Author comments in reply to anonymous referee #2

We thank anonymous referee #2 for their useful comments and the time invested in reviewing our manuscript. We very much appreciate the critical and thorough review of our work. We have addressed each of the referee comments as detailed point by point below, which we believe has significantly improved the quality of the manuscript. We hope our revised manuscript can be accepted for publication.

(Throughout this document, specific modifications to the revised manuscript are shown in blue)

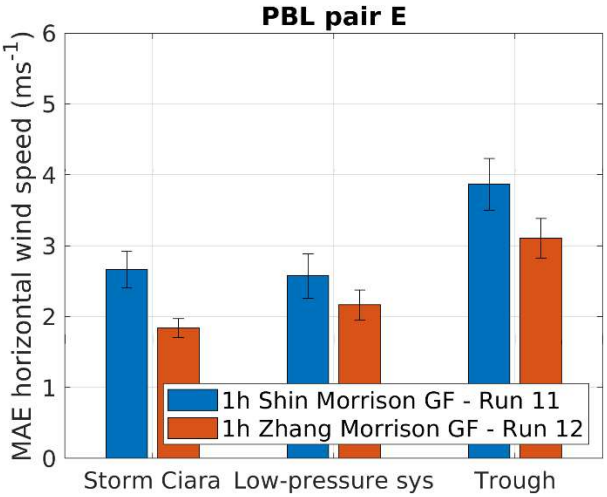
Adithya Vemuri, on behalf of all co-authors

Overarching comments

To fully address both of our referee comments, in response to major comment 2 by referee #1, we have included 2 additional extreme weather events to this sensitivity study. Therefore, the revised manuscript observes significant changes to its paper structure, simulation setups, simulation pairs and the evaluation methodology considered.

With the addition of 2 more events to the revised manuscript, we have also opted for including statistical uncertainties in a more objective and quantitative analysis to assess which trends persist with statistical significance over different events. In this regard, we have refocused our analysis on quantitative comparison of the wind speed and direction MAE. We have removed quantitative discussions on precipitation and Kantorovich distances (for which we cannot define any error bars based on the available data). Furthermore, we have removed the somewhat subjective domain configuration sensitivity in favor of an additional case with the 3D Zhang PBL scheme, resulting in a total of 36 WRF simulations for the 3 events combined. An example plot (Figure 12b in the revised manuscript) is presented below indicating the change in performance evaluation for simulation pairs.

Further, we mention that during the revision, we have checked and refined our post-processing tools, which led to some minor changes in metric values and time-series plots for the case of Storm Ciara.



Specific comments

Comment 1: *There are major inconsistencies in the way radar reflectivity and precipitation (rate) are handled in the manuscript. This is especially visible in some of the figures (captions mentions reflectivity*

while figure legends talk about precipitation with units of precipitation rates, e.g. Figure 1, 4), but also in the text (e.g. line 188-191). A major revision of all elements of the manuscript is needed by the authors with special attention to a consistent usage of atmospheric properties and units.

- We thank the referee for pointing this out and have corrected for the inconsistencies in all figure and precipitation mentions. An example caption from the revised manuscript is presented below.

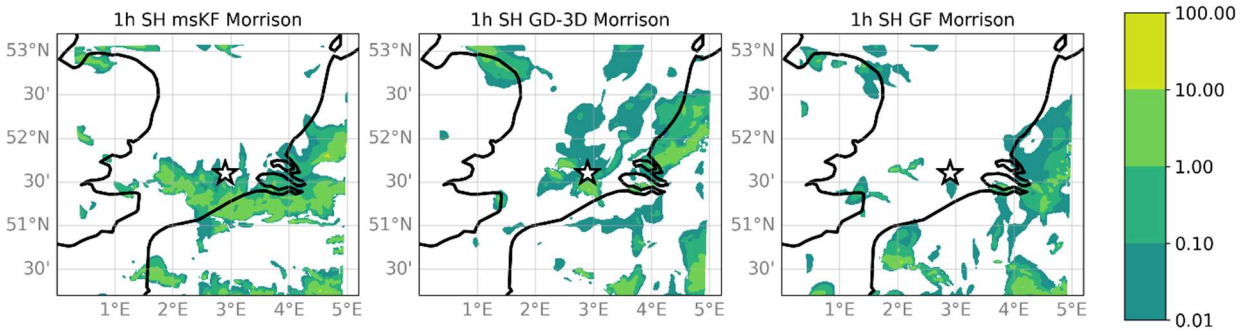


Fig. 19 caption: Contours of WRF precipitation rate in mm h^{-1} for the case of Storm Ciara on 10 February 2020 at 04:40 UTC. The plots are presented for cumulus simulation pair H for domain d04.

