We would like to thank the reviewers for the valuable comments. We have carefully considered every comment by the reviewers. Below we provide the detailed answers to the comments – in bold black the comments from the reviewers, in black our replies to the comments and in italic black passages from the updated manuscript. A tracked-changes version of the manuscript is included as well.

Interactive comment on “Brief communication: Nowcasting of precipitation for leading edge erosion-safe mode” by Anna-Maria Tilg et al.

Anonymous Referee #1

Received and published: 29 March 2020

General Comments:

The authors present an interesting concept that aims to anticipate severe precipitation events. This can be used to inform an erosion-safe mode and reduce the tip speed of a turbine before the event impacts. The concept addresses the limitations of using forecasting approaches. Overall, I believe this paper would be suitable for publication if the following points are addressed.

Thank you for your positive feedback.

(1)
The study builds on work from Bech, 2018 and Hasager, 2020. I would consider including a paragraph introducing their work and findings so that the reader can understand how this work fits into the wider research.
Thank you for pointing to this shortcoming in the manuscript. We added following text to the introduction (line 19 to 27):

Bech et al. (2018) propose to reduce the tip speed during severe precipitation events to limit erosion and to extend blade lifetime. For example, they investigate the influence of turbine control during intense rain events on the annual energy production (AEP). Based on some assumptions, e.g. the precipitation climate, they find that AEP increases when reducing the tip speed during intense rain events compared to no reduction. The suggested turbine control combines wind and precipitation measurements with a damage model. The damage model itself describes the erosion rate in relation to rain parameters (e.g. kinetic energy or accumulated amount of rain) and is based on laboratory measurements. Hasager et al. (2020) find higher erosion rates at coastal stations than inland stations in Denmark due to more intense rain events at high wind speeds at these locations. Furthermore, they show an increase in the profit reducing the tip speed to 60 m/s or lower in case the rain intensity exceeds 1 mm/h.

(2)
The authors need to consider the worst case scenario in this study. If high intensity events cause the most erosion damage, then how the nowcasting would respond to an extreme intensity event needs to be presented. If an extreme, highly damaging event does not provide enough time for the turbine

to be slowed than there is a limit on the application of the erosion-safe mode. The concept has been presented successfully for a moderate intensity event.
Thank you for bringing up this point. Erosion-safe mode depends mainly on two parameters: (i) precipitation load, which is usually described with rain intensity and (ii) damage model, which depends on the material properties. The combination of these two parameters includes various scenarios, for example blade material that erodes fast during light rain intensities and other material that resists longer experiencing harsher conditions. Therefore, from our point of view it is difficult to define a general applicable worst-case scenario. Hasager et al. (2020) also considers the economical aspect of an erosion-safe mode and shows an increase in profit in case the tip speed is reduced at rain intensities of 1 mm/h or higher. Hence, the tip speed is already reduced when heavy rain (rain intensity ≥ 10 mm/h) is observed.
Considering a severe scenario, one needs also to consider the impact of hail and graupel. This type of precipitation occurs rarely but can cause more damage than intense rain events because of their impact behavior. As mentioned in the manuscript (line 132 to 133) it is possible to detect this type with a vertical pointing radar like the MRR from METEK.
To clarify this point in the manuscript, we added following sentence (line 123 to 124):

Based on the results from Hasager et al. (2020) one can assume that at this rain intensity the tip speed will be reduced around this value.

Specific Comments:

(3)
1. Page 1, sentence starting line 18, “Therefore, the method...”.
I do not think that you should say the erosion safe mode is a “solution”. As far as I’m aware, the erosion-safe mode has not been proven on an in-operation wind turbine. It would be more appropriate to present the safe mode as a “theory” e.g. “Bech proposes the idea of reducing tip speeds...”
We agree that erosion-safe mode should be described as possible solution as it has not yet been verified in a full-scale experiment. We reformulated the relevant part in the manuscript to (line 19 to 20):

Bech et al. (2018) propose to reduce the tip speed during severe precipitation events to limit erosion and to extend blade lifetime.

