

Note - Line numbers listed refer to the marked-up manuscript

## **Review 1**

**This study presents an innovative contribution to the understanding of storminess dynamics and their potential links to volcanic forcing, based on peat-core records from coastal Ireland. The integration of multiple sedimentary proxies, radiocarbon dating, and statistical analyses against historical chronicles provides an interesting perspective. The manuscript is clearly written, well-structured, and addresses a relevant question in palaeoclimatology. I commend the authors for the quality of their work and for assembling a dataset that is both original and regionally significant. The identification of sand-rich storm layers through XRF proxies provides compelling stratigraphic evidence for storm activity, while the application of SEA represents an innovative and appropriate study for testing hypothesized volcanic activity and storminess hypotheses links. This research enriches the paleo-storminess record for Ireland and the wider northeast Atlantic.**

Thank you for these positive comments.

**I nevertheless identify several methodological limitations—particularly concerning the chronological framework, the calibration of geochemical proxies, and the treatment of uncertainties—which deserve more attention in the discussion. Addressing these points, either in revision or in future research, would strengthen the robustness and impact of the conclusions.**

**Detailed comments and suggestions:**

### **1. Introduction**

**I've nothing to say about the introduction that is complete and well written. The study interest regarding scientific literature is well contextualized.**

Thank you

### **2. Study Area**

**1) This part is quite short, a more detailed presentation of the geomorphology of the site, with a more precise map of the studied environment (with fieldwork photographs) may help readers to understand the site.**

We agree that more detail is required here. We have added sentences for the study area describing the nature and distance of the nearby beaches. We have added a new map to Figure 2 to show the local features of the bog and surrounding area, including the nearby beach and pebble storm beach, roads and tracks and ditches across parts of the bog. We have photographs of the nearby beaches but don't feel that these would be a particularly useful contribution to the main manuscript, but if required they can be added to supplementary information as a demonstration of the nearby sand sources. We did not get a good photo of the peat bog as the area is flat.

**2) As the subject of this work is related to storminess, some significant storm event recorded recently that hit the area may be discussed here to highlight the interest of this site regarding the stormy thematic.**

Thanks for this suggestion. We have added statistics from the Met Eireann weather service, including the average number of named storms each year affecting Ireland and also details about Storm Eowyn, January 2025, which was the strongest storm on (the instrumental) record in Ireland.

**3) In addition, the Figure 2 could be enhanced by complementing the elevation data related to the isolines shown (maybe from a Digital Elevation Model ?).**

We have added the peak elevation of the islands hills to the study area map. The spacing of the contours is close and therefore we felt labelling the elevation of contours with numbers would be unclear. Instead we have changed the appearance of the contour lines so that 50m intervals are thin lines and 200m intervals are shown by thicker lines. Thank you for your suggestions regarding the study area.

### **3. Methods**

**4) The rationale for using Si, Ca and Br as storm proxies should be supported by a short statistical justification rather than relying solely on qualitative interpretation. As an example in one of our previous work, we tested the correlation matrix + CPA + dendrogram methodology in section 3.2.1 of the <https://www.sciencedirect.com/science/article/abs/pii/S0025322717304759> (this is just an example, no need to reuse or quote it, other statistical methods may also be employed).**

We have applied a statistical approach as you suggest, thank you, and this has shown some interesting results. We have made a correlation matrix and conducted principle component analysis. The methods have been updated, new results described and in the discussion the new findings explored.

The correlations and PCA both support the contention that bromine and calcium are potential proxies for past storminess – the ignition residue proxy for past storminess correlated most strongly with Br and Ca and both had a positive loading on PC2. However, the Br result also correlated significantly with humification. This indicates that both storminess and post-depositional changes caused by humification control the preserved bromine. Si had a weak negative correlation with the IR, which does not indicate that it is picking up variations in sand, however closer inspection for selected intervals (following point 12 below) showed that Si may be a useful storm proxy once sand concentrations surpass a threshold that can be detected by the core scanner.

Finally, we confirmed that the beach sand at the nearest beach and the large beach to the west (Keel) were composed of calcium carbonate shell and quartz sand particles (confirmed by microscopic inspection of the sand), justifying the focus on Si and Ca as indicators of sand in this locality.

**5) One of the main points of vigilance is the radiocarbon chronology, which is currently built with only six bulk radiocarbon ages for the two cores age depth model. This may be sufficient for a single core and hopefully the error margin is low, however the sample is particularly depth (4 meters), and the addition of a few other radiocarbon samples will restrengthening the chronology. This is an important point because the entire discussion, with also the climatological implications, depends on this age-depth model.**

There is unfortunately no material from core BM-1 remaining for further radiocarbon dating (the core was 5cm diameter and material was used up by the loss-on-ignition process) meaning that it is not possible to strengthen the core chronology of this main core further.

