Sea-Effect Snowfall Case in the Baltic Sea Region Analysed by Reanalysis, Remote Sensing Data and Convection-Permitting Mesoscale Modelling

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Abstract

A sea-effect snowfall accumulated a national record-breaking snowdrift of 73 cm in Merikarvia, on the west coast of Finland, in less than one day on 8 January 2016. A good understanding of such heavy sea-effect snowfalls in the present climate is essential if we want to assess the probability of their occurrence and intensity in the future. Since very few in situ observations were made of the Merikarvia snowfall event in the sea area where the convection cells developed, we investigated the case with an ERA5 reanalysis, the Global Navigation Satellite System (GNSS), and the numerical weather prediction model HARMONIE, using weather radar information as a reference. We aimed to study the feasibility of the reanalysis and GNSS methods for investigating the basic characteristics of the snowband. In addition, we examined whether the assimilation of observed radar reflectivities could improve the HARMONIE simulations. In addition to snowfall patterns, the vertical structure of the atmosphere during the sea-effect snowfall case was analysed. HARMONIE was able to simulate the intensity of the sea-effect snowfall situation well, but the spatial spread of the snowfall remained too narrow, and the snowband was located slightly too far north compared to the radar observations. Assimilation of radar reflectivities increased the simulated moisture content in the vertical direction and spread the precipitation area horizontally, especially in the north-south direction, but shifted the most intense precipitation even more to the north. The location of the snowfall area was captured by ERA5, but the intensity was estimated to be considerably weaker, and the site of the most intense snowfall was more offshore compared to the radar observations and HARMONIE simulations. The vertical structure of specific humidity was similar and of the same order of magnitude in HARMONIE and ERA5. The GNSS, ERA5 and HARMONIE showed reasonably good agreement on the precipitable water content. The case study demonstrated that the three methods, and combinations of them, can be useful in order to obtain the best possible view of local severe weather events as possible.

Keywords:

l Introduction

Weather can change rapidly during the cold Nordic winter. Even small changes in the moisture content of the air and slight variations in temperature near zero degrees Celsius may determine whether precipitation will fall as snow, sleet, rain, freezing rain, or ice pellets. Extreme weather events, such as sea-effect snowfall, can have severe impacts on infrastructure and human safety. Prediction and forewarning of intense snow-fall events is highly important, especially for road traffic, because rapidly decreasing road surface friction and reduced visibility increase the probability of severe accidents (*Juga et al.*, 2012).

In Finland, an essential source of energy for sea-effect snowfall is the Baltic Sea. When cold air outbreaks originating from the north or east pour over the still unfrozen, relatively warm Baltic Sea, the moisture flux and instability from the temperature contrast between the air mass and the sea surface build snowbands, which are then deposited downwind from the sea. These kinds of cold outbreaks are quite common over the Baltic Sea in the autumn and winter and have been investigated by several authors. Most of the studies have aimed to understand the associated dynamical processes and thermodynamic aspects by modelling the cases numerically, e.g., *Andersson and Gustafsson* (1994), *Gustafsson et al.* (1998), *Vihma and Brümmer* (2002), *Savijärvi* (2012), *Mazon et al.* (2015) and Olsson et al. (2017).

Based on previous studies, it is possible to sum up a set of local preconditions that favour sea/lake-effect snowfalls (*Jeworrek et al.*, 2017 and the references therein). The large air-water temperature difference is the most important precondition for forming snowbands, but there are other factors that support their formation. Relatively strong wind, higher than 10 m s⁻¹, is often found to be an important factor (*Andersson and Nilsson*, 1990, *Savijärvi*, 2015). The ratio between the wind speed and the fetch (distance over ice-free water) is found to be between 0.02 and 0.09 m s⁻¹ km⁻¹, which means lower wind speeds in the case of shorter fetches (*Laird et al.*, 2003). The directional wind shear from the surface up to 700 hPa is expected to be small, less than 60° (*Niziol*, 1987). The shape and the topography of the coasts surrounding the water body and their exposure to the prevailing wind is also crucial for the mesoscale structures to be formed.

However, in addition to the local preconditions, it has also been noted that the real evolution of processes depends strongly on large-scale atmospheric patterns (*Savijärvi*, 2012, *Mazon et al.*, 2015, *Savijärvi*, 2015). An interesting point, not covered in detail earlier, is the role of water vapor transport from longer distances in causing very severe snowfalls in a relatively cold atmosphere (see section 3.1). The sea-effect snowfall cases typically have temporal and spatial scales smaller than what can be covered by the conventional weather station network and resolved by climate models. Therefore, to analyse them and their impacts, additional high-resolution information is needed. Examples of such observations are precipitation fields from weather radar and integrated precipitable water (IPW) from the Global Navigation Satellite System (GNSS).

This paper is an extension of a former study of a record-breaking snowfall of 73 cm (31 mm as liquid water) that fell in less than a day in Merikarvia, Finland, on 8 January 2016 (*Olsson et al.*, 2017). In the previous study, it was found that the HARMONIE/AROME numerical weather prediction system captured the overall seaeffect snowfall quite well, but the simulated weaker snowfall did not spread as broadly along the coastline as was observed by weather radar. Numerically simulated atmospheric vertical profiles of equivalent potential temperatures indicated that the atmosphere was unstable to vertical motions, with decreasing equivalent potential temperature with height. Together with colliding winds over the relatively warm and ice-free sea, a very localised extreme snowfall was produced. In the current study, we used a newer version of HARMONIE/AROME, and unlike the previous study, where the observations of radar reflectivities were applied only for qualitative evaluation of the model results, here, the radar reflectivities were assimilated into the modelling system. Because very few in situ observations were made in the sea area where the convection cells developed, we examined whether assimilation of observed radar reflectivities could improve the results of the simulations. Since earlier studies suggest that assimilation of the radar reflectivity observations have a beneficial effect on numerical weather prediction, and especially on humidity forecasts (*Ridal and Dahlbom*, 2017, and references there-in), we might expect some improvement in the forecast accuracy.

The Merikarvia snow event evolved relatively quickly and, as shown later, with an extremely low background level of IPW in the atmosphere. Therefore, we have chosen the GNSS as a method that is possibly suitable for detecting small changes in IPW with a high enough temporal resolution to analyse this kind of extreme event (*Guerova et al.*, 2016).

Reanalyses are dynamically consistent methods to reprocess observational data and are therefore widely used in weather and climate research. Improvements in modelling and data assimilation are accommodated into the new generations of reanalysis. With increasing spatial and temporal resolutions, as well as advancing assimilation capabilities, the chance to detect small-scale extreme weather events with reanalysis products increases. In this work, we put the latest reanalysis, ERA5, to the test. The authors of this work are not aware of any published research using reanalyses to reconstruct a severe small-scale snowfall event. ERA5 moisture profiles and maps are investigated here in detail in the snowfall case, and its 2-metre temperature and pressure data are used as an input for the GNSS analysis.

