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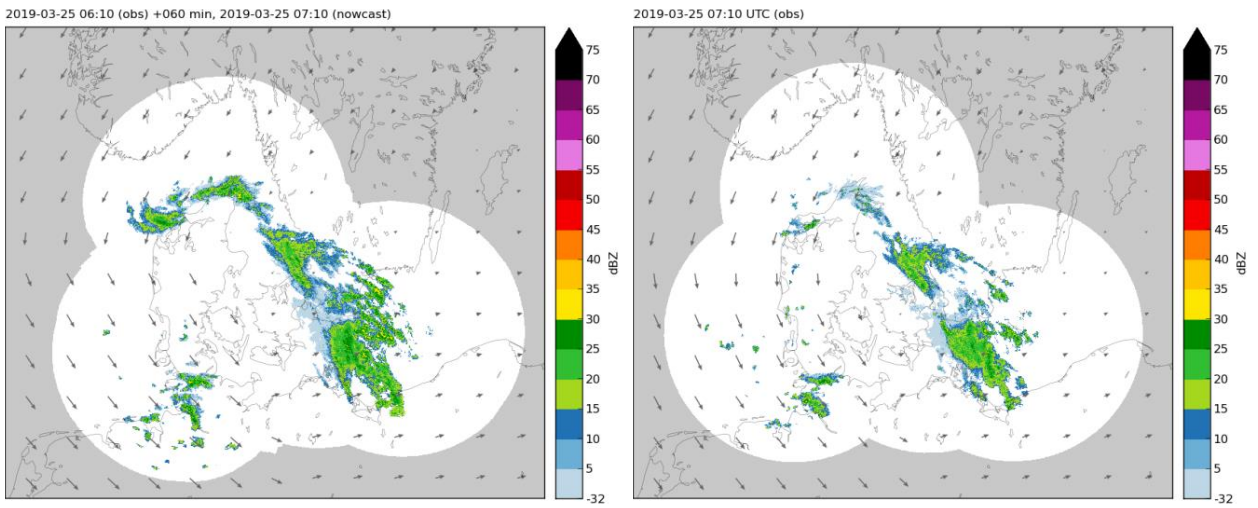
EROSION

D3.2 Regional precipitation erosion forecasts (data)



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D3.2 Regional precipitation erosion forecasts (data)

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Preface

This report describes the **Regional precipitation erosion forecasts (data)** for the EROSION project.

The project is funded by Innovation Fund Denmark and project partners. The project period is from April 1st, 2017 to March 31st, 2020 (3 years).

The aim of the project **EROSION – Wind turbine blade erosion: Reducing the largest uncertainties** is to create knowledge and methods to avoid blade erosion caused by rain and hail. The hypothesis is that by reducing the tip speed of the blades, where rain and hail cause severe blade erosion, a significant extension of blade lifetime can be obtained with reduced maintenance cost and negligible loss of production.

The key objective of EROSION is to enable longer lifetime of wind turbine blades at multi-MW machines. To achieve the objective the project work will include testing of specimen in the rain erosion tester and investigation and analysis of damage on leading edges of blades. Furthermore, the rain in real atmosphere will be investigated from ground-based instruments (disdrometers) and modelling of rain based on rain radar data. Finally a new prototype instrument will be developed in order to measure rain at wind turbines for making decision on control, to set 'erosion safe mode' with regulation of turbines. Much longer lifetime of wind turbine blades and reduced operation and maintenance costs are expected.

Project web-site is http://www.rain-erosion.dk/

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Executive summary

One of the project goals is to develop and 10-min precipitation erosion warning forecasts based on dual-pol radar data. By combining data from the DMI's weather radar network, short term forecasts, or now-casting, will be made for selected wind farm sites every 10 minutes. In particular, the aim of the model is to provide information of the likely precipitation intensities, plus information on the precipitation type at selected wind farm sites with a lead time of 0-2 hours.

The content of this report is a presentation of ideas and scheduled experiments for the development and evaluation of a dual-polarization radar now-casting model for prediction of near-real time potential risk of blade erosion at wind farm level.

A prototype of the radar data based now-casting model developed at DMI will be used as basis to develop a dedicate model for this project. Erosion processes at the leading edge are related to the type, size and velocity of hydrometeors as well as their frequency. Therefore, the work focuses on the potentials of the following dual-polarization radar products; (1) radar reflectivity product, i.e. radar rain rate, (2) hydrometeor type, (3) droplet size and fall velocity, and (4) hail probability.

Some or all of these products complement each other with information about local rain environment, and may also be useful for calculation of kinetic energy and expected level of erosion in a fine spatial and temporal scale. To increase knowledge about quality and uncertainty of the products they will be verified against data from disdrometers, present weather sensors and raingauges collected during the project. This may for example answer the question if it makes sense to calculate kinetic energy of rain from radar data.

An important issue is adjustment of raw radar rain rates against ground measurements. The plan is to use adjustment factors applied by DMI's experimental QPE models (Quantitative Precipitation Estimation). Due to processing time it may be a challenge to apply adjustments in real-time, but various approaches may be possible.

1 Introduction

In the EROSION project the research hypothesis is that large rain drops cause significant erosion at the leading edges of wind turbine blades. The research hypothesis is sketched in Figure 1.

Figure 1: Sketch of the research hypothesis in the EROSION project.

One of the project goals is to develop and demonstrate prototype device for precipitation monitoring on wind turbines and to develop 10-min precipitation erosion warning forecasts based on novel rain radars.

Rain forecasting based on dual-polarization radar will be developed for hourly to day-ahead wind farm operation planning, as supplementary to in-situ rain observations. By combining data from the DMI's weather radar network, short term forecasts (now-casting), will be made for selected wind farm sites every 10 minutes. In particular, the aim of the model is to provide information of the likely precipitation intensities, plus information on the precipitation type at selected wind farm sites with a lead time of 0-2 hours.

Results from WP1, including statistics and data series on key meteorological parameters, will support development of the now-casting model for calculation of potential risk of eroding conditions at wind farm level.

Many studies have shown that droplet size distribution (DSD) and rain intensity is related (e.g. Best, 1950, Kubilai et al., 2013). Key parameters in calculation of droplet kinetic energy and erosion class are drop size disdribution (DSD), liquid volume and terminal fall speed (e.g. Assouline, 2009). Furthermore, hydrometeor type, wind speed and blade tip speed must probably be incorporated to achieve realistic estimates of impact kinetic energy and erosion classes at wind farms.

