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Nowcasting Winter Precipitation with Radar

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Abstract

RainCast, a new method nowcasting with radar is presented. The method has been developed at ETH for extrapolating radar images. Forecasted images and forecasts of probability of precipitation up to 1-2 hours in advance are available every 5 min. The procedure can be applied to summer and winter precipitation. The use in winter precipitation is discussed here. The properties of the radar estimates in rain, melting snow and snowfall, and their impacts on the short-term forecasts are summarized.

In the second part we analyze a sudden snowstorm that was responsible for a series of accidents and chaotic situations in the Swiss morning traffic. The propagating frontal line, associated with the snowstorm, is reliably predicted with RainCast. For effective warning, "snow signatures", retrieved from ground data of temperature and precipitation must be recognized. Incorporated in the RainCast system, this leads to a significant improvement of the effectiveness of storm warnings based on extrapolated radar data.

1. Introduction

Winter traffic may be severely obstructed by snowfall, freezing rain, or by freezing water at temperatures below zero degrees. Therefore, warning procedures have been established by the responsible road services (e.g., Mathis 2000). These procedures include human observations, forecasts of weather services, and automated sensor systems. Many of the warnings are **diagnostic**: the warnings are issued when snowfall has already started, or when water has already been frozen. **Prognostic** warnings might be extremely useful. Salt could be distributed in time, or roads could be blocked in time for traffic. The advantage of prognostic warnings for the avoidance of traffic breakdowns and car damage, or even for the protection of human life, is evident.

Weather radars give an excellent overview about the evolution of precipitation systems. Typical resolutions of the radar data are 2 km in space and 5 min in time. It is almost impossible to reach the same resolution with conventional rain gauges. Therefore, radars and radar networks are now in use by many weather services and other institutions. Radar nowcasting systems (e.g., Wilson and Mueller 1993; Johnson et al. 1998) allow issuing short-term prognostic warnings of precipitation. Up to now, few systems have been optimized for warnings of snowfall or freezing rain (e.g., Neilley and Carson 1993).

Here, we introduce a new and elegant nowcasting system called **RainCast**. This procedure yields probability forecasts of precipitation for any location in the radar range. The forecasts are typically updated every 5-15 min. This system has been developed at ETH for operational and commercial applications. We give a summary of the system, and we discuss the application for winter precipitation (Section 2). In Section 3 we analyze a snowstorm, responsible for accidents and breakdowns in the Swiss morning traffic. We show how additional ground data of temperature and precipitation can improve the effectiveness of the forecasts. Concluding remarks and an outlook are given in Section 4.

2. Nowcasting and winter precipitation

2.1. RainCast

RainCast is the result of a several-year cooperative research activity of ETH and the Swiss Meteorological Institute (SMI). Its actual use for commercial applications are described here, more technical aspects of the procedure are given in the Appendix.

RainCast is a new, automated procedure for forecasting precipitation up to 1-2 hours. Such forecasts are obtained by extrapolating radar images of precipitation. The procedure considers the local motions and changes in intensity of radar echoes. These properties of the radar echoes are retrieved from the immediate radar history. The procedure is optimized for regions with a complex orography. Forecasts of precipitation fields are obtained with a unique resolution: spatial (typically 2x2 km) and temporal (typically 1 min). The computing time for one forecast is typically 30 seconds on a UNIX-workstation of the newest generation. The forecasts may be updated every 5 min. Forecast maps of precipitation or time series of forecasted precipitation probabilities at specific locations can be retrieved. The probability forecasts consider the statistical properties of the forecast errors and can be computed for 5 levels of precipitation intensity (“dry”, “weak”, “moderate”, “strong”, “extreme”). Based on such forecasts, warning thresholds can be established and a warning issued, when a given threshold is reached or exceeded.

The program code has the flexibility to use different size and resolution of radar data. At present, two implementations are operating, one with data from the ETH-radar (see www.radar.ethz.ch), and the second with data from the radar network of the SMI (Joss and Lee 1995). An ETH-spin-off company has been established with the purpose to exploit the procedure (“MeteoRadar Schmid”, for details see www.meteoradar.ch). Present customers stem from agriculture, adventure tourism, community services, gastronomy and winter traffic services.