In general, the ultimate purpose of the simulations is to obtain an upper estimate of how reliable model-based assessments can be with regard to the occurrence and characteristics of sea-effect snowfall events. Case studies of intense snowfall events also increase the scientific understanding of favourable atmospheric conditions for severe wintertime convective weather. This is useful from the viewpoint of developing sea-effect snowfall detection algorithms (e.g., *Jeworrek et al.*, 2017, *Kämäräinen and Jokinen*, 2014), which could be applied to output from high-resolution climate models. In the future, a warmer climate due to climate change might favour the occurrence of snowbands over the Baltic Sea, because the length of the ice season is expected to decrease (*Vihma and Haapala*, 2009, *Mazon et al.*, 2015). This could increase the probability of cold-air outbreaks occurring over the relatively warm open sea in late autumn and early winter.

In this study, we first give a description of the reanalysis data, remote sensing data, and the HARMONIE/AROME model in section 2, as well as the simulations that were run. Then, the results of the simulations are presented and discussed in sections 3 and 4, respectively.

2 Data

2.1 Reanalysis

The European Centre for Medium-Range Weather Forecasts (ECMWF) has developed atmospheric reanalyses of the global climate since the 1980s, starting with FGGE reanalyses (*Bengtsson et al.*, 1982) and followed by ERA-15 (*Gibson et al.*, 1999), ERA-40 (*Uppala et al.*, 2005), ERA-Interim (*Dee et al.*, 2011) and most recently ERA5 (*Hersbach and Dee*, 2016). The latter has been used in this work. It provides gridded estimates of a large number of atmospheric, land and oceanic climate variables. Although the whole ERA5 dataset is not available yet, a first segment covering the period from 2008 to the present day is available for public use. Compared to ERA-Interim, ERA5 has a better spatial resolution as well as higher output frequency (31 km horizontal, 137-layer vertical and 1-h temporal resolution). Moreover, ERA5 takes into account various newly reprocessed datasets and recent instruments (*Hersbach and Dee*, 2016).

In this work, ERA5 products with a 1-h temporal resolution were used, except for precipitation and convective snowfall, which were accumulated over 3 hours. In addition to investigating ERA5 moisture profiles and maps in detail for the snowfall case, its 2-m temperature and pressure data were used as an input for the GNSS analysis. Both were linearly interpolated to the GNSS stations in the horizontal and vertical.

2.2 Global Navigation Satellite System tropospheric products

Meteorological applications of geodetic satellite observations have existed since the early 1990s, after the publication of *Bevis et al.* (1992 and 1994). Zenith total delay (ZTD) can be computed from the Global Navigation Satellite System (GNSS) observations and turned into an amount of water vapour using surface measurements of pressure and temperature.

Observational data acquired from GNSS receivers are processed by GNSS data processing software to obtain the corresponding tropospheric products, i.e., ZTD and their uncertainties (σ). These values, accompanied by additional meteorological data and different physical constants with their uncertainties are used in a second phase of data processing, the conversion of ZTD and σ_{ZTD} to values of IPW and σ_{IPW} .

Approximately 60 GNSS sites between 50–70° N, 10–37° E were chosen to analyse the Merikarvia snow event (Fig. 1). GNSS data (from national and international networks) was processed with the GAMIT/GLOBK software (*Herring et al.*, 2015), with the main attention paid to the evolution of GNSS-IPW in the sub-area of 56–66° N, $16-32^{\circ}$ E in 1-h steps.

Surface meteorological data were initially obtained from in situ measurements at co-located meteorological sites, with a co-location radius <30 km, and interpolated to GNSS antenna heights. Additionally, the 2-m air pressure (Ps) and temperature (Ts) were derived from ERA5 and interpolated to the GNSS antenna heights. These data were used to generate meteorological Receiver Independent Exchange Format (RINEX) files for GNSS data processing. ERA5 data has been compared with in situ meteorolog-

ical measurements, and the differences were found to be ca. 1 hPa for pressure and 1 K for temperature.

Due to non-continuous data streams from several meteorological sites and very small differences compared to in situ measurements, it was considered reasonable to base the IPW analysis on ERA5 data.

From a practical point of view, it is necessary to obtain not only values for GNSS-IPW but also the uncertainty (σ_{IPW}) of these values, especially if we want to compare the results with independent techniques and observations. An extensive overview of the methods and relevant error sources of GNSS measurements can be found in *Ning et al.* (2016). For the Merikarvia case, we selected the theoretical method by *Ning et al.* (2016). The choice was based on the fact that we did not have three or more co-located IPW time series from independent techniques, as would have been required for a statistical analysis. Three somewhat different approaches were adopted (Appendix A).

Usually, the realistic GNSS-IPW uncertainty values stay below 1 mm, which makes the conversion process challenging for a winter-season atmosphere with extremely low background IPW values (usually $\sim 1-3$ mm) in the northern areas.

2.3 Model description

HARMONIE in the ALADIN-HIRLAM NWP system is a non-hydrostatic convection-permitting mesoscale model (*Bénard et al.*, 2010, *Brousseau et al.*, 2011, *Bengtsson et al.*, 2017). In this work, the HARMONIE-AROME model configuration of the HARMONIE model was used. It is run operationally at the Finnish Meteorological Institute (FMI) at 2.5-km resolution. The model has 65 levels in the vertical, and the top is at 10 hPa. In our model setup, the simulation domain covers Finland, Scandinavia and the Baltic countries (Appendix B). Because the HARMONIE model simulates weather conditions in a limited area, information from the lateral boundaries of this area is needed. The boundary conditions for HARMONIE runs are obtained from the IFS (Integrated Forecast System), which is an operational global forecasting system at the ECMWF. These boundary conditions are updated every hour.

High-resolution models, such as HARMONIE, no longer rely on a convection parameterization scheme since the small-scale convective phenomena can now be resolved. This is advantageous, since parameterization of convection is a large source of error and uncertainty in lower-resolution mesoscale models (*Prein et al.*, 2015, *Weusthoff et al.*, 2010).

In our research, the HARMONIE model version 40h1.1 was used. In the model setup, the forecast model and analysis system were those of the AROME model from Météo-France (*Seity et al.*, 2011, *Brousseau et al.*, 2011). Version 7.3 of surface scheme SURFEX was used to calculate atmospheric processes near the underlying surface. SURFEX consists of a set of models for the description of the different types of surfaces: urban environments, soil, and sea and inland water bodies (*SURFEX Scientific Documentation, Masson et al.*, 2013).