Therefore, one basic idea is to utilize dual-pol radar moments, such as rain rates, instead of DSD parameters to process real-time calculation and prediction of droplet kinetic energy and erosion classes. To support and evaluate this idea, disdrometer measurements have been established at selected sites to increase knowledge about the relationship between drop size distribution (DSD), rain intensity and kinetic energy.

The content of this report is a presentation of ideas and scheduled experiments for the development and evaluation of a dual-polarization radar now-casting model for prediction of near-real time potential risk of blade erosion at wind farm level.

2. Development of radar based erosion safe mode warning system

2.1 basic ideas behind now-casting and warning system

A prototype of the radar data based now-casting model is already under development at DMI. It is based on advection of radar observations using a motion vector field from the movement of the precipitation patterns in time sequences of radar images. This model will be used as basis to develop a dedicate model for this project. The model will have focus on the rain events that cause significant erosion on turbines.

Erosion processes at the leading edge are related to the type, size and velocity of hydrometeors as well as their frequency. Therefore, the development of the warning system focuses on dual-polarization radar products useful for now-casting of potential risk of blade erosion:

- Radar reflectivity product, radar rain rate
- Hydrometeor type
- Droplet size and fall velocity
- Hail probability

The key stone of a safe mode decision system is now-casting of rain intensity. Some or all of the above-mentioned radar products are expected to be useful as they can complement each other with information about the local rain environment, and may also be used to calculate kinetic energy and expected level of erosion in a fine spatial and temporal scale.

The present work at DMI have two main goals: (1) develop and establish an erosion safe mode warning system, and (2) do a survey on the potential of different radar products for supporting the warning system.

A number of disdrometers are installed during EROSION WP1, while data from other disdrometers are provided by HOBE project[1] in which DMI is participating. Rain drop sizes, fall velocities, rain rates and hydrometeor types calculated from dual-polarization radar will be evaluated against disdrometer data to increase knowledge about quality and uncertainty of the radar products.

2.2 Presentation of DMI's weather radar network

DMI operates a radar network of five dual-polarization (dual-pol) C-band Doppler weather radars (Figure 2), hereafter called dual-pol. A dual-pol weather radar is a remote sensing instrument that measures reflectivity of objects in two polarizations, horizontal and vertical, in a given volume in the atmosphere. The radar scans in azimuth at a number of elevations and detects the atmospheric content of hydrometeors and their properties.

Various sophisticated parameters (or moments) are measured by dual-pol radar technology, such as: (i) differential reflectivity (uses the difference between vertical and horizontal reflectivity) which is a good indicator of mean size and shape of droplets in a volume; (ii) correlation coefficient which is a measure of

[1] Center for Hydrology - a Hydrological Observatory and Exploratorium. For further information, see website www.hobe.dk.

how similarly the two polarizations are behaving in a pulse volume and that is especially useful for discrimination between meteorological and non-meteorological targets. Dual-pol moments can be used in hydrometeor classification algorithms (e.g. Straka, Zrnic and Ryzhkov, 2000), and the classification method used at DMI is described in Gill, Sørensen and Bøvith (2012). The radar network provides radar data in high temporal and spatial resolution, i.e. 500×500 m^2 pixel size and 10-minute scans up to 240 km range.

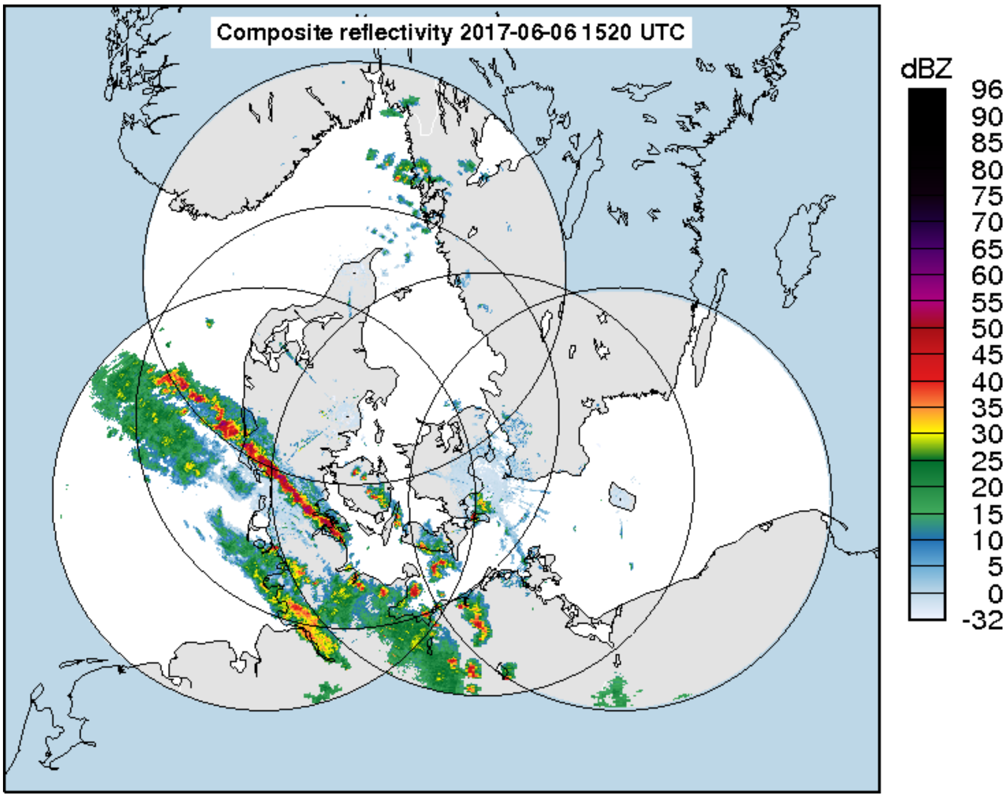

Figure 2: DMI's weather radar network shown with an example from 6 June 2017 at 1520 utc. The unit dBZ indicates the relative rain rate

2.3 Radar now-casting of rain intensity

Precipitation often displays a very high temporal and spatial variability and is therefore difficult to predict accurately at small scales and a long time in advance.

The highest accuracy of precipitation forecasts at fine scale is currently regarded to be obtained from radar-based nowcasting models which rely on a method of simple advection of the most recent radar observations. These models, however, are only superior to more advanced meteorological models at the very short lead times (from 0 to 2-3 hours).