2.2. Use of RainCast in winter precipitation

Winter precipitation systems are, in general, shallow. Radar echoes from clouds with precipitation often extend only 1-2 km above ground. Together with obstacles (mountains), this reduces the radar visibility of winter precipitation. Precipitation in the radar shadow of mountains is invisible. Furthermore, clutter filters may eliminate too many precipitation echoes. Stationary “holes” in the radar pattern may appear.

A second important effect is caused by melting snow, being responsible for a strong radar echo (the so-called “bright band”, see e.g., Rinehart 1991). On the other hand, the radar may underestimate precipitation intensity of “dry” snowfall. **It is, therefore, often questionable to retrieve the type and intensity of winter precipitation from the radar data alone.**

The radar images should be corrected for the discussed effects before a forecast is calculated (Joss and Lee 1995). Additional corrections can be made in the RainCast procedure. Nevertheless, it is unavoidable that the above-mentioned effects may produce additional undesired scatter in the forecast images. Stationary clutter artifacts may slow down the predicted motions of the radar echoes. In addition, it is impossible to identify the type of precipitation (rain, melting snow, snow) in the forecast procedure itself. For this, additional data sources must be considered. In the next section we illustrate how additional ground data of temperature and precipitation can be incorporated to reach the desired forecast of potentially dangerous precipitation.

3. Case study: 27 Jan 1999

In this section, we analyze a snowstorm that led to large impacts in the Swiss morning traffic. The storm was associated with a cold front that crossed Northern Switzerland from west to east. The passage of the front is indicated in Fig. 1 in a cross-section from NW-Switzerland towards Central Switzerland. The ground measurements of temperature and precipitation intensity are shown for four stations along this cross-section. The stations are part of the automatic network ("ANETZ") of the SMI. Note that the plotted data are 10-minutes averages. We deduce from these measurements the short duration of the event (10-20 min) at a specific location. Precipitation intensity was 3-5 mm/h. Snowfall is expected at temperatures below 1 to 2^{o}C above freezing (Hächler, private communication), i.e. at altitudes above 400-500 m. Since the precipitation intensity was quite strong, it is probable that the snow covered the roads quickly at these altitudes although air temperatures remained above 0^{o}C.