It is the results of this main dated core (i.e. the IR record on BM-1) that are used in the discussion as the primary storm record for this site (the XRF element records measured on BM-2 are not discussed as storm records given the influence of humification/poor detection as discussed in the manuscript). As you observe, 6 radiocarbon dates is sufficient for a single core, and there are examples of recent storminess studies with comparable numbers of radiocarbon dates per metre (5 radiocarbon dates in 4m - Kylander et al., 2023; 4 radiocarbon dates + surface Pb210 dates in top 4m – Lachance et al., 2025). It is also common practise in peatland storm studies to sample paired cores from <1m distance apart and consider them as the same core (e.g. Lachance et al., 2025; Sjöstrom et al., 2024). In such publications the potential differences in accumulation rates between the two are not usually considered and the cores are treated as one (rather than both being dated separately).

We have adjusted the text in the methods (section 3.2) and results (section 4.1 and 4.5) to acknowledge that there is an assumption that the two cores had the same accumulation history and that there may be differences in the peat accumulation rates caused by bog surface microtopography (e.g. Foster et al., 1988; Harris et al., 2020). The age uncertainty has also been highlighted within the results discussion: we have added a graph to Figure 9 that shows the 2 sigma age ranges for the storm peaks compared with the major eruptions, to show the reader that while the median probability ages between the eruptions and storm peaks align in many cases, the age uncertainties are indeed large. We have highlighted this in the discussion (section 5.3) and conclusion as a remaining challenge.

**6) In addition, is it possible that the absence of macrofossil dates or may introduce wide age uncertainties and possible reservoir effects? It may be possible to clarify why only bulk material was used.**

We analysed the bulk material for the radiocarbon dates as previous work has indicated that there is no significant difference between the radiocarbon dates for bulk peat and macrofossil samples (Blaauw et al., 2004; Holmquist et al., 2016). We have added a sentence clarifying this to the methods. Blaauw et al. (2004) state that samples from hollows may have a reservoir effect from the influence of CO<sub>2</sub> from deeper layers, however the cores in this study were not sampled from hollows.

**7) The 3.4 and 4.4 geochemistry sections are quite short, XRF scanning limitations in detecting elements should be acknowledged more explicitly, and the results must be**

**more detailed, as they are one of the most significant storminess proxies of this study.**

The limitations of the XRF core scanning method are described in some detail in the introduction and we have added sentences reiterating these limitations to the methods section 3.4 and discussion section 4.4. The element methods and results are now more detailed, with additional description of the sources of error, the moving average calculations/results and the statistical analyses (sections 3.6 and 4.5).

**8) The results suggest that Br is strongly influenced by humification processes rather than marine inputs. This should be highlighted as a significant limitation, and a statistical correction (see previous comments) could be proposed. Is it possible to conserve this proxy even if peat decomposition may affect its concentration along the core?**

Having conducted the statistical analysis there is some indication that both storminess and humification may influence bromine, as bromine correlates significantly with both the humification record ( $R = 0.46$ ) and the IR record ( $R = 0.48$ ). Despite this the visual comparison in the new Figure 7 supports the argument that the variability is more influenced by humification, and we agree that this is a significant limitation to Br as a storminess proxy (hence why it is not used as a storm proxy in the discussion).

We have expanded the discussion paragraph on bromine to include the statistical evidence and the observation that there are differences in the peaks in the IR and bromine records. We also observe however that within the last millennium the uppermost peak in IR does appear to be shown by the bromine record (see Figure 7), so we speculate that the low degree of decomposition in this youngest section of core may mean that here the storm signal is preserved (section 5.1).

We have added a line to propose that a higher resolution humification record could be used to extract a storm record 'although potentially future research could use a high-resolution humification record to normalise the bromine record, with residual bromine showing variability in deposition and thus storminess' (last sentence in section 5.1).

**9) The dataset of historical storm archives is really interesting and it's a real challenge to try to cross geophysical and historical sources. However, potential reporting bias remains a concern. Without correcting variable annal density across centuries, frequency peaks may also reflect source availability, and this concern must be highlighted. This limitation doesn't impact on the result of this study be it may be important to underline it. Furthermore, more information about the historical depletion may be added (writing and language interpretation or translation, choice of sources, cross-data validation, the understanding of if the author witnesses the events or it's a secondary source, etc.)**

We thank the reviewer for highlighting the value, but also the challenges, of using historical sources in making palaeoclimatic inferences. The list of potential biases and concerns is fully correct, and we have ensured that these are highlighted in the paper, as well as our assessment of the extent to which these concerns have been addressed or may influence

our analyses. For example, see Section 1, lines 111-115, for motivations for reporting of storms and Section 3.7, lines 249-290, for the construction of our historical windiness index, including considerations regarding the completeness of the record, changing levels of coverage through time, potential subjectivity or other biases on the part of the original observers, and the likely chronological accuracy of the sources.

The reviewer is certainly correct to note that issues such as the variable density of annalistic coverage through time must certainly be accounted for in order to avoid attributing frequency peaks in storm reporting to a real climatic trend, when it may be (at least partly) the result of a peak in annalistic recording for contemporary economic, political or religious purposes, or a peak in the survival of annalistic records from a given time-period. The reverse is also true for periods of low-density coverage (Ludlow, 2012). We have therefore been careful to avoid offering any formal trend analyses for relative storminess through time, although this is something possible in future work when the total number of records in the available annalistic texts has been counted and may offer interesting opportunities to compare to trends derived from our sedimentary proxies.