The simple advection model is based on 1) the computation of a motion vector field from a time sequence of radar images using an optical flow algorithm and 2) the advection of the most recent radar image along the motion vector field.

Different methods exist for computation of the optical flow. In this implementation the Farneback algorithm is used as implemented in the open source computer vision library OpenCV (Bradski and Kaehler, 2008).

The algorithm is based on approximating the pixel neighborhoods with quadratic polynomials and deriving a displacement field by analysis of the translation of the polynomial. This algorithm assumes and produces a spatially smooth motion vector field. A temporally smooth evolution of the motion field is obtained by exponential smoothing of the motion field as proposed in the STEPS nowcasting scheme (Bowler, Pierce, and Seed, 2006).

The advection step is performed using a semi-Lagrangian, backward interpolation scheme carried out using one-step cubic interpolation from a given lead time and back to the observation time.

An example of a radar-nowcast can be seen in Figure 3 and Figure 4. In figure Figure 3, the observed radar reflectivity is shown, and in Figure 4 the nowcast at lead time 60 minutes and the corresponding observed radar image at the same time is shown. It can be noticed how the rotating precipitation system is detected in the motion vector field and how the motion of the precipitation in the south western region is well captured by the nowcasting model, but the precipitation in Northern Jutland is not very well predicted (probably due to difficulties for the computed motion vector field to describe the rather complex evolving weather system).

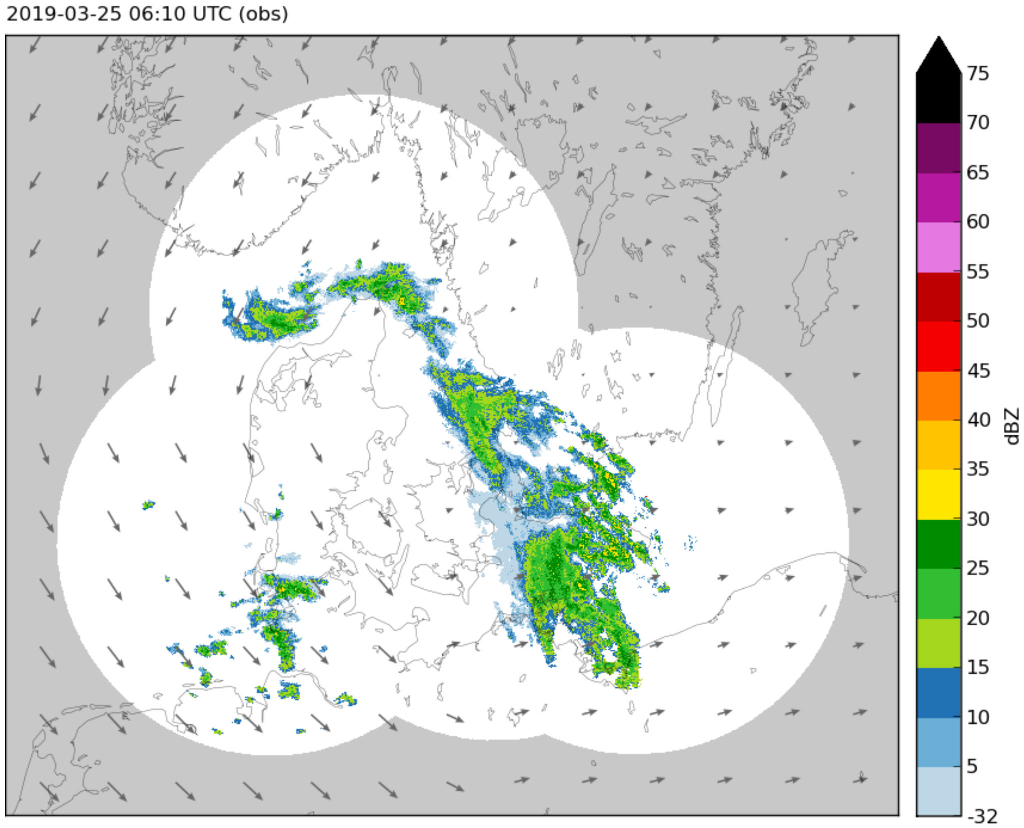

Figure 3: Radar-observation at 2019-03-25 06:10 UTC with overlayed motion vector field (gray arrows).

The radar nowcast method has the potential to provide accurate and timely input for the “erosion safe-mode” algorithm for wind turbine control. However, it should be noted that the uncertainties of the radar nowcast increase quite quickly with leadtime and that the uncertainty depends highly on the type of precipitation. Wide-spread precipitation showing higher predictability that scattered, convective precipitation.

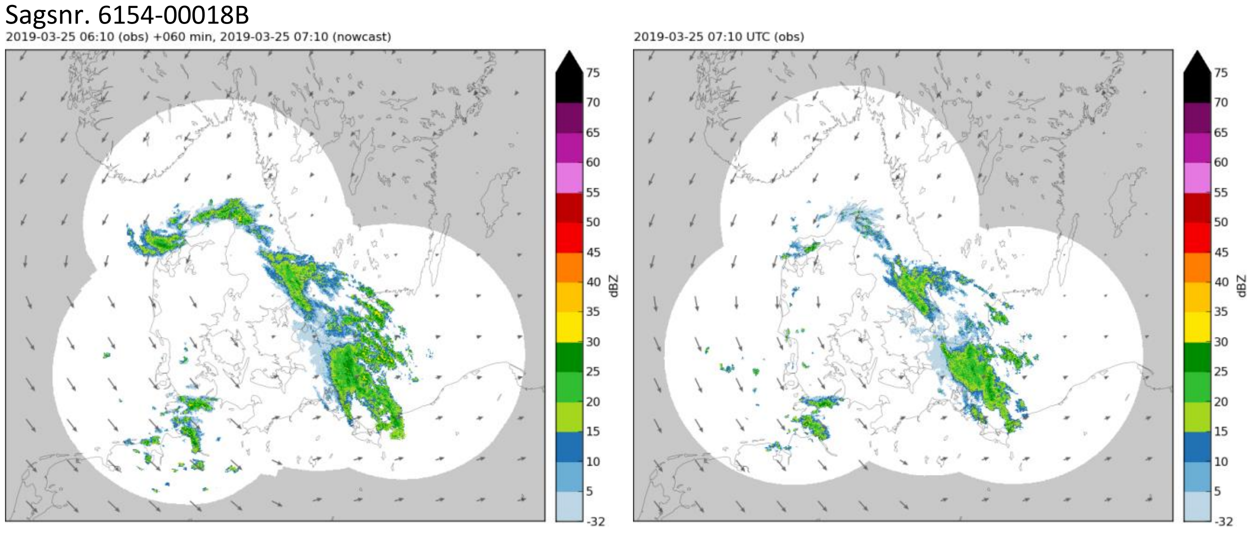

Figure 4: Left: Radar-nowcast showing the advected image at lead time 60 minutes. Right: Radar-observation at the same time.

