.R. Fassnacht (Referee 1)

The authors wish to thank the reviewer for his constructive comments and corrections to the discussion paper. In the following, we have responded to each of the comments from the reviewer. The comment from the reviewer (RC) is in italic font while the author comment (AC) is in blue normal font and changes in the manuscript (CM) as normal text. Revised Figures are added herewith as Appendices.

The authors tackle an important problem of improving radar estimation of rain versus snow. Their word does provide some new insight, but there are some problems, including that the work needs to brought back to hydrometeorology. At present it is a numerical exercise with limited explanation about the possible physical meaning of the results and their implications. There is no Discussion section in this paper, so it is difficult to know how the results compare to those in the literature. The meaning of beta_P and beta_T need to be better clarified; are used to determine the error in the radar-based precipitation estimate compare to the gauge estimate. The authors use the term "rain gauges" throughout. This is incorrect, as they are measuring precipitation. Please correct this accordingly.

AC / CM: The section "Results" will be renamed as "Results and Discussion" and the results will be further discussed in this section. The term "raingauges" will be replaced with precipitation gauges throughout the manuscript. While we have attempted to provide physical arguments through discussion of results, especially by constructing hypothesis tests (such as for precipitation that occurs for temperatures greater than 10^{o} C), we agree with the reviewer that this has not come out clearly enough. Hence, our revisions will try and articulate the reasoning for the hypothesis tests conducted keeping in consideration the physical arguments being tested. We expect the physical reasoning for the data analysis reported here will come out more clearly and strongly and also make the overall paper a stronger contribution as a result.

There is no mention of precipitation undercatch. See SPICE <http://www.wmo.int/pages/prog/www/IMOP/intercomparisons/SPICE/SPICE.html> among other references. This is crucial and without gauge undercatch (and other corrections), winter gauge precipitation estimation can be too low by a factor of up to3. There are data from Haukeliseter, Norway that would be relevant.

AC: We agree with the reviewer that precipitation undercatch is more important for snowfall than for rain. However, for the gauges used in this study, there is lack of data for performing wind corrections. Only 15 out of 88 gauges are equipped with wind speed measurement and thereby are suitable for correction. By using the Nordic correction model (Wolff et al., 2015), we corrected precipitation at temperatures below +3^{o} C for wind induced under catch for these 15 gauges. It was found that 14 gauges out of 15 showed lower correlation between radar precipitation and gauge precipitation after wind correction. Further, the total radar precipitation volume is less than the uncorrected gauge precipitation volume computed from the data used in the study for all those 15 gauges. We think this analysis show that there is a winter underestimation of precipitation by the radar. However, the main arguments being tested still hold with the equal statistical significance as before, and hence the research contributions for the paper are still just as valid.

CM: Text will be included to the paragraph on p3, l1-14 and the precipitation under catch and catch correction will be discussed.

The figures are reasonable, but the captions are too short and it is difficult for the reader to know exact content of the Figures. The improvement in RMSE (Figure 3-5) is somewhat unclear as the same colour ramp is used in Figure 2 that has a very different

meaning. Also, the colour ramp is different in Figures 3-5; be consistent.
AC / CM: Captions will be elaborated further in order to describe the exact content of the Figures. The colour ramp in Figure 2 will be changed and consistent colour ramp will be used in Figures 3-5 (ref. Figure 2,3,4 and 5, Appendix).

page 1, line 19: The term "raingauges" is often correct, as they are usually used. However, these specifically refer to those that designed to measure rain and not precipitation (snow and rain). It is suggested that attention be paid to this throughout the text to ensure that precipitation gauges are distinguished from rain gauges. The paper deals with snow and rain.
AC: We agree with the reviewer that the term "precipitation gauges" is correct. All gauges used in the study are designed to measure precipitation (rain and snow).
CM: "raingauges" will be replaced with "precipitation gauges" throughout the text.

p1, l23-24: The sentence "[t]he backscattered energy is termed as reflectivity and used as the basis to quantify the associated precipitation." is awkward. Its meaning can be understand, but the sentence should be more succinct. "The backscattered energy is measured as reflectivity which is used to estimate precipitation."
AC / CM: The sentence will be updated as suggested by reviewer.

p2, l3: The comments related to error are vague and some of the errors could be listed: "many sources of error. These errors"
AC / CM: Errors will be listed and text will be updated.

p2, l7: "these uncertainties" is ambiguous
AC / CM: The text will be reworded

p2, l9: delete "being made"
AC / CM: It will be done.

p2, l10: in the phrase "uncertainty during conversion from reflectivity to rain rate", the words "during conversion" are unclear. Is this in the "computation of?"
AC / CM: Yes, "computation of" will be used in the text.

p2, l10: As in my comment about p1 l19, be careful with the word "rain" as it is the computation of precipitation (rate), not just rain rate.
AC / CM: Text will be updated with the term "precipitation rate" throughout the manuscript.

p2, l17-19: I do not agree with this statement. Most radar systems have used one Z-R relation for rain and another for snow, often calibrated in situ.
AC: We agree with the reviewer. The Norwegian radars use a single Z-R relationship however, most radar systems in cold climate countries have used two sets of Z-R relation, one for rain and one for snow, often calibrated in situ to measure water equivalent radar reflectivity.
CM: The sentence will be corrected.

