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Intense sea-effect snowfall case on the western coast of Finland

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Abstract. A new national daily snowfall record was measured in Finland on 8 January 2016 when it snowed 73 cm (31 mm as liquid water) in less than a day in Merikarvia on the western coast of Finland. The area of the most intense snowfall was very small, which is common in convective precipitation. In this work we used hourly weather radar images to identify the sea-effect snowfall case and to qualitatively estimate the performance of HARMONIE, a non-hydrostatic convection-permitting weather prediction model, in simulating the spatial and temporal evolution of the snowbands. The model simulation, including data assimilation, was run at 2.5 km horizontal resolution and 65 levels in vertical. HARMONIE was found to capture the overall sea-effect snowfall situation quite well, as both the timing and the location of the most intense snowstorm were properly simulated. Based on our preliminary analysis, the snowband case was triggered by atmospheric instability above the mostly ice-free sea and a low-level convergence zone almost perpendicular to the coastline. The simulated convective available potential energy (CAPE) reached a value of 87 J kg^{-1} near the site of the observed snowfall record.

1 Introduction

The year 2016 started with imposing a new national snowfall record in Finland, located in the Baltic Sea region in northern Europe. The snow depth increased by 73 cm in Merikarvia (61.85° N, 21.65° E), western coast of Finland, in less than a day during 8 January (Punkka, 2016; Ilmastokatsaus, 2016). This accumulation of new snow distinctly exceeded the previous record, 50 cm, measured in a nearby coastline city, Rauma, 100 km to the south, on 21 November 1971. Given in liquid water precipitation amount, the new record corresponded to 31 mm and the previous record to 22 mm.

The Merikarvia snowfall case was caused by a lower tropospheric mesoscale phenomenon, lake-effect (here sea-effect) convection. If a cold air mass flows over a warm ice-free water surface, the water area acts as a source of heat and moisture. This produces an unstable boundary layer over the water body. As a result, the turbulent heat and moisture fluxes from the water surface are large and generate shallow convection that induces small and intensive convective precipitation which can drift to the coast as snowbands (Markowski and Richardson, 2010; Mazon et al., 2015).

Surface heating of cold-air advection over relatively warm water is the most important factor affecting the occurrence of snowbands (Mazon et al., 2015, and references therein). As a rule of thumb, the temperature difference between the 850 hPa temperature and the water surface should be at least 13 °C (Markowski and Richardson, 2010). The most favourable conditions for sea-effect snowfall typically prevail after a warm autumn, if an Arctic air mass reaches a relatively warm water area during early winter. An implication of the phenomena is that coastal areas are more likely to experience intense snowfalls during late autumn and early winter than inland regions.

To form and reach the coast, intense sea-effect snowbands require a sufficient fetch over open water and a suitable wind direction and speed. According to Markowski and Richardson (2010), the former is usually over 75 km and the latter is 7–15 m s^{-1}. For sea-effect snowbands to form in Finland there are several typical restricting factors (Punkka, 2016; Ilmastokatsaus, 2016). First, the sea areas are rather narrow (70–130 km for the Gulf of Finland and 80–240 km for the Gulf of Bothnia, Fig. 1). Second, the sea areas are oriented so that either the fetch over open water tend to be too short

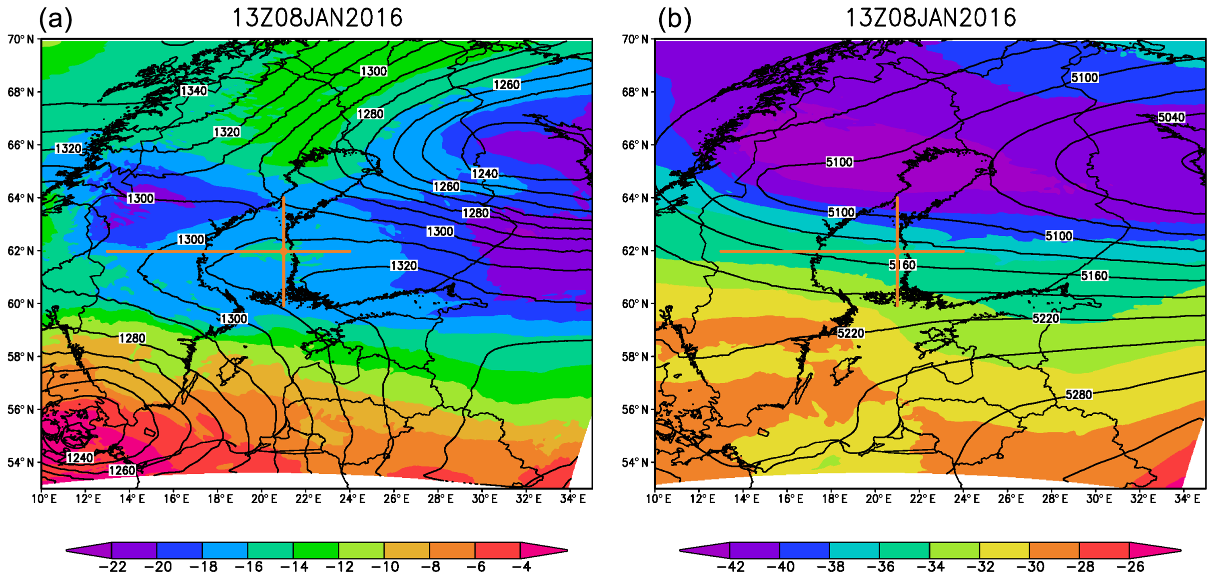

Figure 1. Temperature (in °C, shading) and geopotential height (in m, contours in black) at 850 hPa **(a)** and 500 hPa **(b)** at 13:00 UTC on 8 January 2016, as simulated by HARMONIE. The scales of the axes are latitudes and longitudes. The vertical sections in Figs. 4 and 6a are made along the west-east line segment and those in Fig. 6b along the south-north line segment.