2.4 Radar classification of hydrometeor type

Pixel based hydrometeor classification is carried out using the fuzzy logic methodology (Bringi and Chandrasekar, 2001, Zrnic et. al., 2001, Schuur et. al., 2003, Lim et. al., 2005). In the current approach, a given pixel of hydrometeor class j has a score S_j given by the relation:

$$S_j = \frac{\sum_i w_i P_i}{\sum_i w_i}$$

where P_i and w_i are the value of the parameter i, and the associated weight, for the class j. The radar parameters[2] that have been used in the classifier are: Z_{HH}, Z_{DR}, K_{DP}, ρ_{HV}, plus the texture parameters associated with Z_{HH}, Z_{DR}, Φ_{DP} (Schuur et. al., 2003, Sugier et. al., 2006). In fuzzy logic the values of the Pi for the different hydrometeor classes are described by the membership functions (MF). In the current version the latter are expressed as Beta-functions with the 3 parameters: a, ß and γ indicating the center, half-width at inflection point and the slope of the curve (Lim et. al., 2005). As a way of example, fig. 5 shows the membership functions for the parameter Z_{HH} for the different classes of rain.

Similar membership functions exits for other hydrometeor classes for Z_{HH} and for all the other parameters used in the classification.

In the current version of the algorithm the following 12 hydrometeor classes have been identified: (1) ground clutter, (2) sea clutter, (3) electrical signals from external emitters that interfere with our radars, (4) clean air echoes (CAE) such as from birds and insects, (5) drizzle, (6) light rain, (7) moderate rain, (8) heavy rain, (9) violent rain, (10) light snow, (11) moderate to heavy snow, (12) rain/hail mixture.

The current version of the algorithm does the so-called level 1 and level 2 classifications. In the level 1 classification a radar echo is classified into one of four simple classes: precipitation, clutter, clean air echoes, and external emitters. Figure 5 shows an example of the output.

[2] Z_{HH} = corrected reflectivity, Z_{DR} = differential reflectivity, K_{DP} = specific differential phase, ρ_{HV} = cross-correlation coefficient between the horizontal and vertical polarized waves, Φ_{DP} = differential phase shift.

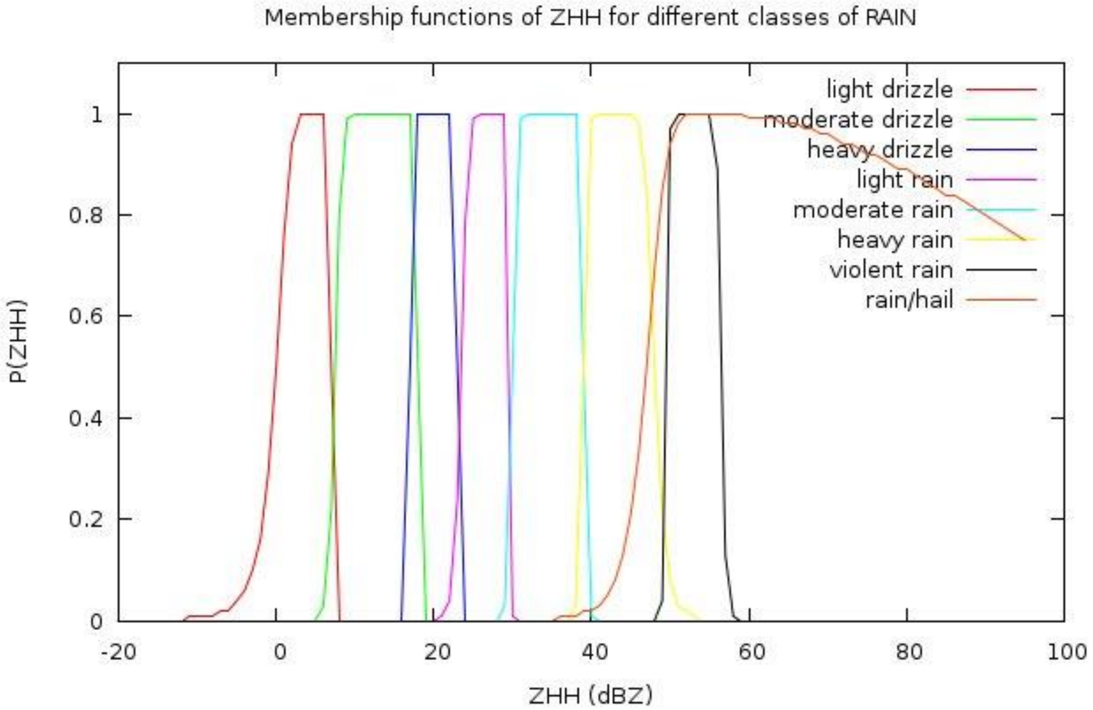

Figure 5: Membership functions for ZHH for different categories of rain.