Data assimilation is used in HARMONIE, meaning that a running model simulation is corrected at regular time intervals with observations. In data assimilation, we compared model predictions and observations and adjusted the model state so that it was closer to the observations. The purpose was to determine the initial state of the atmosphere as accurately as possible to improve the quality of the forecasts. The data assimilation method used in HARMONIE for upper air observations was the 3D-Var data assimilation system. The analysis cycle with data assimilation was performed every three hours. Surface data assimilation was conducted using the optimal interpolation (OI) method. Operationally assimilated in situ observations included surface synoptic observations (SYNOP), sea-based stations (SHIP), aircraft reports (AMDAR, AIREP, ACARS), buoy observations (BUOY), radiosondes (TEMP) and wind profiler (PILOT) observations.



Fig. 1. GNSS sites (left, red triangles, VAA2 - Vaasa, OLK2 - Olkiluoto, FINS - Finstrom, SUR4 - Suurupi, SODA - Sodankylä) used in this study and OPERA radar data (right, yellow spots) from Finland, Sweden, Norway, Denmark and Estonia (radar in use in 2016). Merikarvia is marked with a red spot.

2.4 Pre-processing and assimilation of radar reflectivities

Weather radar observations provide three-dimensional information about precipitation and wind with good temporal and spatial resolution. Observations are made up to 250 km around a single radar location, with sub-kilometre resolution and an interval of 5 to 10 minutes. This makes radar an advantageous tool in detecting sea-effect snowfalls, because they are typically localized and form offshore.

The location and intensity of the precipitation is analysed from radar reflectivities. Radar reflectivities were assimilated using the 1D+3D-Var assimilation method first introduced by *Caumont et al.* (2010) and later operationally implemented by *Wattrelot et al.* (2014). In this method, a one-dimensional Bayesian scheme is first used to retrieve vertical humidity profiles from radar reflectivities, and these humidity retrievals are then assimilated into the 3D-Var assimilation system. Additionally, dry profiles with no reflectivity were assimilated, since an important part of radar assimilation is also to assimilate areas where the model indicates precipitation but the radar does not. Hence, an observation of reflectivity will either moisten the model in areas where the model indicates no precipitation or adjust the intensity in precipitation areas (*Ridal and Dahlbom*, 2017).

Before assimilation, some quality control steps were performed on the radar data. These included checking for errors and format differences in the data from different countries, horizontal thinning, and blacklisting of the lowest elevation angle scans of each volume to avoid clutter. The quality control steps inside the HARMONIE/AROME radar data assimilation system are described in more detail by *Ridal and Dahlbom* (2017) and *Gustafsson et al.* (2017).

In this work, we used OPERA (The Operational Weather Radar in Europe) data, including radar from Finland, Sweden, Norway, Denmark, and Estonia. The radar in use in 2016 can be seen in Figure 1. Near the edges of the visibility area, radar can detect precipitation only if the precipitation falls from a cloud higher than 6 km. For liquid precipitation, this is a good assumption, but not for snowfall. Precipitation from a cloud higher than 2 km can be detected inside a 120-km radius from the radar. During the winter, the visibility area is somewhere between the 120-km radius and the whole visibility area.

2.5 Simulations

The Merikarvia sea-effect snowfall case was simulated by two experiments with the HARMONIE model: a simulation without assimilation of radar reflectivities (NR hereafter) and a simulation where radar reflectivities were assimilated (R hereafter). The results from the simulations were compared to each other and to radar observations to determine whether the assimilation of the radar reflectivities improves the model performance in simulating the sea-effect snowfall case. Three hours on 8 January 2016 were selected for closer examination: 05 UTC, 13 UTC and 21 UTC. These were the same hours as previously studied by *Olsson et al.* (2017). Due to assimilation, both of our simulations consist of several forecast cycles, starting from 00 UTC with 3-hour intervals, each of which lasts 48 hours. Within both simulations, we qualitatively evaluate which cycle gives the best results compared to radar observations.

3 Results

3.1 The overall meteorological situation

In late December 2015, a very large amount of warm and humid air was transported to the Arctic region by storm "Frank", one of the strongest North Atlantic storms on record (*Kim et al.*, 2017). *Binder et al.* (2017) have shown that the 2015/2016 recordbreaking warm winter was the result of a very unusual configuration of large-scale atmospheric flow that came along with other regional extremes. One of these was the Merikarvia heavy snow event (Fig. 2d). A very important role was played by a blocking anticyclone over Scandinavia and NW Russia, which lasted for more than two weeks and enabled cold and dry air masses over the Northern Baltic Sea region. The favourable conditions for sea-effect convective precipitation were lasting for approximately ten days. Since 2 January 2016, the snowbands were mostly over the Gulf of Finland and the Northern Baltic Proper and Åland Sea, then starting on 6 January, they also extended to the Bothnian Bay and the Bothnian Sea. These snowfall events lasted a few days after the Merikarvia event. The mesoscale structures of precipitation were very variable depending on the larger scale air flow direction and the characteristics of the prevailing air masses. The structure of the cloudfield from MODIS Terra on the morning of 8 January 2016 is given by Figure 2a. All favourable conditions for cold-season convection (*Jeworrek et al.*, 2017) were fulfilled on 8 January: the 10-m wind was stronger than 10 m/s, the 2-m temperature was lower than 278 K, the temperature difference between the



Fig. 2. (a) MODIS Terra RGB showing various types of convective snowbands over the Northern Baltic Sea on 8 January 2016 at 10:20 UTC. (b) GNSS-IPW fields (mm) at 13 UTC. (c) Copernicus CMEMS sea surface temperature (K) at 00 UTC. (d) One-hour accumulated precipitation (mm/h) observed by weather radar at 13 UTC. Merikarvia is marked with a red spot.

surface and 850 hPa was more than 15 K, the boundary layer height exceeded 1000 m and there was a wind shear in the layer between 10 m and 700 hPa. Due to the warm autumn, the Baltic Sea was still open, enabling a long fetch over relatively warm water (Fig. 2c) when cold arctic air masses reached the area.

3.2 Atmospheric moisture fields

As seen from Figure 3, the most intense snowfall (as measured by the weather radar network) is well captured by ERA5. Regarding the timing and location, there is a good agreement between ERA5 and the HARMONIE output and radar observations. However, ERA5 estimates precipitation to be considerably weaker (more than 7 times), showing the highest values above the sea (approximately 3 mm from 12 to 15 UTC on



Fig. 3. Three-hour accumulated precipitation (mm, top left) and convective snowfall (mm of water equivalent, top right) estimated by ERA5 on 8 January 2016 at 15 UTC. For comparison, three-hour accumulated precipitation from radar images (bottom left) and the HARMONIE simulation with assimilated radar reflectivities (bottom right) are shown. The sea level pressure (hPa) is also shown for HARMONIE (bottom right). The vertical sections along 21° E and 62° N used in Figures 4 and 7 are marked in the top left figure.