(typical in the southern coastline of Finland with southerlies and southeasterlies) or the airflow is too warm (with westerlies). Third, an ice cover prevents the snowband formation (typical in the western coastline of the country with northerlies).

Predicting and understanding of sea-effect snowfall is important as these events can cause serious problems for the fluency and safety of coastal transportation (road/train/aircraft) and electricity transmission lines. Several factors affect the formation of sea-effect snowfall. The aims of this case study are to identify the main triggering factors that induced these snowbands and to qualitatively verify weather prediction simulations with the aid of hourly radar images. In this paper only preliminary results are presented as the study is still ongoing. In the future, more snowband cases will be selected and evaluated.

2 Data and methods

Hourly radar reflectivity images from the weather radar network of the Finnish Meteorological Institute (FMI, Saltikoff et al., 2010; Gregow et al., 2017) were used to preliminary identify the sea-effect snow case on 8 January 2016. Moreover, radar-based hourly accumulated precipitation images were qualitatively compared to simulations of precipitation with a weather prediction model (HARMONIE; see below). Observational information about the sea ice cover extent and sea surface temperatures over the Gulf of Bothnia were provided by ice charts of FMI (Fig. 1). In order to explore the synoptic situation during the Merikarvia event, air pressure and temperature fields from the HARMONIE simulations and from the operational ECMWF medium range forecasts were used together with analyses made by FMI meteorologists (fronts, temperature, precipitating areas, clouds, weather symbols, and wind barbs).

HARMONIE (ALADIN-HIRLAM system, version 38h1.2) is a non-hydrostatic convection-permitting limited area Numerical Weather Prediction (NWP) model (Bénard et al., 2010; Brousseau et al., 2011). It has been developed in collaboration by ALADIN and HIRLAM NWP model consortia including multiple European weather centres. Physical parametrizations of the HARMONIE model include radiation, surface, shallow convection, turbulence and microphysics schemes (Seity et al., 2011). In HARMONIE, the radiation parametrizations of ECMWF are used (Iacono et al., 2008; Mlawer et al., 1997; Morcrette et al., 2008). The surface scheme SURFEX simulates fluxes of heat, moisture and momentum between the surface and the atmosphere (Masson et al., 2013). Shallow convection parametrization uses scheme by Pergaud et al. (2009). The turbulence parametrization scheme, which is based on the TKE equation, was developed by Cuxart et al. (2000). For microphysics, three-class ice parametrization scheme ICE3 (Pinty and Jabouille, 1998) is applied. The data assimilation system used in HARMONIE for upper air observations is 3D-Var. In surface data assimilation the Optimal Interpolation (OI) method is used.

In this work the AROME configuration of the HARMONIE system was used. We run the model for the Merikarvia case following the operational practise at FMI, i.e. 2.5 km horizontal resolution and 65 model levels in vertical, with the model top at 10 hPa, and a domain that cov-