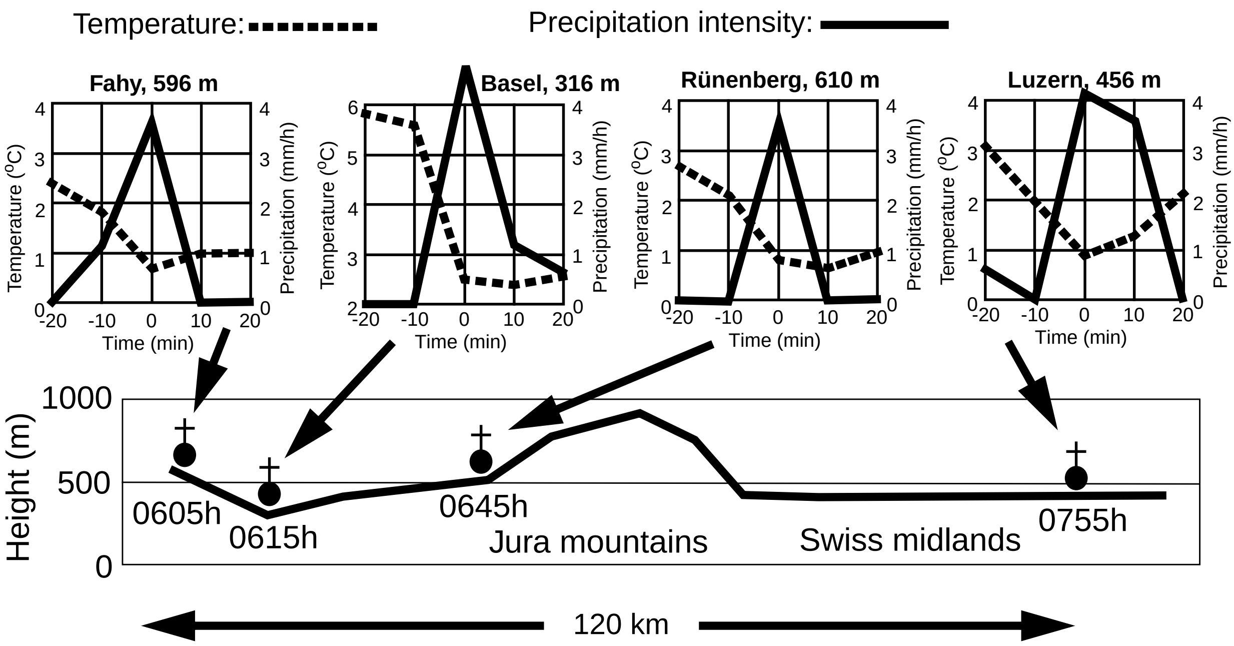

Fig. 1: The propagation of the cold front from 27 Jan 1999 along a cross-section from NW to Central Switzerland. The top diagrams show temperature and precipitation intensity at four ground stations. The bottom diagram shows the location of the stations along the cross-section.

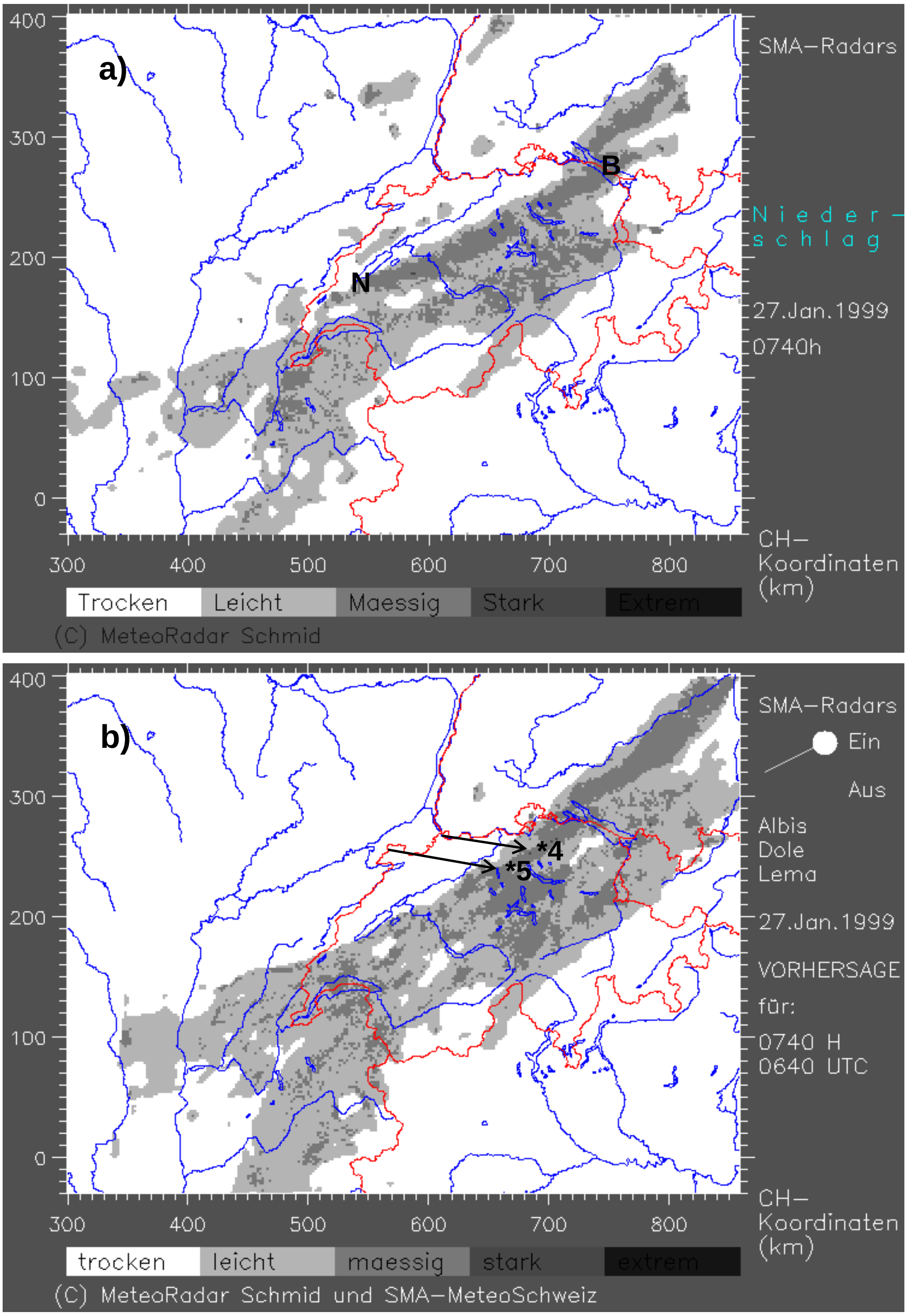

Fig 2: (a) Radar image of precipitation on 27 Jan 1999, at 0740 local time. The labels "N" and "B" mark the end of the precipitation band over central Switzerland. (b) One-hour forecast image obtained with RainCast, valid for 0740 local time. "Snow signatures" are included in the figure. For details see Section 3.

