# Nowcasting snow for airports at heterogeneous terrain

*Elena Saltikoff[1], Martin Hagen[2], Heikki Juntti[1], Rudolf Kaltenböck[3] and Seppo Pulkkinen[1]*

[1]Finnish Meteorological Institute P.O. Box 503, FI-00101 Helsinki, Finland
[2]Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany
[3]Austro Control, Wien, Austria

## *Abstract*

*The forecast of snow events at airports is a major challenge in airport operation during winter time. In contrast to rain, snow has to be actively removed from aircraft or operation areas. Short term forecasting – or nowcasting – of snow events is required for airport operation. Airport stakeholders need to know the start and duration of snow events, but they need also an estimate of the snow accumulation during the event. Extrapolation techniques based upon weather radar observations are used to generate a probabilistic nowcast for airports. These techniques assume a linear propagation of the precipitation fields. In case of intensifying, decaying or non-linear propagation the forecast quality is considerably reduced. In this paper we show that lake effects along the coastlines or flow within the proximity of mountains degrade the forecast quality and the lead time for reliable nowcasts is shorter than for situations which are not affected by heterogeneous terrain.*

## *1      Introduction*

Forecasting weather for airports is an interesting but demanding area of meteorology. Most of the users are highly trained professionals in a well known location. Weather has a large contribution to decision-making, which can in extreme cases affect life and death but frequently punctuality, environmental issues and economical savings. If an intercontinental flight has to be rerouted to another airport due to bad weather conditions, the costs to the airline are in the order of tens of thousands of euros.

International Civil Aviation Organization (ICAO) has defined minimum criteria for meteorological services for international air navigation. In addition to those well-defined services, many airports use additional services, which can be tailored for each user group. Those removing snow from runways need different forecasts from those controlling approaching and departing flights.

In this work we have looked into different aspects of very short (0–3h) forecasts of snow, based on movement of weather radar echoes. Extrapolative methods have their limits, but in the very short range forecasting they have the ability to forecast short-lived phenomena, such as a 45 minute pause in snowfall. Very few other methods can do that. Numerical weather prediction is not suited to cover these short time periods since the models need time to adjust to the observations and to the hydrodynamic state of the atmosphere. Numerical weather prediction is well suited for lead times beyond 2 or 3

hours, depending on the weather situation. However, it should be kept in mind that the forecast quality of precipitation is still lower than for parameters like pressure or temperature.

This paper is organized as follows: the needs of different user groups are discussed in chapter 2, and extrapolation as a forecasting method in general in chapter 3. Chapter 4 discusses two different features of terrain affecting predictability: sea without ice cover as a source of heat and moisture, and land formations such as mountains. Conclusions and future work follow in chapter 5.

## 2      Needs for probabilistic nowcasting

Probabilistic forecasting is nowadays used in meteorology to quantify uncertainty. In contrast with deterministic forecasting, probabilistic forecasts take into account the natural intrinsic variability of weather as well as the uncertainty in the observations used in the forecast and the forecast process itself. Probabilistic forecasts also remind the user of the impossibility of providing an absolutely reliable deterministic forecast for a point location like an airport. A probabilistic forecast can be created by generating an ensemble of forecasts or by applying statistical post-processing to a deterministic forecast. For the post-processing, the user must choose thresholds for the considered phenomenon, such as "5 cm snow". With appropriate thresholds the probability forecast will describe the user-specific risks related to a specific situation (such as the probability of snowfall exceeding 5 cm). An objective assessment of uncertainty in forecasts enables the user to take into account various potential scenarios with varying risks. Compared to a deterministic point forecast, a probabilistic forecast supports the decision making much more extensively.

In the two-year project PNOWWA (Probabilistic Nowcasting of Winter Weather for Airports) various professionals at airports were approached to discuss their needs and interest in using probabilistic forecasts. Three major groups of users were identified. The *runway maintenance* needed the accumulation of snow in millimetres during each 15-minute step. Thresholds were expressed separately for dry snow, wet snow and slush. In addition, they were interested in the probability of freezing rain, which cannot be determined by an algorithm solely based on weather radar measurements. The *aviation control tower* was most interested in the probability of low visibility procedures (LVP). In winter, LVP is related to clouds, fog or snowfall. An algorithm based only on weather radar measurements is only able to express the visibility reduction related to snowfall. The *deicing managers* at airports have in operation a Deicing-weather index (DIW). The DIW index is related to the type and amount of precipitation and the main purpose of it is to help to assess the time needed for the deicing of an individual aircraft in a specific weather situation.

Based on the interviews, PNOWWA team prepared various kinds of very short (0–3h) forecasts of snow, based on the extrapolation of movement of weather radar echoes, organized demonstration campaigns and discussed the experiences with the user

groups. The participating airports were located either at coastal areas (Helsinki) or in hilly or mountainous areas, which added challenges to forecasting by extrapolation.

In the demonstration periods, point forecasts of snowfall-related phenomena were delivered in real-time for selected users.. After the demonstrations, the users expressed their need for areal products "to see the bigger picture". Both in table format and map format, there is one dimension too many to be visualized: it is not possible to show all probabilities of all intensities. Two approaches are shown in Figure 1: either calculating from the most probable intensity, or, to show the numeric value of probability of snowfall intensity exceeding a certain threshold.