Figure 1. This caption is uninformative. Also, what are "greater" and "lower" rain gauges?
AC: "greater" – greater regression slope for rain data pairs than for snow data pairs
"lower" – lower regression slope for rain than snow data pairs in a linear regression analysis for data pairs of radar precipitation rate and gauge precipitation at gauge locations.
CM: Caption will be updated (ref. Figure 1, Appendix)

p3, first paragraph: the wording is confusing as to what was done here. The "linear regression analysis of observed hourly pairs of gauge precipitation and radar rain rate

measurement" is difficult to understand. Later it is stated that "the raingauge locations with a greater regression slope for rain than snow are displayed with red open circles." Is the regression slope the best approach? This may or may not be the same as the net quantity estimated from gauges versus radar. What is the length of record used in this analysis? The terms "pairs" is not clear. Is this pairs of stations?

AC: This was a preliminary investigation of radar precipitation rate and gauge precipitation data pairs at gauge locations using simple linear regression. We agree with the reviewer that the linear regression results (regression slope or correlation coefficient) may or may not be the same for the net quantity estimated (precipitation corrected for catch error) from gauges. However, we did catch correction for precipitation at temperatures below +3° C and performed a similar comparison as done for the total gauges presented in the manuscript. The results of the comparison of correlation coefficient before and after wind correction were same for all these 15 gauges. As mentioned above, the radar underestimates the precipitation.

The entire dataset (the six-year period from January 2011 to April 2017) was used for this analysis.

The term data "pair" denotes a pair of values of gauge precipitation and radar precipitation at a timestep at a gauge location.

CM: Text will be reworded. Additional discussion will be included on the changes that occur by consideration of catch correction on the selected stations where wind measurements exist. We will better emphasise that this is a motivational result that aims to illustrate why there are differences in radar estimates for precipitation and snow, to be followed by the more thorough analysis presented later.

p3, l18-21: Fassnacht et al. (1999) used weather radar from continuous (winter and summer) hydrological modeling.

AC / CM: Text will be updated together with citation (Fassnacht et al., 1999).

p3, l25: The phrase "the rain drop is shaped by temperature" should be expanded to consider the snow crystal. This is mentioned in the next sentence, but seem to present a rain-centric approach.

AC / CM: The term "rain drop" is changed to "rain drop or snow crystal"

p3, l31-32: "The probability of occurrence of snowfall versus temperature shows an approximately 'S' shaped structure in these studies." This is not always true, as it can be linear (e.g., Fassnacht et al., 2013).

AC / CM: Text will be updated.

p4, l8-11: instead of telling us what is in the rest of the paper, give us some objectives or specifics about what research questions are asked.

AC: We will add text to provide objectives of the study, however we want still to keep the paragraph which briefly outline the contents of the paper.

CM: Text will be added to the Introduction on p4, l8.

p4, l14-15: "Theoretically, radar reflectivity measurement of rainfall and snowfall do not differ much." I disagree. Justify this comment

AC: What we meant by this sentence is that the radar is a single instrument measures both rain and snow using the same methodology. We agree that there are differences in reflectivities and how these are handled.

CM: Text will be reworded. The above sentence in the manuscript will be replaced with "radar is a single instrument that measures both rain and snow using the same methodology".

p5, l2-3: yes, near surface air temperature can be used to estimate phase, but lapse rates including inversions must be considered.
AC: The present study used near surface air temperature (gridded air temperature at 2 m above ground) at gauge location. Gridded temperature is derived by interpolation where the terrain elevation information is used.

p5, l12-13: This sentence comes out of nowhere. Provide a context for this statement
AC / CM: A topic sentence will be added to the paragraph on p5, l12.

p5, l18-19: Is this for rain only or precipitation? Please clarify and be consistent.
AC / CM: This is for precipitation in general. "radar rain rate" is replaced with "radar precipitation rate".

p5, l32: state which "an additional covariate." I assume that it is temperature.
AC / CM: Yes, it is air temperature. Sentence will be reworded.

p5, l2-4: delete these, we don't need a foreshadowing of the next section
AC / CM: Text will be updated.

p6, l6: be careful with words like "prediction." I think you mean "estimation"
AC / CM: Yes, "Prediction" will be changed with "estimation".

p6, l12: you may want to include a location sub-script, such as i or i, j, if you think 2-D space is necessary.
AC: Yes, subscript i,j can be included to specify spatial space, but we prefer to keep the equations as they are because we think this makes them more tidy and easy to read. We will state it in the text.
CM: Text will be modified on p11, l12 as "…. at a given geographical location in the two-dimensional space (x, y).

p7, l18: state how many precipitation gauges in the "relatively dense network of raingauges." Again, be careful with the word "rain" gauge.
AC: The maximum is roughly 0.25 gauges/km^2 near Oslo and approximately 0.1 gauges/km^2 near other major cities. See Figure 1 for the distribution of gauges.
CM: Text will be updated.

p7, l13: the RSME equation has been published often enough. It does not need to reappear here. Remove equation 4.
AC / CM: Eq.4 will be removed and related text will be updated.