8 January), where most of the precipitation occurs due to the convective snowfall. The latter contributes up to 65% of the total precipitation. According to ERA5, precipitation above land was less pronounced, reaching its maximum intensity three hours later (approximately 1.8 mm from 15 to 18 UTC at 62.2° N 21.5° E, not shown).

Vertical cross-sections of specific humidity along 62° N and 21° E up to the 700 hPa level reveal that the maximum values appeared at approximately 12 UTC near the surface (approximately 2.2 g/kg, Fig. 4). The humidity decreased linearly with height. Such layering was present roughly two degrees in the northward/southward and westward/eastward directions from 62° N, 20.5° E. A very similar situation was detected in the temperature fields. The 2-m temperature at this point is just below 273 K, while the temperature 200 km farther is 5–10 K lower (not shown).



Fig. 4. Vertical cross-sections of specific humidity (g/kg) up to 700 hPa along 62° N (left) and along 21° E (right) based on ERA5 data (top row) and the HARMONIE simulation with assimilated radar reflectivities from forecast cycle 2016010812 on 8 January 2016 13 UTC.

The time evolution of IPW, as generated using the GNSS method in 1-hour time steps, is presented in Figure 5 for a selection of GNSS stations over Finland. A rapid increase in IPW during a 16-hour time period can be seen. An interesting feature is the more humid air that approached from the south (Fig. 2b). We note an advection of moisture from Sweden over the Turku archipelago at 05 UTC. The well-developed IPW peak over Olkiluoto (the closest GNSS site to Merikarvia) developed within a few hours,

reaching the peak value at 13 UTC and completely disappearing at 21 UTC. No similar peaks that are clearly distinguishable from the background can be noticed in adjacent GNSS sites (Finstrom and Vaasa, Fig. 5) or the eastern GNSS sites inland. This coincides well with the information obtained from the radar and from the HARMONIE model. Unfortunately, we do not have GNSS data from the open sea.



Fig. 5. Top panel: Integrated precipitable water (IPW) time series for 7–10 January 2016 are shown for five GNSS sites (VAA2 - Vaasa, OLK2 - Olkiluoto, FINS - Finstrom, SUR4 - Suurupi, SODA - So-dankylä) with error bars for the nearest site, Olkiluoto (red). Comparison of GNSS-IPW with IPW extracted from ERA5 and HARMONIE for the Olkiluoto (middle panel) and Vaasa (bottom panel) GNSS sites. Three different forecast cycles (red, yellow and pink, 2016010812, 2016010800 and 2016010700, respectively) are shown for HARMONIE with assimilated radar reflectivities. DOY stands for day of the year.

An analysis of the uncertainty σ_{IPW} in the IPW values obtained from GNSS measurements was performed using three methods (Appendix A). The results for temporal averages of σ_{IPW} at seven GNSS stations during 7–9 January 2016, given in Table A1, show slight differences between the methods. In the top panel of Figure 5, the GNSS-IPW uncertainty ranges are depicted for Olkiluoto, the nearest GNSS site to Merikarvia.

To gain better confidence in the GNSS results, we compared the GNSS-IPW at two sites (Olkiluoto and Vaasa) with the IPW extracted from ERA5 and HARMONIE simulations (middle and bottom panels in Figure 5). The comparison of IPWs from GNSS, ERA5 and HARMONIE shows relatively small differences (~1 mm), while the uncertainty σ_{IPW} in the GNSS values at Olkiluoto stay within ± 0.5 mm during the peak of the snow event (top panel Fig. 5). Similar tendencies, such as that described in Figure 5, were noticed for all sites – the ERA5 results were smoother, but the differences stayed within ~1 mm. It can be concluded that the GNSS-IPW values used in this analysis are reliable.

3.3 Outcomes from the HARMONIE simulations

Radar observations of the Merikarvia snowfall case at 05, 13, and 21 UTC on 8 January (Fig. 6) were chosen for closer analysis. At 05 UTC, the snowfall band was directed from the south to the north and was still located in the sea area in front of Merikarvia. At 13 UTC, the snowfall had intensified and was partly located over land areas. At 21 UTC, the snowfall area had grown smaller and slightly weaker.

Throughout 8 January, according to the HARMONIE simulations, the sensible heat flux over the sea was directed upwards to the atmosphere (i.e., heat loss from the sea) due to the cold south-westerly flow over the relatively warm Baltic Sea, supporting convection. The sensible heat flux was strongest during the night, 00–06 UTC, over the sea area from Åland to the west coast of Finland (not shown). The highest values, up to 350 W/m^2 , were found near the west coast, decreasing there towards the end of the day to $60-140 \text{ W/m}^2$. The upward latent heat flux from the sea had a temporal and spatial variability similar to that of the sensible heat flux. The highest values, up to 160 W/m^2 , occurred during the night and decreased to $50-80 \text{ W/m}^2$ over the course of the day. The correspondence between HARMONIE and ERA5 was good for temporal and spatial patterns of the heat fluxes, but in ERA5, the values were distinctly smaller, 80 W/m^2 at the highest for the sensible heat flux.

There is a good agreement of the HARMONIE output with ERA5 and the GNSS method. Although ERA5 estimates precipitation to be relatively weaker in contrast to HARMONIE simulations (Fig. 3), the vertical profiles of specific humidity (Fig. 4) are very similar in ERA5 and the HARMONIE simulation according to shape and maximum values. The greatest difference comes from the resolution, as HARMONIE is able to simulate more distinct variations in the specific humidity fields.

Additionally, the IPW time series show good agreement between ERA5, the GNSS method and HARMONIE simulations, with GNSS showing the largest variations. Thus, the greatest differences can be found between different forecast cycles and simulation with (R) and without (NR) radar assimilation (Fig. 5). The R simulation ini-

tiated at 7 January at 00 UTC (2016010700) was not able to forecast the highest peak of IPW in Olkiluoto at approximately noon on 8 January, as the simulated values were 0.8–0.9 mm lower compared to ERA5, the GNSS method and forecast cycles initiated later. Nevertheless, in Vaasa, the forecast cycle 2016010700 performed as well as the other methods. In both locations, the forecast cycle initiated on 8 January 00 UTC (2016010800) simulated the cycle and variation of IPW closest to ERA5 and the GNSS method. The cycle initiated closest to the most intense precipitation (2016010812) simulated the peak values close to ERA5 and the GNSS method, but the forecast for the following hours was too moist in both locations.

Adding radar assimilation to HARMONIE increased the moisture content, especially in the lower model levels and within the precipitating cloud. HARMONIE NR simulations had IPW values that were too low (0.5–1 mm lower), especially between 12–24 UTC on 8 January, compared to ERA5, GNSS and HARMONIE with R.