## 3 Extrapolation

The approach taken is based on extrapolation of the movement of snowfall areas in consecutive radar images. The extrapolation is divided into two parts. First, the past movement is analyzed by comparing consecutive radar images, and thus producing a vector field. Then the future movement is forecasted by moving the latest radar image into the direction of the movement field. The past movement does not fully describe the future movement, and the related uncertainty can be assessed from properties of the vector field, as explained in *Hohti et al.* (2000). In the new method implemented in this project, also the uncertainty related to the growth and decay of precipitating systems is assessed, based on the STEPS method described by *Bowler et al.* (2006).

It is known that forecast uncertainty increases with lead time, and predictability is proportional to spatial scale (i.e. small-scale features have shorter lifetime and their predictability therefore lower). In the stochastic ensemble method this is modeled by auto-regressive process in each spatial scale. Unexplained variance is gradually replaced with spatially and temporally correlated noise field. Perturbations are added to the deterministic nowcast based on the motion field. 25 ensemble members are obtained by perturbing precipitation intensities and motion field. The ensemble mean represents the "most probable" precipitation intensity. The mean field becomes smoother when the forecast time increases: badly predictable scales are filtered out. The ensembles also yield probability distributions of precipitation intensities. At a given location, an empirical probability distribution for precipitation intensity can be constructed from the ensemble members.

For the research demonstrations of PNOWWA project, a simple method introduced by *Andersson and Ivarsson* (1991) was used. In this method, the wind at 850 hPa level is used to describe the movemen of the precipitation field. The wind is taken from HIRLAM (High Resolution Limited Area Model) numerical weather prediction model. The uncertainty is introduced with 60 degree movement uncertainty sector. The sector in each airport is divided to sections corresponding to the movement of radar echoes during each 15 minute nowcast interval. The content of each section is analyzed to get the probability distribution of precipitation intensity.
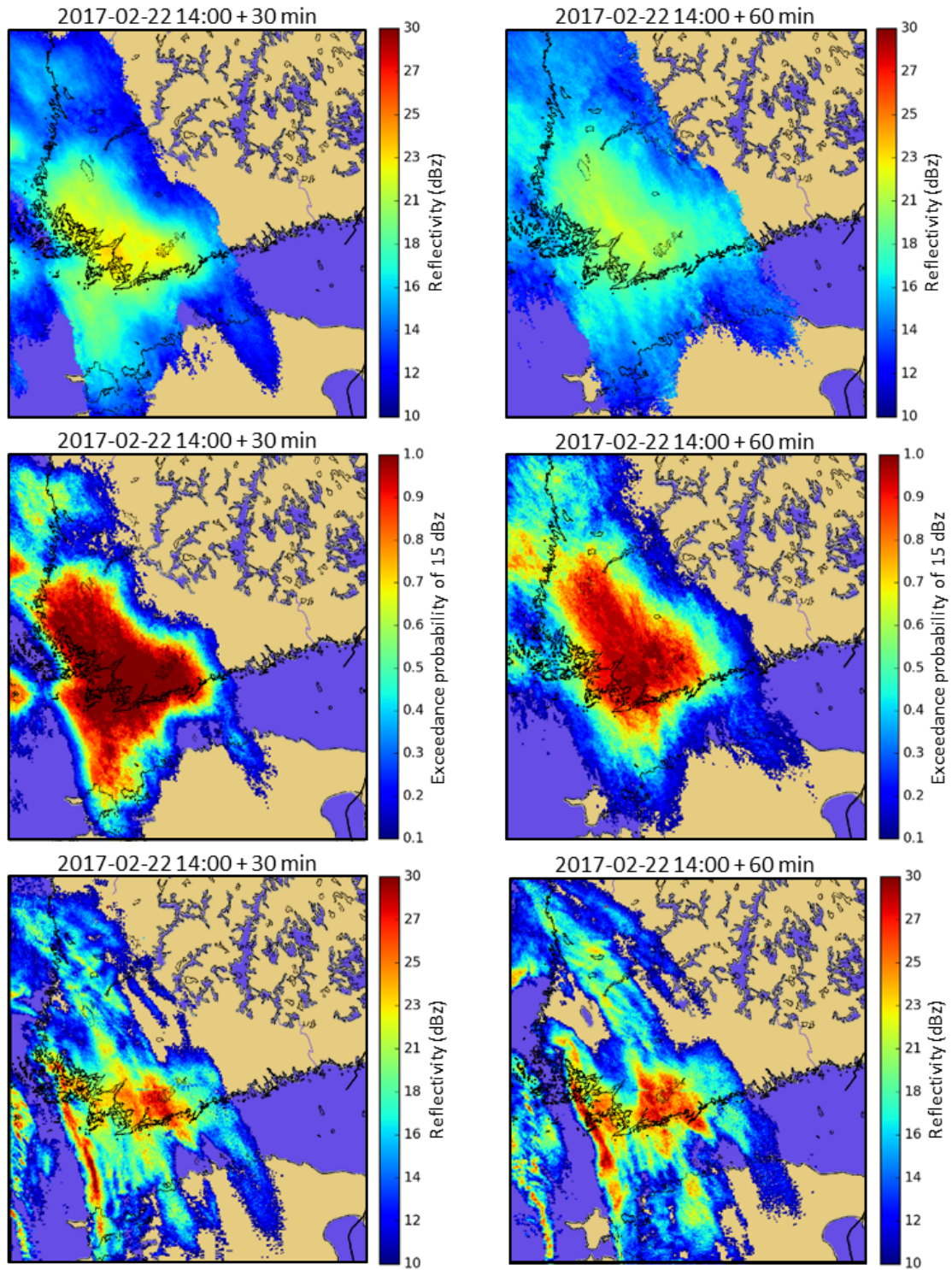
Fig. 1. Different forecast visualizations for 30 min (left) and 60 min (right) lead times with the Stochastic ensemble method. The image on the top tells the most probable precipitation intensity in each point, calculated as an average of the 51 slightly different forecasts contributing to the ensemble. The image on the middle row shows the areas, where the probability of significant snowfall (over 15 dBZ) is most likely. These two visualization approaches can also be used for other weather phenomena, for example thunderstorms. The lowest panel is a radar image for verification.