Comment 2: *Throughout the paper, the term "horizontal resolution" has been used to describe the grid spacing of the WRF domains (among others in Table 1, line 145/146 and elsewhere). This is misleading since horizontal (effective) resolution and grid spacing are not equivalent for numerical models like WRF (see e.g. Skamarock 2004 for details). Please replace the term "horizontal resolution" with "grid spacing" where needed.*

- Indeed, we agree that grid spacing and horizontal resolution are not equivalent, and have corrected this throughout the revised manuscript, also in Table 1 (presented further in this reply).

Comment 3: *As mentioned earlier, the descriptions in the methodology section are quite convoluted with model setup, evaluation metrics, introduction and processing of measurements and WRF post-processing all described in the same section. I would suggest to introduce subsections for the model setup (incl. WRF post-processing of radar reflectivity), evaluation metrics and the measurements to enhance readability and to make space for more details, especially with respect to data availability for the radar and SCADA data (publicly available data, protected data or similar). If publicly available, please also state the access point of the data and provide more details about the wind farm.*

- We agree with the referee to split the methodology section for better readability. In the revised manuscript we split the methodology into 3 sub sections, as: Common model setup, individual run setups, and performance metrics and observations. We also clarify that SCADA and radar data are currently data-protected under a non-disclosure agreement. Unfortunately, this agreement also disallows revealing specifics of the wind farm considered.

<u>The following lines are added to highlight data-protection in the methodology section:</u>
Line 128: The selection of the events in this study is motivated by the occurrence of fast changes in wind direction accompanied by severe yaw misalignment leading to significant power loss as observed by a Belgian offshore wind farm in the North Sea. The methodology utilized to identify these events modifies the approach defined by Hannesdóttir and Kelly (2019) to include yaw misalignment. The

wavelet analysis considers a minimum threshold to identify anomalous changes in wind direction accompanied by severe yaw misalignment experienced by several wind turbines. Severe yaw misalignment potentially has adverse effects on the operational lifetime and fatigue loading of a wind turbine (Wan et al., 2015; Bakhshi and Sandborn, 2016; Laino and Hansen, 1998; Damiani et al., 2018), highlighting its importance and relevance in this study. The SCADA analysis for the identification of these events includes confidential error codes and data that are protected under a non-disclosure agreement, therefore no further details can be provided herein.

Highlighting non-disclosure on radar data:
Line 137: Three case studies are considered in this sensitivity analysis, namely, Storm Ciara on 10 February 2020, a low-pressure system on 24 December 2020, and a trough passage on 27 June 2020. The radar data presented therein is not publicly available, but was retrieved through a bilateral agreement with the Royal Meteorological Institute of Belgium (RMI-B). A brief synopsis of these events is presented in the following sub-sections.

Remarks addressing specific lines

Comment 1: *Line 30: The reference (Skamarock et al. 2008) points towards Version 3 of the WRF model, but in your methodology section, you mention that you are using Version 4.2. Is there a particular reason why the Version 3 reference is used here and not Version 4?*

- This is indeed incorrect. The reference for WRF has been updated to point to the right reference.

The following lines have been updated in the introduction of the revised manuscript:
Line 34: This study utilizes the public domain Weather Research and Forecasting - Advanced Research WRF (WRF-ARW) model developed by the National Center for Atmospheric Research (Skamarock et al., 2019; Powers et al., 2017).

Comment 2: *Reference(s) for the statements/quoted numbers of wind gust, travel path, effects etc. are missing. Please consider adding.*

- This is correct, we update the revised manuscript to the correct reference, RMI-B.

The following lines have been updated in the description of Storm Ciara in the revised manuscript:
Line 142: Storm Ciara is one of the first extratropical cyclones to hit the European continent in the year 2020, occurring on 10 February 2020 over the Belgian North Sea. Storm Ciara originated in the Atlantic Ocean, moving from the North American continent (starting 3 February 2020) to the European continent (16 February 2020). Storm Ciara swept across the majority of western Europe including United Kingdom and Norway, bringing in heavy precipitation and strong winds with a maximum recorded wind gust of 219 km h^{-1} at Cap Corse, Corsica, France (footnote 1). Over Belgium, the RMI-B (footnote 2) reported wind gusts of up to 115 km h^{-1} in Ostend, located at the Belgian coast, with heavy precipitation accompanied by strong winds and thunderstorms.