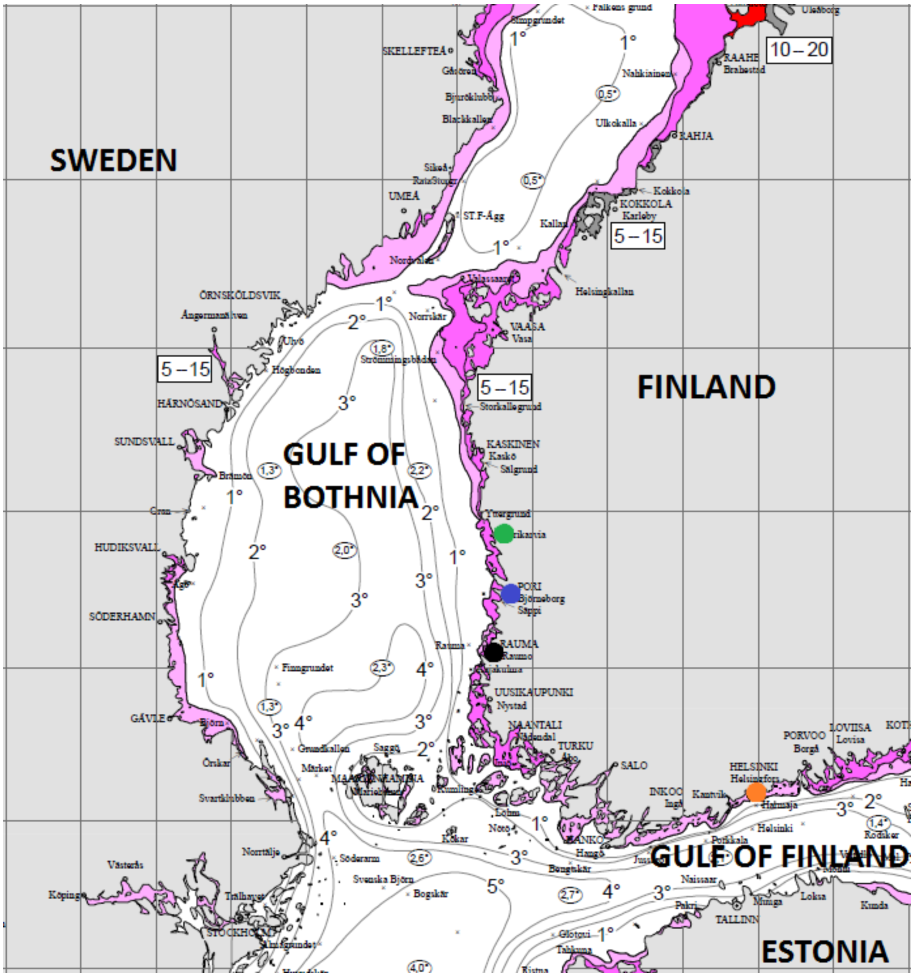

Figure 2. Ice chart on 8 January 2016. Water temperature isotherms are shown with black solid lines along with the sea surface mean temperatures (1971–2000) encircled. Purple/red shades indicate different ice formations (new ice, grey ice, very close ice). Ice thickness is shown in squares (cm). Merikarvia is marked with a green dot, Pori with a blue dot, Rauma with a black dot, and Helsinki with an orange dot.

ers Finland, Scandinavia and the Baltic countries. The lateral boundary conditions were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) global NWP model. The data assimilation system used in HARMONIE for upper air observations is 3D-Var. In surface data assimilation the Optimal Interpolation (OI) method is used. The assimilated observations included surface synoptic observations both on land and sea (SYNOP and SHIP), aircraft reports (AMDAR, AIREP, ACARS), buoy observations (BUOY), radiosondes (TEMP) and wind profiler (PILOT) observations.

It would be possible to run the HARMONIE system also as a climate model. The HARMONIE Climate system (HCLIM, Lindstedt et al., 2015) is an active development branch in the ALADIN-HIRLAM community.

3 Results

3.1 Synoptic situation

During the turn of the year from 2015 to 2016, a high-pressure area started to approach the Fennoscandia from the east, which enabled a flow of very cold and dry air masses. High sea-level pressure values (1040–1050 hPa) were observed over Finland a week before the Merikarvia event but those had decreased to 1010–1015 hPa over the Bothnian Sea, a part of the Gulf of Bothnia in front of Merikarvia, until 8 January. A ridge of high 850 hPa geopotential heights extended from southern Finland to central Sweden, while there were centres of low geopotential heights in the north-eastern and southwestern corners of the domain (Fig. 1). At the level of 500 hPa westerly winds prevailed.

The autumn and early winter had been exceptionally warm in 2015. The mean autumn temperatures in western coast of