The number of pixels exceeding a given reflectivity threshold was divided by the number of pixels in the entire section (assuming that each pixel has an equally large

probability to arrive at the target point at the validity moment of the forecast), and the result is interpreted as probability.

Even though the approach is very simple, the results were encouraging. In Fig 2. three different lengths of nowcasts for 21–22 February 2017 in Innsbruck are shown. The onset and the end of snowfall in the evening of 20th Feb is forecasted fairly accurately even in the 3h nowcasts. During the intermittent snowfall on 21st Feb, probabilities are larger during periods when it was snowing than on periods when it was not snowing, but especially in the longest forecast the difference between these (forecast sharpness) is not that good. Most importantly, during the long periods of no snowfall, zero probabilities were also forecasted.
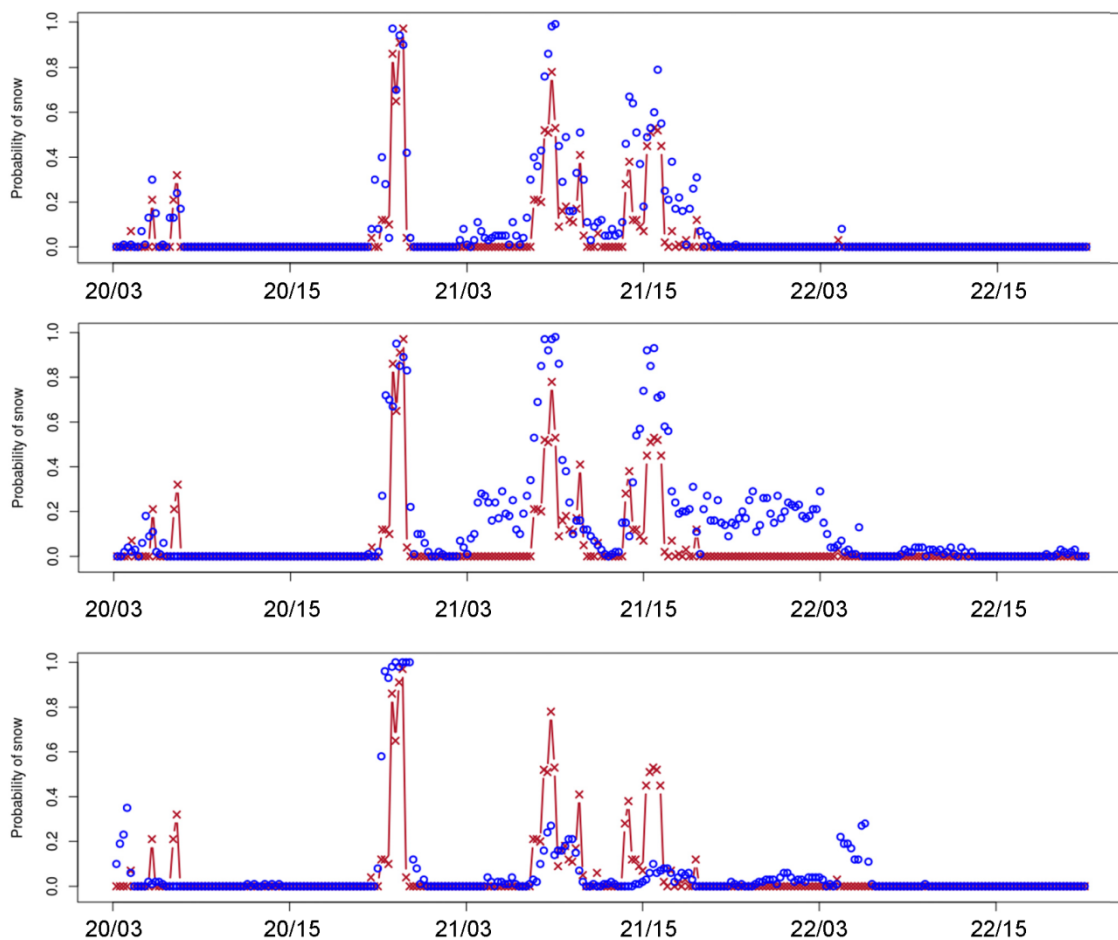


Fig 2. Probability of snowfall exceeding 15 dBZ in Innsbruck 20–22 February 2017. Red line and crosses represent distribution of the pixels within 15-minute range from the airport, blue circles the nowcast for 30 min (top), 90 min (middle) and 180 min (bottom). Horizontal axis is the valid time of the forecasts, from 20 Feb 03:00 to 22 Feb 21:00 UTC.

## 4      Terrain effects

Pure extrapolation methods are only relying on observed motion, assuming that the precipitation systems will continue moving with the observed speed and direction

retaining the same intensity. In a real precipitating system, there are areas where the movement and intensity are changing due to properties on underlying terrain.

