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Area-intensity probability distributions of rainfall based on a large sample of radar data

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1 Introduction

The history of weather radar is, among other applications, a manifestation of quantitative precipitation estimation (QPE), shown e.g. by Collier and Hardaker (2003). The main objective in such activities is to develop quantitatively accurate hydrological applications, especially nowcasting and warning systems of flash floods. The advantage of weather radars compared to conventional gauge networks is the availability of measurements in real time, which exhibit typically 100 times better time resolution and 10 000 times better spatial resolution than national gauge networks. High resolution facilitates the derivation of rainfall intensities from small areas and short time periods. On the other hand, the absolute accuracy of radar based rain rate in a randomly selected bin is not very good. Two dBs is considered a good achievement as commonly at long ranges the bias is of the order of 5-10 dBs - figures which were generally not accepted prior to the work of Joss and Waldvogel (1990). Much work has been devoted in removing systematic biases and random errors from the radar estimates of rainfall rate (R) and accumulated precipitation e.g. due to clutter and non-meteorological targets (Peura (2002)), calibration errors (Huuskonen (2001)) and sampling differences between gauges and radar (Germann and Joss (2003), Koistinen et al. (2003a)). As sufficient absolute accuracy can't be guaranteed radar data has not yet been widely used for deriving climatologically reliable statistics of precipitation. Those would be valuable as national hydrological planning standards are typically based on, let's say, 50 years old gauge data. If the challenge of inaccuracy can be solved to an acceptable level, radar measurements will provide several orders of magnitude larger data samples than gauges. The implication is that extremely rare events can be detected in the data i.e. reliable probability estimates of the order of 1/100 000 - 1/10 000 000. From the hydrological point of view such rainfall events are often the most devastating ones. Probability distributions of rainfall are the basis of hydraulic and hydrological planning of construction structures needed in heavy rain and flood mitigation. In this study we present probability distributions of rainfall in areas of 1 km^2 - 1024 km^2 where the length of accumulation period is instantaneous - 24 h. The data set covers 6 summers from 7 Finnish weather radars. As the amount of unpacked radar data in each quality control and processing phase of this work was the order of 10 TB, the calculations met practical difficulties which were slow to overcome. Thus the results which were available during the writing of this abstract are preliminary and mostly cover only 1-2 years long subsets of the whole data.

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2 Quality control of the data

The radar data applied in this study consists of the measurements performed in the Finnish C-band Doppler radar network of 7 systems in the years 2000-2005. Applying 24 hour gauge measurements the FMI climate research has found that precipitation statistics during the six summers of radar data do not deviate from those of the 30 year long climatic reference period. We assume that short time interval and areal rainfall climatology is also representative in the data sample of 6 summers.

2.1 Lower limit of rainfall reflectivity and clear air echoes

The product in this study is the national PseudoCAPPI composite at the height of 500 m (asl). At each horizontal grid point the vertically closest radar measurement (bin) has been selected from all PPI scans (the lowest elevation angle is usually 0.4 degrees). Radial resolution of radar measurements is 500 m up to the range of 250 km and azimuthal resolution 1 degree (beamwidth is usually 0.95° and with one of the radars 0.7°). Time interval in the archived data is usually 5 minutes but during the first 2 years only 15 minutes. Major assumption in the data is that individual bins are considered independent samples of precipitation. Radar measurements can't be used as such for quantitatively reliable precipitation statistics. Specific attention must be paid to the quality control and to the selection of the radar data sample to minimize the effects of various biases.

The first difficulty in the derivation of rainfall statistics from radar reflectivities is to define the reflectivity limits of precipitation. Physically no lower limit exists but from the practical point of view extremely weak rain rates will not be detectable in hydrological or meteorological processes. In this study we have made the crude assumption that 10 dBZ is the lower limit of rain rate. Probability distributions of rain from Nimbostratus or Cumulonimbus clouds will obviously not be biased due to this arbitrary selection. On the other hand major part of weak drizzle cases (usually from Stratus or Stratocumulus clouds) will be excluded from the data. Thus the results are valid only in rainfall containing "large" drops. Selection of the threshold 10 dBZ implicates two benefits. The results will not be biased due to the limited sensitivity of the radars at varying distances as 10 dBZ is larger than the minimum detectable signal at all ranges applied. The second implication is elimination of major part of clear air echoes, which originate from insects and birds. Koistinen et al. (2003b) made a study of a very large sample of the vertical profiles of reflectivity (VPR) showing that approximately 50 % of all VPRs at close ranges to a radar are clear air echoes. Their reflectivities are in most cases below the threshold of 10 dBZ. Thus a significant bias is avoided by thresholding small reflectivities from the measurements.