We instead restrict our current use of the annalistic storm record to create a presence—absence time-series to assess (using superposed epoch analyses) whether there is a statistically non-random correspondence between dates of known storminess from the annals and dates of explosive volcanism inferred from ice-core evidence at annual resolutions. This analysis does not require us to assume that either record is fully complete, but rather that each source (the annals and ice-cores) captures (1) a sufficient sample of stormy years and explosive eruptions and (2) that these events are independently and sufficiently accurately dated in each source, so that any recurrent association between eruptions and storminess will be identifiable, if in fact it exists. This is indeed what we find in our results, with a further indication that the magnitude of volcanic forcing is also important.

Nonetheless, our superposed epoch analyses could be advanced in future exploratory work by weighting (or otherwise attaching probabilities) to presence-absence time-series according to varying density of annalistic coverage through time, as well as exploring spatial considerations, such as whether there are meaningful biases in the likelihood of a storm being recorded depending upon where in Ireland the surviving annals derive from (e.g., when recording largely shifts to the west and north of the island after the thirteenth century (McCarthy, 2008). These considerations are noted in our discussion.

#### 4. Results

##### **10) A more comprehensive presentation of the core stratigraphy's would be valuable, including a photograph, core log, and calibrated proxies together.**

We have changed figure 3 (the age-depth model) to include a stratigraphic diagram and the age model. Figure 4 now shows all the proxies plotted together against age (IR, humification and 11 centred-log ratio element results) along with moving average results. We kept the age model and stratigraphy separate from the core results as the latter figure is already big.

**11) Figure 3 (age-depth model) lacks precision: it may be enhanced to better read the link between depth, estimated ages, and error margins which is not entirely clear.**

We have re-made the age-depth model to improve the clarity of this information.

**12) The differences between IR-detected storm layers and XRF signals should be more systematically quantified, as this is central to the proxy evaluation. For selected intervals, it would be instructive to show a direct comparison of IR, XRF signals, and humification. The Figure 4 might be a few more precise, and geochemical data normalized or averaged to be more readable.**

Statistical analysis (Pearson correlations and Principle Component Analysis) has been applied to quantify the relationships between the element, IR and humification records (new figure 5 and table 2). We present all the results in Figure 4 (now including the high resolution and 1cm moving average results for each element) and have added figure 7 in the discussion to present a more direct comparison of results as suggested (e.g. normalised Br, IR and humification on the same plot rather than separate plots). We have also added the moving average to the element records in this figure, which helps to show variations in the data, particularly the noisy Si data. Finally, we have presented the full records as well as two selected intervals (1-0 and 4-2 ka BP).

We thank Dr Pouzet for this suggestion because it has shown that Si does show increases coinciding with IR increases within the last millennium when the mineral content is highest (i.e. IR >5%), although the concentration of sand within the peat prior to this interval appears to have been too low for detection by the core scanner. This result has been added to the text of the discussion (section 5.1, lines 452-455), the abstract and conclusion.

## **5. Discussion**

**Interpretation of the volcanic forcing signal may appear a few deterministic given the current chronological uncertainties. Is it possible to obtain a probability ranges of eruption–storm alignment or is it not necessary?**

We have added a subplot to figure 9 which shows the alignment and age uncertainty of the storm peaks and global volcanic eruptions over the last 2.5 ka BP (as identified by Sigl et al., 2015 and Mackay et al., 2022). This shows that while there is reasonably good alignment of the median ages of the Bullsmouth and Roycarter records of storminess, the 2-sigma age uncertainties are wide. The peaks in storminess align closely with many, but not all of the major eruptions. One of the challenges in making this figure was that some increases in the IR (storm peaks) have multiple peaks, or span several cm's of peat, and we selected just the peak value. Therefore, this may be a factor causing some difference between the eruption date and median age points. Regardless of this the figure helps to show the age uncertainty associated with the results and we highlight the age uncertainty as a remaining challenge in the discussion (lines 587 and 683).

**It is also possible that storm layers may reflect not only atmospheric circulation changes but also indirect eruption effects such as dune destabilization or other paleoenvironmental changes, which could amplify sand influx (I'm not an expert of**

**the site studied but is this limitation may be also discussed?). This is also why the geomorphological local context have to be developed in the section 2.**

This is a point we have discussed in the current manuscript within discussion section 5.3 (*'A factor that may have amplified, and perhaps prolonged, the deposition of sand to the Irish and Welsh peatlands following eruptions may have been vegetation responses to the eruptions. Colder temperatures and reduced sunlight caused by stratospheric aerosols potentially reduced coastal vegetation cover and may have promoted sand dune instability, leading to enhanced sand erosion and transport inland'*). We here consider altered temperature/light as a potential influence on vegetation cover and dune stability following eruptions. We have added some text to explain that there are no available records of dune development from Achill Island with which to explore this further (line 563), as well as added more to the conclusion about this as a challenge. The sand dunes and machair at Keel have been mentioned in the study area (section 2) to expand the geomorphological context.