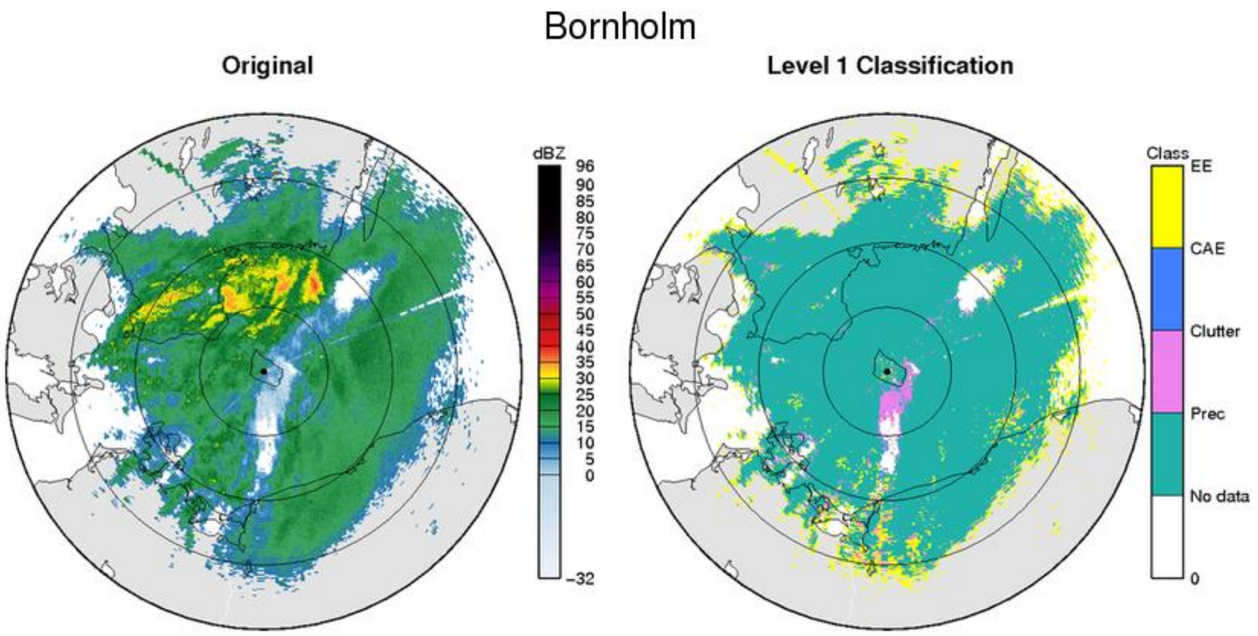

Figure 6 shows radar image on the left (original) and its corresponding level 1 hydrometeor classification into four classes: external emitters (EE), clean air echoes (CAE), clutter and precipitation (prec), colour code: yellow, blue, purple and green, respectively.

In the level 2 classification, the echoes that are classified as precipitation in level 1 are further sub-classified into different precipitation classes mentioned above. In this case the heights of the melting layer computed by the local NWP model are used to strengthen the classification between the different classes of rain and snow. In the current version of the level-2 classification only the parameters Z_{HH}, Z_{DR}, K_{DP}, and ρ_{HV} are used. In particular, in this case score S_j is given by the relation:

$$S_j = \frac{P^j_{Zhh} \cdot P^j_{height}\left[W_{Zdr} \cdot P^j_{Zdr} + w^j_{\rho hv} \cdot P^j_{\rho hv} + w^j_{Kdp} \cdot P^j_{Kdp}\right]}{w^j_{Zdr} + w^j_{\rho dr} + w^j_{Kdp}}$$

Figure 7 shows an example of the level 2 classification. Note that the radar data used to illustrate the classifications results are the same in Figure 6 and Figure 7.

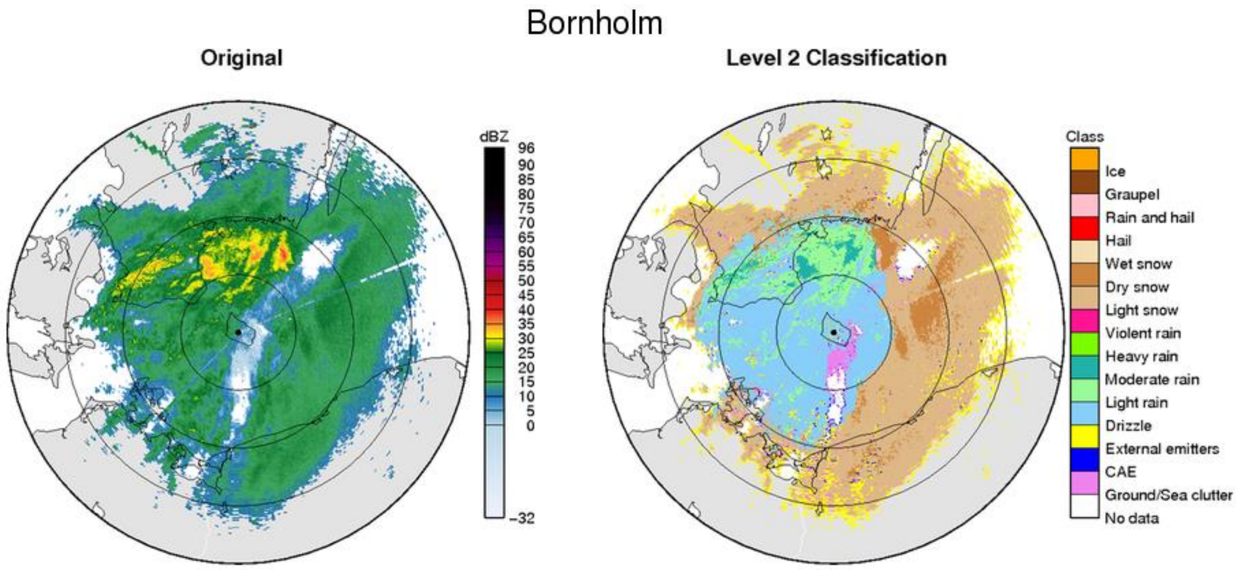

Figure 7 shows radar image on the left (original) and its corresponding level 2 hydrometeor classifications into eleven classes.

In addition to the above level 1 and 2 classifications, the algorithm can make use of the above classification output to remove the non-meteorological echoes in the original radar reflectivity product, Z_{HH}, shown on the left in each of the Figure 6 and Figure 7. This is illustrated in Figure 8 below. Concerning the latter product, it was the first product that was requested for routine operational use by the DMI end users, namely its meteorologists.

Hydrometeor classifier using the fuzzy logic method has been developed. The classifier make use of the dual-pol parameters Z_{HH}, Z_{DR}, K_{DP}, ρ_{HV}, plus the texture parameters associated with Z_{HH}, Z_{DR}, K_{DP} and the melting layer heights computed using the local NWP model forecasts. The latter are update every hour. In the current version of the algorithm, a radar echo can be classified into one of 12 classes. The subsequent versions of the algorithm will also include the following classes: hail, graupels, ice and rain/snow mixture.

