Response to both referees for NHESS-2020-345

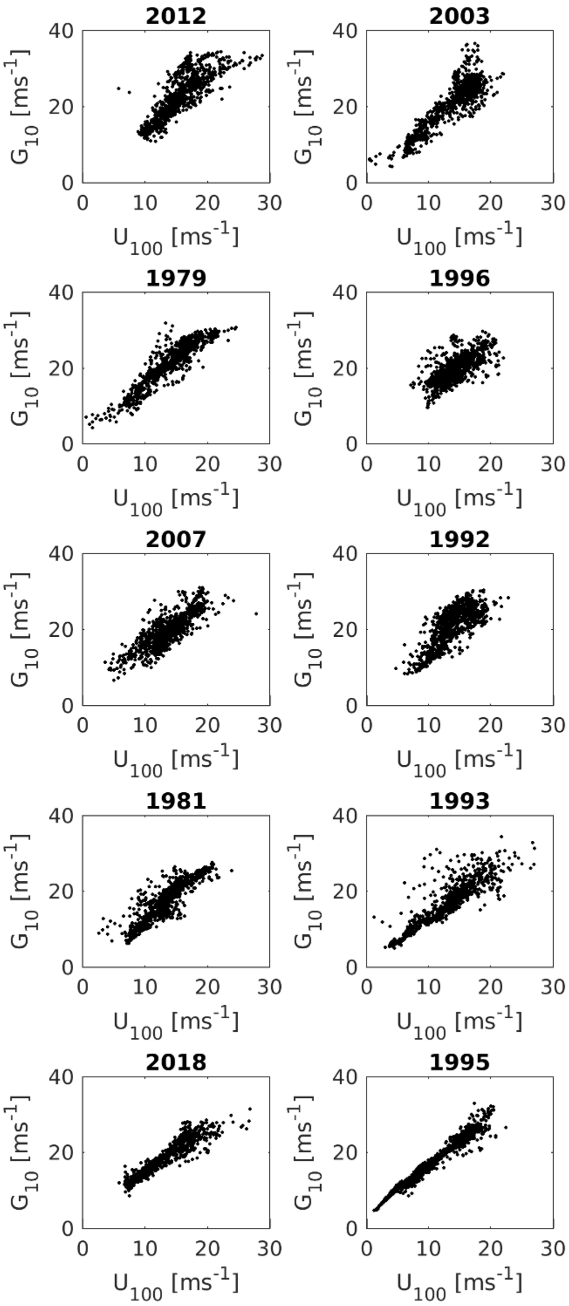
Intense windstorms in the Northeastern United States

Thank you both for your thoughtful comments on our work. Before going on to address your specific comments, we would like to address our use of (i) a wind speed threshold of the local 99.9th percentile (rather than 98%) and (ii) 100-m once-hourly sustained wind speeds rather than 10-m gusts. Regarding point (i) our research is seeking to identify truly exceptional windstorms. Use of a 98th percentile value is not very discriminatory (see details below). Regarding point (ii) while ERA5 like many reanalysis systems does generate wind gust estimates, when derived at a grid resolution of approximately. 30 by 30 km they are systematically negatively biased relative to observations. Further 10-m wind speeds are strongly dictated by the roughness lengths used in the reanalysis models. Thus, we feel it is appropriate to use variables that are likely to be more presentative and simulated with higher fidelity. We hope this clarifies our perspectives and elaborates on materials within the submitted document that discuss the latter point. Quoting from the original submission;' However, it is important to acknowledge that wind parameters from any model do not fully reflect all scales of flow variability (Skamarock, 2004) and underestimate extreme wind speeds (Larsén et al., 2012), particularly in areas with high orographic complexity and or varying surface roughness length. Here we use wind speeds at 100-m because flow at this height is less likely to be impacted by sub-grid scale heterogeneity in surface roughness length and uncertainties induced by unresolved sub-grid scale variability. Near-surface wind speeds are strongly coupled to wind speeds at 100-m (i.e., within the PBL) but wind speeds at 100-m are less strongly impacted by inaccuracies and/or uncertainty in surface roughness length (z_0) (Minola et al., 2020;Nelli et al., 2020). Applying an uncertainty of a factor of two to z_0 can lead to mean differences of up to 0.75 ms^{-1} for near-surface (40 to 150 m a.g.l.) wind speeds (Dörenkämper et al., 2020).'