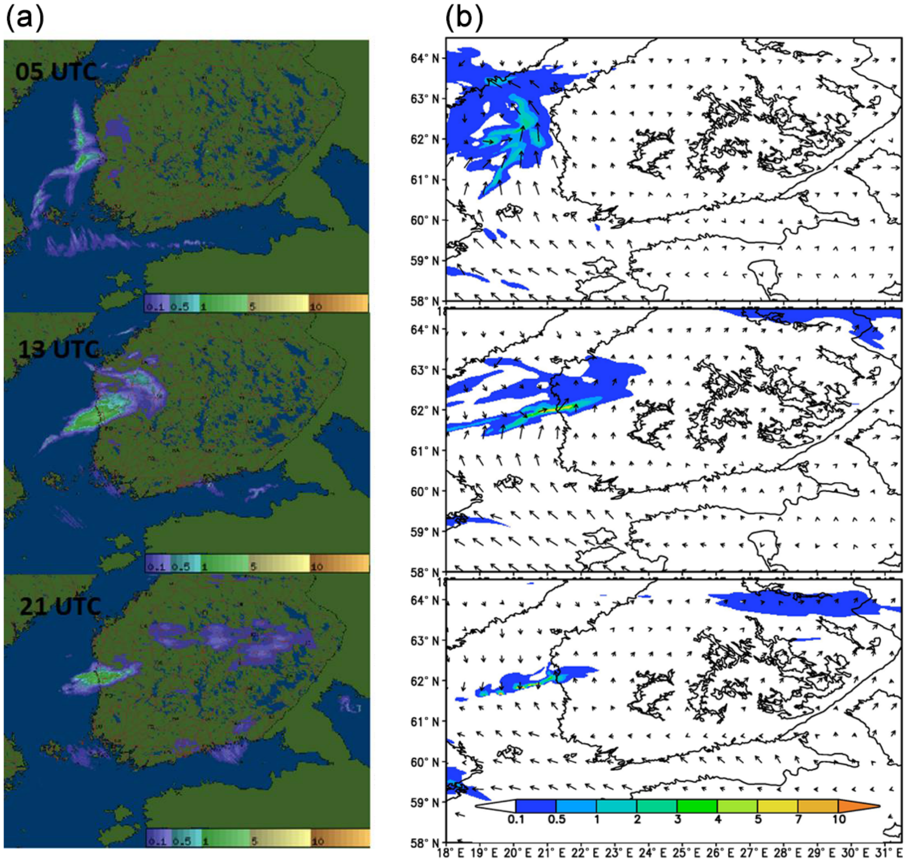

Figure 3. One-hour accumulated precipitation (mm h^{-1}) as observed by weather radar **(a)** and simulated with HARMONIE **(b)** for 05:00 UTC (top panels), 13:00 UTC (middle panels), and 21:00 UTC (bottom panels) on 8 January 2016. Simulated wind field at 10 m (arrows) is also shown. The latitudes and longitudes are given in the axes on the right.

Finland were 2–2.5 °C higher compared to the mean seasonal temperatures during 1981–2010. Thus the sea was still almost ice free and relatively warm (sea surface temperature was 2–4 °C, Fig. 2) when the Arctic air mass reached the Gulf of Bothnia. At the nearest radiosonde station (Jokioinen), about 160 km from Merikarvia to the southeast, the 850 hPa air temperature was −15.5 °C, i.e. almost 20 °C lower, at 00:00 UTC on 9 January (Punkka, 2016).

On 8 January the snowband event had several hours to form. According to the radar images (FMI, 2016), snowfall started in Merikarvia at about 09:30 UTC and finally ended after about 18 h when the westerly flow turned to southerly. Small intense snowbands were detected by radars still on 10 January over the Gulf of Bothnia. On 10 January, a low pressure system started to approach from the southwest, causing southeasterly flow with warm advection, which led to less favorable conditions for convection to form.

3.2 Simulated features

HARMONIE could capture the snowband event quite well when compared to the radar observations (Fig. 3). According to the simulation, separate cells of convective precipitation were formed over the Gulf of Bothnia during the night between 7 and 8 January. The convective cells evolved to one narrow snowband which hit the Finnish coastline perpendicularly on 8 January. The hourly accumulated precipitation intensity is comparable to radar images and the timing and shape of the snowband was correctly simulated (Fig. 3). The simulated total 24 h accumulation (30 mm) corresponded very well the observed (31 mm) value at Merikarvia. The location of the snowband was simulated well although slightly north to the observed snowband.

The simulated 2 m temperatures were low: the minimum over the western coast of Finland was around −20 °C during the preceding night. The temperature increased over 10 °C as the snowband approached the Finnish coastline, and was highest, around −4 °C, during the most intense simulated snowfalls (12:00–15:00 UTC). The air temperature difference between 2 m above the sea surface and the height of 850 hPa increased from the Swedish coast towards the Finnish coast and was simulated to be 12.5 °C at its highest. A vertical cross-section of the equivalent potential temperatures along the latitude of 62° N from the Swedish to the

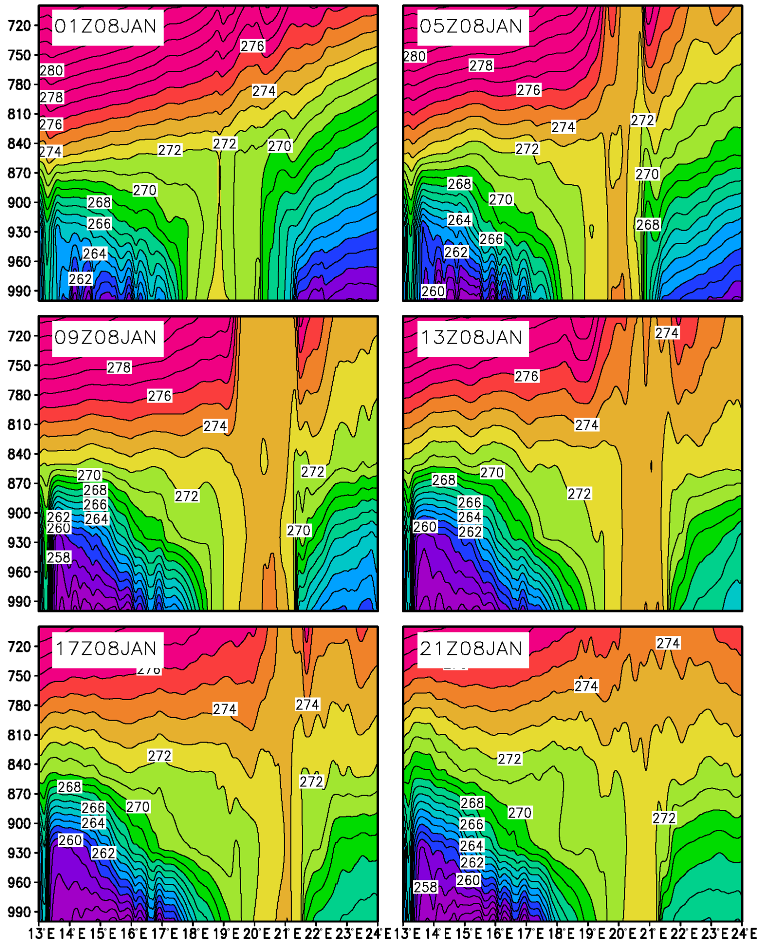

Figure 4. Vertical cross section from 1000 to 700 hPa of the equivalent potential temperature (K) along 62° N, as simulated by HARMONIE, from 01:00 UTC (top left panel) to 21:00 UTC (bottom right panel), with 6 h increments, on 8 January 2016. The sea is located between 17.3 and 21.2° E, Finland to the east and Sweden to the west. For the latitude of 62° N and the longitudes, see the horizontal segment line in Fig. 1.