(4)
2. Page 2, sentence starting line 54, “Raindrops have diameters...”.
A reference to a study where 8mm and 10mm droplet diameters have been recorded is required. Alternatively, data validating this sentence should be provided.
We added a relevant publication (line 61 to 62):

Raindrops have diameters up to 8 mm, although raindrops with 10 mm have been observed in tropical areas (Jones et al., 2010).

(5)
3. Page 3, paragraph starting line 73, “Assuming a raindrop with...”. How does the fall time change when you take a worst case scenario (i.e. largest recorded droplet size, minimum aerodynamic drag from the altitude, etc)? If the erosion-safe mode is only intended to be used in severe precipitation events, the severe case needs to be presented.
As mentioned in point (2) it is difficult to define a general applicable worst-case scenario. Furthermore, it is shown that profit is already gained by reducing the tip speed at rain intensities around 1 mm/h. As our intention is to show frequent occurring rain conditions, we do not see a need to re-calculate the theoretical fall time for more extreme values.

(6)
4. Page 4, paragraph starting line 108, “Figure 1 shows the...” Can you show a radar reflectivity for a high intensity event? You present a plot for an intensity of 5 mm/h and calculate that rain arrives at the ground after two minutes. As with the previous comment, the worst-case scenario needs to be presented. How would this differ for an extreme intensity of e.g. 100mm/h? Is it still possible to reduce the tip speed of the turbine before the event arrives? Also, you should consider the height of a turbine in your calculation, rather than time to the ground.
As mentioned in point (2) our assumption is that the tip speed of the wind turbine blades is already reduced at lower rain intensities. This consideration is based on theoretical calculations presented in Hasager et al. (2020). Furthermore, Herring et al. (2020) mention “… that erosion damage is not driven solely by heavy and violent precipitation …”. Therefore, not only rain events with a rain intensity ≥ 20 mm/h are interesting, but also events with a moderate rain intensity, which occur more often.

Good point about taking turbine height instead of ground to determine the fall time. However, calculations show that a drop with 1.5 mm diameter and 5 m/s fall velocity needs 320 s from 1600 m to ground and 300 s from 1600 m to 100 m hub height. This is 6.25% reduced fall time. From our point of view this value does not significantly influence the general conclusion. Nevertheless, we changed the formulation to (line 117 to 118):

Rain that was registered at the lower boundary of the melting layer for example at 17:34 arrived around 2 min later at turbine hub height (approximately 100 m above ground).

Reference
Herring, R., Dyer, K., Howkins, P., and Ward, C.: Characterisation of the Offshore Precipitation Environment to Help Combat Leading Edge Erosion of Wind Turbine Blades, Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-11, in review, 2020.

(7)
5. Page 4, sentence starting line 123, “The MRR measurements are...”. Can you provide a reference to flow disturbance around disdrometers?
Testik and Rahman (2016) assume based on modelled wind field disturbances for the two-dimensional video disdrometer that the housing of the Ott Parsivel

disdrometer introduces also disturbances in the measurement volume. We included this reference in the manuscript (line 129 to 130):

The MRR measurements are not disturbed by the flow around the sensor in contrast to in-situ sensors like disdrometers (Testik and Rahman, 2016).

(8)

6. Page 6, sentence starting line 145, “This nowcasting technique...”.You mention that the technique can be applied offshore. However, earlier in the paper you discuss uncertainties in offshore radars, which indicates there are challenges to using this offshore. Can you extrapolate on this point to clear up the confusion?

Weather radars operated by national weather services are usually C-band or S-band radars having a temporal resolution of ≥ 5 minutes. The advantage of C-band and S-band radars is that they can cover large areas. Some relevant disadvantages of these weather radar types for a nowcast of precipitation at offshore wind farms are:

(1) Beam filling: The scanned volume increases with increasing distance from the radar. A precipitation event (like small showers) can be smaller than the scanned volume. This leads to an underestimation of the reflectivity and related parameters like rain intensity.
(2) Overshooting: The height of the radar beam increases with distance, because of the scan elevation angle and the curvature of the earth. This leads to an underestimation or even failure to detect shallow precipitation.
(3) Clutter by wind farm: Echos produced by wind farms can wrongly indicate precipitation (Hall et al. 2017)

These and other limitations like anomalous propagation of the radar beam can be detected. In some cases they can be corrected (like clutter by wind farm), for some cases a correction is difficult (e.g. beam filling).