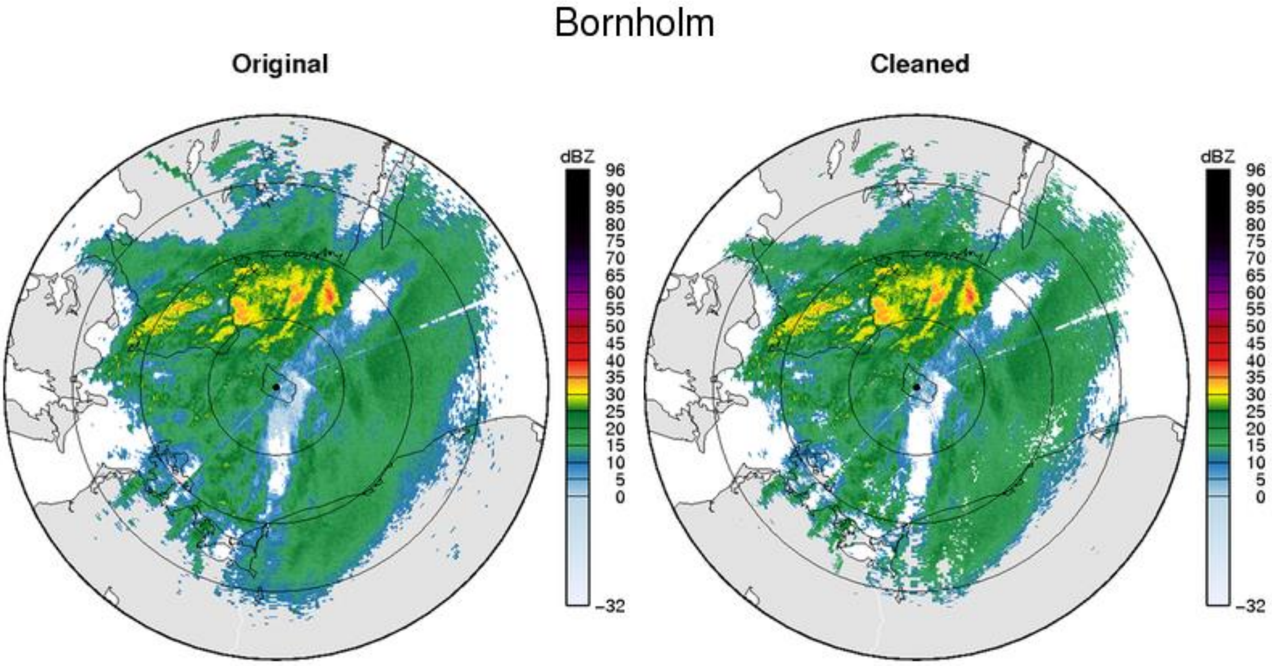

Figure 8 shows the original radar product on the left and corresponding "cleaned" version on the right which has non-meteorological echoes removed.

Finally, the hydrometeor classifier described above has been developed with partial funding by the EU BALTRAD project which requires the software is made available according to open source principles (Michelson et. al, 2010). The software is thus available to the interested users. The Gnu Lesser general Public License policy shall apply.

2.5 Estimation rain drop size and the fall velocity using DMI weather radars

Leinonen e. al. (2012) have proposed a relationship between rain drop size, D_0 (mm), and the dual polarization parameter, differential reflectivity, Z_{DR} (dB). This relationship has been used to compute the rain drop size. Furthermore, knowing the drop size, it is possible to estimate the terminal fall velocities of the drops (Brandes et. al., 2002). Figure 9 below shows an example of the typical results.

It should be noted that in the figure on the left showing the drop size, there are small regions where drop size is depicted in "red" in the colour scale, indicating drop sizes of > 2.5 mm. These are also regions with the highest fall velocities. Needless to say, such regions will be of great interest in the EROSION project.

The work on this algorithm is in early stage. One of the main challenges is having good quality Z_{DR} data and its routine calibration to account for potential biases. For the latter, a dedicated radar scan where the radar is pointing 90° vertically, the so-called bird bath scan, need to be set up for all the DMI's weather radars.

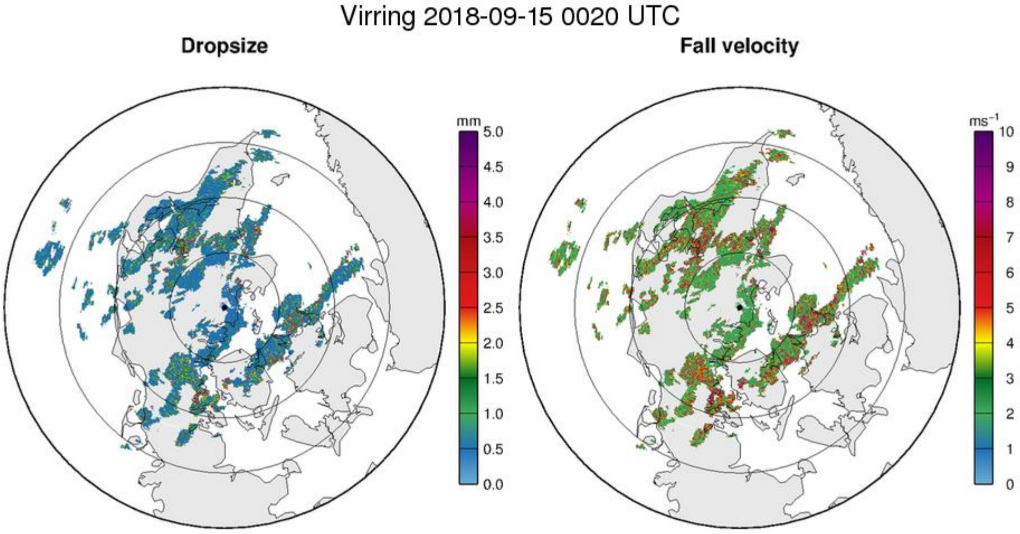

Figure 9: Example of typical results of drop size and fall velocity calculated from dual-pol radar data.

2.6 Hail probability product

An experimental product is under development, showing the probability of hail given in percent. In the example in Figure 10 several heavy showers are seen, and especially one with very high rain rate (dBZ>40) near Køge is also associated with a hail probability of 70-75 percent. It is interesting that there were reports of hail damage along the track of this shower. This product may supplement a warning system with useful information, even though it is still an experimental product that requires further development plus verification against ground measurements.