Figure 6 shows the hourly accumulated total precipitation for a simulation with assimilation of radar reflectivities (R) and the difference between the R and NR simulations for the cycle initiated at 03 UTC on 8 January 2016. When the results from the simulations are compared with the radar observations at the same hour (the left panel in Fig. 6), we note that the location of the strongest snowband offshore of Merikarvia is well captured by HARMONIE in both simulations. The assimilation of radar reflectivities spread the total area of simulated precipitation, produced a clearer hook to the coastline, and the area of maximum precipitation grew slightly stronger. In particular, the HARMONIE with an R simulation intensified the precipitation north of the NR simulation.

In Figure 6, convergence zones are also shown. In these zones, near-surface winds converged, which led to vertical air movement that further enhanced the convective snowfall. In both simulations, NR and R, the offshore convergence zones were located very close to the snowband. When the snowfall reached the coast at approximately 10 UTC, two convergence zones formed, one along the coastline on both sides of the strongest snowfall and another along the strongest snowband, perpendicular to the coastline.

Figure 7 illustrates the vertical cross-section of the simulated sum of cloud ice and water, as well as the meridional wind speed. The convergence zones near the coastline can be seen distinctly as the meridional winds show a sharp gradient in wind speed and direction. Data assimilation intensified the near-coastline cloud water and ice (Fig. 7, columns A and B) and spread them in a south-north direction (Fig. 7, columns C and D) compared to the simulation without assimilation of radar reflectivities. In addition, the assimilation of radar reflectivities removed an upper-level tail from cloud water and ice content above the sea (Fig. 7, columns A and B). The cloud water and ice content was higher in the lower model levels with assimilated radar reflectivities, and the cloud water er and ice were preserved longer during the day (Fig. 7). Assimilation of radar reflectivities increased the southerly wind speeds in all forecast cycles compared to HARMONIE with NR.

When the results from other forecast cycles (not shown) were compared with radar images, it was found that the location of the snowband differed from the radar observations the most in the first four forecast cycles, initiated 23–41 hours before the time of analysis. The simulated location of the snowband was far too north in both the simulations, and the precipitation area was smaller than in forecast cycles initiated later. The last three forecast cycles were more accurate with the location of the snow band, but the extent of the strongest snowfall area was still narrower than observed and located slightly too far north (not shown).



Fig. 6. One-hour cumulative precipitation (mm/h) in the radar images (left panel) and forecast cycle 2016010803 at 05 (top), 13 (middle), and 21 (bottom) UTC on 8 Jan 2016 simulated with HARMONIE with assimilated radar reflectivities (middle panel). Simulated convergence zones are shown with red contours. The difference between HARMONIE with (R) and without (NR) radar assimilation is in the right column (mm/h).



Fig. 7. Vertical cross-section from model levels 29–65 (up to ~700 hPa) of cloud water and ice (g/m2) and meridional wind speed (m/s, southerly in red, northerly in blue) along 62° N ($13^{\circ}-24^{\circ}$ E, columns A and B) and along 21° E ($60^{\circ}-64^{\circ}$ N, columns C and D), as simulated by HARMONIE for NR (columns A and C) and R (columns B and D). The forecast cycles are 2016010806 (top row), 2016010809 (middle row), and 2016010812 (bottom row) at 13 UTC on 8 Jan 2016.

4 Discussion

The source of the moisture for precipitation above the sea cannot be distinguished in the detection process of past sea-effect cases. The moisture can drift long distances instead of originating from the non-frozen Baltic Sea, and remote sources of moisture hamper the detection. Since very few in situ observations were made in the sea area where the convection cells developed, we investigated this case with an ERA5 reanalysis, the Global Navigation Satellite System (GNSS), weather radar, and the numerical weather prediction model HARMONIE to the best possible view of the snowband.

We treated radar measurements as a reference method because they provide the needed temporal and spatial coverage to monitor precipitation on a regional scale. The typical measurement resolution and coverage over sea areas of an operational weather radar (~500 metres, ~5 minutes) is superior in comparison, e.g., to a network of precipitation gauges. Nevertheless, quantitative snowfall estimates with weather radar are still a challenge because of the variability in the properties of snow crystals and snowflakes

that evolve inside a snowstorm (*von Lerber*, 2018). The challenge stems from the large uncertainty in the microphysical properties of snowfall, i.e., the effect of the density and size of snow particles on the measured back-scattered power. In addition, since radar observes precipitating clouds above the ground and the measurement height increases with distance from the radar, the actual accumulated snowfall on the ground might be some kilometres off depending on the wind speed and direction.

From radar snowfall images, it can be seen that the area of the actual snow event was extremely narrow, not exceeding ca. 35 km. Taking into account the temporal and spatial scale of such a sea-effect case, ERA5 as a global reanalysis with a 30-km horizontal resolution showed good agreement with the other methods used. The timing and location of the snowfall were accurately estimated. This suggests that reanalyses are able to detect not only regional long-term trends but also local short-term extreme weather events. This benefit is clearly overlooked, and more is yet to be discovered in the future as reanalyses keep improving. On the other hand, the magnitude of the snowfall intensity was underestimated, and correctly capturing it still appeared to be beyond the capabilities of ERA5.

The GNSS-IPW maps generated for 7–9 January 2016 show the evolution of IPW fields during this time period. Local peak values of IPW can be observed on 8 January at Olkiluoto. The density of GNSS sites situated in and around the Merikarvia area is not sufficient for a more detailed analysis of the precipitation process at this scale. It is also impossible to obtain GNSS-data from the sea area. However, the GNSS results can be used to calibrate NWP models at GNSS sites at the areas of interest (OLKI, VAA2, FINS, etc.). Additional benefit from GNSS observations can come for operational weather services if the GNSS data could be assimilated in near real time.

According to the WMO Rolling Review of Requirements for IPW (http://www.wmo-sat.info/oscar/variables/view/162), the goal for nowcasting, NWP and climate research is to reach uncertainty values below 1 mm. A theoretical analysis (*Ning et al.*, 2016) of GNSS-IPW uncertainty for Merikarvia case demonstrates that these requirements are fulfilled, but it is not the final truth, because statistical analyses (with three or more independent methods) may give higher uncertainty values. A statistical analysis of the results could be possible only for the Sodankylä site (has at least three independent techniques for obtaining the IPW time series), but it would be too far to make decisions about the extremely local Merikarvia snow event.

However, there is great improvement to be gained for data availability and quality. One issue is the density of the GNSS sites in the network, but it is equally important operatively to have high-quality meteorological data for these GNSS sites. Ideally an automatic weather station (AWS) should be installed together with the GNSS receivers (which is true for the majority of Estonian sites used in this analysis) to avoid interpolation errors from co-located meteorological sensors in a radius of ca. 10–30 km. Highquality meteorological data will ensure more accurate ZTDs thanks to realistic *a priori* meteorological constraints for the GNSS data processing software.