### 4.1     Sea

During cold-air outbreaks over a warmer water surface an unstable boundary layer is formed. The large turbulent fluxes of sensible and latent heat from the surface generate shallow convection that induces convective precipitation or enhances existing precipitation systems. So called lake effect snow, observed also at the Baltic Sea (see e.g. *Jeworrek et al*, 2017, *Mazon et al.,* 2015), is a challenge for nowcasting for two reasons: as it is related to a stationary source of energy and moisture, the growth and decay areas may stay in one place, and  small features may be moving in different direction from the larger precipitation area. . What is more, the systems can be very shallow. Fig. 3 shows an example where the Kesälahti radar data are missing and the shallow snowfall at Lake Ladoga is not seen by the other radars. *Kristovich et al.* (2017) report extreme snowfall from clouds reaching only up to 3 km, while we have observed significant precipitation from systems as shallow as 1 km. Such systems can stay unnoticed under the radar beam, which creates artificial borders of growth and decay.
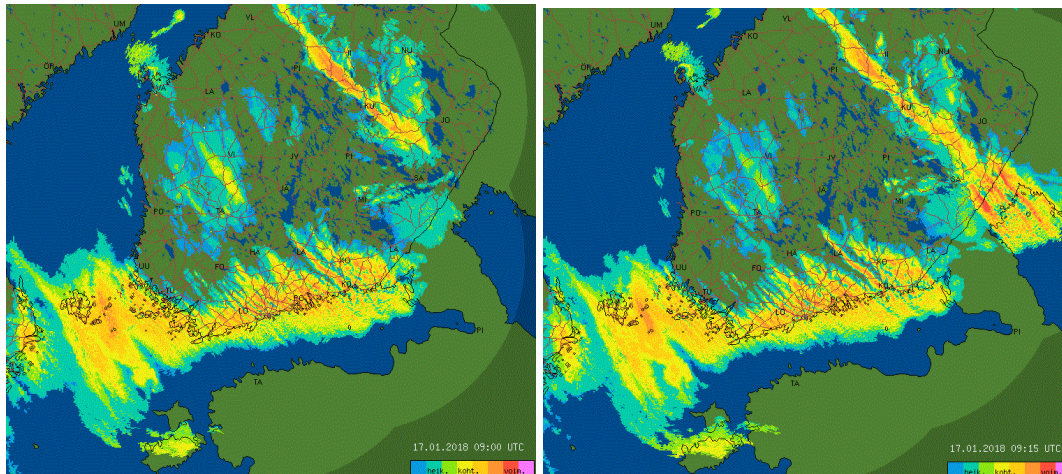


Fig. 3. Lake effect snow case 17 January 2017. Flow is from southeast, and Gulf of Finland and Lake Ladoga act as sources of heat and moisture. In the radar composite at 09:00 UTC (left) radar Kesälahti (easternmost radar in the composite) is not included, and the shallow snowfall at Lake Ladoga is not covered by other radars. In the image 15 minutes later (right) all radars are working.

### 4.2     Mountains

The presence of mountains in the vicinity of airports can considerably influence the behavior of precipitating systems and thus the predictability in short time ranges. This is studied in detail for the airports of Oslo in Norway and Rovaniemi in Northern Finland. Even more complex is the situation for the airports of Munich in Southern Germany and Salzburg in Austria where a strong interaction between the Alps and synoptic-scale precipitation systems is present.

### 4.2.1 Quantitative studies

When airflow approaches or passes over mountains, snowfall is more difficult to forecast than in other situations. This is due to additional lifting and/or blocking of the flow (e.g. *Nurminen,* 1948). The predictability is then worse for all studied methods: extrapolation of radar images, but also for Terminal Area Forecast (TAF) forecasts made by human forecasters, and for numerical weather prediction models.

The quantitative effect of sea and orography was estimated using the nowcasting system developed for an earlier aviation-related project, which was run on additional periods for Rovaniemi (EFRO) and Oslo Gardemoen (ENGM) airports to study orographic effects. The forecasted parameter is DIW, de-icing weather, which is an index with values 0-3. Here we use $DIW_e$, which is calculated from extrapolating the movement of radar echoes using the method described by *Andersson and Ivarsson* (1991).

Days were counted as orographic effect days if at 850 or at 925 hPa (in the case of EFRO also 950 hPa was taken into account, as the terrain and height differences are rather low there) air flow was from the sector (180° – 250°) in Rovaniemi and from (80° – 180°) in Oslo. In most days the direction of the flow varies with time; the flow was considered coming from the valley when it remained in the sector for at least two hours.
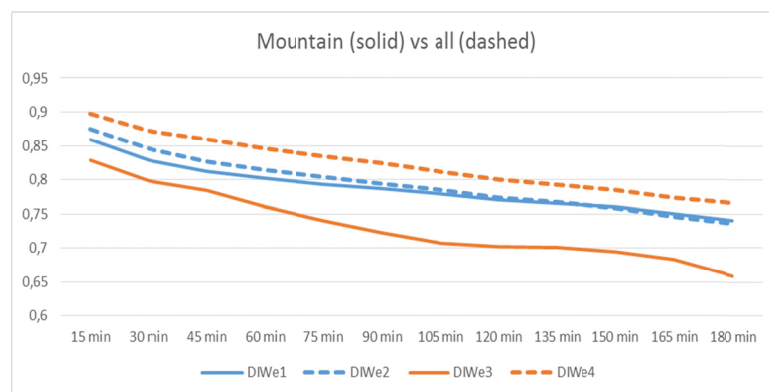


Fig. 4. Summary showing the extrapolation performance (hit rate) of $DIW_e$ in Oslo (red) and Rovaniemi (blue). Forecasts when the flow was affected by orography are shown as solid lines, forecasts for all days are shown as dashed.

