Norrköping, 2014-03-12

Response to Reviewer #1

We thank the reviewer for her/his constructive comments and suggestions that led to improvements in the manuscript. Please find below point-by-point reply to your comments.

1. General comments

Weather radar network data for a relatively long period of similar remote sensing equipments is interesting to see. The data filtering seems to be done by "BRDC", and some of the criteria are discussed in this paper. The most problematic areas in radar estimnated precipitation are related in the vertical difference between the radar volume and surface. In this material the gauge-to-radar ratio has been used in corrections, which may be the best method you can have. However, in the Baltic area the effects of the water areas, lake-effect, may not be taken into account if relatively few observations on the surface are available over the sea. The manuscript does not in my eyes clearly say whether the sea areas are included in the analysis or not.

We have included radar range rings in Figure 1 showing the extent of the areas used for the analysis. Since the data up to 80 km in radius are used from each radar station, some of the coastal stations do include data from sea areas as well.

At least the strong snowfall events regularly observed in easterly flows at the north- eastern coast of Sweden does not seem to cause any comments. The relationship between NAO or AO, and precipitation in Sweden is on the other hand something closely related to the relation with wind direction, especially when the upper layer winds are used. This may also explain why there is not much to be said about the lake-effect snowfall that may be below the 85 kPa pressure level surface. Similarly summertime mesoscale phenomena near the coasts, where most of the cities in the northern side of Sweden are, may not show in the analysis. Sea-breeze fronts may also have quite strong echoes from biological targets, insects and birds, that the standard radar data filtering techniques can not handle, and satellite may see the clear weather cloud line as the precipitation source.

Please see response to first question under 3.4 below. Echos from biological targets are occasionally present but they are usually very weak and have negligible effect on our results.

At some point I was not certain if only the liquid water component of precipitation discussed in this paper, as "rain" or "rainfall" is used, but the title and knowing that at some seasons the northern part of the country should get some snow seems to hint that snowfall is considered as well. If this is not the case some more dramatic revisions in the text should be done. On the other hand long term time series of rain gauges have probably been used in similar analyses, and can still be used perhaps.

To clarify, we analysed precipitation (both liquid rain and snowfall). The words rain and rainfall are replaced by precipitation in the revised manuscript.

The positive impact that the radar network data can provide in these studies could be discussed more in this paper. To me it looks like that the better spatial resolution and coverage of large water areas are the strong points. Some weak points exist of course, and perhaps they have been more present in this paper and in my comments.

2. Details
(2) The weather radar data set
- I was surprised to see "constant altitude plan polar indicator", while in every weather radar (and even in other fields of radar research) "plan position indicator" has been used. I was afraid that I have got really old already. On the other hand I though that maybe the modern scientist try to avoid using terminology that people could understand, but I still think that "position" is the standard word used in this context.

Changed to constant altitude plan position indicator.

- Reflectivity factor in this chapter, I was wondering but not checking if the equivalent reflectivity factor has been used. At least it is much easier to deduce from the radar measured quantity, which is reflectivity, as you do not have to decide is the source water drops, ice crystals, sleet, hail or some other stuff. This is probably already decided in the processing of the data set, and the any author just have to use it as it is.

Changed to equivalent radar reflectivity factor.

- Page 1073 lines 21-26, it is probably clear that what is adjusted is a week long accumulation period of precipitation, but this may be clarified, especially if this is not the case.

No, individual point pairs from rain gauges and radars (available every 12 hr) from one week worth of time (to ensure enough point pairs exist) are used. This is clarified in the revised text.

- Filtering was done for the dataset, and the authors may have to deal with that. However, the limits, page 10704 lines 9-10, seem to be quite close to the maximum observed by rain gauges at the ground. The radar data set itself, of course, can show how critical filtering this might be. In general absolute maxima of short periods in this kind of climate could be the most critical ones in this sense.

The filters are applied to remove pixels that display reflectivity very frequently. Such pixels are almost certainly contaminated by clutter. As the filter thresholds are set quite high it is unlikely that real data are removed.

The comment "far fewer" on line 17 makes me ask, compared to what.

The text has been rephrased:

The number of pixels for any radar station is approximately 5150. However, the above described filter can reduce the actual number of pixels on a given year and month. Figure A1 shows the number of pixels used for each of the radars as a function of time. The smallest number of pixels for any radar at any time was 3499 but for the majority of the time the numbers of pixels removed were far fewer. The average number of pixels used per month per radar was 5024. The smallest number of pixels (3499) is still more than enough to statistically represent rainfall distribution (the calculated margin of error remains less than 1.6 %). Furthermore, probability distribution functions (PDF) of rainfall for all stations look very similar (as reflected in Fig. 3), in spite of different number of samples.