To clarify our initial text, we added following information to the manuscript (line 93 to 96):

Furthermore, the use of C- and S-band based weather radars, which are usually installed onshore, includes some limitations, e.g. precipitation does not fill completely the scanned volume, height of radar beam is above precipitation and reflections caused by the wind farm infrastructure wrongly indicate precipitation. These limitations can be corrected only to some extend and lead to some uncertainty in the precipitation parameters.

Reference

Hall, W., M. A. Rico-Ramirez, and S. Krämer, 2017: Offshore wind turbine clutter characteristics and identification in operational C-band weather radar measurements: Offshore Wind Turbine Weather Radar Clutter Characteristics. Q.J.R. Meteorol. Soc., 143, 720–730, https://doi.org/10.1002/qj.2959

Technical Corrections:

(9)

1. Page 3, sentence starting line 63, “The fall velocity of a...”
Change to: "Besides its shape, the fall velocity of a hydrometeor is controlled by three forces:..."
Done

(10)
2. Page 3, sentence starting line 66, “This increase is linearly...”
Replace "linearly" with "linear"
Done

(11)
3. Page 6, line 136.Remove extra line after "4 Conclusion’"
Done

Thank you for considering my comments. I found this work interesting and believe it could help in addressing leading edge erosion.

Interactive comment on “Brief communication: Nowcasting of precipitation for leading edge erosion-safe mode” by Anna-Maria Tilg et al.

Anonymous Referee #2

Received and published: 13 April 2020

The manuscript is well written and presents its idea and concept in a clear and concise fashion.

We are happy for the kind assessment!

(12)
It could be beneficial to present a study indicating the loss of AEP of the turbine when using a controller of this kind to decrease the blade tip velocity vs the loss of AEP and expected costs for repair of erosion for a current case with no nowcasting controller. This way, the financial benefits would be clearer.
Bech et al. (2018) do some simplified calculations about the influence of an erosion-safe mode on the AEP. The calculated AEP values range from negligible reductions to significant increases depending on the erosion-safe mode of the wind turbines. In their calculations they assume “… that the duration of the tip speed reduction is 3 times the duration of the heavy precipitation, because the turbine cannot react instantaneously”. A nowcast, like with the vertical pointing radar, provides information in advance when tip speed reduction is needed. We assume that this has a positive influence on the AEP. However, the proposed erosion-safe mode has not yet been verified in a full-scale experiment. More research on that is needed.

We added following text about the AEP to the introduction (line 19 to 22):

Bech et al. (2018) propose to reduce the tip speed during severe precipitation events to limit erosion and to extend blade lifetime. For example, they investigate the *influence of turbine control during intense rain events on the annual energy production (AEP). Based on some assumptions, e.g. the precipitation climate, they find that AEP increases when reducing the tip speed during intense rain events compared to no reduction.*

Brief communication: Nowcasting of precipitation for leading edge erosion-safe mode

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Abstract. Leading edge erosion (LEE) of wind turbine blades is caused by the impact of hydrometeors, which appear in solid or liquid phase. A reduction of the wind turbine blades' tip speed during ~~severe~~defined precipitation events can mitigate LEE. To apply such an erosion-safe mode, a precipitation nowcast is required. Theoretical considerations indicate that the time a raindrop needs to fall to the ground is sufficient to reduce the tip speed. Furthermore, it is described that a compact vertical pointing radar that measures rain in different heights with a sufficient high spatio-temporal resolution can nowcast rain for an erosion-safe mode.

1 Introduction

Leading edge erosion caused by precipitation impinging on blades with high tip speed results in rougher blades and a loss in annual energy production. According to Chen et al. (2019), the most expensive and most time-consuming process within maintenance of wind turbines is blade repair. Durable leading edge coatings are not yet available (Herring et al., 2019).