**I think that the potential influence of NAO or AMO modes alongside volcanic forcing may also be specified.**

In the discussion we have added more discussion of the NAO through the addition of a supplementary information figure comparing the timing of major eruptions and the identified regional storm events with the NAO reconstructions by Trouet et al. (2009) and Olsen et al (2012). This indicates that eruptions occurred at times of positive, negative and neutral NAO, however we acknowledge that these reconstructions may not be detecting sub-decadal excursions in the NAO that might be expected following eruptions due to their resolution. The periods of storminess also do not appear to coincide with the NAO in any one state (i.e. peaks occur when the NAO is both negative and positive and increasing/decreasing). These observations are now included in the discussion section (line 597).

We have also now included acknowledgement that variations in Atlantic SST's may be important. In section 5.3 (line 631) in the paragraph about the possible vegetation response to cooling, we state that episodes of explosive volcanicity have been associated with cooling of the North Atlantic and a negative AMO in model simulations, observations and reconstructions since the LIA (Knudsen et al., 2014; Birkel et al., 2018; Mann et al., 2021), which results in part from enhanced evaporative cooling from stronger westerly winds (Birkel et al., 2018). This may have enhanced the cooling over surrounding regions such as western Ireland. We have also referenced these papers and mentioned cooler Atlantic SST's in the paragraph about ice-rafting (line 652), as this may have also influenced the southward distance travelled by ice.

**The SEA statistical approach is interesting, but is it possible to integrate uncertainties models in this statistical approach? Or may it not be needed regarding the precise date obtained in archives?**

We are fortunate that both sources for our superposed epoch analyses, the Irish annalistic record and polar ice-core record of volcanic forcing, are considered broadly chronologically accurate and precise on annual scales for our study period (600 CE onwards), to within a small error margin of approximately +/-1 years for the earlier centuries of our concern. This

confidence arises from the considerable work undertaken in the past 20 years revising and then validating both chronologies against independent evidence. For the annals, this includes comets and solar and lunar eclipses of independently known date (McCarthy, 2008) and for the ice-cores it includes well dated historical observations of candidate volcanic dust veils and radionuclide spikes produced by large cosmic ray events that produced  $^{10}\text{Be}$  spikes in the ice that could be linked to equivalent  $^{14}\text{C}$  spikes in securely dated tree ring chronologies (Sigl et al., 2015). Small isolated chronological errors that might arise from unrecognised transcription errors in the annals or isolated layer counting errors in the ice cores should “average out” as an intrinsic part of the superposed epoch analysis (SEA) approach. If such errors are, however, more systematic than recognised, then the SEA approach is also appropriate for identifying this, in plotting not only the average incidence of storminess in the nominal years of eruptions, but also the years immediately before and after.

This approach is also diagnostic of whether there are lags in the climatic response to major eruptions (which are not chronological errors per se, but which can still cause an off-set in timing between a volcanic signal and potentially associated storminess) as well as negative-lags. These might arise from potential differences between eruption dates inferred from the year in which elevated sulphate registers notably in the ice, and the date of the eruption itself, which will precede the sulphate deposition date by a variable amount (Ludlow et al., 2013). This can depend on the distance of the source volcano from the poles and the state of the prevailing atmospheric circulation. Indeed, our results show a notable and statistically significant clustering of stormy years in the range of -1 to +1 years around the available ice-core-inferred eruption dates. This suggests the existence of (expected) minor chronologically uncertainty, as well as lag effects (such as those just noted). Identifying exactly what mix of such processes and effects are responsible for this apparent diffusion of the storminess response (across superposed years -1 to +1) is a remaining challenge, which we now emphasize in the main text. However, we also emphasize that this does not undermine the main finding of our superposed epoch analyses, i.e., that there is a recurrent association between explosive volcanism and human-documented storminess for Ireland’s northeast Atlantic location.

**The replication of this work is limited, which makes it difficult to generalize the results (two cores in BM bog). This limitation should be acknowledged, with maybe a suggestion to integrate additional sites from the Irish coast in future work?**

In figure 8 and section 5.2 we bring together regional records (including the Roycarter site by Sjostrom et al. (2024) located 10 km away and the records from Wales, Scotland and Sweden) to identify periods of enhanced storminess in northwest Europe more broadly (these are the blue bars in figures 8 and 9). More records from Ireland and elsewhere would certainly help to strengthen the confidence we have in the identified past periods of storminess and show regional differences, and several such storm records are currently being developed. We have emphasised the benefit of regional compilations of records in discussion section 5.2 (line 566).

## **6. Conclusions**

**In the conclusions, the evidence that storminess peaks align with some volcanic episodes is compelling regarding the entire paper, but I think that precaution is to rappel in the conclusion regarding each uncertainties combined, and the main limitation and uncertainties of this study may be detailed here.**

We have added text to the conclusions that a limitation is the chronological uncertainties associated with storminess reconstructions and a lack of knowledge about the environmental conditions and processes responsible for the sand deposition.