In response to your comments regarding this matter, we have added new analysis of 10-m gusts and a comparison of our storm-ranking algorithm to one using a 98th percentile threshold. Related changes are as follows;

1) In section 2.1 we describe the data; 'Wind gusts at a nominal height of 10 m are generated as a post-processing product from the ERA5 reanalysis product. Wind gusts estimates are derived from the sustained wind speed at 10 m along with a term representing shear stress and a convective term (Molina et al. 2020). They are also presented herein to provide a link to previous research on European windstorms that has focus on wind gusts. The association between these wind gust estimates and sustained wind speeds at 100 m are also presented. '
2) Wind gust values at 10 m for each storm are now briefly summarized in Table 2 and described in the associated text. 'Maximum wind gusts at 10 m a.g.l. exceed the sustained wind speeds at 100 m a.g.l. at both the peak hour and over the entire windstorm. Maximum wind gusts from ERA5 for all windstorms are well above the U.S. National Weather Service 'damaging winds' threshold of 25.7 ms^{-1} 1 (Trapp et al., 2006) (Table 2). The spatial correlation coefficient between 100-m sustained wind speeds and wind gusts at 10 m at t_p is > 0.68 for all storms and > 0.8 for 8 out of the 10 storms, indicating that the 100-m sustained wind speeds analyzed herein are strongly related to near-ground wind gusts in the ERA5 reanalysis.
3) The high degree of association between 10-m wind gusts and 100-m sustained wind speeds is now made explicit (see above.).

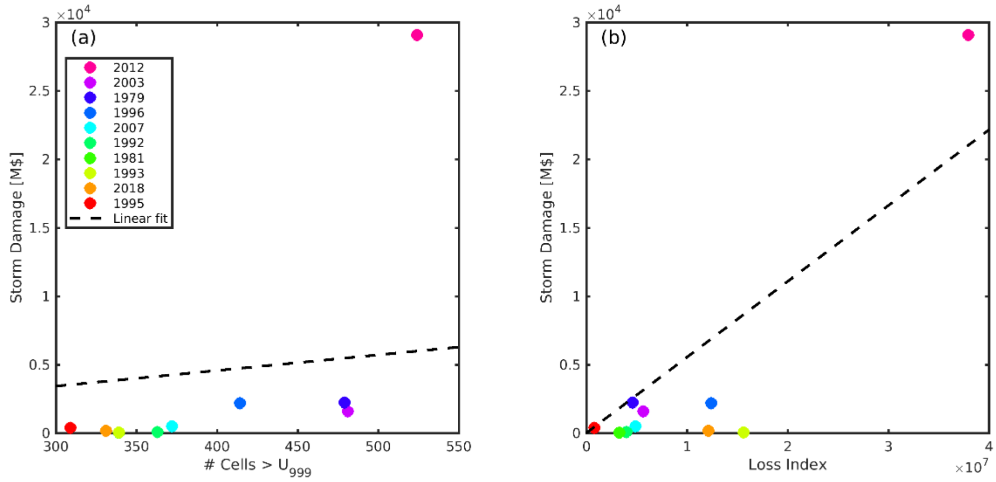
For the reviewers' interest (and that of any readers who have sought out this document) in the following figure we show the relationship of 10-m gusts to 100-m hourly winds at the peak time of each windstorm.