Bech et al. (2018) propose to reduce the tip speed during severe precipitation events to limit erosion and to extend blade lifetime. For example, they investigate the influence of turbine control during intense rain events on the annual energy production (AEP). Based on some assumptions, e.g. the precipitation climate, they find that AEP increases when reducing the tip speed during intense rain events compared to no reduction. The suggested turbine control combines wind and precipitation measurements with a damage model. The damage model itself describes the erosion rate in relation to rain parameters (e.g. ~~Therefore, the method of reducing the tip speed during severe precipitation events to limit erosion and to extend blade lifetime is a solution (Bech et al. 2018).~~ kinetic energy or accumulated amount of rain) and is based on laboratory measurements. Hasager et al. (2020) find higher erosion rates at coastal stations than inland stations in Denmark due to more intense rain events at high wind speeds at these locations. Furthermore, they show an increase in the profit reducing the tip speed to 60 m/s or lower in case the rain intensity exceeds 1 mm/h.

The method of erosion-safe mode control is only possible to implement based on adequate precipitation nowcasting at minute to second scale. To limit the power production loss it is important to reduce the tip speed as early as possible, as long as needed and as short as possible.

Nowcasting of rain characteristics for leading edge erosion-safe mode control based on radar and Doppler lidar ~~are brand new opportunities for the wind energy industry. These nowcasts are at the minute to second scale. In relation to erosion-safe mode it is important to reduce the tip speed during severe precipitation events as early as possible, as long as needed and as short as possible to limit power production loss.~~

is a brand new topic in wind energy. The proposed precipitation nowcasting for erosion-safe mode has similarity to short-term forecasting for power production based on ground-based remote sensing technologies like dual-Doppler radar (Valldecabres et al., 2018a) and long-range scanning lidar at the minute scale (Valldecabres et al., 2018b). Also lidar-assisted yaw control, wake steering and induction control at the minute to second scale observed from turbine-mounted lidars (Würth et al., 2019) are comparable to precipitation nowcasting.

Radars are traditional instruments for precipitation observations while coherent Doppler lidar is novel in relation to rain (Aoki et al., 2016; Sjöholm and Mikkelsen, 2018). This brief communication focuses on the radar-based precipitation nowcasting for erosion-safe mode.

2 Theory

The time until a hydrometeor hits the ground is governed by three parameters: distance between cloud base height and the ground and the type and size of the hydrometeor, which determine the resulting fall velocity.

The distance between the cloud base height and the ground depends mainly on the location, the storm type and the related cloud type. It can vary between a few hundreds to some thousands of meters. Depending on the storm type and the related growth mechanisms of cloud droplets, hydrometeors falling out of the cloud are liquid (drizzle, rain) or solid (snow, graupel, hail). Solid hydrometeors start to melt when they pass the 0°C isotherm, which is the upper boundary of the melting layer. In weather radar measurements this layer is identified by high reflectivity values and is therefore called bright band. Thurai and Iguchi (2000) present a seasonal- and latitude-dependent distribution of the bright band height for stratiform events based on satellite measurements where the bright band height is the height with the highest reflectivity value. They find large seasonal variations of the bright band height for higher latitudes. Furthermore, they show that the 0°C isotherm from Recommendation ITU-R P.839-1 is usually 500 m or less above the bright band height. According to an updated version, P.839-4, the mean annual 0°C isotherm is around 2000 m above sea level for Denmark (International Telecommunication Union, 2013). This distance leads to a bright band height of about 1500 m, which can be taken as a rough approximation for the distance a raindrop falls until it reaches the ground. The bright band height in Denmark varies from about 3500 m in summer to 0 m in winter (Rashpal S. Gill, Danish Meteorological Institute, personal communication).

Rain consists of different raindrop sizes due to collision-induced breakup and coalescence of raindrops. Raindrops have diameters up to 8 mm, although raindrops with 10 mm have been observed in tropical areas~~.~~ (Jones et al., 2010). Small drops up to around 1 mm are spherical, while larger drops have the shape of a flattened sphere. Bringi et al. (2003) compare raindrop size distributions (DSD) from different climates. They find for convective storm types a mass-weighted mean diameter (D_m) between 1.50-1.75 mm for maritime-like environments and slightly larger D_m between 2.00-2.75 mm for continental-like environments. For stratiform storms they report D_m values between 1.25 and 1.75 mm but no clear distinction between different environments. These D_m variations show that beside location dependent influences, raindrop formation processes related to specific storm types play a major role in determining the DSD.

