Response to Referee 2

Developing an atlas of rain-induced leading edge erosion for wind turbine blades in the Dutch North Sea (wes-2024-174)

Dear Reviewer,

Thank you for reviewing our article. In response to Referee 1's comments, we have made significant revisions to the paper, addressing your specific suggestions and proposed changes too. Below, you will find details on the modifications related to your comments.

Sincerely,

Marco Caboni and Gerwin van Dalum

Specific comments and proposed revisions:

-The weather modeling used captures large-scale meteorological trends and spatial patterns in wind and precipitation, especially the northeast-southwest gradient in the Dutch North Sea. The paper clearly states that both LES and mesoscale simulations compared to rainfall experimental measurements underestimate accumulated LEE damage related to a referenced wind turbine, particularly due to underrepresentation of extreme events and large raindrops. The summary rightly identifies the Marshall–Palmer distribution's inability to represent large droplets (>3 mm), which is a key limitation discussed in the paper.

-In one hand, authors employed Whiffle's ASPIRE model, a GPU-accelerated large-eddy simulation (LES) and mesoscale weather modeling platform, to simulate weather conditions over two timeframes: a high-resolution one-year LES (2022–2023) for validation purposes and a lower-resolution ten-year mesoscale simulation (2014–2023) for long-term trend analysis. These simulations were compared against real experimental measurements of wind and rainfall collected at offshore, coastal, and onshore sites in the Netherlands. While the LES simulations more accurately captured extreme weather events and aligned better with observational data, the mesoscale simulations were deemed sufficient for long-term trend analysis and atlas development. However, an important result is that both simulation types underestimated accumulated damage compared to measurements. This discrepancy is primarily due to two factors: the underrepresentation of large raindrops in the Marshall-Palmer drop size distribution used in the model, and the lower frequency of extreme events in the simulations compared to observations.

---The authors should clearly identify the novelty of this result and explain how LES and meso-scale simulations serve as complementary tools in atmospheric research, each appropriate for different types of studies and objectives.

We have included a new section that focuses on a detailed comparison between meso-scale simulations and high-resolution LES performed over 1 year over the Dutch North Sea. In this section, we specifically compare annual rainfall and total annual damage, categorized into bins based on wind speed and rain rate, and analyze the contour maps. The year-long comparison of meso-scale simulations and high-resolution large eddy simulations (LES) at selected sites in The Netherlands showed that the accumulated damage estimated from meso-scale simulations is 7 to 20% lower than that obtained from LES. These differences can be attributed to the LES setup's ability to capture more extreme events due to its finer spatial and temporal resolution. Moreover, the side-by-side comparison of the contour maps obtained using meso-scale simulations and

LES reveals alignment in the spatial patterns of erosion-related parameters, confirming that meso-scale simulations produce satisfactory atlases where regional differences are consistently captured with LES.

We have discussed the distinctions between LES and meso-scale simulations, contextualizing them within the framework of current literature as outlined below:

By conducting 10-year long meso-scale simulations to account for long-term climatology, our study has highlighted the variation of rain-induced erosivity across the Dutch North Sea. Examining the portion of the Dutch North Sea covered in the reanalysis-based erosion atlas by Hannesdóttir et al. (2024b), no clear trends can be inferred within this region. This is because their atlas focuses on Scandinavian regions and only marginally and partially covers the Dutch North Sea. According to this atlas, the incubation period is approximately 4 years over the covered Dutch North Sea, which is about 40% lower than the incubation period resulting from our meso-scale based erosion atlas. These differences can be attributed not only to the weather model with specific resolutions and periods but also to assumptions regarding DSD, drop falling speed, damage model, and fatigue characteristics of the LEP system. Such assumptions have a dramatic effect on the resulting incubation period. Due to the complexity of the calculations behind an erosion atlas, considering the assumptions and models used to generate it, it is not possible to detail where the differences between our atlas and the one by Hannesdóttir et al. (2024b) come from. Future research should aim at dedicated comparisons of erosion atlases, systematically breaking down the calculation chain and comparing results for each portion.

Our study indicates that a LES setup with finer spatial and temporal resolution enhances the ability of simulations to capture more extreme events. This is because the smaller temporal resolution allows the simulations to detect more short-term extreme events with high rain intensity. Such high-intensity events contain larger and more erosive droplets. With larger temporal resolutions, these events are averaged out.

---However, despite effectively reproducing these trends, a significant limitation of the study that should be clarified is its systematic underestimation of absolute leading-edge erosion (LEE) damage.