(3.1) Diurnal variations in precipitation
- "Often times", page 10706 line 14, ?

The sentence is rephrased.

(3.3) Correlation with NAO and AO indices
- I would need some short clarification about what is meant by these indices, some describtions I have heard are very simple, but this may have evolved a lot during the period of reduced observations and increased modelling.

The AO index is computed as follows. The Empirical Orthogonal Functions (EOF) analysis is carried out on the standardized 1000 hPa geopotential height anomalies poleward of 20N. The first mode from this analysis, which is the leading mode of variability, is used to construct daily indices by projecting daily 1000 hPa height anomalies onto this mode. These indices and the details of the methodology are obtained from here: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml

In case of NAO index, the Rotated Principle Component Analysis (RPCAm using Varimax rotation) is carried out on 500 hPa geopotential height anomalies to obtain the leading teleconnection pattern. The NAO index is further calculated using Least Squares regression.
(http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml)

These definitions are added in the revised text to improve clarity.

- In my opinion the indices are determined by the circulation, and I would not use terms like "impact" and "influence" in the opposite meaning as is in this paper.

The sentences are rephrased to make them coherent.

- Why ERA analysis is not used for temperature and water vapour? I see no positive impact of using always a bit hazardous remote sensing outside the ECMWF's model frame, and combine it with other parameters from the model analysis, but perhaps similar fields are not provided by ERA analyses (page 10709).

Our experience shows that the temperature and water vapour profile retrievals from the AIRS sensor are of best accuracy over the study area. The AIRS-AMSU sensor suite is in fact providing main constraint to ECMWF's reanalysis model used to calculate T and q estimates in the free troposphere, so the differences between satellite and ERA estimates are expected to be minimal.

(3.4.) Rainfall response to wind direction
- Wind in this chapter is obviously at 85 kPa level, should be clarified. If this is the case then the coastline related sea-/land-breeze and wintertime lake-effect snowfall may not be included at all in this comaprison. This should be commented.

Yes, the winds are from 850 hPa. It is now clarified in the revised text. In winter, the northeasterly winds do occasionally lead to lake-or-sea effect snowfall. These very narrow yet powerful snow bands are observed over Sweden, and we believe that we do capture these events. The filtering criterion for quality control is set so high that it should not filter out even the strongest of such events (including the record event over the city of Gävle when snowfall increased from 1 cm on 4th Dec 1998 to 131 cm on

7th). To convince the referee, we show below one such prominent event occurred on 13th Nov 2007 (15:00 hours). It can be seen that the radar is able to capture temporal evolution of such event. Please note that such events are not very common. The most of the northern lakes/sea areas are frozen during winter.

- Daily "rain rate" is perhaps OK, even though some wintertime snowfall events, north of Stockholm for instance, I think, have high daily precipitation rate as well (p. 10711).

Rain rate has been replaced by precipitation rate.

(4) Conclusions and outlook

- Positive and negative correlations (p. 10712 lines 19- 23), the text looked quite contradictory at first glance, while "majority" was so and so in different intensities but north high positive and southeastern high negative at the same time. However, I understand this so that the later sentence refers to the correlations stated in the previous lines. Perhaps needs to be clarified.

The text in question is rephrased.

Response to Reviewer #2

We thank the reviewer for her/his constructive comments and suggestions that led to improvements in the manuscript. Please find below point-by-point reply to your comments.

General comments:
This paper presented information regarding large-scale spatial and temporal variabilities of precipitation in Sweden. The information was based on analyses of 10-year radar-based precipitation estimates. The objective was clearly defined. The results are complimentary to previous findings from gauge data and may provide useful information to the climate modeling and hydrological communities. However, the presentation of methods and data information needs refinements and clarifications are needed for some figures (see detailed comments below). I would recommend the paper being accepted for publication after the following issues are addressed.

We appreciate the encouraging comments by the reviewer.

Detailed Comments:
1. Line 60: Zhang et al. "2013" or "2011"?

Zhang et al. 2011. Corrected in the revised manuscript.

2. Line 94: It would be helpful to show the 80km radar range rings in Fig.1.

This has been included.

3. Line 136-141: On what time scale (e.g., 1hr or 3hr accumulations) was the gauge adjustment applied?

The adjustment is based on 12hr gauge accumulations from the past 7 days. This adjustment is then applied to the 3hr radar accumulations images. The text has been revised to clarify this.

4. Line 144: "filer" or "filter"?

Corrected.