p7, l21: specifically which wavelengths are used?
AC: The wavelength of the Hurum radar is 5.319 cm.
CM: The specific wavelength of Hurum radar will be added to the text.

p8, l1, l14, etc.: the word "data" is plural.
AC / CM: It will be corrected.

p8, l1-2: Fix this sentence, "[t]he radar data [are] corrected for VPR that includes handling the bright band correction," as the radar data are not corrected directly for VPR, but issues that appear in the VPR, such as bright band.
AC / CM: Sentence will be fixed.

p8, l3: add an "s" to product"s"
AC / CM: It will be corrected.

p8, l10-11: so, no snow Z-R coefficients are used, only rain (Marshall-Palmer) Z-R? Be more clear with this statement, as "[i]t can be noted that there are no seasonal variations in the Z-R relationship in any of the Norwegian radars" is vague.
AC: Yes, only rain (Marshall-Palmer) Z-R relationship is used.
CM: Text will be reworded as "The Norwegian radar uses the single Marshall-Palmer Z-R relationship for rain for all seasons"

p8, l12: so only some of the period 2010-2017 are used? Which period: "[a] subset of accumulated hourly radar rain rate."
AC: We have used the entire period of 2010 - 2017. We meant a spatial subset for the study area.
CM: Text will be reworded, "subset" will be replaced with "spatial subset".

p8, l17-18: consider showing the hypsometric (elevation) distribution of the precipitation (and temperature) gauges. This could be included in Fig 1.
AC / CM: Distribution of gauges against elevation (hypsometric curve) will be added to Figure 1 (ref. Figure 1, Appendix).

p8, l21: How many temperature gauges are there? Consider using a different symbol in Fig 1 to show which ones are precipitation only.
AC: This study uses gridded air temperature. As we did not use gauge temperature records, we have not shown temperature gauges in this paper.

p8, l21-26: This section on temperature data should be a separate paragraph from the precipitation data. Also, provide more details on how the 1x1 km gridded temperature dataset is derived - how are these data interpolated? This is important, especially since there is some elevation change across the domain (Fig. 1).
AC: Temperature data will be described in a separate paragraph and additional details will be added (Lussana et al., 2016).
CM: The paragraph on p8, l12-26 will be divided into two paragraphs and additional details will be added to the second paragraph, starting on p8, l22.

p8, l28: are there locations with more than one precipitation gauge per 1 km2? Clarify if there are or are not.
AC: Yes, one location near Oslo has three precipitation gauges falls within a 1 km x 1 km pixel. Except for that one, pixels consist of a single gauge.

CM: This information will be added to the text on p8, l29.

p8, l30 and afterwards: define the term "timestamps" or use a different word.
AC: "timestep" can be better term since radar precipitation rate is accumulated over the period (hour).
CM: "timestamp" will be replaced with "timestep".

p9, l1: reword this sentence to something like:" corresponding hourly gauge precipitation, radar precipitation rate estimate, and air temperature for ..."
AC / CM: The sentence will be reworded.

Figure 2: define what the partial weights mean here, likely also referring back to equation 3. Add more in the caption, including that beta_T is beta_P minus 1. I would scale beta_P from 0 to 1 (the true range), rather than 0.2 to 1.
AC / CM: Caption will be updated (ref. Figure 2, Appendix).

p9, l13: "[n]early 70% of the raingauge locations" what "were estimated with associated partial weight for air temperature timestamps." Is this the precipitation adjustment?

AC: It was meant by this sentence that, estimated partial weight is greater than zero at 70% of the gauge locations (62 gauge locations out of 88).
CM: Sentence will be reworded.

p9, l14: I don't see "the circles filled with brown tone colour." I see orange and yellow
AC / CM: It will be corrected. "brown tone colour" will be changed with "orange colour".

p10, l4-5: how does the regression slope in Fig 1 compare to the beta_P in Fig 2? This could be an important comparison.
AC /CM: Unless data are linear, direct comparison is not possible. Regression slope is a measure of linear dependency. Partial weight (beta_P) is derived from partial informational correlation. The partial informational correlation provides a generic measure of statistical dependence of predictors of a general linear or nonlinear system (Sharma, 2000, Sharma and Mehrotra, 2014). An added explanation of this will be included.

p10, l8: I can't see the "dark blue colour circles."
AC / CM: The colour ramp in Figure 2 will be changed. According to the new colour ramp, those four stations are still shown with dark blue colour circles (one in Drammen, two in Fredrikstad and one in Rygge) (ref. Figure 2, Appendix).

p10, l7-10: As my comment on Figure 2 above, this paragraph does not make sense: is beta_P = 0 for these four stations or equal to 0.2? If 0.2, then beta_T is not equal to 1 and temperature is not the single predictor.
AC: Partial weight, beta_P assumes a numerical value of zero for these four stations. This is a result of sampling variability and defies our physical understanding of how radar measurements and ground precipitation is related. To correct for this, a minimum coefficient value of 0.2 is adopted, analogous to the use of a well defined prior distribution on regression coefficients in Bayesian applications.
CM: Sentence will be reworded.

p10, l11: showing Table 1 (the summary statistics) in a figure (histogram) would be more informative, especially due to the discussion of non-parametric approaches in section 2.2
AC / CM: A histogram will be presented with Table 1 (ref. Figure *new nr.* Appendix).