Models are a powerful tool in estimating the state of the atmosphere and investigating possible changes in it, as well as in making physical sense of observational data. This is especially true for areas where the scarcity of observing systems restricts investigation (e.g., seas, large lakes, polar regions). We performed two HARMONIE simulations: one with the assimilation of radar reflectivities and the other without. The assimilation of radar reflectivities did not significantly improve the skill of the forecast in this particular case, as HARMONIE performed well even without radar reflectivities. Nevertheless, the assimilation of radar reflectivities lowered the top of the cloud water and ice and added moisture to lower model levels. It also spread the precipitation area in the south-north direction on the coastline and intensified the strongest snowband over the land, which improved the results compared to ERA5, the GNSS method and radar images.

The forecast cycles that were initiated more than 24 hours before the event gave the weakest results, especially concerning the location of the snowband when compared to radar observations. The results in the forecast cycles that were initiated closer to the event corresponded best with the radar observations in both simulations. In these cycles, the location and the pattern of the precipitation area was well simulated but still slightly too far north.

When radar reflectivities were assimilated to HARMONIE the most intense precipitation area was shifted even more to the north. The reason for this behaviour is beyond the scope of this study. One possibility is that increased southerly winds drive the precipitation towards the north. Some of the difference in the location originates from the analysis of the precipitation, because radar sees the precipitating cloud and HARMONIE simulates the accumulated snow cover over land. In addition, because the radar reflectivities are assimilated into HARMONIE at the time of analysis, the effect of added/reduced moisture fields might not be long-lasting in model simulations as added moisture is precipitated out. Due to this fact, the impact of the assimilation of radar reflectivities might not be visible many hours after the analysis time. However, the forecast cycle with radar reflectivities initiated as close to the maximum intensity of the snowband as possible did not improve the accuracy of the simulation, because the maximum intensity of the precipitation added to the HARMONIE increased the moisture content too much, preserving IPW values that were too high for too long compared to ERA5 and the GNSS method. The snowband was still visible, although distinctly weaker, in radar images on 9 January, but because the radar reflectivities were assimilated to HARMONIE only at the analysis time, the information of the evolution of the snowband observed with radar was not added to the simulation.

Advanced methods are required in order to be able to produce a comprehensive view of the probability of occurrence of sea-effect snowfall in the past and to assess the influence of climate change in the future. In the future, we plan to perform a similar analysis of simulations of known past sea-effect cases in Finland. It would be of great relevance to see whether and how the assimilation of radar reflectivities affects simulated precipitation and air flow patterns in several recent past sea-effect snowfall cases. The findings would increase the scientific understanding of favourable atmospheric conditions for the occurrence of severe wintertime convective weather. They would also be useful from the viewpoint of developing sea-effect snowfall detection algorithms (as

in *Jeworrek et al.*, 2017), analogous to the freezing rain algorithm developed and utilized by *Kämäräinen et al.* (2017a, 2017b).

5 Conclusions

We analysed a strong small-scale sea-effect snowfall case in Merikarvia, Finland. In this work, we had three main questions: 1) Is ERA5 reanalysis capable of reconstructing a severe snowfall event? 2) Is the density of the GNSS sites in and around Merikarvia sufficient for a detailed analysis of IPW within such a small area? 3) And finally, could assimilation of observed radar reflectivities improve HARMONIE simulations? The last question was motivated by the fact that no assimilation of radar reflectivity data in HARMONIE has been previously performed in Finland for the purpose of studying sea-effect snowfall.

We treated radar as the reference method in this study. Regarding intensity and location, radar may give the most accurate precipitation estimate, but it does not provide much information about the origin of the event. Hence, it is useful to pair radar observations with models and the GNSS output.

Reanalysis involves significant time latency – it cannot give any improvement for severe weather forecasting, but it can be used afterwards to check whether the forecasts and measurements (including possible measurement errors) were realistic. The state-of-the-art ERA5 reanalysis should presently be the most reliable reference, at least on a larger scale. However, it is a result from a model. In this case study, ERA5 showed good agreement with other methods, but the magnitude of the small-scale snowfall intensity was distinctly underestimated.

The GNSS method for IPW is based on in situ measurements, and the results can be obtained in near real time. An uncertainty analysis shows that the IPW values obtained from GNSS measurements can be trusted over land and satisfy the requirements set for NWP and climate research. However, in our Merikarvia example, it is observed that the GNSS data is problematic for processes evolving over the sea. As an example, we could detect a clear increase in IPW at only one coastal site (Olkiluoto), without any idea about the true horizontal scale of the anomaly. The results with given uncertainties could be compared with different independent techniques (including calibration of numerical models). It may help in forecasting severe weather events if the GNSS products could be assimilated into the forecast model. They can also serve as a near real-time reference and in early warning systems for severe weather events.

Finally, adding data assimilation of radar reflectivities did improve the HARMONIE simulations by increasing the moisture content of the boundary layer and spreading the most intense precipitation area. We found, however, that the cycle that initiated the closest (12 UTC) to the most intense precipitation did increase the precipitable water content of the forecast too much and preserved it for too long compared to ERA5 and GNSS data. The forecast cycle initiated 12 hours prior to the most intense precipitation simulated the snowfall case well and outperformed the HARMONIE simulation without data assimilation of radar reflectivities.

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References

- Andersson, T. and N. Gustafsson, 1994. Coast of departure and coast of arrival: two important concepts for the formation and structure of convective snowbands over seas and lakes. *Mon. Weather Rev.* 122, 1036–1049.
- Andersson, T. and S. Nilsson, 1990. Topographically induced convective snowbands over the Baltic Sea and their precipitation distribution. *Weather Forecast.*, 5, 299– 312.
- Bénard, P., J. Vivoda, J. Masek, P. Smolíková, K. Yessad, C. Smith, R. Brozková, and J.-F. Geleyn, 2010. Dynamical kernel of the Aladin-NH spectral limited-area model: Revised formulation and sensitivity experiments. *Quart. J. Roy. Meteor. Soc.*, **136**, 155–169.
- Bengtsson, L., M. Kanamitsu, P. Kållberg, and S. Uppala, 1982. FGGE research activities at ECMWF. *Bull. Amer. Meteor. Soc.*, 63, 277–303. doi:10.1175/1520-0477-63.3.277.
- Bengtsson, L., U. Andrae, T. Aspelien, Y. Batrak, J. Calvo, W. de Rooy, E. Gleeson, B. Hansen-Sass, M. Homleid, M. Hortal, K.-I. Ivarsson, G. Lenderink, S. Niemelä, K.P. Nielsen, J. Onvlee, L. Rontu, P. Samuelsson, D.S. Muñoz, A. Subias, S. Tijm, V. Toll, X. Yang, and M. Ødegaard Køltzow, 2017. The HARMONIE–AROME Model Configuration in the ALADIN–HIRLAM NWP System. *Mon. Wea. Rev.*, 145, 119–1935. doi:10.1175/MWR-D-16-0417.1.
- Bevis, M., S. Businger, T. Herring, C. Rocken, R. Anthes and R. Wave, 1992. GPS meteorology: remote sensing of atmospheric water vapor using the global positioning system. J. Geophys. Res., 97, 15787–15801, doi:10.1029/92JD01517.
- Bevis, M. S. Businger, S. Chiswell, T.A. Herring, R.A. Anthes, C. Rocken and R.H. Ware, 1994. GPS meteorology–Mapping zenith wet delays onto precipitable water. J. Appl. Meteorol., 33, 379–386.
- Binder, H., M. Boettcher, C.M. Grams, H. Joos, S. Pfahl and H. Wernli, 2017. Exceptional Air Mass Transport and Dynamical Drivers of an Extreme Wintertime Arctic Warm Event. *Geophysical Research Letters*, 44, 12028–12036.