Fig. 4 shows the hit rate of of $DIW_e$ forecasts for Rovaniemi and Oslo. If the flow is affected by mountains forecast quality is less than for all cases. This effect is more pronounced in Oslo since there the mountains are considerably higher than in Rovaniemi, where only moderate hills affect the flow and precipitation.

### 4.2.2 Dynamical studies

For the airports of Munich (EDDM) and Salzburg (LOWS) the effect of the Alps on the behavior of cold fronts approaching from northerly directions was investigated. From previous studies it is known that cold fronts can be delayed when approaching the Alps, some systems cross the Alpine Foreland and the Alps without delay, and even acceleration can be observed for fronts passing along the Alpine Foreland (e.g. *Schumann,*

1987 or *Volkert et al.,* 1991). Delayed systems can generate long-lasting (up to a few days) continuous rain or snow fall events.

22 cases from the winters (December - March) 2013–14, 2014–15, 2015–16, and 2016–17 (April) were investigated where cold fronts approached the Alps in the Munich/Salzburg region. To increase the number of samples both situations with rain and snowfall at ground were considered. In about half of the cases the fronts passed the Alpine Foreland without noticeable delay (cf. Fig. 5), whereas the other cases showed considerable delay of the frontal motion leading to long lasting precipitation events (cf. Fig. 6). The duration of the events was between 8 and 46 hours.
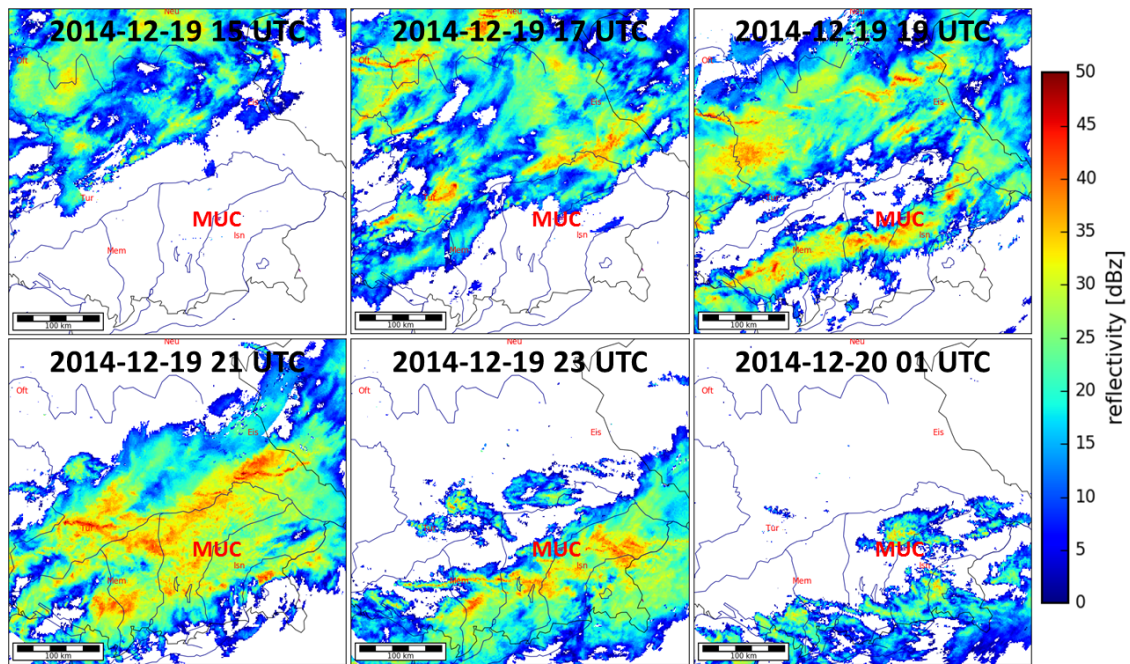


Fig. 5. 3-hourly radar images of a frontal system passing South-Eastern Germany without major delay from 15 UTC on 19 until 01 UTC on 20 December 2014. MUC indicates the location of Munich airport.

Even though on the case of 19 to 20 Dec. 2014 the front passed without any noticeable delay, the precipitation along the front experienced considerable modification in terms of growth and decay. During the second event shown in Fig. 6 precipitation grew upstream or backwards (11 Jan. 04 UTC) within the Alpine Foreland when the cold front reached the Alps. Nowcasting precipitation by linear extrapolation of the observed motion was difficult for both situations since the precipitation pattern showed a highly non-linear behavior. The technique described by *Andersson and Ivarsson* (1991) was used to generate a probabilistic nowcast for the next 2 hours for both cases.

Figure 7 shows the observations at Munich airport and the nowcast for 30, 60, and 120 minutes. The observed and forecasted reflectivity values were empirically transformed to the accumulation height of dry snow within 15 minutes (Table 1). Snow will be assumed to be dry when the temperature and dewpoint are below 0°C. The conversion equations are based on work reported by *Tiira et al.* (2016) and undocumented operational experience of forecasters at FMI. A similar table exists for wet snow. The ob-

servations at the airport also show a distribution of snow accumulation since the area of Munich airport (app. 17 km$^2$) is covered by several radar pixels (resolution 1x1 km$^2$). The distribution of nowcasted snow accumulation shows that it was only partially possible to nowcast dry snow accumulation. For the December 2014 case precipitation before 19 UTC and after midnight is overestimated for lead times of 30 and 60 minutes. The 2 hour nowcast does not provide any further useful information in this situation. For the January 2015 case the onset of precipitation is met with the 30 and 60 minutes nowcast, however the duration and intensity is underestimated for the morning hours (07-10 UTC) on 11 Jan. 2015. On the other side precipitation around noon on 11 Jan. 2015 is considerably overestimated.