Figures 3, 4 and 5: add to the captions. It is unclear how these Figures are different.
AC / CM: Captions will be updated (ref. Figure 3,4 and 5, Appendix).

p16, l8: the Beven (2012) citation is incomplete, see below.
AC / CM: Reference will be updated.

References

Fassnacht, S., Soulis, E. & Kouwen, N. 1999. Algorithm application to improve weather radar snowfall estimates for winter hydrologic modelling. *Hydrological processes,* 13**,** 3017-3039.

Lussana, C., Ole, E. T. & Francesco, U. 2016. seNorge v2.0: an observational gridded dataset of temperature for Norway. Norway: Norwegian Meteorological Institute.

Sharma, A. 2000. Seasonal to interannual rainfall probabilistic forecasts for improved water supply management: Part 1 — A strategy for system predictor identification. *Journal of Hydrology,* 239**,** 232-239.

Sharma, A. & Mehrotra, R. 2014. An information theoretic alternative to model a natural system using observational information alone. *Water Resources Research,* 50**,** 650-660.

Wolff, M. A., Isaksen, K., Petersen-Øverleir, A., Ødemark, K., Reitan, T. & Brækkan, R. 2015. Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: results of a Norwegian field study. *Hydrol. Earth Syst. Sci.,* 19**,** 951-967.

Appendix – Revised Figures

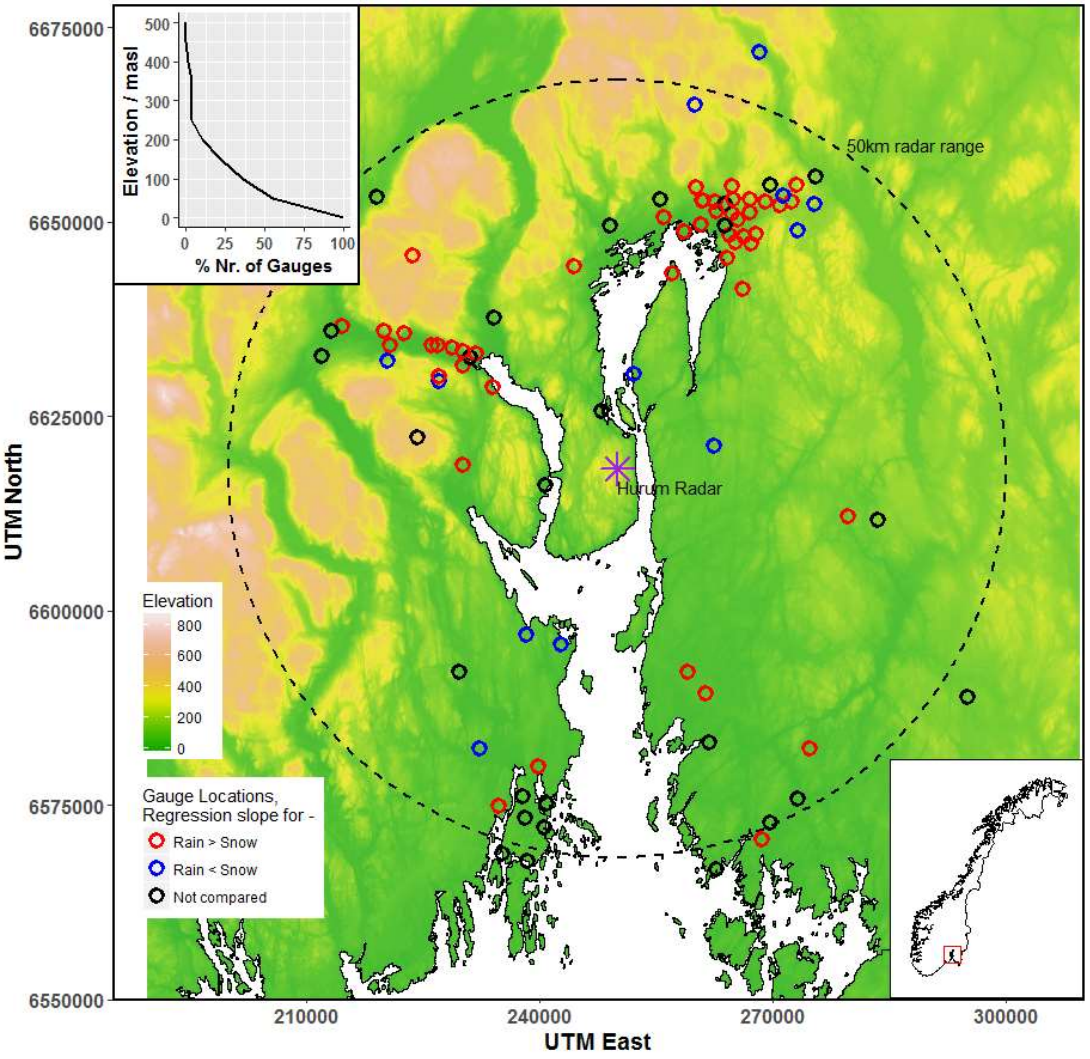

Figure 1. Comparison of regression slope for rain and snow data pairs of precipitation gauges overlaid on topography of the study area, Oslo region of Norway. Hypsometric (elevation) distribution of the gauges is on the top left corner.