Currently, we lack sufficient information to explain why both meso-scale and LES models tend to underpredict the accumulated damage compared to actual measurements. Besides uncertainties in the simulations, we cannot rule out that these differences may also result from significant uncertainties affecting the measurements (see Caboni et al., 2024). In the discussion section, we acknowledge the uncertainties present in both the measurements and simulations as follows:

Our comparative analysis with actual measurements reveals that both meso-scale and LES models tend to underpredict the accumulated damage. One reason is that the Marshall-Palmer distribution assumed by both numerical models significantly underestimates the amount of large droplets compared to what is measured. Another reason is that more extreme events are recorded than those simulated, especially at the instrumented offshore location. Significant uncertainties still exist in detecting such events in both measurements and simulations. Detailed measurements of rain in offshore locations are new, and further research is required to improve these measurements and establish confidence bounds.

-In the other hand, the erosion model used in the study estimates the incubation period—the time before visible erosion begins—based on ASTM regression equations and assumes a polyurethane leading edge protection (LEP) system on a 15 MW reference wind turbine. The results reveal a clear spatial variation in erosion risk across the Dutch North Sea. The estimated incubation period ranges from 8–9 years in the southwest to 6–7 years in the northeast. This variation is attributed to higher average wind speeds and greater rainfall in the northeastern regions. The study concludes that although there are uncertainties in absolute damage estimation, the rainfall simulations effectively capture spatial trends in erosion risk due to weather conditions.

---The authors should clearly outline the aspects of their work that have been validated: whether it is the comparison of rainfall observations to simulations, or the progression of erosion damage, which is not currently depicted in the work.

In our study, we did not validate either the weather model or the erosion model. As part of our paper's scope, we compared weather simulations to measurements. Given the significant uncertainties and differences observed, we believe that the term "validation" is not appropriate in this context. Therefore, we have replaced "validate" (or "validation") with "compare" (or "comparison").

-Moreover, the use of normalized incubation resistance (NOR) derived from rotating-arm rain erosion tests (Slot et al., 2025) may not fully reflect the complex real-world conditions encountered offshore, potentially contributing to the observed discrepancies. The paper emphasizes that while the rainfall model captures trends, the absolute values of damage remain uncertain without direct validation from experimental observations in operational wind turbines. Moreover, authors state future work will focus on improving the representation of drop size distributions and fall velocities in the ASPIRE model and exploring real-time erosion forecasting to enable adaptive turbine operation during extreme weather events.

---The authors should clarify first how rainfall simulations relate to damage progression uncertainty analysis for future work, as this is not detailed or validated in the paper.

In the discussion section, we have addressed the uncertainties of our approach as follows:

Our comparative analysis with actual measurements reveals that both meso-scale and LES models tend to underpredict the accumulated damage. One reason is that the Marshall-Palmer distribution assumed by both numerical models significantly underestimates the amount of large droplets compared to what is measured. Another reason is that more extreme events are recorded than those simulated, especially at the instrumented offshore location. Significant uncertainties still exist in detecting such events in both measurements and simulations. Detailed measurements of rain in offshore locations are new, and further research is required to improve these measurements and establish confidence bounds.

As previously mentioned, the estimates of incubation periods provided by this study, whether derived from measurements or simulations, are based on various methods and several assumptions. Unfortunately, these estimates have not been validated in real-world conditions yet. However, we can say that these figures are roughly in line with the leading edge repair interventions of wind turbines in the Dutch North Sea.

-Additionally, the simplified linear damage accumulation approach adopted by the incubation period (IP) model (Caboni et al., 2024), based on the Palmgren–Miner rule, may not accurately capture non-linear effects associated with severe meteorological events. As a result, without direct validation through observed erosion damage on operational wind turbine blades, these predictions related to material damage evolution remain theoretical. The reliability and practical applicability of these estimations are consequently limited, underscoring the critical need for direct comparison with actual erosion observations from operational offshore wind farms under comparable environmental conditions to validate and refine the predictive capabilities of the proposed model.

---The authors should consider these limitations and clearly state the scope of the proposed study in the paper.

The limitations of the approach are discussed in the discussion section as mentioned above. Related to the approach limitations, future work is outlined in the conclusion section as follows:

Future work will involve implementing a more representative drop size distribution and fall velocity in the weather model. In this context, models will need to be validated with more reliable measurements, which is also a topic of ongoing and future research.