**Possible recommendations for the second version of this manuscript, or for further work:**

**Overall, this is an original study that provides an important contribution to the understanding of past storminess and its potential links to volcanic forcing in coastal Ireland. The authors developed an interdisciplinary framework that combines sedimentological, geochemical, chronological, and historical sources. To further strengthen the manuscript, I would encourage the team to consider reinforcing the chronological framework, propagating age uncertainties into the SEA, and calibrating the XRF-derived proxies with independent chemical and grain-size data, or to confirm it with other statistical measurements. It may also be valuable to explore statistical corrections for the humification effect on Br, to expand replication across additional cores or archives, and to normalize the documentary record for reporting bias. Finally, more advanced statistical approaches and future comparisons with climate model simulations could provide an even stronger basis for causal attribution. These suggestions do not diminish the quality of the present work but rather highlight promising avenues for further development and expansion of this already interesting contribution.**

Thank you for these recommendations for the current manuscript and future research. We have strengthened the manuscript by conducting statistical analyses to test further whether the XRF proxies are detecting storminess. This has helped to positively show that while Si and Ca in the current study are not effective storm proxies, this is likely due to the low concentration of sand in the lower core that is below the detection limit of the core scanner, and these are likely to be useful at sites receiving a little more sand. We have also acknowledged the suggestion that humification data could be used to correct the Br record resulting in a storm record, although perhaps higher resolution (e.g. 1cm) humification data would be needed to do this properly.

We are unable at the present time to address some of these points (strengthening the chronology and calibrating the XRF results) due to funding and material constraints, although we hope that the chronological concerns are somewhat satisfied by the adjustments made to the manuscript and explanations above. While we will consider doing a calibration of the XRF core scanner data using XRF measurements in future, this has not been possible for this study. We note that there are examples of similar peatland studies that have core scanning XRF results without being calibrated (e.g. Stewart et al., 2017; Lachance et al., 2025).

The known age uncertainties for the SEA analysis are very small ( $\pm 1$  year for both the ice core records and documentary records) and this is discussed in the original manuscript. This, alongside potentially lagged post-eruption climatic responses and lagged deposition of volcanic sulphate to the polar ice, can provisionally explain the peak in recorded storminess occurring within a -1 to +1 year range relative to our ice-core-based eruption dates, rather than solely in the inferred year of the eruption or shortly thereafter. Normalizing the documentary record to account for reporting bias arising from variable record density through time is a valuable suggestion. This, however, requires a counting of all annalistic entries through time in order to properly characterize this density, work on which is ongoing. We agree that this would be essential for credible palaeoclimatic inference (e.g., for trends in storminess) from the frequency of reported storms and stormy seasons. However, as explained earlier, for our present purposes, such a normalization is not essential for our SEA approach.

The research of the authors currently includes development of additional storm records from Ireland to improve the replication and comparison with model simulations for causal attribution.

### References Cited in Our Responses

- Birkel, S.D., Mayewski, P.A., Maasch, K.A., Kurbatov, A.V. and Lyon, B., 2018. Evidence for a volcanic underpinning of the Atlantic multidecadal oscillation. *NPJ Climate and Atmospheric Science*, 1(1), p.24. <https://doi.org/10.1038/s41612-018-0036-6>
- Blaauw, M., van der Plicht, J. and van Geel, B., 2004. Radiocarbon dating of bulk peat samples from raised bogs: non-existence of a previously reported 'reservoir effect'?. *Quaternary Science Reviews*, 23(14-15), pp.1537-1542. <https://doi.org/10.1016/j.quascirev.2004.04.002>
- Foster, D.R., Wright Jr, H.E., Thelaus, M. and King, G.A., 1988. Bog development and landform dynamics in central Sweden and south-eastern Labrador, Canada. *The Journal of Ecology*, pp.1164-1185. <https://doi.org/10.2307/2260641>
- Harris, L.I., Roulet, N.T. and Moore, T.R., 2020. Mechanisms for the development of microform patterns in peatlands of the Hudson Bay lowland. *Ecosystems*, 23(4), pp.741-767. <https://doi.org/10.1007/s10021-019-00436-z>
- Holmquist, J.R., Finkelstein, S.A., Garneau, M., Massa, C., Yu, Z. and MacDonald, G.M., 2016. A comparison of radiocarbon ages derived from bulk peat and selected plant macrofossils in basal peat cores from circum-arctic peatlands. *Quaternary Geochronology*, 31, pp.53-61. <https://doi.org/10.1016/j.quageo.2015.10.003>

Knudsen, M.F., Jacobsen, B.H., Seidenkrantz, M.S. and Olsen, J., 2014. Evidence for external forcing of the Atlantic Multidecadal Oscillation since termination of the Little Ice Age. *Nature communications*, 5(1), p.3323.