Adding the footnote 1: https://www.meteo-paris.com/actualites/retro-meteo-2020-les-evenements-climatiques-marquants-en-france, website consulted on 21 April 2022.
Adding the footnote 2: https://www.meteo.be/nl/info/nieuwsoverzicht/storm-ciara, website consulted on 21 April 2022.

Comment 3: *"Subsequently, the model is run …". Please consider reformulation since the current formulation could be misinterpreted as two separate independent simulations (one 24h long simulation and one 21h long simulation). I assume the WRF simulation has been run in one continuous block?*

- The simulations have been runs as a continuous block.

We highlight this point in the common WRF setup section:
Line 185: The simulations have been performed as a continuous run including spin-up and evaluation periods.

Comments 4: *Line 153/154: "The land surface interactions are kept constant". Please reformulate since it is the parameterization scheme that is kept constant, not the interactions themselves.*

- We thank the referee for pointing this out, the phrasing of these sentences has been changed to reflect these comments.

We highlight this point in the common WRF setup section:
Line 189: The Rapid Radiative Transfer Model (RRTMG) (Iacono et al., 2008) for longwave and shortwave radiation physics is used by all simulations. Similarly, the land–surface interactions are defined by the unified Noah land surface model (Tewari et al., 2004). The PBL, cumulus, and microphysics schemes are varied amongst the mentioned options as described in Table 1 (in the revised manuscript).

Comment 5: *Line 213: Make sure that you are talking about the correct boundary conditions (temporal resolution of the LATERAL boundary conditions not the INITIAL boundary conditions). Please correct.*

- We thank the referee for pointing this out. Throughout the revised manuscript we have adopted the term "update interval of lateral boundary conditions" to clearly outline what is meant, and remove any possible connotations with temporal resolution of the ERA5 product itself (see also first comment to Language corrections below). Since the number of occurrences in the manuscript are high, this is not presented in detail here.

Technical corrections

Language corrections:

We thank the referee for their critical review on the manuscript's written English. The typos, comma style, abbreviation definitions and technical detail have been corrected in the revised manuscript. In addition to the specific points raised by the referee, we have thoroughly revised the use of English throughout the manuscript with the help of a native English speaker.

We have amended all the textual changes suggested by the referee. For brevity, we only mention the ones that require further explanation.

- *Line 5: while the resolution of the reanalysis products is important, it is the temporal resolution of the lateral boundary condition updates that is investigated here (which is not necessarily identical), so I would suggest a formulation like "update interval of lateral boundary conditions" instead of "temporal resolution of re-analysis data".*

Indeed, it is the update interval of the lateral boundary conditions that are varied and not the temporal resolution of initial ERA5 re-analysis itself. We correct for this throughout the revised manuscript.

- *Line 34: I am not sure what you mean by "expanse of physics parameterizations". Do you mean variety? I would suggest reformulation.*

Yes, we mean the different available options. This sentence is modified as:
Line 38: Therein, an array of physics parameterizations and model parameters are available to adequately represent a local weather system.

- *Line 62: "[…] explores; redistribution […]". Sentence structure is unclear, please consider reformulation*.

The sentence is revised as follows:
Line 82: The GF cumulus parameterization (Grell and Freitas, 2014) is an adjustment type parameterization that redistributes compensating subsidence derived from GD-3D to neighboring grid cells using a Gaussian distribution function and adapts the scale-aware cloud representations from Arakawa et al. (2011).

- *Line 333: Unclear what "wind-farm power excursions" means. Please reformulate.*

We replaced this term with "variability in power production".

Tables

Comments (1-3): *Table 1: Number of nested domain is misleading. Following WRF naming conventions (see e.g. http://dx.doi.org/10.5065/1dfh-6p97), it would be one parent domain (d01) and 3 nested domains (d02-d04). Furthermore, it would be good to mention if 1-way or 2-way nesting has been used.*

Table 1: Time-step information incomplete. It is not clear which domain uses the 20s time step. I would suggest to either mention the time-steps for the four domains explicitly or state the domain which uses the 20s time step and provide the time step ratio.