- Brousseau, P., L. Berre, F. Bouttier and G. Desroziers, 2011. Background-error covariances for a convective-scale data-assimilation system: AROME–France 3D-Var. *Q.J.R. Meteorol. Soc.*, **137**: 409–422. doi:10.1002/qj.750.
- Caumont, O., V. Ducrocq, É. Wattrelot, G. Jaubert and S. Pradier-Vabre, 2010. 1D+3DVar assimilation of radar reflectivity data: a proof of concept. *Tellus A*, 62(2). doi:10.3402/tellusa.v62i2.15678.
- Dee, D.P., S.M. Uppala, A.J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M.A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A.C.M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A.J. Geer, L. Haimberger, S.B. Healy, H. Hersbach, E.V. Hólm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A.P. McNally, B.M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thépaut, F. Vitart, 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quart. J. R. Meteorol. Soc.*, 137(656), 553–597. doi:10.1002/qj.828.
- Gibson, J.K., P.W. Kållberg, S. Uppala, A. Hernandez, A. Nomura and E. Serrano, 1999. ERA 15 description. *ECMWF Reanalysis Project Report Series* 1, 86 pp. https://www.ecmwf.int/sites/default/files/elibrary/1997/9584-era-description.pdf.
- Guerova, G., J. Jones, J. Douša, G. Dick, S. de Haan, E. Pottiaux, O. Bock, R. Pacione, G. Elgered, H. Vedel and M. Bender, 2016. Review of the state of the art and future prospects of the ground-based GNSS meteorology in Europe. *Atmos. Meas. Tech.*, 9, 5385–5406. doi:10.5194/amt-9-5385-2016.
- Gustafsson, N., L. Nyberg and A. Omstedt, 1998. Coupling of a high-resolution atmospheric model and an ocean model for the Baltic Sea. *Mon. Weather Rev.* **126**, 2822–2846.
- Gustafsson, N., T. Janjić, C. Schraff, D. Leuenberger, M. Weissman, H. Reich, P. Brousseau, T. Montmerle, E. Wattrelot, A. Bučánek, M. Mile, R. Hamdi, M. Lindskog, J. Barkmeijer, M. Dahlbom, B. Macpherson, S. Ballard, G. Inverarity, J. Carley, C. Alexander, D. Dowell, S. Liu, Y. Ikuta and T. Fujita, 2017. Survey of data assimilation methods for convective-scale numerical weather prediction at operational centres. *Q.J.R. Meteorol. Soc.* Accepted Author Manuscript. doi:10.1002/qj.3179.
- Herring, T.A., R.W. King, M.A. Floyd and S.C. McClusky, 2015. GAMIT Reference Guide, Rel. 10.6, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology.
- Hersbach, H. and D. Dee, 2016. ERA5 reanalysis is in production. *ECMWF Newsletter* No. **147**, 7.
- Høyer, J.L. and J.She, 2007. Optimal interpolation of sea surface temperature for the North Sea and Baltic Sea. *J. Mar. Sys.*, Vol **65**, 1–4, pp. 176–189.
- Jeworrek, J., L. Wu, C. Dieterich A. and Rutgersson, 2017. Characteristics of convective snow bands along the Swedish east coast. *Earth Syst. Dynam.*, 8, 163–175. doi:10.5194/esd-8-163-2017.

- Juga, I., M. Hippi, V. Karsisto and P. Nurmi, 2014. Weather factors triggering the massive car crashes on 3 February 2012 in the Helsinki metropolitan area, in: Proceedings Of the 17th SIRWEC conference, 30 January-1 February 2014, La Massana, Andorra.
- Kim, B.-M., J.-Y. Hong, S.-Y. Jun, X. Zhang, H. Kwon, S.-J. Kim, J.-H. Kim, S.-W. Kim and H.-K. Kim, 2017. Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm. *Sci. Rep.*, 7, 40,051. doi:10.1038/srep40051.
- Kämäräinen, M. and P. Jokinen, 2014. Severe winter weather in Finland. PART II: Freezing rain and lake-effect snowfall. EXWE/SAFIR2014 project report 2014, Finnish Meteorological Institute.
- Kämäräinen, M., O. Hyvärinen, K. Jylhä, A. Vajda, S. Neiglick, J. Nuottokari and H. Gregow, 2017a. A method to estimate freezing rain climatology from ERA-Interim reanalysis over Europe. *Nat. Hazards Earth Syst. Sci.*, 17, 243–259. doi:10.5194/nhess-17-243-2017.
- Kämäräinen, M., K. Jylhä, O. Hyvärinen and A. Vajda, 2017b. Present-day and future probabilities of severe freezing rain at the nuclear power plant sites in Finland. EXWE/SAFIR2018 project report 2017, Finnish Meteorological Institute.
- Laird, N.F., D.A.R. Kristovich and J.E. Walsh, 2003. Idealized model simulations examining the mesoscale structure of winter lake-effect circulations. *Mon. Weather Rev.* 131, 206–221.
- von Lerber, A., 2018. Challenges in measuring winter precipitation: Advances in combining microwave remote sensing and surface observations, Finnish Meteorological Institute Contributions 143. http://hdl.handle.net/10138/231104.
- Masson, V., P. Le Moigne, E. Martin, S. Faroux, A. Alias, et al., 2013. The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. *Geosci. Model Dev.*, 6, 929–960. doi:10.5194/gmd-6-929-2013
- Mazon, J., S. Niemela, D. Pino, H. Savijarvi and T. Vihma, 2015. Snow bands over the Gulf of Finland in wintertime. *Tellus A*, **67**, 25102. doi:10.3402/tellusa.v67.25102
- Ning, T., J. Wang, G. Elgered, G. Dick, J. Wickert, M. Bradke, M. Sommer, R. Querel and D. Smale, 2016. The uncertainty of the atmospheric integrated water vapour estimated from GNSS observations. *Atmos. Meas. Tech.*, 9, 79–92. doi:10.5194/amt-9-79-2016.
- Niziol, T.A., W.R. Snyder and J.S. Waldstreicher, 1995. Winter weather forecasting throughout the eastern United States. Part IV: lake-effect snow. *Weather Forecast*. 10, 61–77.
- Olsson, T., T. Perttula, K. Jylhä and A. Luomaranta, 2017. Intense sea-effect snowfall case on the western coast of Finland. *Adv. Sci. Res.*, 14, 231–239. doi:10.5194/asr-14-231-2017.