~~The~~Beside its shape, the fall velocity of a hydrometeor is controlled~~ beside its shape mainly~~ by three forces: gravity, buoyancy and the aerodynamic drag force. The fall velocity of a raindrop in still air, called terminal fall velocity, increases with the drop diameter. This increase is ~~linearly~~linear for small sizes and non-linear for large sizes. One of the most used empiric equations to calculate the fall velocity of raindrops is based on investigations from Atlas et al. (1973) . However, this equation does not take into account the altitude dependence of the fall speed due to the reduced aerodynamic drag force with decreasing air density with increasing altitude. ~~Lhermitte (1990) provides an equation considering a density ratio factor compared to the standard atmosphere to consider this altitude dependent change.~~Jones et al. (2010) provide an equation considering a density ratio factor compared to the standard atmosphere to consider this altitude dependent change. Raindrops might not achieve terminal fall velocity during (heavy) rain, because the collision-induced breakup and coalescence of drops causes repetitive increase and decrease of the fall velocity (Jones et al., 2010). Furthermore, as rain consists of different drop sizes, there will be always raindrops that are faster and slower.

Assuming a raindrop with a diameter of 1.5 mm, its terminal velocity is around 5 m/s taking the equation of Atlas et al. (1973). Considering a rain height of 1500 m, the raindrop needs 300 s (5 min) to fall to the ground. This time can be used to decelerate the tip speed of the wind turbine blades to reduce the impact energy by the drop and therefore the erosion of the leading edges.

~~In practice, the erosion-safe mode model combines wind and precipitation measurements with a damage model. The damage model itself describes the erosion rate in relation to rain parameters (e.g. kinetic energy, accumulated amount) and is based on laboratory measurements (Hasager et al., 2020). Hence, depending on the applied erosion-safe mode model different rain parameters have to be determined based on the nowcast.~~

Solid hydrometeors have different properties than raindrops. This difference results in different fall properties and impact behaviours on the leading edge of the wind turbine blade. The impact of hail and graupel causes more damage compared to rain. The focus of this publication is on the nowcasting of rain, as hail and graupel are less frequent (Macdonald et al., 2016) and snow is not relevant.

3 Application

Operational nowcasting provided by national weather services, like Integrated Nowcasting through Comprehensive Analysis (Haiden et al., 2011), combines available observations from weather stations, weather radars and satellites with forecasts of numerical weather prediction models. They provide values of precipitation amount and type beside other parameters in real time. However, in offshore environments, where enhanced leading edge erosion is observed, observations from weather stations are ~~not available and the considered weather radar volume is large due to the long distance to the weather radar location. Sensors~~usually not available. Furthermore, the use of C- and S-band based weather radars, which are usually installed onshore, includes some limitations, e.g. precipitation does not fill completely the scanned volume, height of radar beam is above precipitation and reflections caused by the wind farm infrastructure wrongly indicate precipitation. These limitations can be corrected only to some extend and lead to some uncertainty in the precipitation parameters. Local installed sensors measuring vertical profiles of precipitation are therefore an interesting option for nowcasting using the described time difference between the detection and impact of raindrops. Takahashi (1990) presents the Precipitation Particle Image Sensor (PPIS). This sensor measures like a radiosonde the precipitation at a certain height while ascending through the atmosphere. In contrast, vertical pointing radars provide continuous precipitation measurements in different altitudes at the same time.

An example for a ground-based vertical pointing radar is the Micro Rain Radar (MRR) from METEK. It is a compact 24 GHz (K-band) frequency modulated continuous wave (FM-CW) Doppler radar with a parabola antenna pointing vertically (Peters et al., 2002). The latest model MRR-PRO has a vertical resolution of > 10 m and can provide an averaged Doppler spectrum of the hydrometeors in ≥ 1 s, i.e. a Doppler spectrum roughly each 10 m for each second is available.

In case of rain, the first moment of the measured Doppler spectra allows the estimation of the fall velocity of the raindrops via the Doppler velocity. Based on the calculated fall velocity, the raindrop size can be estimated using the previously mentioned relation between these two parameters inversely. The availability of the raindrop size and fall velocity allows the calculation of further rain parameters like the rain reflectivity and rain intensity (assuming Rayleigh approximation) for different heights. These calculations assume that only raindrops and no solid hydrometeors or mix of both (i.e. sleet) backscatter the signal.