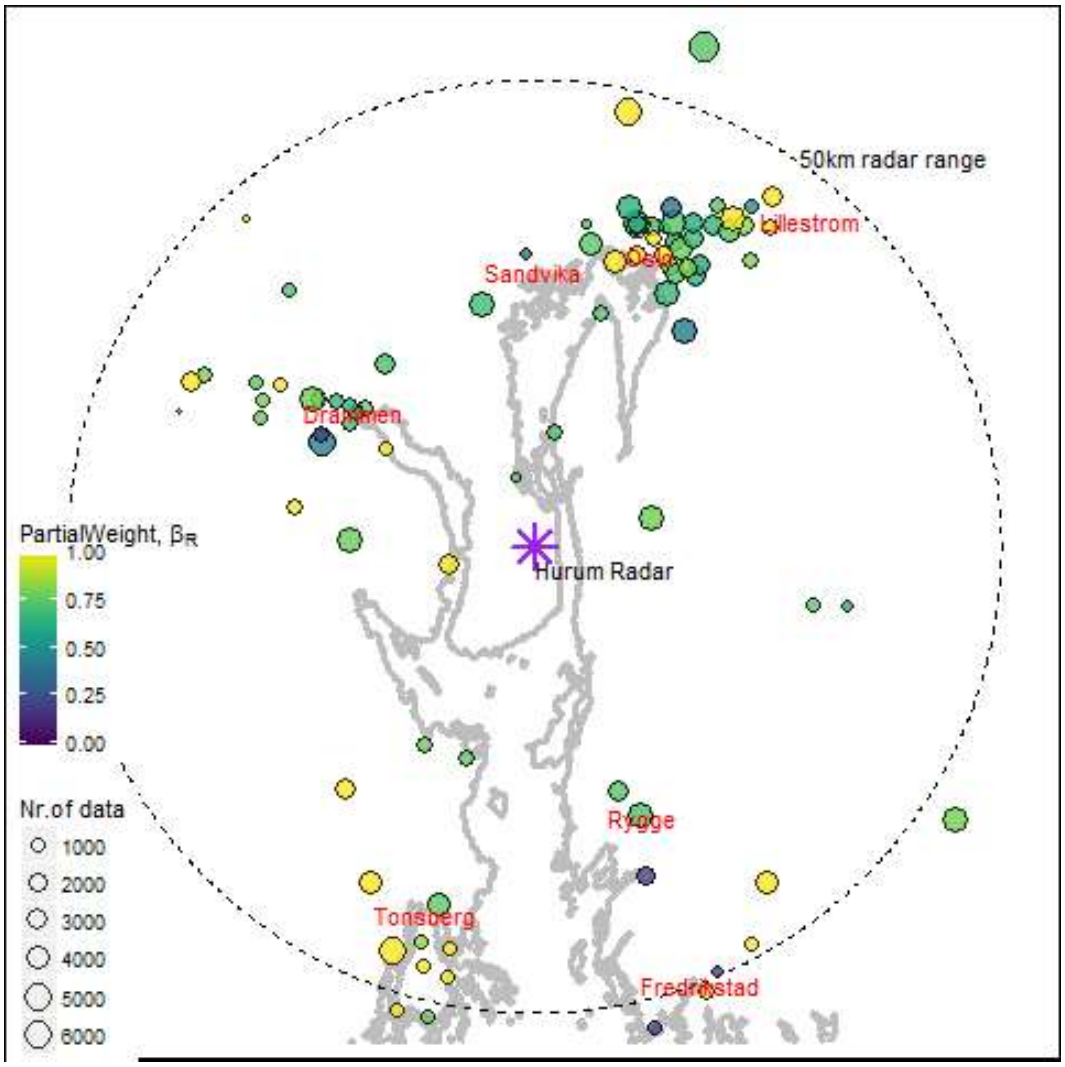

Figure 2. Partial weights of radar precipitation rate (beta_R) for precipitation gauge locations (colour scale) and number of data pairs (circle size), which are used to estimate partial weight at each gauge location, overlaid on the coastline of the study area. Partial weights provide a measure of relative importance of predictor variables on the response and the summation of partial weights (beta_R + beta_T =1) is equal to 1.