Finnish coast (Fig. 4) shows that the air layer was mostly stable except that above eastern part of the Gulf of Bothnia the atmosphere was unstable to vertical motions, with decreasing equivalent potential temperature with height (Fig. 4).

Over the sea near Merikarvia, convective available potential energy (CAPE; calculated as pseudoadiabatic with ice) and the lifted condensation level (LCL, in hPa) increased in time from early morning values of 10 J kg^{-1} and 973 hPa, respectively, to the maximum values of 87 J kg^{-1} and 980 hPa at 19:00 UTC. According to the HARMONIE simulation, the most intense snowfall at the coast took place at 13:00 UTC. At that time the CAPE was 69 J kg^{-1} and the LCL was 975 hPa over the sea approximately 30 km offshore (Fig. 5). The simulated sum of cloud ice and water was at maximum at about 3 km (Fig. 6).

Resulting from colliding winds from the south and north, there was a zone of low-level convergence extending from the sea to Merikarvia (13:00 and 21:00 UTC in Figs. 3 and 6). The convergence zone was almost perpendicular to the Finnish coast. The air mass south of it was distinctly drier (relative humidity (RH) of 60–70 % at 2 m height and 20–70 % at 850 hPa) than the air mass north of the zone (RH of 80–100 % at 2 m and 80–100 % at 850 hPa). At the height of 2 m the strongest RH gradient was found in the same area as the snowband and at the 850 hPa level the RH gradient was tilted towards south. The snowband was simulated to form along the convergence zone and it drifted towards the coastline as the southerlies and southwesterlies were dominating during the first half of the day. Towards the evening the southerlies turned to southeasterlies, the northerlies intensified (Figs. 3–6), and the area of maximum wind velocities moved from the Finnish coastline towards the Swedish coast. Directional wind shear with height varied along the day over the Gulf of Bothnia. During the most intense snowfall, the wind direction was almost the same at 850 and 1000 hPa i.e. from the southwest (Fig. 5).

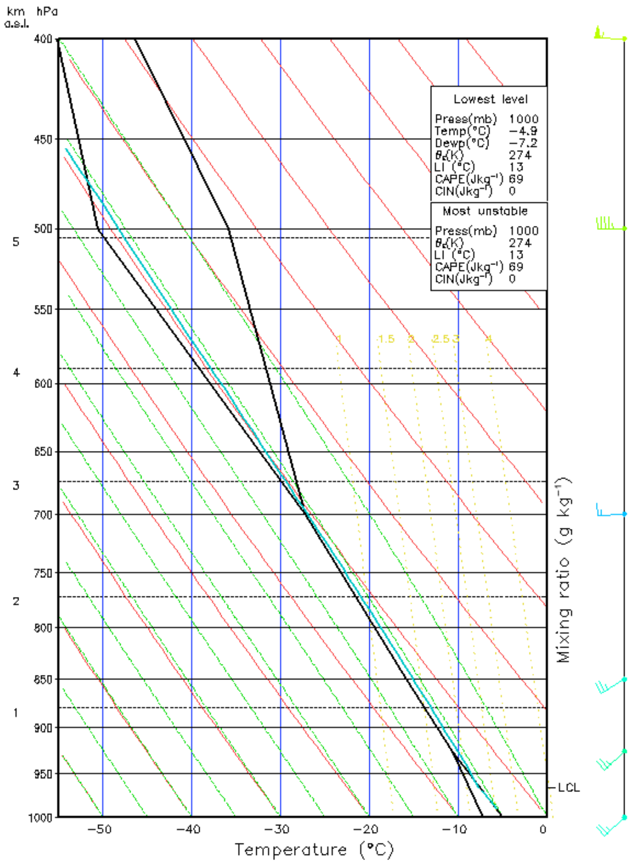

Figure 5. A thermodynamic diagram taken over the sea at 62° N, 21° E (see Fig. 1) at 13:00 UTC from 1000 to 400 hPa. Height (in km and in hPa, dashed and solid black horizontal lines, respectively) is shown in the left vertical axis, temperature (blue) in the horizontal axis, and mixing ratio (yellow) in the right vertical axis. Wind barbs are shown on the right. Other contours shown are dry adiabats (red), moist pseudo-adiabats (green), simulated temperature and dew point soundings (black), and a parcel path from the most unstable level upward (light blue). Thermodynamic indices for surface (1000 hPa) and the most unstable level are shown in the top right boxes. The 2 m temperature was −4 °C and the sea level air pressure 1005 hPa.