While retaining the 99.9^{th} percentile wind speed threshold central to this work, we have presented information about use a the 98^{th} percentile. See table 2 and the related text; ‘In previous work, the local 98^{th} percentile value has been used to identify windstorms as it roughly corresponds to wind gusts at 10-m gusts that may cause property damage (Klawa and Ulbrich, 2003). Events with widespread exceedance of the 98^{th} percentile threshold are common within the 40 years of ERA5 output. 139 events have sustained wind speeds in excess of their local 98^{th} percentile in over half of all ERA5 grid cells over the Northeastern states. Herein, a higher threshold (99.9^{th} percentile) is used to distinguish ten extraordinary windstorms. All ten also appear on the list of storms chosen using a 98^{th} percentile threshold, with nine of the ten appearing in the top 50 (Table 2).’

At the reviewers request we have also included a Loss Index calculation based on Klawa and Ulbrich’s 2003 work. This is described in the methods section (2.7) and results are reported in section 3.4.

The following figure shows the relationship between storm damage and number of cells exceeding U_{999} and Loss Index. We have elected not to include this figure in the manuscript because it only confirms the fact the much of the variance in storm damage is not well represented by either metric. As with the figure above, we have included this figure in our response for the reviewers' interest and for any future readers who seek out this document.



A tracked-changes version of the manuscript is included at the end of this response.

Responses to specific comments below are in **bold.**

Anonymous Referee #1

Received and published: 7 January 2021

This study presents an identification of severe windstorms over northeastern North America. Objective cyclone identification and wind speed exceedance methods are used to identify these phenomena and their dynamical features and impacts are put into the context of the wider climatology. The aims of the paper are good and I believe it could make an interesting publication that is appropriate for the journal and would provide a good piece of analysis to partner the numerous similar studies over Europe. However, I believe many of the methods used are inconsistent with these other studies and are not sufficiently justified or argued for in the text. All the methods used are slightly different from those established in the literature, such as tracking at 700 hPa instead of 850 hPa, analysing wind gusts at 100 metres instead of 10 metres, and using an extremely high exceedance threshold of the 99.9th percentile instead of the more commonly used 98th percentile. I would like to see some evidence for the choice of the methods. Furthermore, the introduction and framing of the paper (especially the first half) feels very incoherent and I believe requires significant re-structuring. In addition, the presentation of the figures feels clumsy and very difficult to interpret with numerous similarly styled lines and colours overlayed on similarly shaded fields, which needs rectifying. My full points can be found below. I therefore recommend that this study requires major corrections.

Please see our comments above regarding use of 10 m v 100 m and sustained wind speeds v wind gusts. Additionally, the reviewer mentions use of RV at 850 hPa in prior research over northern Europe for cyclone tracking. This level is not appropriate for use in North America because of the high terrain elevation that means the 850 hPa is frequently below the land surface. It is deemed preferable by the authors to use a level that is more typically realized in the atmosphere. Finally, we regret you had difficulty reading the figures, and have modified some as appropriate, and enlarged those that we could, to aid clarity.

Individual points

1. L43 – I feel the reference here to Fig. 1a should illustrate the two different types of cyclone tracks you are describing. As the figure is for wind gusts it in no way illustrates the differences in the genesis location

The Purpose of Figure 1a Is to explicitly communicate the locations of the Northeast states to readers less familiar with U.S. geography. The state names and abbreviations are used throughout the paper. We believe that changing the scale of this map to include cyclone genesis locations would make the state borders and labels difficult to interpret. The classification of storm tracks into; Alberta Clippers, Colorado Lows and tropical cyclones is consistent with past cyclone climatologies and is described at length in the introduction (lines 34 to 54)

2. L47-49. How is the influence of post-tropical cyclones in the USA consistent with Europe? Are less than 1% of cyclones also post-tropical in this region? Perhaps it is best to remove the 1% statement.