The radar image at 0740 h (Fig. 2a) shows the frontal band over central Switzerland, extending from the southern end of the lake of Neuchatel (label “N” in Fig. 2a) to the lake of Bodensee (“B” in Fig. 2a). The figure also shows that precipitation already occurred ahead of the front (rainfall up to about 700-1000 m altitude, deduced from the ANETZ in central Switzerland (not shown)).

Fig. 2b shows a 1 hour forecast for 0740 h obtained with RainCast. This forecast can be directly compared to the radar patterns observed at the same time (Fig. 2a). We note that the echo band associated with the front is somewhat less marked and a bit delayed in position, compared to the observation. Such differences between the forecasts and the observations are unavoidable and have to be attributed to unpredictable modifications of the internal dynamics of the precipitation systems. In spite of these differences, we note a good overall agreement between the forecast and the corresponding observation.

The interpretation of Fig. 2b poses the following question: which parts of the precipitation echoes are rain, where is the snow? The radar cannot answer this question. However, the ground measurements give the desired information. We added in Fig. 2b stars and black numbers, indicating the altitude (in units of 100 m) at which the boundary between rain and snow is expected. These **snow signatures** are retrieved from the ground measurements in the following manner:

a) Only precipitation intensities > 3 mm/h are considered.
b) A temperature of +1.5^{o}C, separating rain and snow, is assumed.
c) A vertical temperature gradient of -0.7^{o}C/100m is assumed.
d) Data between 0600 and 0640 h (time of last available radar image) are used.
e) The signatures are advected with the motion field obtained with RainCast.

The two snow signatures shown in Fig. 2b stem from the ground measurements of the stations Fahy and Basel, shown in Fig. 1. The arrows indicate the path of advection of the snow signatures. Hence, we expect snowfall down to 400-500 m altitude, associated with the radar band, bounding the overall precipitating region towards the northwest.

The described procedure is a good way to include information from ground-based instruments into RainCast images for forecasting. Details about the above-mentioned criteria a)-e) have to be discussed further. Adaptations to different weather situations may be necessary. The principle is promising: it consists in advecting ground-retrieved snow signatures with the motion field of RainCast, and to display the signatures in the forecast images.

4. Conclusions

RainCast, a new method nowcasting with radar is presented. The use of the method for nowcasting winter precipitation is discussed. An analysis of a cold-frontal snowstorm, responsible for heavy impacts on the Swiss morning traffic, has been presented. It has been shown:

1) that the 60 min forecast obtained with RainCast is in a reasonable agreement with the observed radar patterns of precipitation.
2) that “snow signatures” were visible well in advance in the ground data of temperature and precipitation.

3) that these signatures can be incorporated in the RainCast procedure to appear in the forecast images.

Present work customizes the described procedure. The concept needs to be optimized with data from additional events. We believe, nevertheless, that the procedure is useful for fast-moving, cold-frontal precipitation systems. We note that advection may lead to sudden changes of air-mass at a specific location. Local measurements of temperature alone are unable to predict such changes in time. Therefore, temperature measurements from neighboring regions (especially in upwind direction) are required to foresee sudden changes in temperature and type of precipitation. A combination of radar forecasts with proper ground data is, therefore, an important building block in a warning system for snow or freezing rain.

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Appendix: Technical aspects of RainCast

A.1. Tracking radar patterns

The basic data for the tracking are a series of radar images. At least two images are required. In a first step, the motion of the radar patterns from one image to the next image is retrieved with a cross-correlation technique (Rinehart and Garvey 1978; Li et al. 1995). The result is an array of motion vectors, describing how the radar patterns in the first image have to be moved for the best match with the corresponding radar patterns in the second image. In a second step, the mean growth or decay of radar echo patterns is retrieved in a Lagrangian manner. That is, the change of the average intensities of the echo patterns is calculated following them along the defined motion vectors.