Kylander, M.E., Martínez-Cortizas, A., Sjöström, J.K., Gåling, J., Gyllencreutz, R., Bindler, R., Alexanderson, H., Schenk, F., Reinardy, B.T., Chandler, B.M. and Gallagher, K., 2023. Storm chasing: Tracking Holocene storminess in southern Sweden using mineral proxies from inland and coastal peat bogs. *Quaternary Science Reviews*, 299, p.107854. <https://doi.org/10.1016/j.quascirev.2022.107854>

Lachance, A., Peros, M.C., St-Jacques, J.M., Francus, P. and Sanderson, N.K., 2025. High-resolution paleo-storm reconstructions from Eastern Canada align with late Holocene northwestern Atlantic hurricane records. *Climate of the Past*, 21(11), pp.2407-2439. <https://doi.org/10.5194/cp-21-2407-2025>

Ludlow, F., 2012. Assessing non-climatic influences on the record of extreme weather events in the Irish Annals. At the Anvil: Essays in Honour of William J. Smyth. Geography Publications, Dublin, Ireland, pp.93-133.

Ludlow, F., Stine, A.R., Leahy, P., Murphy, E., Mayewski, P.A., Taylor, D., Killen, J., Baillie, M.G., Hennessy, M. and Kiely, G., 2013. Medieval Irish chronicles reveal persistent volcanic forcing of severe winter cold events, 431–1649 CE. *Environmental Research Letters*, 8(2), p.024035. DOI 10.1088/1748-9326/8/2/024035

Mackay, H., Plunkett, G., Jensen, B.J., Aubry, T.J., Corona, C., Kim, W.M., Toohey, M., Sigl, M., Stoffel, M., Anchukaitis, K.J. and Raible, C., 2022. The 852/3 CE Mount Churchill eruption: examining the potential climatic and societal impacts and the timing of the Medieval Climate Anomaly in the North Atlantic region. *Climate of the Past*, 18(6), pp.1475-1508. <https://doi.org/10.5194/cp-18-1475-2022>

Mann, M.E., Steinman, B.A., Brouillette, D.J. and Miller, S.K., 2021. Multidecadal climate oscillations during the past millennium driven by volcanic forcing. *Science*, 371(6533), pp.1014-1019. <https://doi.org/10.1126/science.abc5810>

McCarthy, D.: The Irish Annals: their genesis, evolution, and history. Dublin, Four Courts Press, 2008.

Olsen, J., Anderson, N.J. and Knudsen, M.F., 2012. Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience*, 5(11), pp.808-812. <https://doi.org/10.1038/ngeo1589>

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., and Fischer, H.: Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature*, 523, 543–549, doi:10.1038/nature14565, 2015.

Sjöström, J.K., Gyllencreutz, R., Cortizas, A.M., Nylund, A., Piilo, S.R., Schenk, F., McKeown, M., Ryberg, E.E. and Kylander, M.E., 2024. Holocene storminess dynamics

in northwestern Ireland: Shifts in storm duration and frequency between the mid-and late Holocene. *Quaternary Science Reviews*, 337, p.108803. <https://doi.org/10.1016/j.quascirev.2024.108803>

Stewart, H., Bradwell, T., Bullard, J., Davies, S.J., Golledge, N. and McCulloch, R.D., 2017. 8000 years of North Atlantic storminess reconstructed from a Scottish peat record: implications for Holocene atmospheric circulation patterns in Western Europe. *Journal of Quaternary Science*, 32(8), pp.1075-1084. <https://doi.org/10.1002/jqs.2983>

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D. and Frank, D.C., 2009. Persistent positive North Atlantic Oscillation mode dominated the medieval climate anomaly. *science*, 324(5923), pp.78-80. <https://doi.org/10.1126/science.1166349>

## Review 2

### General Comments

The overall impression of the manuscript is very good. It provides valuable additional insights for climate studies, and particularly for research on storminess. The authors assess several methodological approaches for identifying storm signatures, which is an important contribution. The paper is well written, and the number of references is both impressive and up to date.

My main suggestion would be to consider dividing the paper into two separate manuscripts. There appears to be sufficient material to support this: one paper could focus on the methodological aspects, while the other could concentrate on the climatological results. This is, of course, only a suggestion rather than a requirement. So, the decision is up to you.

Thank you for your assessment of our manuscript. We prefer to keep the manuscript as a single one rather than splitting into two, however there is certainly potential to explore in more detail the methods and results (particularly the documentary archive) in future papers.

### Specific Comments

- **In the *Introduction*, the overview of volcanic influences could benefit from some geographical context. It would be helpful to indicate where the volcanoes that influenced the NAO or the North Atlantic jet stream were located. Does the location of the eruptions play a role in the observed effects?**

In general, the literature has credited major tropical eruptions as having the biggest impact on storminess, principally through an enhanced winter westerly airflow that arises from a meridional (north-south) asymmetry in stratospheric temperatures. In this, the fact that sulphate aerosols can absorb outgoing longwave terrestrial radiation causes a stratospheric heating that is initially confined to lower latitudes with tropical eruptions. This effect is inherently transient as the sulphate aerosols spread slowly northward but has been credited with inducing a positive NAO-like pattern with warmer and potentially windier winters in the first post-eruption winter season (e.g., Robock, 2000). The regularity or even existence of this mechanism is, however, contested (e.g., Tejedor et al., 2024), but other mechanisms have been recently proposed by which extratropical Northern Hemispheric eruptions might also induce enhanced westerly flow via a local stratospheric top-down mechanism (Guðlaugsdóttir et al., 2025). We have added this to the main text and provide coverage of these mechanisms in Sections 4.5 and 5.3, adding a more explicit pointer in the Introduction to this later coverage.