Table 1. Empirical relation between radar reflectivity and parameters of interest for airport operation for dry snow (temperature and dew point below 0°C).

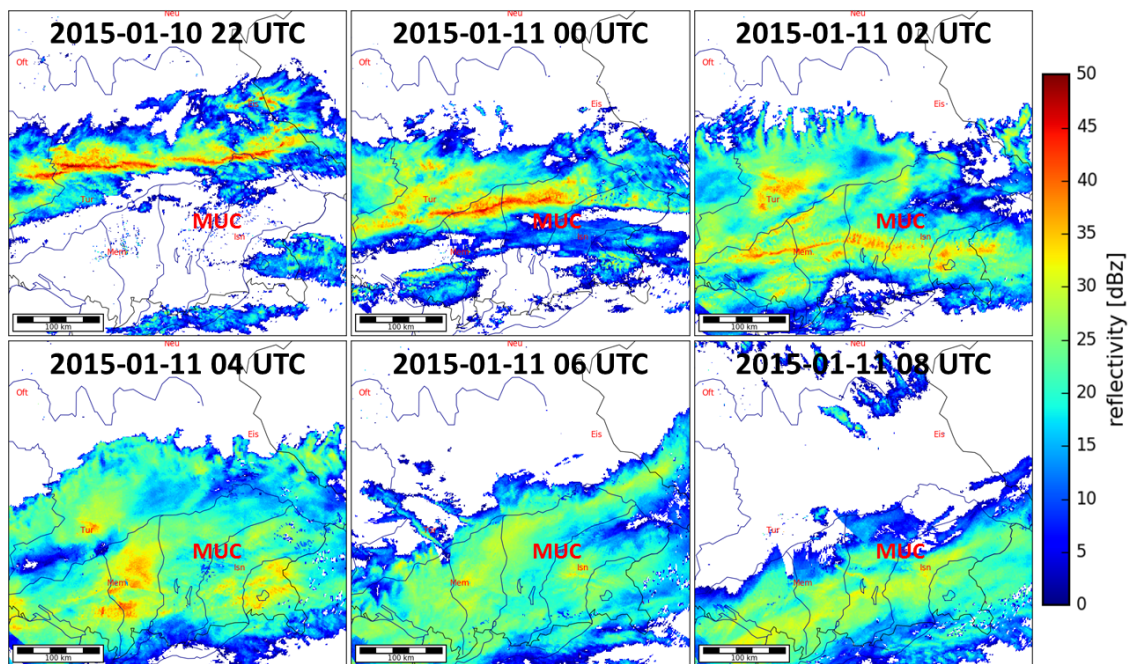| Radar reflectivity | Snow accumulation | Water equivalent | Visibility class |
|---|---|---|---|
| > 29.0 dBz | > 10 mm / 15 min | > 4 mm/h | < 600 m |
| 24.5 − 29.0 dBz | 5 − 10 mm / 15 min | 2 − 4 mm/h | 600 − 1500 m |
| 15.5 − 24.5 dBz | 1 − 5 mm / 15 min | 0.4 − 2 mm/h | 1500 − 3000 m |
| < 15.5 dBz | < 1 mm / 15 min | < 0.4 mm/h | > 3000m |



Fig. 6. 2-hourly radar images of a frontal system passing South-Eastern Germany with delay and enhancement at the Alps from 22 UTC on 10 to 08 UTC on 11 January 2015. MUC indicates the location of Munich airport.

The corresponding consistency tables for both cases are shown in Table 2 (observations refer to radar measurements over the airport). The numbers along the highlighted diagonal correspond to perfect forecasts. In general the forecasts slightly overestimate the snow accumulation or give false alarms (numbers below the diagonal). Num-

bers above the diagonal indicate underestimation of snow fall or missed events. From the tables Hit Rate (HR) and critical success index (CSI) can be calculated. HR is 0.44 (0.37) for the 30 (90) minutes forecast for the December 2014 event; and 0.42 (0.34) for the January 2015 event. Corresponding CSI are 0.32 (0.30) and 0.25 (0.23).
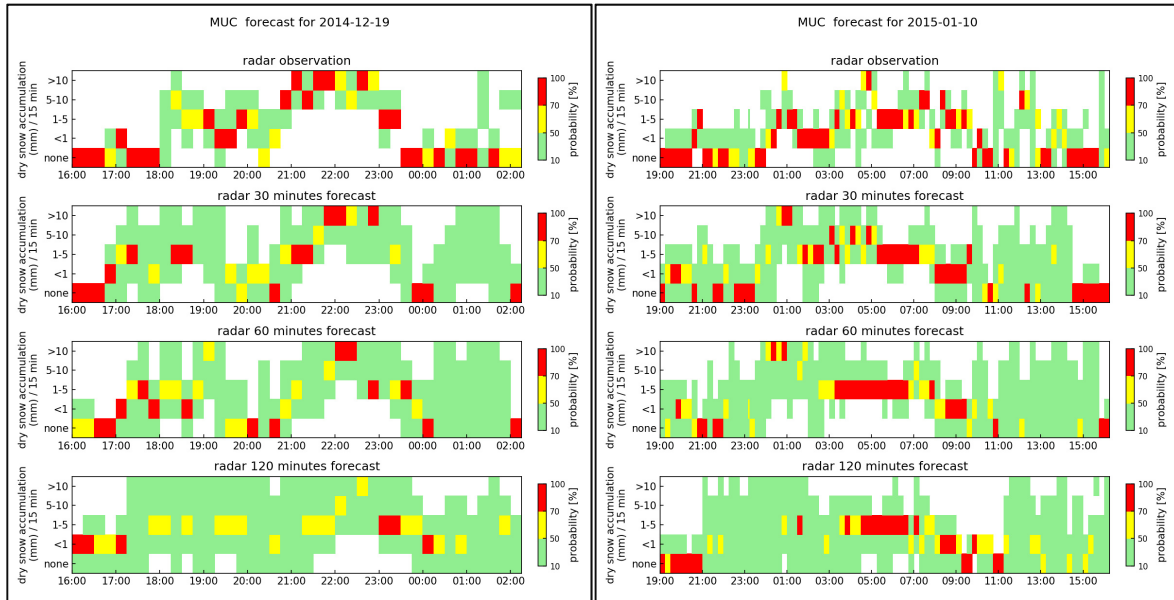