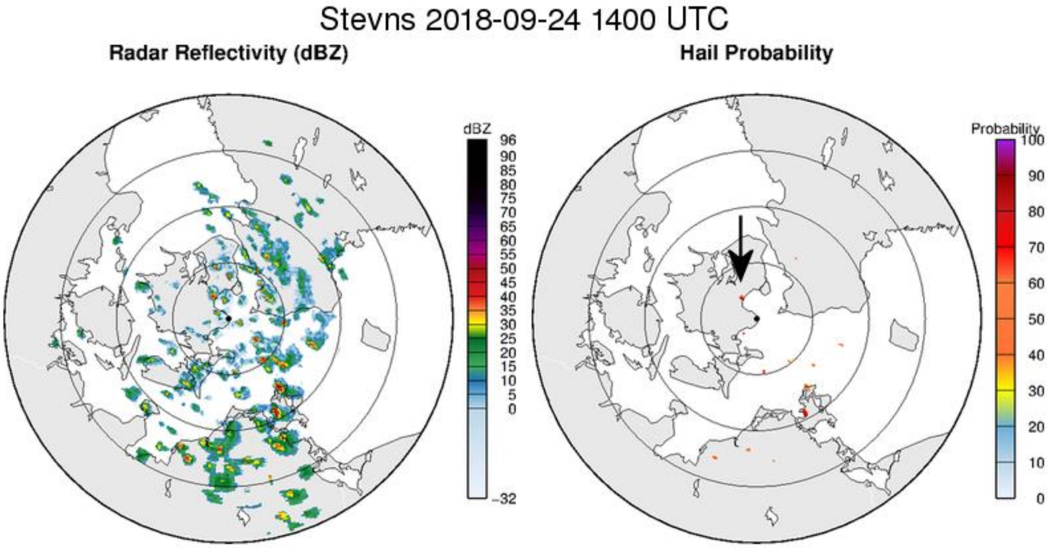

Figure 10: Radar products showing radar reflectivity and hail probability. The arrow is pointing at a heavy shower with high probability of hail. Damage caused by hail was reported in an industrial area in Køge (arrow).

2.7 Verification of dual-pol products and now-casting

The disdrometer data from WP1 and the HOBE project collected for surveillance of the regional precipitation erosion potential will be used to verify radar based calculation of hydrometeor type, droplet size, fall velocity and hail probability.

It is assumed that these products can support radar now-casting of heavy rainfall with useful information about the local weather conditions. This enables the decision-making basis for controlling wind turbines in relation to erosion safe mode to be strengthened.

In WP1, disdrometer data was analyzed in order to obtain increased knowledge about the relationship between DSD (drop size and fall velocity), rain intensity and kinetic energy. It may seem obvious to use the radar products for rain intensity, droplet size and drop rate to calculate kinetic energy and thus get a measure of the erosion potential of a given rain.

The droplet size and fall velocity radar products are still under development and there is a lack of experience about quality and uncertainty. The calculation method is based on algorithms developed in Finland, but the different climate of Denmark and Finland may give rise to biases. Droplet size and fall velocity is represented by one value respectively, and can be regarded as the accumulated effect, or “average”, of all droplets in a radar bin. Normally, DSD is described by a Gauss distribution, thus using “averages” of droplet size and fall velocity for calculation of kinetic energy may give rise to large scatter and biased estimates.

It may be possible that kinetic energy can be calculated from radar-based droplet size, fall velocity and rain rate. But the products must be verified against disdrometer data to provide the basis to decide if they with reasonably results can be included in a warning system.

Work in WP1 based on 5 years disdrometer data from Voulund test site has shown that universal conversion from these parameters to kinetic energy cannot be established. The reason is that seasonal-dependent relationships between DSD parameters and kinetic energy were found.

It is planned to verify hydrometeor type against disdrometer data and present weather sensors installed at DMI weather stations (see Figure 11). In addition, it should be examined whether there is a correlation between probability of hail and observed weather type.

Results from radar-nowcasting have been stored for the past 14 month, and verification of now-casting of selected events has been initiated. This verification is made for small areas near 4 selected wind farms. Figure 10 shows the location of these areas. Small sections of N×N pixels are extracted from radar- and now-casting data with a lead time of 0-2 hours.

Rain events of different types have been selected to test the now-casting model at different weather conditions: (1) heavy isolated showers, (2) more widespread heavy rain, (3) heavy rain popping up in the radar horizon, (4) fast evolving heavy rain with very short warning time.

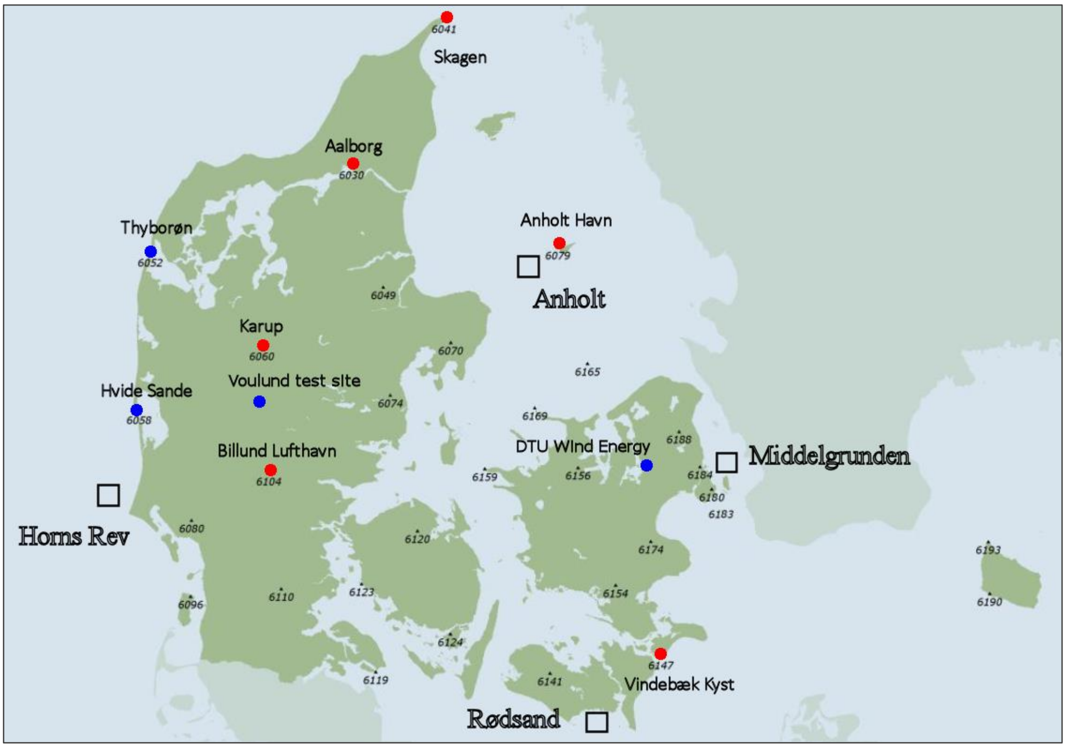

Figure 11: Location of DMI weather stations (dots with numbers), disdrometers (blue dots) and sections for evaluation of radar now-casting near selected wind farms (black boxes). Wind farm names are shown, but not the exact location.