We regret the ack of clarity and have re-worded to; 'Research on windstorm risk in Europe found that although less than 1% of cyclones that impact Northern Europe are post tropical cyclones, they tend to be associated with higher 10-m wind speeds (Sainsbury et al., 2020). Tropical cyclones are a major driver of extreme wind speeds along the U.S. eastern seaboard (Barthelmie et al. 2021) and events such as Hurricane Sandy have been associated with large geophysical hazards in the Northeast (Halverson and Rabenhorst, 2013;Lackmann, 2015).'

3. L61-63. Can a trend line or some evidence of the trend from the data in Fig. 1b also be included/quoted? Due to the large inter-annual variability of the data it is hard to tell from the figure you have presented that there is a positive trend. Furthermore, you quote the 98th percentile in the text (perhaps this refers to the results of Bronnimann et al., 2012), yet the figure in question (I assume Fig. 1b?) uses number of grid points exceeding the 99.9th percentile of U. Please clarify these differences,

or make the figure consistent with the text.

We believe the reviewer was confused by the reference to Figure 1 and Table 1 that emphasized/described the GEOGRAPHICAL region. We have removed those to avoid the possibility of confusion.

4. Section 1.3. From your introduction there is limited evidence of where this study fits within the established research and scientific literature. I think it could be framed better to give a clear narrative as to where the gaps in the literature are and how this study addresses those gaps.

We are very explicit in our objectives and links to past research have been clarified and extended in the revised version of the manuscript.

5. L123-124. I feel this statement is incorrect for the last 10-15 years with the introduction of more advanced and homogenous reanalysis products. Please make it clearer how ERA5 is beneficial compared to previous generation products such as ERA-Interim, etc.

We believe the real advantages of ERA5 are those we state in section 2.1. Assimilation of a massive suite of data; 'The ERA5 reanalysis is derived using an unprecedented suite of assimilated in situ and remote sensing observations (Hersbach et al., 2020). '. Its relatively high demonstrable skill for wind speeds; 'It exhibits relatively high fidelity for wind speeds (Kalverla et al., 2020;Olauson, 2018;Kalverla et al., 2019;Pryor et al., 2020;Jourdier, 2020;Ramon et al., 2019)'. AND the relatively high resolution; 'a spatial resolution of 0.25°×0.25°'. This latter point – as the reviewer will know, compares very favorably with past global reanalysis products. Eg.; MERRA-2; 0.625°×0.5°, ERA-Interim (approximately 80 km).

6. I am a little confused as to why the 100 metre level is being used throughout this study as you are specifically interested in damaging windstorms. You have justified this in the text, however I feel it may be better to be consistent with previous studies, which generally use the 10 metre level. Does using 100 metres lead to drastically different results to using 10 metres? Furthermore, as you are using near-surface ground observations as a validation, surely it would make sense to also use the 10-metre product from ERA5 as there could be significant differences in the 100m and 10m distributions.

Please see above.

7. As above, doing the tracking at 700 hPa instead of 850 hPa is also confusing to me. Using the Hodges method tracking is mostly done at 850 hPa. Are there specific issues with representing the flow in the orographic regions? Are all cyclones identified at 700 hPa the same as those that would be identified at 850 hPa?

Please see above. In the text we note this justification briefly where we state; 'RV values at 700 hPa are used rather than 850 hPa as in the XWS European analysis due to the presence of high elevation areas in U.S. cyclone source regions.'

8. I feel the methodology section can be condensed significantly. You introduce the tracking on line 148 and then describe it in detail, several pages later. It feels very incoherent and should be re-structured for conciseness.

We briefly introduce use of the ERA5 data for the cyclone tracking in section 2.1 and then present the methodology in section 2.5. We believe that is appropriate, but have edited the Data and methods section for brevity.

9. L210 – you use the 99.9th percentile, what is the justification for this? As you mentioned in the text your method is similar to numerous other storm severity assessments, however most use the 98th percentile. Due to the relative short extent of data from ERA5, are there not chances that the 99.9th percentile is exceptionally skewed by very large events?