In Merikarvia the maximum fetch was ∼ 300 km over open water as the wind blew there from the southwest (13:00 UTC, Figs. 3 and 5). This wind direction is typically associated with warm advection to Finland and therefore usually unfavourable for sea-effect snowfall. In this case, however, warm advection did not occur since the cold air mass prevailed over most of Fennoscandia (Fig. 1). In Merikarvia the simulated wind speed was between 9 and 15 m s^{-1}, which is regarded by Markowski and Richardson (2010) as the optimal velocity for snowbands to form.

The offshore snowfall over the Bothnian Bay during the morning (05:00 UTC in Fig. 3) was found to be related to scattered zones of low-level convergence. Besides, in addition to the very intense snowfall on the western coast, some weaker sea-effect snowfall areas were also observed on the southwestern and southern coastline of Finland. HARMONIE simulated some low-level convergence there but no snowfall.

4 Discussion

Weather radars observed several snowbands over the Gulf of Finland near the southern coast for almost two weeks before the Merikarvia event. However, at that time the wind direction had not been favourable for the snowbands to hit the coast. With a more south-easterly flow, the new snow record could have taken place in the Helsinki metropolitan area on the southern coast of Finland and severe weather might have lasted for several days there. Snowfalls had also been detected over the Gulf of Bothnia near the western coast of Finland already three days before the Merikarvia event, with almost the same intensity, but those snowfalls remained over the sea.

Fortunately, the impacts of the record snowfall in Merikarvia remained small. The intense snowfall area was very limited (∼ 50 km diameter) and the municipality of Merikarvia has only slightly over 3000 habitants. Besides, despite the high increase in the snow depth, the accumulated amount of snow corresponded only to 31 mm of liquid water, owing to the fact that the fallen snow was light powder snow. No car crashes were registered, only few cars were jammed to the snow, and no electricity transmission lines were broken by the light powder snow. Neither there are any train or aircraft traffic which could have been troubled. Nonetheless, if the snowband had hit to larger cities nearby, Pori or Rauma (Fig. 2), the effect of the snowfall would have been more harmful for the traffic and could have caused several accidents, like happened on 3 February 2012 in the Helsinki metropolitan area (Juga et al., 2014). Rapidly worsening driving conditions due to intense snowfall resulted in a large number of car crashes with 690 vehicles and 43 injured persons (Juga et al., 2014).

It is intriguing that the two most intense daily snowfalls have happened almost at the same place; the distance between Rauma and Merikarvia is only 100 km (Fig. 2). So, what are the factors favouring intense sea-effect snowfalls in this area? The Gulf of Bothnia is 80–240 km wide and has an average depth of 60 m. In addition, the topography around the gulf is flat. Usually the westerly and southwesterly airflow is too warm for snowbands to form in this area but when the air mass is sufficiently cold and the gulf is still ice-free, the fetch over the open Gulf of Bothnia can be much longer than on the narrower Gulf of Finland.

The roles of colliding land breezes from the coasts of Finland and Sweden or Finland and Estonia; orographic lifting; and a concave shape of a coastline in promoting offshore convergence and formation of snowbands have recently studied by Savijärvi (2012, 2015) and Mazon et al. (2015). Based on