Figure 1 shows the temporal and vertical evolution of the radar reflectivity, fall velocity and rain intensity of an event in December 2019 in Plymouth (United Kingdom) measured with a MRR-PRO. This MRR-PRO provided data every 10 s up to

3200 m above ground. The high values of the derived parameters reflectivity and rain intensity between 2000 m and 1600 m indicate a melting layer. Below this layer, precipitation falls as rain, where rain intensity close to the ground is above 5 mm/h for several consecutive minutes. Rain that was registered at the lower boundary of the melting layer for example at 17:34 arrived around 2 min later at ~~the ground.~~turbine hub height (approximately 100 m above ground). This time difference is shorter than the expected time based on the above calculations. One reason is the reduced air density and therefore reduced aerodynamic drag in higher altitudes that leads to a higher fall velocities. Additionally, because of break-up and coalescence processes, the actual fall velocity can differ from the terminal fall velocity with velocities even above terminal fall velocity (Montero-Martínez et al., 2009). Nevertheless, in principle the measured time difference would enable the erosion-safe mode control to reduce the tip speed of the wind turbine blades in due time. Based on the results from Hasager et al. (2020) one can assume that at this rain intensity the tip speed will be reduced around this value. Furthermore, the height information of the melting layer can also help to identify the risk of blade icing, especially in cold climates.

The calculations of the rain parameters assume still air. In stratiform rain events the vertical wind speed is quite low, whereas vertical wind speeds during convective events like thunderstorms can be high. This assumption introduces some uncertainty in the calculated rain parameters in situations with high vertical wind speeds. The MRR measurements are not disturbed by the flow around the sensor in contrast to in-situ sensors like disdrometers~~.~~ (Testik and Rahman, 2016).

The automatic detection of solid hydrometeors with an MRR is still challenging as these precipitation types have different fall properties than rain. However, they can be detected by the synopsis of different rain parameters provided by the MRR.