This is an important point. We have amended the introduction to read; 'This research is a part of the HyperFACETS project which uses a storyline-based analysis framework. Storylines are "physically self-consistent unfolding of past events, or of plausible future events or pathways" (Shepherd et al., 2018).

They provide a method of framing a research inquiry in terms of three elements: A geographic region, a historically important or notable event, and a set of process drivers for that event.' To clarify we are indeed seeking to identify and characterize truly exceptional events.

10. L223 – is it possible that by using such a high threshold some spatially large events (p98<U<p99.9) are missed and events with a very small area of U>99.9 are counted instead? It may be that in some of these cases could the large, yet slightly lower intensity events have larger impacts than small scale high-wind events.

This is an important point. Use of any threshold inherently dictates the type of event that will be identified. As shown in Table 1 none of our events are confined to very small areas. Indeed, all of them cover at least a third of land grid cells. Nevertheless, we have added a discussion regarding the link between our events and their ranking using a different threshold (p98).

11. L225 – a 14 day restriction seems rather large. Have you tested this criteria to see if any high impact storms are excluded as a result of this threshold? Several studies have shown that more intense cyclones are more likely to cluster (e.g. Mailier et al., 2006), therefore this could be removing events from your set.

The 14-day exclusion window is used to ensure that all storms on the top ten list are independent of one another, and this window is reduced to two days when the serial correlation of storms is considered. There is one storm which would have been included in the top ten, were it not for this 14-day window. This is noted in the new text:

"A larger sample of 50 windstorms was also drawn from the 40-year time series to examine the serial dependence. This analysis reduces the 14-day exclusion window used in the identification of the top 10 windstorms to a 2-day window. One windstorm (on January 19th, 1996) is excluded by use of a 14-day separation window from the list of the top ten storms but is included if a 2-day exclusion period is used. It would have been ranked number ten."

12. L235 – further references are needed here such as Vitolo et al. (2009), Mailier et al. (2006), Pinto et al. (2014).

We understand there have been other articles published on serial clustering of windstorms in Europe. Given our work is focused on North America and we already have 109 references, we think it is sufficient to refer to one of those studies.

13. L265 – do you have specific requirements for each of these cyclone classes (i.e. genesis location). If so please state this in the text.

We regret this lack of clarity. We have added the following text; 'A cyclone is identified as an Alberta Clipper (AC) if the cyclone track originates over the North American continent north of 40°N, as a Colorado low (CL) if the track originates over the North American continent south of 40°N, and as a decaying tropical cyclone (TC) if the track originates south of 30°N over a water grid cell. The term nor'easters (NE) is applied if the cyclone retrogrades towards the coastline after moving offshore and/or is associated with strong northeasterly flow over the Northeastern states.'

14. Fig 2. I find the layout and organisation of this figure very messy. The legends should be moved outside of the panel boundaries and all text on the panels be made clearer as it is very hard to decipher any of the information.

We regret you had difficulty reading this figure. We have made it much clearer by moving the legends, removing damage estimates (since they are in the table) and increasing the size of the figure.

15. L317 – reference should be outside of brackets.

Typographic error corrected.

16. L348-349 – as discussed above. If your systems traverse your region of interest in ~72 hours, why the 14 day separation? Please clarify this.

We did not know before we did the analysis how long any individual storm would take to traverse the region. We wanted to set a sufficiently large window to ensure independence.

17. Fig 4 and throughout – is it worth referring to each storm by its ranking in the text and figures. I find it hard to keep track of which year is which through the text, this may be a simple way to avoid this.

We think that using the consistent color scale is effective in this regard but have added some information about ranking to the text also.

18. L396-406 – would the authors be able to illustrate these results in some way instead of just giving a description. Furthermore, commonly dispersion is calculated as counts per month, or counts per winter season, and not counts per calendar year. Vitolo et al. (2009) Fig. 15 demonstrates how dispersion (and surrounding uncertainty) commonly increases with aggregation period and as these storms you are interested in are only features of approx. 6 months of the year is it likely that this dispersion value is representative?