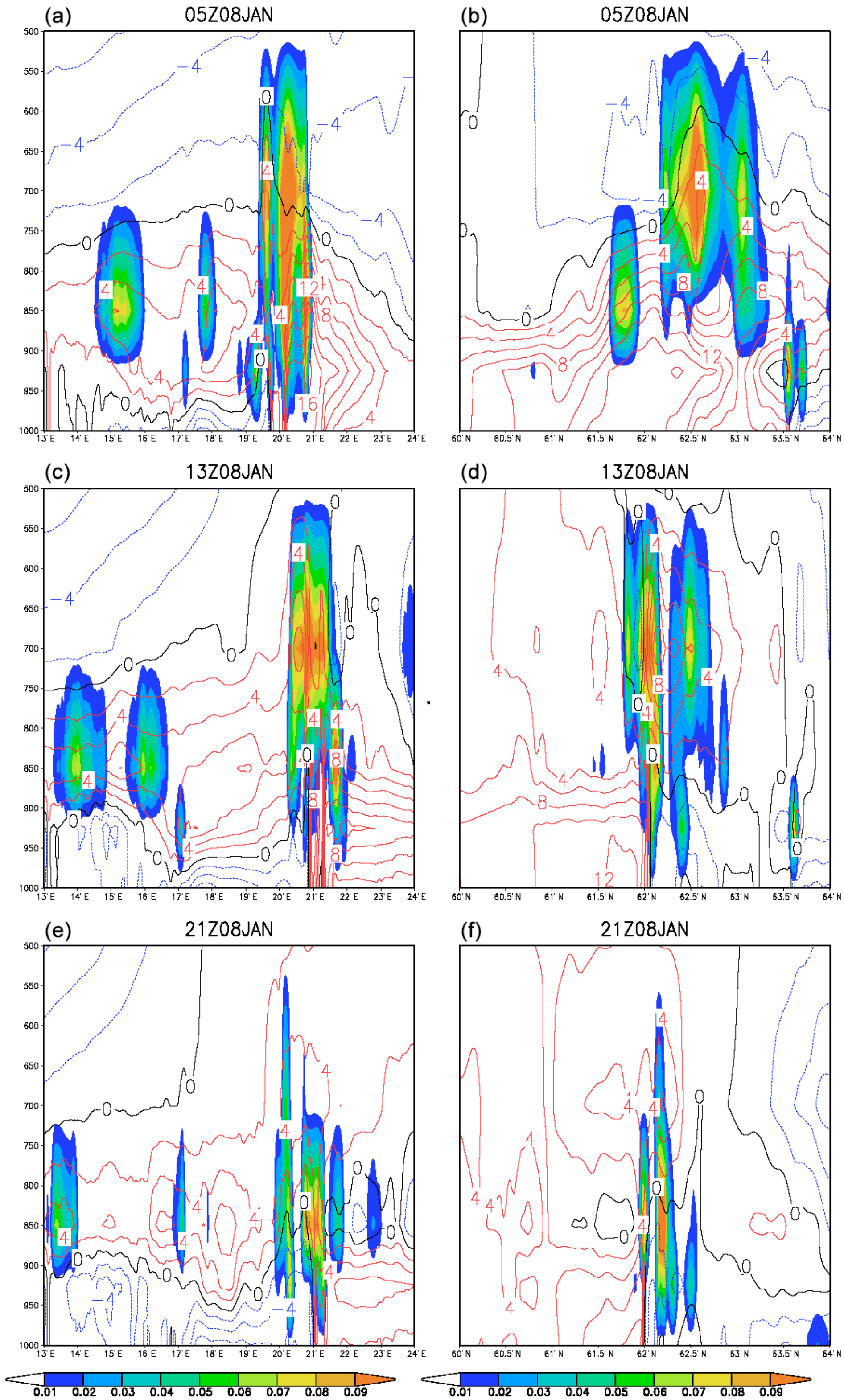

Figure 6. Vertical cross section from 1000 to 500 hPa of cloud water and ice (g m^{-2}) and meridional wind speed (m s^{-1}, southerly in red, northerly in blue) along 62° N **(a, c, e)** and along 21° E **(b, d, f)**, as simulated by HARMONIE for 08:00 UTC **(a, b)**, 13:00 UTC **(c, d)**, and 21:00 UTC **(e, f)** on 8 January 2016. For the latitude and the longitudes, see segment lines in Fig. 1.

our preliminary analysis, the Merikarvia snowfall case was triggered by atmospheric instability above the mostly ice-free sea and a low-level convergence zone. The zone was located almost perpendicular to the Finnish coastline and to the east of a concave part of the Swedish coast. Whether synoptic, mesoscale or smaller-scale factors, or all them, contributed to the formation of the convergence zone remains as a topic beyond the scope of this paper.

Finally it may be noted that the simulated CAPE of $87\,\mathrm{J\,kg^{-1}}$ cannot be considered high. On the other hand, CAPE values are typically modest in Finland. Even in mesoscale convective systems (MCSs), most frequently occurring in July and August, median values of most unstable CAPE are about $800\,\mathrm{J\,kg^{-1}}$ for intense MCSs and about $500\,\mathrm{J\,kg^{-1}}$ for non-intense MCSs, the median values for smaller thunderstorm clusters falling between (Punkka and Bister, 2015).

5 Summary and conclusions

The weather conditions were favourable for snowband to form over the whole Bothnian Sea (a part of the Gulf of Bothnia) as the sea was relatively warm and ice free, and arctic air mass prevailed over most of Fennoscandia. Due to colliding winds over the Bothnian Sea a very localised extreme of snowfall was produced and drifted towards Merikarvia as the maximum winds blew from southwest. The narrow snowband perpendicular to coast line caused record snowfalls to the small area of Merikarvia in the western coast of Finland. The non-hydrostatic convection-permitting weather prediction model HARMONIE captured the overall sea-effect snowfall situation quite well. Both the timing and the location of the most intense snowstorm was correctly simulated. In addition the accumulated precipitation was simulated correctly. Nevertheless, the simulated weaker snowfall did not spread as broadly along the coastline of Finland as was observed.

The preliminary results discussed here suggest that HARMONIE is able to simulate sea-effect snowfall sufficiently accurately and thus can be used to examine prominent weather situations to form snowbands. According to our plan, more sea-effect snowfall cases will be selected and evaluated.

Data availability. The modelled data (in grib format) and the hourly radar reflectivity images used in this study can be provided upon request to the corresponding author. The source code of the HARMONIE model is not publicly available.

Competing interests. The authors declare that they have no conflict of interest.

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References

Bénard, P., Vivoda, J., Masek, J., Smolíková, P., Yessad, K., Smith, C., Brozková, R., and Geleynv, J.-F.: Dynamical kernel of the Aladin-NH spectral limited-area model: Revised formulation and sensitivity experiments, Q. J. Roy. Meteorol. Soc., 136, 155–169, 2010.