Table 1: Consider replacement of "update frequency" with "update interval" to be consistent with the values given in the second column (1h and 3h are intervals, not frequencies)

- We thank the referee for pointing out discrepancies and indicating opportunities to improve our tables. The table 1 has been updated as shown below to comply with these suggestions.
- Further, we mention 1-way nesting at:

Line 176: The common model parameters considered for all WRF simulations are summarized in Table 1 (presented below). The baseline horizontal grid spacing of the parent domain d01 is 27 km, while the 1-way nested domains are sequentially refined by a factor of 3 …

Line 180: A time step of 20 s is considered for parent domain d01, while the time step of nested domains is sequentially refined by a factor of 3.

Numerical setup	
Nested domains (1-way nesting)	4
Horizontal grid spacing	27 km (d01) × 9 km (d02) × 3 km (d03) × 1 km (d04)
Terrain following vertical levels	57
Model top pressure	1000 Pa
Time-steps for domain configuration	20 s (d01), 6.67 s (d02), 2.22 s (d03), 0.74 s (d04)
Spin-up period	24 h
Lateral & boundary conditions	ERA5 reanalysis
Evaluation time, additional to spin up	21 h (Storm Ciara) and 6 h (Low-pressure system and trough passage)
Domain size	*type 1 / type 2* (Fig. 4)
Boundary update interval	*1h / 3h*
Physics parametrizations	
Radiation	RRTMG radiative
Land surface	unified Noah land-surface
PBL	*MYNN / Shin-Hong / Zhang*
Microphysics	*WSM5 / Thompson / Morrison*
Cumulus	*KF / GD-3D / msKF / GF*

Comment 4: *Units for MAEs, NEDs and Kantorovich distances are missing, please add. I would also suggest to change the E notation of the Kantorovich distance (rather uncommon in scientific literature) to decimal notation. The differences in scales of magnitude are not large enough to justify such notation to the expense of readability.*

- All tables have been updated to indicate metric units. As discussed in the overarching comments, we focus on MAE and omit the Kantorovich distance in the revised manuscript.

Figures

In general, the font sizes in some of the figures are too small (especially Figure 1, 2 and the time series plots). Please adjust to increase readability.

Figure 1: Mismatch in time statement in caption (4:00) and reference in main text (4:40,l. 137). Please double-check. A description of the meaning of the star-symbol and the red lines is missing in the figure caption (and other figures captions as well). Please also consider changing the coastline color, which is too similar to colors used in the color map of the variable you are plotting.

Figure 1,6,8,10,11: Since the focus region is rather small, please add latitude and longitude information to make it easier to locate features.

Figure 3: insert "are" before "shown"

- We thank the referee for their suggestions on how to improve the quality of our figures. We have incorporated all these in the revised manuscript. Presented below are some example plots (Figures 19 in the revised manuscript) to illustrate the changes implemented.

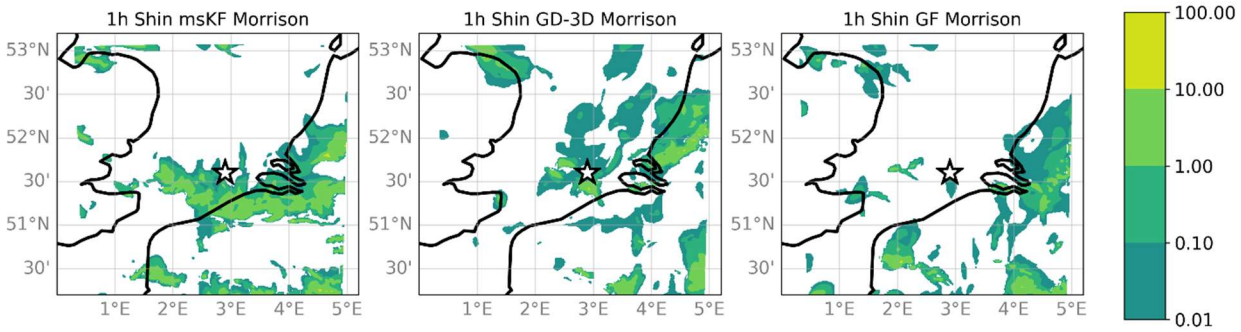


Fig. 19 caption: Contours of WRF precipitation rate in mm h^{-1} for the case of Storm Ciara on 10 February 2020 at 04:40 UTC. The plots are presented for cumulus simulation pair H for domain d04.