2.2 Elimination of snow and VPR effects

To make the statistics representative in rainfall only we have limited the data to the warmest summer season in Finland i.e. June-August. Although sleet or snow is very rare at ground level during this period the radar beam meets it regularly at longer ranges as the height of the freezing level is typically 1.5-3 km in summer. We have not performed any VPR correction to the data. Thus a bias due to snow in the beam or negative vertical reflectivity gradient in general and beam overshooting should appear as decreasing reflectivities and as decreasing number of rainfall bins at increasing measurement distances. The limiting distance is the one where overestimation in the lower part of the beam due to the bright band not any more compensates the underestimation in the upper part of the beam due to dry snow or partial beam overshooting. We have located this distance at each radar by analysing monthly averages of the relative frequency f (%) of rainfall bins compared to all measurement bins at 10 km wide range belts. At all radars and during each individual month the values of rainfall frequency are fairly constant at ranges 30 - 200 km from the radars. In this region the relative frequency (f) is in the range of 3-7 %. These figures denote the probability of rainfall in a single radar bin at any random time moment. When compared to monthly gauge accumulations figures 3-4 % indicate dry months in climatological terms whereas high figures of 6-7 % indicate wet months, respectively. Beyond the distance 200 km the frequency of rainfall bins exhibits a decreasing trend proving that the VPR effects dominate. As a consequence we have excluded from the statistical analysis all bins whose distance from the nearest radar is larger than 200 km.

2.3 Removal of clutter

An important quality step in the reflectivity measurements is elimination of the bins representing non meteorological targets. The first step is Doppler filtering of ground clutter in the signal processor. Although vast majority of ground clutter is removed, residual targets remain at the locations of the strongest ground signals like high buildings near to the radars. This is proved by the higher relative frequency (f) of "rainfall" bins in the lowest elevation PPI scan at the range interval of 0-30 km from the radars, typically 10-20 %. In order to minimize the occurrance of non meteorological targets close to the radars we have used the 500 m CAPPI instead of the lowest elevation PPI, which is used beyond the distance of 30 km. All data closer than 10 km to the radars have been excluded to avoid residual non-precipitating bins. Luckily the topography of Finland is relatively flat so that residual ground clutter in normal propagation conditions is very rare and relatively weak beyond the distance of 30 km from the radars. In cases of anomalous propagation over the cold sea areas steep coasts may sometimes introduce remaining ground clutter patterns at longer distances (in extreme cases even second trip clutter). Doppler filtering does not eliminate moving clutter, such as ships and sea surface, which are relatively frequently met, especially in cases of anomalous propagation. The huge steel ferries carrying parabolic antennas exhibit reflectivities easily up to 50-70 dBZ so that the regular ship routes become visible lines in the accumulation products of precipitation. Radar reflectivity factor has been set to zero in the remaining measurement bins dominated by non meteorological scattering from ships, sea, aircraft, external transmitters, birds and insects. The diagnosis of these phenomena is based on pattern recognition and fuzzy logics implemented by Peura (2002). The most difficult of these is sea clutter during anomalous propagation conditions. In such circumstances it may form quasi-stationary large patterns which resemble precipitating areas, shown e.g. by Alberoni et al. (2001), and are relatively difficult to be diagnosed with the existing system at FMI. Therefore we have made a further limitation to the main data set by excluding all bins located over the sea. As a comparison we aim to derive rainfall statistics also for sea areas to see the possible land-sea differences.

2.4 Removal of hail

The quality steps explained above are assumed to eliminate from the precipitation statistics all non meteorological echoes or precipitation bins biased due to VPR effects. Additionally, the algorithm for the diagnosis of hail by Holleman et al. (2000) has been applied in our data. The algorithm needs the height of freezing level as an independent parameter. Those have been interpolated from the NWP model fields of height and temperature in the Mars data archive of the ECMWF. We calculated the cumulative probability distributions (CDF) of rain rate without and with the hail bins obtained from the Holleman's algorithm. Occurrance of hail has a significant influence on the CDFs although only 0.8 % of all bins indicated presence of hail. When the measured reflectivity is more than approximately 40-45 dBZ hail will on average introduce a significant enhancement in the CDF of "rainfall" . For example, at 45 dBZ and at 70 dBZ the CDF of rain is enhanced by a factor of 1.1 and 10, respectively, if hail cases are not excluded from the data. It can be approximated roughly that the difference between the two distributions gives the average scattering fraction of rain ($Z_{e,rain}$) in the measured reflectivity (Z_e). Fitting an exponential curve to the diagnosed frequency of hail bins as a function of reflectivity gives a statistically significant relation ($r^2 = 0.9992$)