Fig. 7. Probabilistic nowcast of dry snow accumulation (mm/15 minutes).

Fig. 8 left side shows the distribution of the events in relation to the direction of approach of the frontal systems. To find relations between flow and behavior of the precipitation system, the wind profile as measured by the radio sonde München-Oberschleißheim (located in the Alpine foreland about 50 km north of the Alps) was investigated. However, as can be seen from Fig. 8 center and right side, there is no clear relation between the propagation direction of the fronts and the wind direction at the 500 hPa level (about 2 km above the main Alpine ridge). This is mainly caused by the fact that during winter when the tropopause is low the Alps act as a major obstacle and cause a considerable distortion of the atmospheric flow. Especially during the conditions which are classified as up-slope or delay,low pressure systems often develop in the Alpine region causing long-lasting precipitation and no more distinctive motion characteristics. It should also be considered that on the pre-frontal side the flow is parallel to the front, i.e. a front approaching from North-West will have south-westerly flow ahead of the front resulting in lee effects (Foehn flow).

Table 2. Consistency tables for forecast of dry snow accumulation (mm/15 minutes) for Munich airport for 2014-12-19 (left column) and for 2015-01-10 (right column).

| 30 minutes nowcast MUC 2014-12-19 | | observation (mm/15 minutes) | | | |
|---|---|---|---|---|---|
| | | none | < 1 | 1-5 | > 5 |
| forecast (mm/15 minutes) | none | 7 | 1 | 1 | 0 |
| | < 1 | 5 | 3 | 1 | 0 |
| | 1-5 | 3 | 2 | 4 | 4 |
| | > 5 | 1 | 1 | 2 | 6 |

| 30 minutes nowcast MUC 2015-01-10 | | observation (mm/15 minutes) | | | |
|---|---|---|---|---|---|
| | | none | < 1 | 1-5 | > 5 |
| forecast (mm/15 minutes) | none | 20 | 1 | 1 | 2 |
| | < 1 | 12 | 2 | 6 | 2 |
| | 1-5 | 3 | 10 | 11 | 3 |
| | > 5 | 0 | 2 | 6 | 4 |

| 90 minutes nowcast MUC 2014-12-19 | | observation (mm/15 minutes) | | | |
|---|---|---|---|---|---|
| | | none | < 1 | 1-5 | > 5 |
| forecast (mm/15 minutes) | none | 4 | 0 | 1 | 0 |
| | < 1 | 9 | 3 | 1 | 2 |
| | 1-5 | 3 | 2 | 5 | 4 |
| | > 5 | 0 | 2 | 2 | 3 |

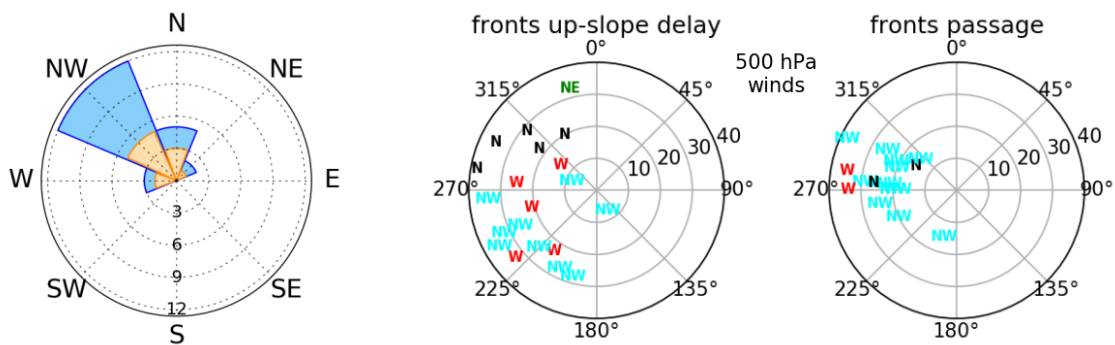| 90 minutes nowcast MUC 2015-01-10 | | observation (mm/15 minutes) | | | |
|---|---|---|---|---|---|
| | | none | < 1 | 1-5 | > 5 |
| forecast (mm/15 minutes) | none | 12 | 1 | 2 | 0 |
| | < 1 | 17 | 5 | 9 | 4 |
| | 1-5 | 4 | 9 | 12 | 7 |
| | > 5 | 2 | 0 | 1 | 0 |



Fig. 8. Left: Direction of approach for cold fronts in winter for the Munich/Salzburg region, Blue: total number of events; orange: number of events being delayed/blocked by the Alps. Center and right: wind direction and speed (markers) as measured by München-Oberschleißheim radio sounding during the events. Letters of markers indicate the arrival direction of the fronts.