5. Line 173: What are "the pixels around an individual radar station"?

The data set consists of composite images. From these images, pixels around individual radar stations were extracted.

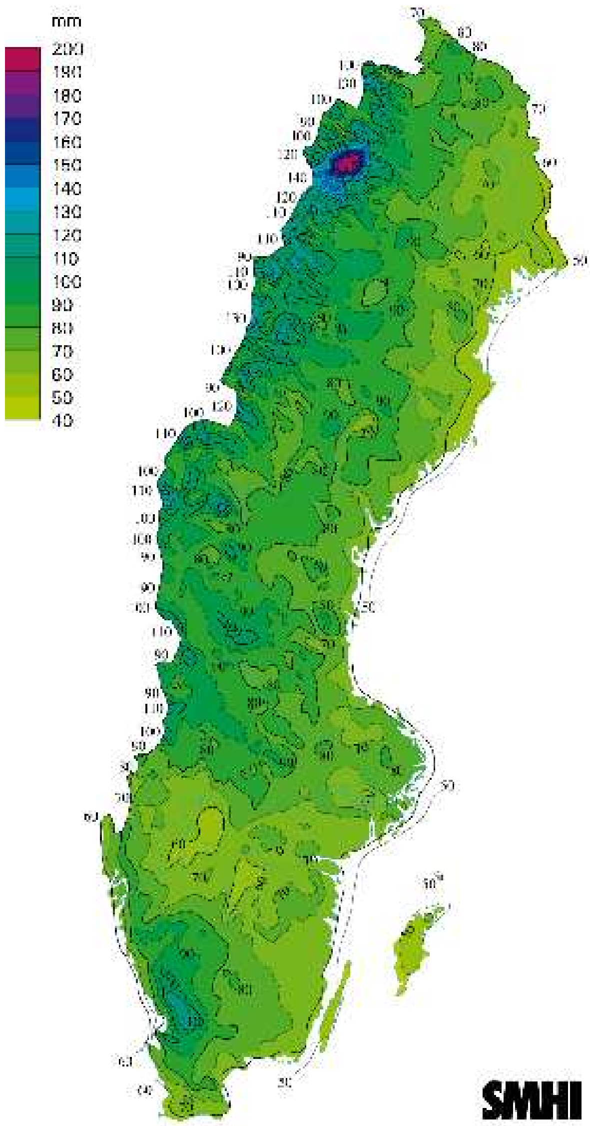
6. Line 210-212: Please describe how the "absolute precipitation frequency" in Fig.2 was calculated.

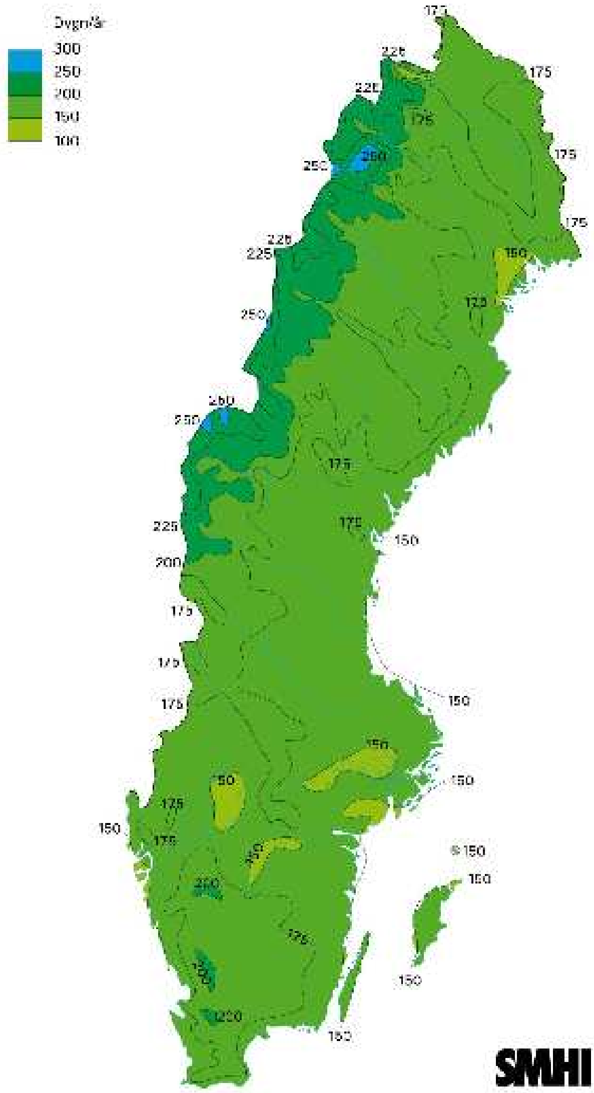
The absolute precipitation frequency is computed as the number of observations when precipitation was encountered divided by total number of observations. This is now clarified in the revised text.