Brousseau, P., Berre, L., Bouttier, F., and Desroziers, G.: Background-error covariances for a convective-scale data-assimilation system: AROME–France 3D-Var, Q. J. Roy. Meteorol. Soc., 137, 409–422, https://doi.org/10.1002/qj.750, 2011.

Cuxart, J., Bougeault, P., and Redelsberger, J.-L.: A turbulence scheme allowing for mesoscale and large-eddy simulations, Q. J. Roy. Meteorol. Soc., 126, 1–30, 2000.

FMI: Video animation of radar reflectivity images during the Merikarvia sea-effect event at 10 minute intervals, available at: http://www.ilmastokatsaus.fi/wp-content/uploads/2016/01/merikarvia_lumisade_tutka.gif (last access: 3 July 2017), 2016.

Gregow, E., Pessi, A., Mäkelä, A., and Saltikoff, E., Improving the precipitation accumulation analysis using lightning measurements and different integration periods, Hydrol. Earth Syst. Sci., 21, 267–279, https://doi.org/10.5194/hess-21-267-2017, 2017.

Iacono, M., Delamere, J., Mlawer, E., Shephard, M., Clough, S., and Collins, W.: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models, J. Geophys. Res., 113, D13103, https://doi.org/10.1029/2008JD009944, 2008.

Ilmastokatsaus: Merikarvialla ennätyksellinen lumisade, available at: http://www.ilmastokatsaus.fi/2016/01/15/merikarvialla-ennatyksellinen-lumisade/ (last access: 21 March 2017), 2016.

Juga, I., Hippi, M., Karsisto, V., and Nurmi, P.: 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, 2014.

Lindstedt, D., Lind, P., Jones, C., and Kjellström, E.: A new regional climate model operating at the meso-gamma scale; performance over Europe, Tellus A, 67, 24138, https://doi.org/10.3402/tellusa.v67.24138, 2015.

Markowski, P. and Richardson, Y.: The Boundary Layer, in: Mesoscale Meteorology in Midlatitudes, John Wiley & Sons, Ltd, Chichester, UK, 93–102, https://doi.org/10.1002/9780470682104.ch4, 2010.

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F., Brousseau, P., Brun, E., Calvet, J.-C., Carrer, D., Decharme, B., Delire, C., Donier, S., Essaouini, K., Gibelin, A.-L., Giordani, H., Habets, F., Jidane, M., Kerdraon, G., Kourzeneva, E., Lafaysse, M., Lafont, S., Lebeaupin Brossier, C., Lemonsu, A., Mahfouf, J.-F., Marguinaud, P., Mokhtari, M., Morin, S., Pigeon, G., Salgado, R., Seity, Y., Taillefer, F., Tanguy, G., Tulet, P., Vincendon, B., Vionnet, V., and Voldoire, A.: 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, https://doi.org/10.5194/gmd-6-929-2013, 2013.

Mazon, J., Niemelä, S., Pino, D., Savijärvi, H., and Vihma, T.: Snowbands over the Gulf of Finland in wintertime, Tellus A, 67, 25102, https://doi.org/10.3402/tellusa.v67.25102, 2015.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., and Clough, S. A.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-*k* model for the longwave, J. Geophys. Res., 102, 16663–16682, 1997.

Morcrette, J.-J., Barker, H., Cole, J., Iacono, M., and Pincus, R.: Impact of a new radiation package, McRad, in the ECMWF Integrated Forecasting System, Mon. Weather Rev., 136, 4773–4798, 2008.

Pergaud, J., Masson, V., Malardel, S., and Couvreux, F.: A parameterization of dry thermals and shallow cumuli for mesoscale numerical weather prediction, Bound.-Lay. Meteorol., 132, 83–106, 2009.

Pinty, J.-P. and Jabouille, P.: A mixed-phased cloud parameterization for use in a mesoscale non-hydrostatic model: Simulations of a squall line and of orographic precipitation, Preprints, Conf. on Cloud Physics, Amer. Meteor. Soc., Everett, WA, 217–220, 1998.

Punkka, A.-J.: Merikarvian lumitykki, available at: http://www.myrskyvaroitus.com/index.php/blogit/taivasasioita/item/20-merikarvian-lumitykki, (last access: 21 March 2017), 2016.

Punkka, A.-J. and Bister, M.: Mesoscale convective systems and their synoptic-scale environment in Finland, Weather Forecast., 30, 182–196, 2015.

Saltikoff, E., Huuskonen, A., Hohti, H., Koistinen, J., and Järvinen, H.: Quality assurance in the FMI Doppler Weather Radar Network, Boreal Environ. Res., 15, 579–594, 2010.

Savijärvi, H.: Cold air outbreaks over high-latitude sea gulfs, Tellus A, 64, 12244, https://doi.org/10.3402/tellusa.v64i0.12244, 2012.

Savijärvi, H.: Cold air outbreaks along a non-frozen sea channel: effects of wind on snow bands, Meteorol. Atmos. Phys., 127, 383–391, https://doi.org/10.1007/s00703-015-0370-8, 2015.

Seity, Y., Brousseau, P., Malardel, S., Hello, G., Benard, P., Bouttier, F., Lac, C., and Masson, V.: The AROME-France convective-scale operational model, Mon. Weather Rev., 139, 976–991, 2011.