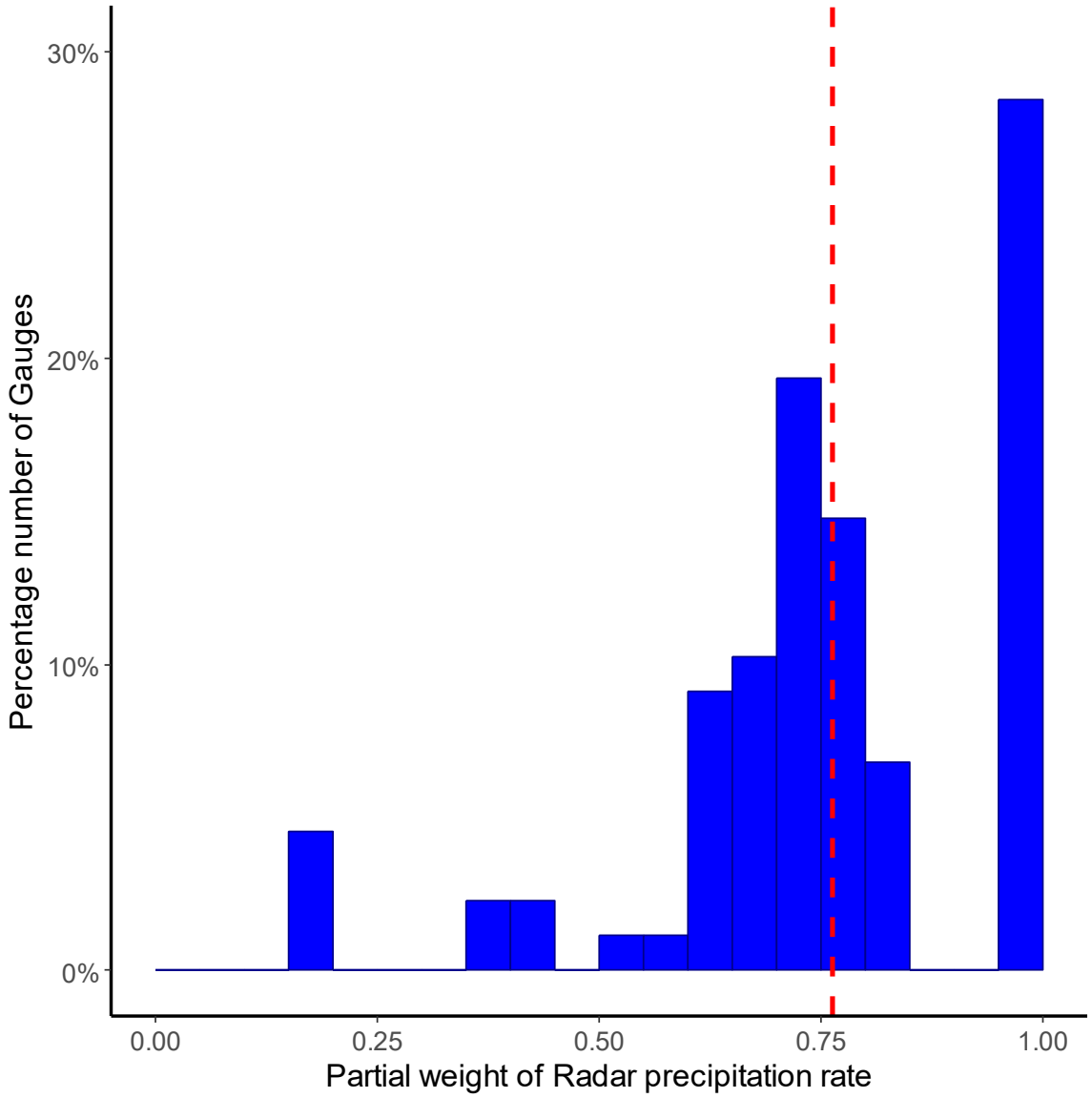

Figure *new nr.* Percentage number of precipitation gauges against estimated partial weight of radar precipitation rate (beta _R) for those gauge locations and the mean partial weight (red dash line) for the study area. Total number of gauges used in the study = 88.