- **In the *Study Area* section, you mention that Bullsmouth Bog has a small area. Please specify its approximate size.**

Thank you, we have added that its area is  $\sim 0.2\text{km}^2$ .

- **What is the distance between the coring point and the coastline? Has this distance changed over time? If so, could this have influenced the storminess signal? Similarly, could regional geomorphological changes or variations in the sand source have influenced the storm indicators?**

We have addressed the first question here by adding the distances between the bog and beaches to the study area. The original manuscript discussed how changes in sea level potentially caused the lower peaks in the IR in the early part of the record when the sea level was 7m below present at 7 ka BP, however we have stated more explicitly now that the lower sea level may have resulted in greater distance from the coastal beaches and sand dunes in the older part of the record, which may have influenced the storm signal (line 562).

In discussion section 5.2 we discuss the possible influence from changes in the sand dunes and sand source, and we have now added a sentence to acknowledge that there are no studies on the timing of sand dune formation or geomorphological changes at the dunes of Keel Beach, Achill island, with which to explore this (line 563). Changes in sand dune vegetation and instability are also discussed in section 5.3, which is related to this point (line 620). We have added text to the conclusion highlighting the uncertainty regarding coastline/sand source change.

- **In the section 4.5. *Documentary Evidence*, the first paragraph seems more appropriate for the *Materials and Methods* section. Additionally, volcanism data have not been discussed in the *Materials and Methods* so far.**

We have moved the first paragraph to the materials and methods section 4.6 (previously 4.5) and edited it so that it summarises the documentary data and SEA analysis. This includes reference to the Sigl et al. (2015) dataset that is the volcanism record used in the SEA analysis.

- **Caption of Figure 7: “... c) *Reconstructions of storminess from the Bullsmouth Bog record (Black – this study) ...*”. Could you please clarify what “black” refers to? All graphs (a–d) appear to be black.**

Apologies for the confusion; we specified black here because in this subplot C the storm records are shown by the black line (Bullsmouth Bog record) and the blue shaded bars show the regional storminess compilation from the previous figure. This is confusing we agree, so the caption has been edited to remove the word black. We refer to the blue shaded bars now later in the caption.

- **“*The nearest meteorological station, Belmullet, 25 km north of Achill Island, shows that between 1981 and 2010 the mean annual temperature was 10.3°C (ranging from 6.3°C in January to 15°C in August),...*”. Could it be possible that, for example, during the LIA, the region experienced sea ice and snow cover on land, which might have influenced sand movement - niveo-aeolian movement?**

Thank you for raising this idea. It seems likely that enhanced snow and ice cover following eruptions may have allowed greater niveo-aeolian sand transport (Bjorck and Clemmensen,

2004; Vaasma et al., 2025). The documentary evidence for Ireland (Ludlow et al., 2013) supports the contention that greater snow and ice cover occurred in the winters following eruptions. We have added this to the discussion (line 641).

- **In the *Conclusion*, could you also mention something about the 7–4 ka and up to 2.8 ka periods?**

We have added a couple of sentences to the conclusion highlighting the low variability in the early record up until 4.5 ka BP and the possible causes (low sea level, forest cover) and also mentioned the storm events between 4.5 and 3 ka BP that are observed in the records from western Ireland but not elsewhere.

### Notes on the References

- **Lines 41 and 46: *Bronnimann* should be *Brönnimann*.** Thank you, this is changed.
- **The citation (*DAHG, 2013*) could not be found in the list of *References*.**

Thank you. We had this as 'Department of Arts, Heritage and the Gaeltacht (DAHG)' in the references. We have now put DAHG at the start and the full name in brackets.

- ***Cole-Dai et al., 2021* – should this be 2024?** Sorry, we had the wrong citation listed. We have replaced the citation in the bibliography with Cole-Dai et al. (2021) published in *Journal of Geophysical Research: Atmospheres*.
- ***Gao et al., 2020* – should this be 2021?** Yes, changed now thank you.
- ***Hansom and Hall, 2007* – should this be 2009?** Yes, changed now thank you.
- ***Payne and Egan, 2017* – should this be 2019?** Yes, changed now thank you.
- **Line 152: the citation (*Met Éireann, 2020*) could not be found in the list of *References*.** This has been added now thank you.
- ***McCarthy, D. and Breen, A.: An Evaluation of Astronomical Observations in the Irish Annals, *Vistas in Astronomy*, 41, 117–138* — the publication year is missing.** Added, thank you.
- ***Zhong, Y., Miller, G. H., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Schneider, D. P., and Geirsdottir, A. (2011): Centennial-scale climate change from decadal-paced explosive volcanism: a coupled sea ice–ocean mechanism, *Climate Dynamics*, 37, 2373–2387, doi:10.1007/s00382-010-0967-z, 2011* — should this be 2010?** It was published on 31<sup>st</sup> Dec 2010, but the *Climate Dynamics* journal website says to cite using the year 2011. We have kept the year to 2011 and changed the reference in the text to this.