## 5    Conclusions and future work

The professionals working at an airport are an ideal audience for probability forecasting: they are a limited audience at a well-defined location. The needs between different user groups are, however, remarkably different. Due to the workload and fast decision making, clear and easy to interpret forecast products are required. Thus snowfall as observed by the weather radar must be processed to user-friendly parameters, such as snow depth and visibility. Conversion equations linking e.g. visibility to reflectivity are a large source of uncertainty. Further interaction with end users should focus in way of expressing the temporal changes in reliability of the forecasts related to these known factors. One way to express uncertainty is to forecast exceedance probabilities over certain thresholds (e.g. probability of visibility being under 3000 m), which are agreed upon with the particular users.

Extrapolation methods are based on the assumption that precipitation moves along a constant velocity field and the intensity does not change. If the flow is affected by sea or mountains this is often not granted. It was found that, depending on the flow direction forecast quality can be reduced. In the case of the Alps this is even more difficult. Due to the complex interaction between large scale atmospheric flow and the Alps the predictability of precipitation does not reach the values obtained for airports in flat regions.

Even though the numerical weather prediction methods have been developing fast during the last decades, there is still need for extrapolative methods. In a recent study by *Simonin et al.* (2017) it was found that in the UK the NWP-based nowcasting system becomes more skillful than an advanced extrapolation-based nowcasting system from T + 1.5 to T + 2 h depending on the weather type.

Weather radar alone cannot fulfill all the user needs. Data fusion with additional sources of information is needed. Natural candidates for merged data are numerical weather prediction models for longer forecasts (12 to 24 h) or specialist models for parameters which cannot be forecasted with traditional weather prediction models, such as drifting snow or freezing of runway surface, and airport observations for latest temperature and humidity observations. Future activities on probabilistic extrapolation methods will include additional terms of uncertainty depending on geographical features and flow direction.

## 6     Acknowledgements

### 6.1     References

Andersson T. and K. Ivarsson, 1991: A model for probability nowcasts of accumulated precipitation using radar. *J. Appl. Meteorol.*, **30**, 135-141, DOI: 10.1175/1520-0450(1991)030<0135:AMFPNO>2.0.CO;2.

Bowler N, C. E. Pierce and A.W. Seed, 2006: STEPS: A probabilistic precipitation forecasting scheme which merges an extrapolation nowcast with downscaled NWP. *Q. J. R. Meteorol. Soc.*, **132**, 2127–2155, DOI: 10.1256/qj.04.100.

Hohti H., J. Koistinen, P. Nurmi, E. Saltikoff and K. Holmlund, 2000: Precipitation Nowcasting Using Radar-Derived Atmospheric Motion Vectors. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, **25**, 1323–1327, DOI: 10.1016/S1464-1909(00)00202-1.

Jeworrek, J., L.C. Wu, C. Dieterich and A. 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.

Kristovich, D.A., R.D. Clark, J. Frame, B. Geerts, K.R. Knupp, K.A. Kosiba, N.F. Laird, N.D. Metz, J.R. Minder, T.D. Sikora, W.J. Steenburgh, S.M. Steiger, J. Wurman, and G.S. Young, 2017: The Ontario winter lake-effect systems field campaign: Scientific and educational adventures to further our knowledge and prediction of lake-effect storms. *Bull. Amer. Meteor. Soc.,* **98**, 315–332, https://doi.org/10.1175/BAMS-D-15-00034.1.

Mazon J., S. Niemelä, D. Pino, H. Savijärvi and T. Vihma, 2015: Snow bands over the Gulf of Finland in wintertime, *Tellus A: Dynamic Meteorology and Oceanography*, **67**, 25102, DOI: 10.3402/tellusa.v67.25102.

Nurminen, A., 1948: Stauwirkung der Salpausselkä-Hügelkette. *Geophysica*, **3**, 180–192.

Schumann, U., 1987: Influence of Mesoscale Orography on Idealized Cold Fronts. *J. Atmos. Sci.*, **44**, 3423–3441, DOI: 10.1175/1520-0469(1987)044<3423:IOMOOI>2.0.CO;2.

Simonin, D., C. Pierce, N. Roberts, S.P. Ballard, and Z. Li, 2017: Performance of Met Office hourly cycling NWP-based nowcasting for precipitation forecasts. *Quart. J. Roy. Meteorol. Soc.*, **143**, 2862–2873, DOI: 10.1002/qj.3136.

Tiira J., D.N. Moisseev, A. v. Lerber, D. Ori, A. Tokay, L. F. Bliven and W. Petersen, 2016: Ensemble mean density and its connection to other microphysical properties of falling snow as observed in Southern Finland. *Atmos. Meas. Tech.*, **9**, 4825–4841, DOI: 10.5194/amt-9-4825-2016.

Volkert H., L. Weickmann and A. Tafferner, 1991: The Papal front of 3 May 1987: A remarkable example of fronto-genesis near the Alps. *Quart. J. Roy. Meteorol. Soc.*, **117**, 125–150, DOI: 10.1002/qj.49711749707.