7. Line 214-218: There appear to be some "outliers" in Fig. 2 (e.g., radar #11 in winter, #1 and #9 in

summer, and #12 in autumn). What could have caused the differences for these radars?

As shown in our results investigating the influence of winds on precipitation, southwesterly winds contribute most to the total accumulated precipitation. The radar stations #11 and #12 located on the Swedish western coast are among those that experience highest precipitation amount and frequency from these winds. Therefore, it is expected that these stations will “stand out”. The same applies for station #1 that is additionally influenced by northwesterly winds and thus also shows high precipitation amount and frequency during summer. Comparatively, radar #9 located over Gotland experiences much less precipitation frequency. These facts are visible in the figures below that average number of days per year with precip > 0.1 mm (right) and the average amount of precipitation during July (reference period: 1906-1990).





The flatness of the diurnal cycle of precipitation over Gotland in summer can be explained by the fact that, being an island, it is influenced by oceanic regimes that respond differently to solar heating (due to higher heat capacity of water) compared to land areas that show distinct peak in convection in the late afternoon due to strong solar heating of the land surfaces in summer.

8. Line 236-237: Are there any physical reasons behind the timing and geographical distributions of the bin 8 events? The information would be helpful to readers since these events may have large impacts.

We agree that these events potentially have largest impacts. However, since there is no systematic pattern in the observed timeliness of the precipitation peaks across stations and seasons, it is very difficult at this stage to explain physical reasons behind them. We are in fact currently investigating this in detail in collaboration with experts from the hydrology field to understand which meteorological and surface conditions drive such events, to eventually gauge if we could find any commonalities that can be exploited to better constraint forecast models. We feel that such investigations are the beyond the scope of the present study which was to present climate statistics of precipitation.

9. Line 297: Spell out ECMWF and ERA.

Done.

10. Line 318-319: Radar #1 seemed to be an exception (Fig.7). What could be the reason?

Radar #1 is located farthest in the north in the study area. The AO-type variability has the first order impact on the precipitation characteristics over this region. The Atlantic storms reaching far easterly regions over the Norwegian Sea during positive phases of the AO and subsequent baroclinic instabilities affect not only high intensity precipitation events, but also meteorological regimes that lead to persistent drizzling. In addition, during the last decade, the center of action of AO is shifted more towards easterly regions such that it has greater impact on this northerly station.

This text is now added in the revised manuscript.

11. Line 321: In Fig.7, the confidence level appeared to be low in the high-intensity category of radars #8, 9, and 10, especially for the correlation with “NAO” index. What could be the reason?

It is well-known that the precipitating systems under south- and northwesterly winds during positive phases of NAO/AO often make most of the landfall along the western coastal and inland areas. By the time such large-scale systems reach the eastern parts, they are transformed into regimes that drizzle but do not significantly contribute to heavy precipitation, unless the system is quite strong and persistent. This is possible explanation that in spite of slightly positive correlation with high intensity events with NAO/AO, due to high underlying variability, the confidence level of such correlation is low.

12. Line 351-352: Over what time period were the PDFs derived? Were the wind direction and wind speed averaged over the radar domain (80km umbrella) or just from one point at the radar location?

The PDFs were computed for the same time period as that of radar data (i.e. 2000-2010). The grid boxes covering the radar domain were averaged. This is added in the revised text.

13. Line 365-366: Please specify how the relative contribution in Fig.10 was calculated, otherwise the

statement in line 369-370 is not clear. Also, there is an inconsistency between the Fig.10 caption ("average daily") and the text in line 366 "average seasonal").

For results shown in Fig. 10, for a given radar station, we first compute average daily precipitation rate under different wind conditions. Then in case of each wind condition, we divide average daily precipitation rate by the sum of average daily precipitation rates under all wind conditions. This gives us the relative importance of a particular wind condition.

Since a particular wind condition that produces high precipitation rate may not necessarily lead to most frequent precipitation occurrence, we investigated the latter in Fig. 11. For a given radar station, we computed relative contribution of each wind condition to the total number of precipitation events.

This text is added in the revised manuscript.

The inconsistency between figure caption and the text is corrected.

14. Line 384-385: See comment #13. This statement is not clear without a description of how the contributions in Figs.10 and 11 were calculated. Also, what defines a "precipitation occurrence" (see Fig.11 caption)? Was it a radar domain-averaged 3hr accumulation of greater than 0.1mm?

Please refer to the explanation above.