$$Z_{e,rain} = 1,2934 Z_e^{0.9351} \qquad (1)$$

Equation 1 could be used in the absence of a hail algorithm to estimate the scattering fraction of rain only. We have not done that but excluded all bins which indicated any probability of hail larger than 0. If the quality controlled data set still contain individual hail bins they will increase the probability of heaviest rainfalls. On the other hand we have not tried to correct the recently confirmed effects of attenuation due to wet radome by Kurri and Huuskonen (2006) and precipitation itself. Significant attenuation effects are rare on average in the relatively cool climate of Finland. It occurs perhaps during a few days in each summer, mostly in cases of intensive mesoscale convective systems (MCS, see Punkka and Bister (2005)). We assume that the effects of remaining hail bins and attenuation partly compensate each other in the PDFs of precipitation.

3 Methods and results

The archived raw radar data covering the selected time period of 6 summers consist of $1.5 \cdot 10^{11}$ measurement bins. After all quality steps and applying only the best bin in the areas or overlapping radar measurements the final data set consists of approximately $4 \cdot 10^9$ measurement bins of radar reflectivity factor in rainfall. We have converted that to rainfall intensity applying a fixed R(Z) conversion based on a large sample of Central European drop data according to Dölling et al. (1998):

$$Z = 316 R^{1.5} \qquad (2)$$

We assume here that the average drop size distribution (DSD) in summer in Finland does not deviate systematically from that in Central Europe. Although the validity of this assumption has not been proved the role of the selected $Z(R)$-relation is not crucial as we have performed a window probability matching method (WPMM) with ground based measurements according to Rosenfeld et al. (1993). Thus the more general assumption is that natural time-space variations in the DSD will not introduce any bias in the shape of the rainfall CDF based on radar measurements. The instantaneous areal radar bin measurement has been transformed to point intensity by assuming an average velocity of 10 m/s for rainfall patterns, by obtaining the horizontal length scale (L) of a bin from the square root of the bin area (Rosenfeld et al. (1993)) and multiplying L by the factor 1.3, which on average optimizes the size of the gauge-radar matching domain (Zawadzki (1975)). In this way, on average, a radar bin measurement represents a 2 minute point measurement at ground level in the selected range interval 30-200 km from the radars.

The only available short period ground based rainfall intensity measurements, which could provide reasonably large reference data for WPMM were three optical scatterometers of the type Vaisala FD12P. They provide 10 minute intensities. The distance between the scatterometers and the closest radar was 20-51 km. The 10 minute reference value from the radars was obtained using the bin closest to each scatterometer and calculating the average intensity from 2 successive radar scans of 5 minute time interval. Although sampling differences between radars and optical scatterometers introduce large random variations in individual comparisons we assume that the shape of the CDF of rainfall from both sensors (in quality corrected data) is not biased. This is also proved by the fact that R(Z) conversion obtained by WPMM does not differ much from the fixed R(Z) in Eq. 2 applied in the radar data. Still we have removed the small statistical bias from radar measurements by applying the window probability matching method (WPMM) for the two sensors. In this way we have also avoided the selection of the "climatologically optimal $R(Z)$" which, anyway, remains unknown. The WPMM fitting range is narrow covering only the rainfall intensities of 0.5-20 mm/h as the optical scatterometer measurements outside this range may contain too large errors according to the manufacturer. The results show a good fit of the PDFs of radar based instantaneous rainfall intensity to lognormal distribution, a result similar to those of e.g. Kedem et al. (1994). The results also indicate reliable figures of the probability of very rare rainfall occasions, which are practically impossible to detect with much smaller ground based rainfall sensor data. For eaxmple, the repeat time of 1.5 minute point rain rate 1000 mm/h, according to a three year subset of the radar data, is 2000 years. When the radar based PDFs of point rain rates are compared to the Finnish gauge based hydrological "standard" figures the preliminary results suggest that the probabilities of high rainfall intensities (repeat time > 50 years) have been underestimated by a factor of 2. Finally we have repeated the CDF calculations for a set of area-intensities. The coverage area of the radar network, partly limited by the quality control as explained in Sec. 2, was divided to squares of 1 km^2, 9 km^2, 100 km^2 and 1024 km^2. In these areas we calculated PDFs of the instantaneous rainfall intensity as well as of the accumulation periods of 15 min, 30 min, 1 h, 3 h, 6 h, 12 h and 24 h. Unfortunately the results of these calculations were not yet finalised at the time of writing this abstract.

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