### Additional References

**Additionally, here are some references that also address aspects of storminess research:** Thank you for pointing to these additional references.

Vaasma, T.; Vandel, E.; Sugita, S.; Tõnisson, H.; Suursaar, Ü.; Kont, A.; Vilumaa, K. (2025). Storminess reconstruction in the northeastern Baltic Sea region over the past 7600 years based on aeolian sand influx into coastal bogs. *The Holocene*, 35 (1), 61–74. DOI: 10.1177/09596836241285783. We have referenced this manuscript now in our discussion of whether niveo-aeolian transport contributed to peaks in storminess following eruptions and in the introduction (line 641).

**Paper from Poland: Leszczyńska et al, 2025: A review of storms and marine coastal flooding in the Baltic Sea – Insights from instrumental, historical and sedimentary record.** We have referenced this paper as an example of where compilations of multiple sites and records can demonstrate greater certainty (line 565).

Vandel, E; Vaasma, T; Sugita, S; Tõnisson, H; Jaagus, J; Vilumaa, K; Anderson, A; Kont, A (2019). Reconstruction of past storminess: Evaluation of an indicator approach using aeolian mineral grains buried in peat deposits, Estonia. *Quaternary Science Reviews*, 218, 215–227. DOI: 10.1016/j.quascirev.2019.06.026. We have added Vandel et al. (2019) as valuable evidence that there is a good correlation between aeolian sand deposits and instrumental storm records (line 211). This has been added to the methods and the paper also referenced in the introduction. We have also referenced this paper as an example of where compilations of multiple sites and records can demonstrate greater certainty.

#### References Cited in Responses

Björck, S. and Clemmensen, L.B., 2004. Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia?. *The Holocene*, 14(5), pp.677-688. <https://doi.org/10.1191/0959683604hl746rp>

Guðlaugsdóttir, H., Peings, Y., Zanchettin, D., and Magnusdóttir, G.: Stratospheric circulation response to large Northern Hemisphere high-latitude volcanic eruptions in a global climate model, *Atmos. Chem. Phys.*, 25, 3961–3980, <https://doi.org/10.5194/acp-25-3961-2025>, 2025.

Leszczyńska, K., Alexanderson, H., Clemmensen, L., Giza, A., Lorenz, S., Moskalewicz, D., Oliński, P., Paprotny, D., Rosentau, A., Rutgersson, A. and Stattegger, K., 2025. A review of storms and marine coastal flooding in the Baltic Sea—Insights from instrumental, historical and sedimentary record. *Earth-Science Reviews*, p.105137. <https://doi.org/10.1016/j.earscirev.2025.105137>

Ludlow, F., Stine, A.R., Leahy, P., Murphy, E., Mayewski, P.A., Taylor, D., Killen, J., Baillie, M.G., Hennessy, M. and Kiely, G., 2013. Medieval Irish chronicles reveal persistent volcanic forcing of severe winter cold events, 431–1649 CE. *Environmental Research Letters*, 8(2), p.024035. DOI 10.1088/1748-9326/8/2/024035

Robock, A.: Volcanic eruptions and climate, *Reviews of Geophysics*, 38, 191-219, doi:10.1029/1998RG000054, 2000.

Sigl, M., Winstrup, M., McConnell, J.R., Welten, K.C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D. and Fischer, H., 2015. Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature*, 523(7562), pp.543-549. <https://doi.org/10.1038/nature14565>

Tejedor, E., Polvani, L. M., Steiger, N. J., Vuille, M. and Smerdon, J. E.: No evidence of winter warming in Eurasia following large, low-latitude volcanic eruptions during the last millennium, *J. Climate*, 37, 5653–5673, <https://doi.org/10.1175/JCLI-D-23-0625.1>, 2024.

Vaasma, T., Vandiel, E., Sugita, S., Tõnisson, H., Suursaar, Ü., Kont, A. and Vilumaa, K., 2025. Storminess reconstruction in the northeastern Baltic Sea region over the past 7600 years based on aeolian sand influx into coastal bogs. *The Holocene*, 35(1), pp.61-74. <https://doi.org/10.1177/09596836241285783>

Vandiel, E; Vaasma, T; Sugita, S; Tõnisson, H; Jaagus, J; Vilumaa, K; Anderson, A; Kont, A (2019). Reconstruction of past storminess: Evaluation of an indicator approach using aeolian mineral grains buried in peat deposits, Estonia. *Quaternary Science Reviews*, 218, 215–227. DOI: 10.1016/j.quascirev.2019.06.026