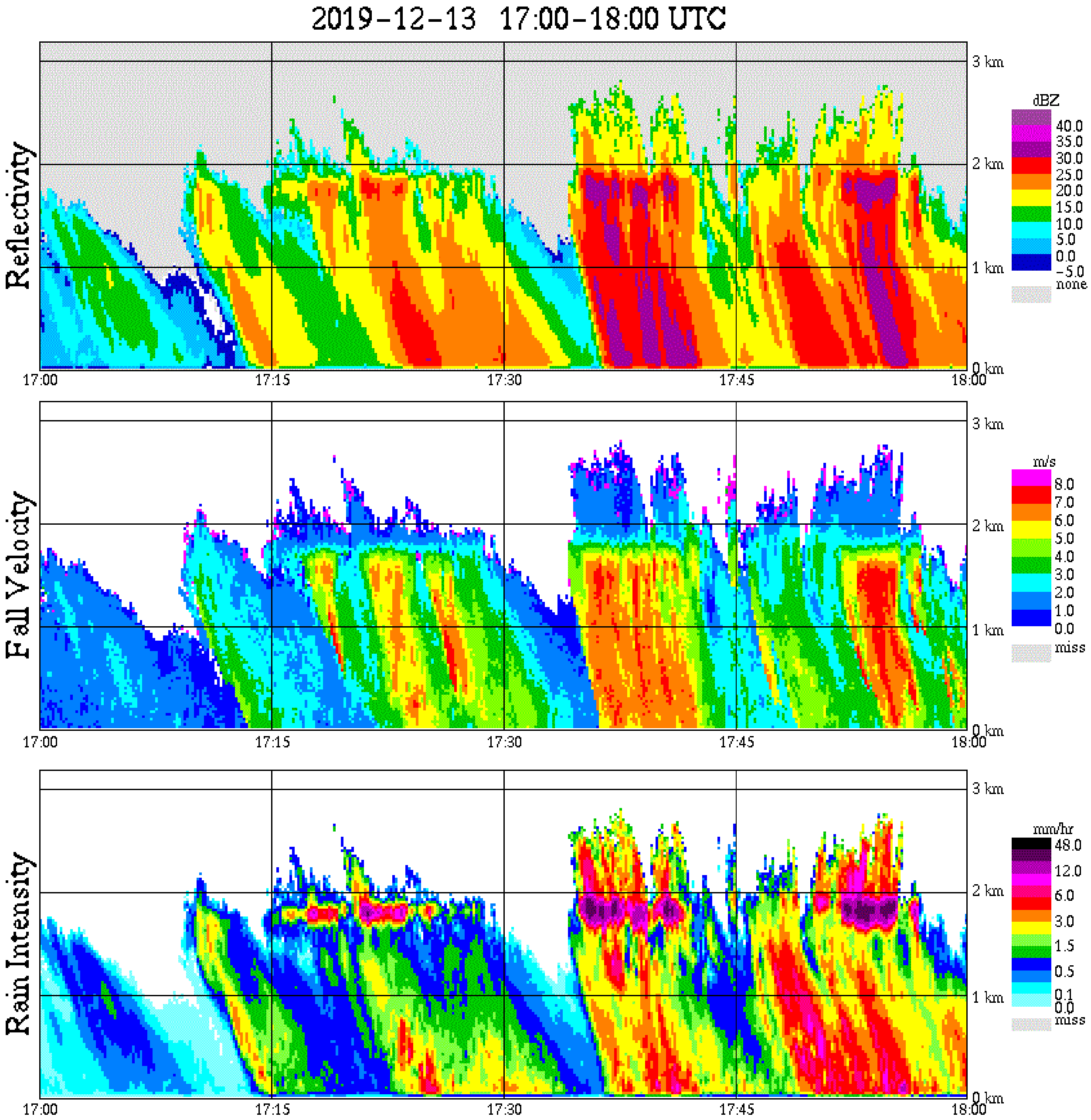

Figure 1: Radar reflectivity [dBz], fall velocity of raindrops [m/s] and rain intensity [mm/h] based on Micro Rain Radar measurements in Plymouth (United Kingdom). The vertical axis describes the vertical distance from the sensor and the horizontal axis the time in UTC.

4 Conclusion

Erosion-safe mode needs, like other parameters in wind turbine controlling, a nowcasting with high temporal and spatial resolution. Theoretical investigations showed that it takes a raindrop around five minutes (or less) to cover the distance between the cloud and the ground. If the raindrop is detected when it starts to fall, this time difference is sufficient to enable erosion-safe mode with reduced tip speed. Vertical precipitation profiles can be obtained using vertical pointing radars. For example, the Micro Rain Radar (MRR) from METEK points strictly vertically and measures Doppler spectra up to three kilometres with a resolution > 10 m. Due to the high temporal resolution, the Doppler spectra and the related rain parameters are updated frequently and can be used for nowcasting. Using a vertical pointing radar also allows capturing the height and temporal evolution of a possible present melting layer and solid hydrometeors. Based on these reflections it is possible to measure and nowcast rain where vertical precipitation profiles with a high spatio-temporal resolution are essential. This nowcasting technique can be applied onshore and offshore. Future work includes the combination of vertical pointing radar measurements and damage models to improve erosion-safe mode models and their operational use.

Author contribution

A.-M. Tilg: developed and discussed the concept, wrote main parts of the text. **C. Hasager:** discussed concept, wrote and edited text. **H.-J. Kirtzel:** discussed the concept, edited text. **P. Hummelshøj:** discussed the concept, edited text.

Competing interests

The author **H.-J. Kirtzel** is employed by the private company METEK GmbH and author **P. Hummelshøj** is employed by the private company METEK Nordic ApS. The companies develop, produce and sell the Micro Rain Radar (MRR). The authors declare that they have no other known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Chris Kidd (University of Maryland, NASA) for providing us the measurement example of the Micro Rain Radar installed at the Plymouth Marine Laboratory where Tim Smyth is responsible for the observations. This work was supported by the Innovation Fund Denmark grant 6154-00018B for the project EROSION (http://www.rain-erosion.dk; last access 13 January 2020). We thank two anonymous reviewers for their comments.

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