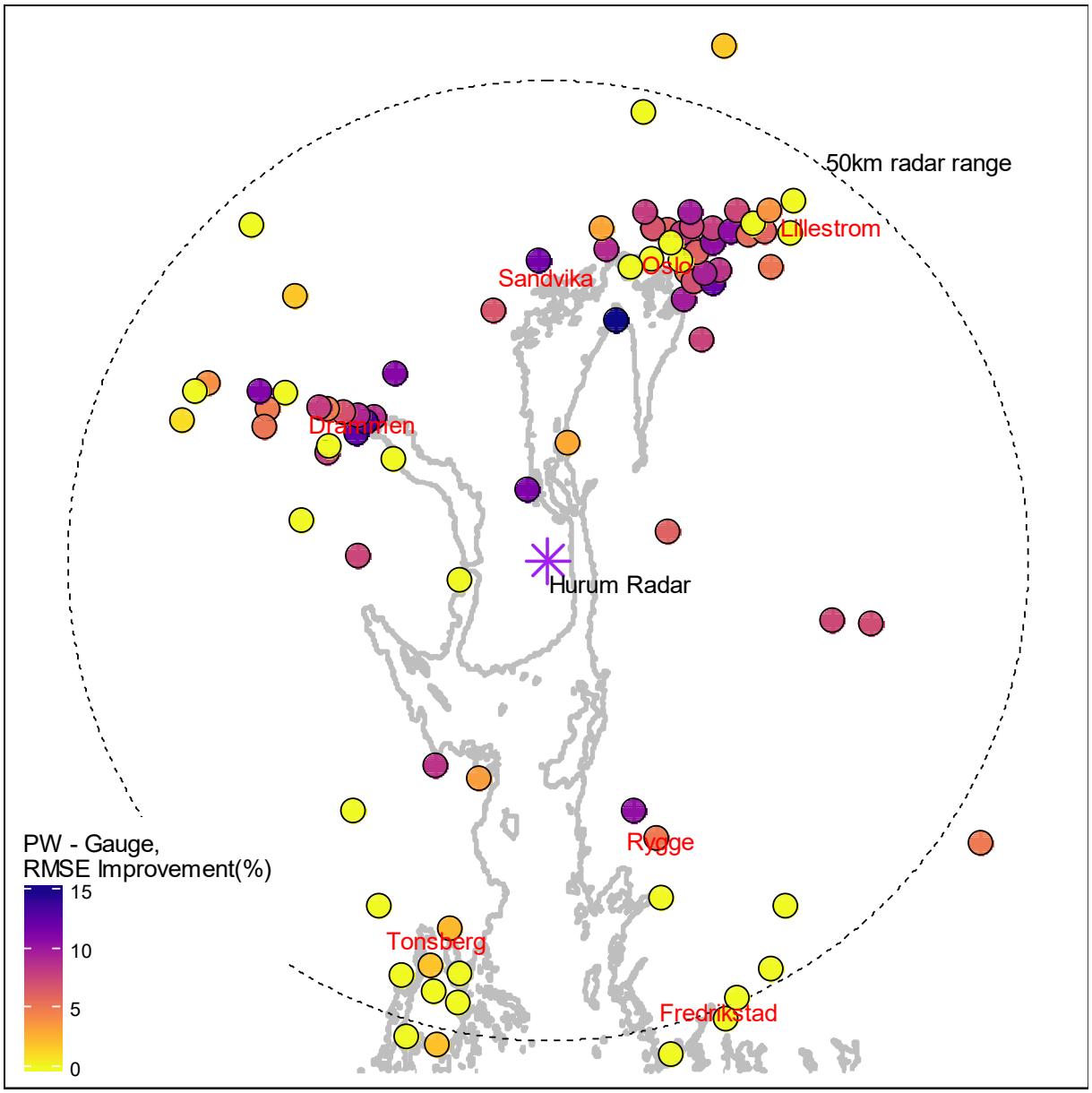

Figure 3. Percentage of improvement in RMSE when an estimated Partial Weight (PW) at each gauge location is used for predictive model with radar precipitation rate and air temperature as the two predictors, compared to radar precipitation rate as a single predictor.