- Prein, A.F., W. Langhans, G. Fosser, A. Ferrone, N. Ban, K. Goergen, M. Keller, M. Tölle, O. Gutjahr, F. Feser and et al., 2015. A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. *Rev. Geophys.*, 53, 323–361. doi:10.1002/2014RG000475.
- Ridal, M. and M. Dahlbom, 2017. Assimilation of Multinational Radar Reflectivity Data in a Mesoscale Model: A Proof of Concept. Journal of Applied Meteorology and Climatology. doi:10.1175/JAMC-D-16-0247.1.
- Savijärvi, H.I., 2012. Cold air outbreaks over high-latitude sea gulfs, *Tellus A: Dynamic Meteorology and Oceanography*, **64**:1, 12244. doi:10.3402/tellusa.v64i0.12244
- Savijärvi, H., 2015. Cold air outbreaks along a non-frozen sea channel: effects of wind on snow bands. *Meteorol. Atmos. Phys.* 127, 383–391. doi:10.1007/ s00703-015-0370-8.
- Seity, Y., P. Brousseau., S. Malardel, G. Hello, P. Bénard, F. Bouttier, C. Lac and V. Masson, 2011. The AROME-France Convective-Scale Operational Model. *Mon. Wea. Rev.*, **139**, 976–991. doi:10.1175/2010MWR3425.1.
- SURFEX Scientific Documentation: http://www.cnrm.meteo.fr/surfex/spip.php?rubrique11
- Uppala, S.M., P.W. Kållberg, A.J. Simmons, U. Andrae, V. da Costa Bechtold, M. Fiorino, J.K. Gibson, J. Haseler, A. Hernandez, G.A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R.P. Allan, E. Andersson, K. Arpe, M.A. Balmaseda, A.C.M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Hólm, B.J. Hoskins, L. Isaksen, P.A.E.M. Janssen, R. Jenne, A.P. McNally, J.-F. Mahfouf, J.-J. Morcrette, N.A. Rayner, R.W. Saunders, P. Simon, A. Sterl, K.E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo and J. Woollen, 2005. The ERA-40 re-analysis. *Quart. J. R. Meteorol. Soc.*, 131, 2961–3012. doi:10.1256/qj.04.176.
- Vihma, T., and Brummer, B., 2002. Observations and modelling of on-ice and off-ice flows in the northern Baltic Sea. *Bound. Layer Meteorol.* **103**, 1–27.
- Vihma, T. and J. Haapala, 2009. Geophysics of sea ice in the Baltic Sea a review. *Prog. Oceanogr.* **80**, 129–148.
- Wattrelot, E., O. Caumont and J.-F. Mahfouf, 2014. Operational Implementation of the 1D+3D-Var Assimilation Method of Radar Reflectivity in the AROME Model. *Monthly Weather Review*. Vol. 142. 1852–1873.
- Wessel, P. and W.H.F. Smith, 1998. New, improved version of Generic Mapping Tools released, *EOS Trans. Amer. Geophys. U.*, vol. **79** (47), pp. 579.
- Weusthoff, T., F. Ament, M. Arpagaus and M.W. Rotach, 2010. Assessing the Benefits of Convection- Permitting Models by Neighborhood Verification: Examples from MAP D-PHASE. *Mon. Wea. Rev.*, **138**, 3418–3433. doi:10.1175/2010MWR3380.1.

Appendix A. Uncertainty analysis of integrated precipitable water from GNSS

The temporal mean uncertainties σ_{IPW} in the IPW values obtained from GNSS measurements were calculated by three methods: A) obtained directly from GAMIT *metutil*, B) derived from calculated ZTD and σ_{ZTD} by a method described by Ning et al. (2016) and C) by method B, but with a constant $\sigma_{ZTD} = 4$ mm, as claimed by the International GNSS Service (IGS) for their tropospheric product.

In this work, the method developed by Ning et al. (2016) for the GRUAN GNSS product is currently used without information on additional uncertainties from orbital errors (adding ca. 3 mm to the σ_{ZTD} values calculated by EPOS8 software for GRUAN). Not using these additional uncertainties is compensated for by the use of different methods by GAMIT for deriving realistic uncertainties and optionally by the use of the IGS-supported $\sigma_{ZTD} = 4$ mm (method C).

Table A1.	GNSS-IPW	mean	uncertainties	(in mm)	, as	calculated	by	methods	A, B	and	C and	average	d
over the 7	th to 9 th of Jar	nuary 2	.016.				-					-	

Site	σ_{IPW} (method A)	σ_{IPW} (method B)	σ_{IPW} (method C)		
OLKILUOTO	0.45	0.51	0.63		
TUORLA	0.45	0.5	0.62		
VAASA	0.44	0.49	0.62		
FINSTROM	0.43	0.5	0.64		
SUURUPI	0.39	0.45	0.63		
SODANKYLÄ	0.56	0.6	0.62		

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Appendix B. Model domain in the HARMONIE-AROME simulations

The model domain in the simulations is shown in Figure B1.



Fig. B1. Example of a surface air temperature (K) in HARMONIE showing the size of the model domain.

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ECMWF	European Centre for Medium-Range Weather Forecasts
EPOS8	Earth Parameter and Orbit System Software, developed by GFZ
FMI	Finnish Meteorological Institute
GAMIT/GLOBK	a comprehensive suite of programs for analyzing GNSS measurements, developed by MIT, Scripps Institution of Oceanography and Harvard University with support from the National Science Foundation
GNSS	Global Navigation Satellite System
GRUAN	Global Climate Observing System (GCOS) Reference Upper-Air Net- work
IFS	Integrated Forecast System
IGS	International GNSS Service
IPW	integrated precipitable water
OI	Optimal Interpolation method
OPERA	The Operational Weather Radars in Europe
RINEX	Receiver Independent Exchange Format - a data interchange format for raw satellite navigation system data
WMO	World Meteorological Organization
ZTD	Zenith total delay

Appendix C. Abbreviations