2.8 Conversion between radar reflectivity and rain rate

Radar measurements of backscattering by hydrometeors are directly related to radar reflectivity Z. Both the reflectivity and the rain rate R is related to integrations of DSD; R through the sum of droplets per time unit, and Z through the total backscattering from droplets in a volume. It is found, that $Z=\sum nD^6$, where n=number of droplets and D=droplet diameter (Battan, 1973). Extensive research on the data structure of Z and R has employed a general empirical expression of the form $Z=AR^b$, where A and b are constants (Battan, 1973). A widely used expression for stratiform rain, $Z=200R^{1.6}$, was developed by Marshall and Palmer (1948). Z-R relationships have been developed for a large range of precipitation types (e.g. Šálek et al., 2004).

Due to the Earth curvature and the propagation of the radar beam, radar QPE may not represent surface rainfall properly because the radar beam is far above the ground at longer ranges. During non-standard atmospheric conditions, such as temperature and humidity inversions, propagation of radar beam is downward bended. This may result in severe false echoes from ground targets. Furthermore, targets near the radar station may cause persistent false echoes. Range-dependent errors are mainly due to the vertical variation in the reflectivity profile with distance, and at longer distances the radar may overshoot shallow precipitation areas. A comprehensive summary of errors in radar detection of hydrometeors can be found in Šálek et al. (2004). Fortunately, severe false echoes do not normally occur during precipitation.

Systematic bias in estimation of radar rain rates is introduced by using uniform Z-R relationship to represent varying Z-R relationships. Range dependent errors are related to the decreasing correlation between what the radar measures aloft and the surface rain. Also radar beam occultation may play a role in reliable rain rate estimation. Random errors come from the radar signal noise referred to above such as false echo effects.

Many techniques for estimation of reliable radar rain products have been proposed (Brandes, 1975, Krajewski, 1987, Smith and Krajewski, 1991, Rosenfeld et al., 1994, Gabella and Amitai, 2000, Sinclair and Pegram, 2005, Chumchean et al., 2006, Haberlandt, 2007).

Because Z is related to n and D^6 in a volume of air, i.e. Z is related to the behavior of DSD, and because of the large variability of DSD in time and space, significant uncertainty is introduced into the conversion of Z to R. Therefore, it is necessary to adjust radar estimates of rain rate R against ground measurements of rain. Normally, raingauges are used.

Two experimental QPE estimation techniques (Quantitative Precipitation Estimate) are under development at DMI. One is based on the so-called BALTEX approach (Michelson et al., 2000), and another is based on Kriging of local adjustment factors (Delobbe et al, 2008). Both methods are based on geostatistical analyses of the spatial structure of biases between unadjusted radar QPE and data from a raingauge network. An example of a QPE field is shown in Figure 12.

Data series from a certain number of raingauges are required to keep the uncertainty of the adjustment as low as possible. It is a common experience, that isolated and short living rain is associated with much higher uncertainty than widespread rain. Adjustment of radar images is quite time consuming and it may be a challenge to apply it to the now-casting product as close to real-time as required. One solution could be to use the latest estimate of adjustment factors even though these are not strictly real-time estimates.

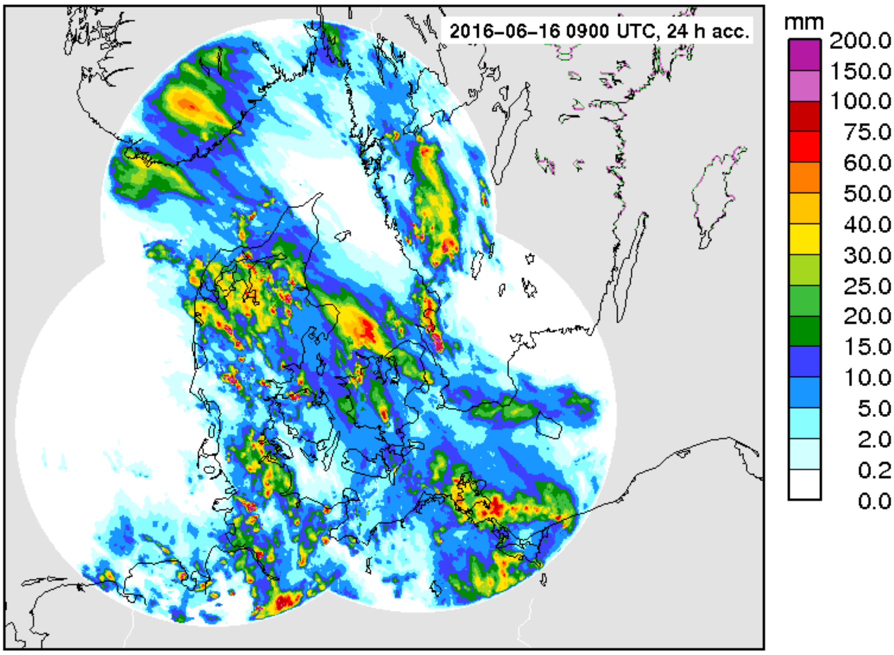

Figure 12: Radar QPE (quantitative precipitation estimate) field on 16 June 2016 at 0900 utc.

3. Further work

Dual-pol radar products, required or potentially useful for an erosion safe mode warning system, are reflectivity (rain rate), hydrometeor classification, droplet size, fall velocity, and hail probability. The data series established from disdrometers, weather stations and weather radars will be used for evaluation of radar products, and to decide if it makes sense to develop a model for calculation of kinetic energy based on radar parameters.

Due to the lack of agreement between elevated dual-pol radar measurements at larger ranges and the conditions near the ground surface, uncertainties of estimated parameters must be considered and addressed. The challenge is to establish reliable estimates of radar rain rates and hydrometeor classification at the same height as wind farms.

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