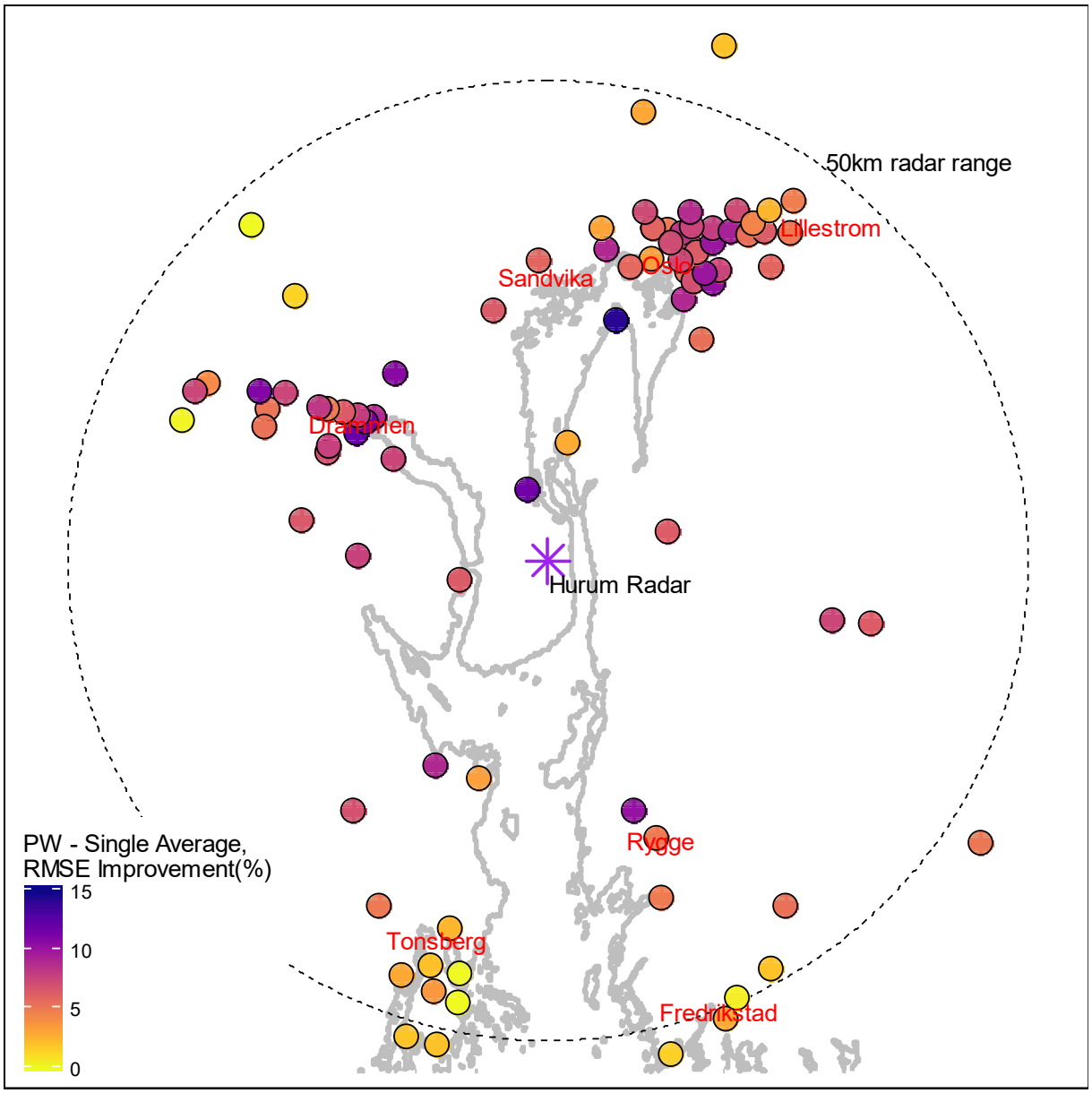

Figure 4. Percentage of improvement in RMSE when a single average Partial Weight (PW) for the study area is used for predictive model with radar precipitation rate and air temperature, compared to radar precipitation rate as a single predictor.

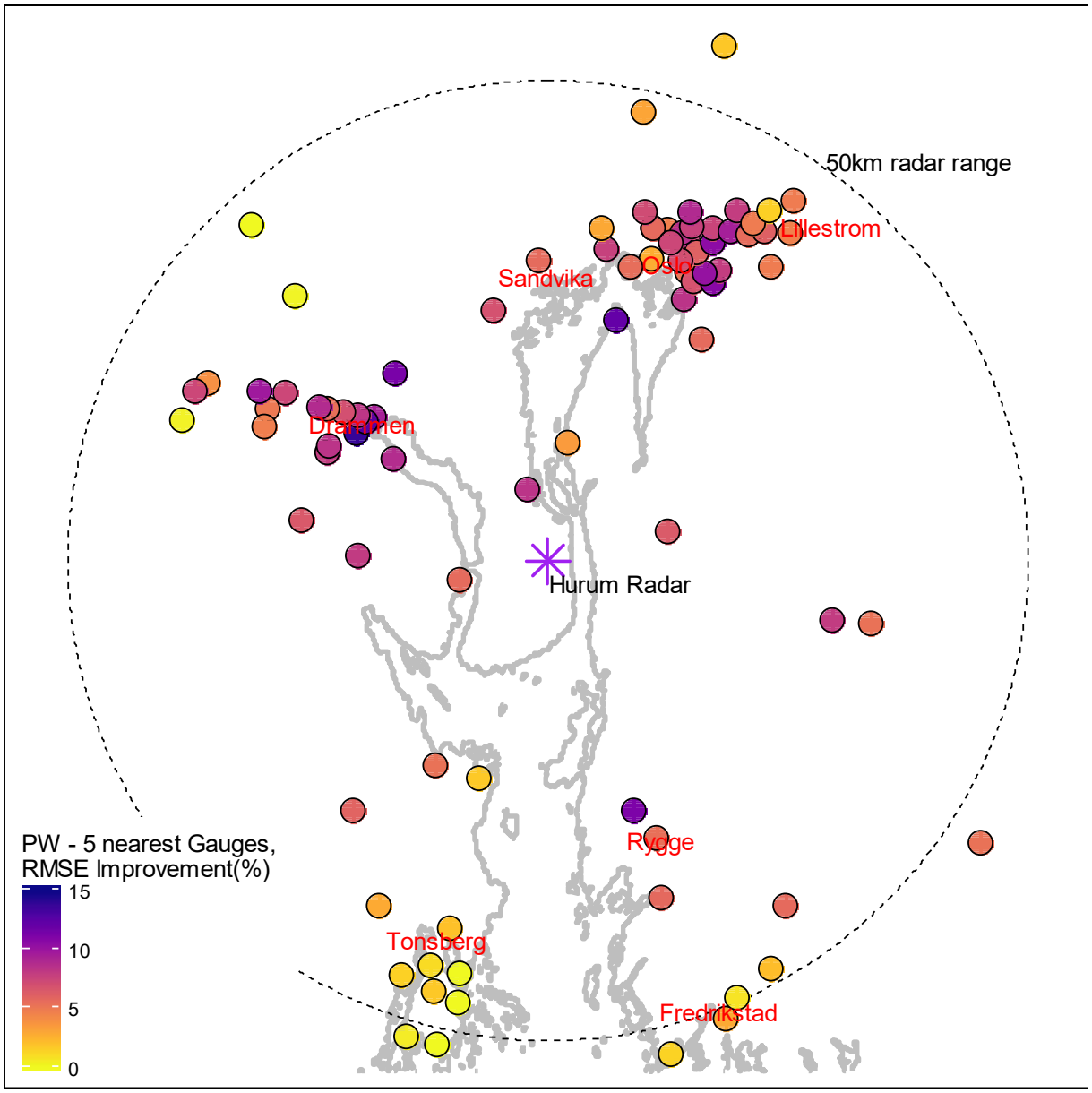

Figure 5. Percentage of improvement in RMSE, when an average Partial Weight (PW) of 5 nearest neighbouring gauges is used for predictive model with radar precipitation rate and air temperature, compared to radar precipitation rate as a single predictor.