A.2. Optimizing the tracking

There are several quantities that influence the properties of the tracking algorithm. In order to judge the forecast quality of the tracking algorithm, one needs to introduce **quality parameters measuring the deviations between the predicted and the observed radar patterns**. The predicted radar patterns are obtained by using the “linear forward-backward” scheme (see Section A.3.). We refer to Mecklenburg et al. (2000) for details about the quality parameters and the optimization of the tracking algorithm. We summarize here actions to improve the quality:

1) smooth the radar images in space (average over 5-15 km) and in time (average of 2-4 images).
2) select a proper “representative area” for each motion vector (typically 40x40 km).
3) restrict the “search area” for finding the motion vectors.
4) eliminate mismatches in the tracking procedure with proper criteria.

A.3. Extrapolate into the future

The basic information for extrapolation is:

1) The most recent, unsmoothed radar image.
2) An array of motion vectors.
3) A field of echo growth.

With this information, we can select the optimum method. Below we summarize methods for extrapolating the location of the radar patterns. Then we outline how regions of growth can be determined.

1) Linear forward (Neilley and Carson 1993): for each grid point of the image, an interpolated motion vector is calculated. The radar value at a grid point is extrapolated using this motion vector, i.e. assuming constant direction and speed during the extrapolation time. The resulting image has gaps and pixels with several radar values. Therefore, additional processing is required to interpolate and to get the average values for the pixels with several estimates. Such a processing is time-consuming and can be avoided in the subsequent methods.

2) Linear forward-backward: in a first step, only a few pixels, regularly distributed over the image, are linearly extrapolated. The extrapolated pixels will form an irregular grid on the extrapolated image. It is assumed that the motion vectors represent the motion at these grid points. These vectors are interpolated to each grid point of the extrapolated image. A linear backward scheme is performed to find the pixel in the original image that can be attributed to a grid point in the extrapolated image. At the end, the radar values are shifted from the original image to the extrapolated image along the defined array of vectors.

3) Trajectory backward, stationary motion field: an alternative to the linear extrapolation is a trajectory-based extrapolation (Hamill and Nehrkorn 1993; Zgonc and Rakovec 1998). It is assumed that the motion field remains constant in time. A pixel is extrapolated along the trajectory defined by the motion field (instead along straight lines as in the case of linear extrapolation). A backward scheme similar to method 2) is used, thus avoiding the treatment of gaps and multiple data values in the extrapolated image. The time step within the extrapolation must be small (typically 1 min) to minimize discretisation errors. A Lagrangian approach can be used to further reduce the discretisation error (Hamill and Nehrkorn 1993).

4) Trajectory backward, propagating motion field: this method is almost the same as method 3) with the difference, that the motion field is assumed to propagate with constant direction and speed. Which direction and speed should be taken? We found an average of all motion vectors to yield a good estimate for the "overall propagation vector".

Regions of growth can be found by adding a "trend function" to the extrapolation. Several trend functions have been tested by Mecklenburg (2000). None of them led to a significant improvement of the forecast for longer extrapolation periods. Therefore, we use an "exponentially decaying" trend function with the assumption of a short persistence (a few minutes) whereas, later on, the echo intensity is pretended to remain constant.

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A.4. Concluding remarks

When the motion field is (almost) homogeneous, it is irrelevant which of the extrapolation techniques is used. The differences between the methods become evident when, for instance, a cold front separates two different motion regimes (e.g., south-north ahead of the front, west-east behind the front). Linear extrapolation may lead to artifacts, especially for longer extrapolation periods, since the extrapolation paths may merge or cross-over. These artifacts can be avoided with the trajectory method. However, assuming a stationary motion field is often not realistic: a stationary motion field approximates a stationary frontal line, not a propagating one. We believe that in most cases the overall propagation vector yields a fairly good estimate for the propagation speed of frontal lines. As an alternative, we could use external information on the propagation of frontal lines, e.g., delivered by a numerical prediction model.

In RainCast, we have implemented all four extrapolation techniques. Only the method "*Trajectory backward, propagating motion field",* however, is presently used. Our experience with that method is good. The extrapolated images look reasonable and are free of artifacts in most cases, even for longer forecast intervals (about 1 hour). The task remains to show in a quantitative way that this latter method can reduce the forecast errors better than other extrapolation methods.

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