Possibly. Given the D value is small we prefer not to expand the discussion greatly.

19. Figs 6 and 7 – legibility of these figures is very difficult. Often green lines are plotted above an area of green (especially figure 7a) and also with text on the figures it makes it very difficult to distinguish and correctly identify features. I would recommend a redesign of these figures to aid legibility.

Thank you, the background colors in these figures (now combined into Figure 6) have been changed to reduce confusion, and the track outline color has been changed from white to black. The overall size of the figure has also been increased.

20. Fig 7b and table 3 – are the mslp units in hPa the anomaly from the background field? This needs to be made clearer as the magnitude of the values are confusing.

We have clarified by adding; 'These are anomalies identified in the filtered fields. RV cyclone intensities are shown in units of 10^{-5} s^{-1}, and MSLP intensity estimates are given in hPa scaled by -1. These anomalies are relative to removal of the large-scale background for $n \leq 5$, where n is the total wavenumber in the spherical harmonic representation of the field.'

21. L412 – again, do you have requirements for these cyclone classes. It would be useful to define these earlier in the text instead of just approximating by eye if they are one class or the other. This is also applicable for L416 where you state a cyclone transitions to the NE class.

Please see response above.

22. L464-465 – please display this information somewhere in either a figure or table, with it being stated as is it feels unjustified. Also you state how all storms have RP >50 years in some location, is this evident in figure 8 as the colorbar does not extend beyond 50? Perhaps to make this clearer the authors should extend the colorbar beyond 50 years and then highlight the regions which exceed 50 years.

The extent of the color scale in all panels of Figure 8 (Now Figure 7) has been increased to 60 years.

23. Figure 8 and table 3 – what is the uncertainty on the return period calculations? As with ERA5 there is only 40 years of data the uncertainty must be very large for the 100 year event. Please clarify and quantify this in the text and figures.

Quite. We have added this comment to methods; 'Uncertainty intervals on the return period wind speeds are assigned using the 95% confidence intervals on the α and β parameters as derived using maximum likelihood estimation.' And have added results to Table 3.

24. All figures – the visualisation and colour clashes at times makes for figures that are very

hard to interpret. Fig. 8 the red lines of states over the map is almost impossible to clearly distinguish. Fig 6 and 7 the track lines an intensity circles are hard to see as they overlap and also clash with the background colours. Figure 2 has legends overlapping figure space and also text on figures that cannot be read. I feel a redesign of these figures is required to accurately present the authors results.

All figures have been made larger to aid visibility. The red lines in Figure 8 (now Figure 7) have been changed to white to reduce visual clutter. Background colors in Figures 6 and 7 (now combined into Figure 6), have been changed to make the tracks, track labels, and intensity markers much more legible.

25. The storm severity metrics (following Klawa and Ulbrich, 2003) are introduced but in no way used in the analysis and I feel could be a strong contribution to the results. Performing an SSI-like calculation to compare ERA5 ranking to actual ranking would be a useful addition to the analysis. It would be good to compare the U_999 spatial extent and maximum wind speed to this storm loss metric.

At the reviewers request we have added a Loss Index based on their work in Europe (introduced in section 2.7) and results described in section 3.4. Our results suggest that for these ten windstorms the Loss Index is not very highly predictive of NOAA storm damages.

References

Mailier, P. J., Stephenson, D. B., Ferro, C. A., & Hodges, K. I. (2006). Serial clustering of extratropical cyclones. Monthly weather review, 134(8), 2224-2240.

Pinto, J. G., Gómara, I., Masato, G., Dacre, H. F., Woollings, T., & Caballero, R. (2014). LargeâĂ Řscale dynamics associated with clustering of extratropical cyclones affecting Western Europe. Journal of Geophysical Research: Atmospheres, 119(24), 13-704.

Vitolo, R., Stephenson, D. B., Cook, I. M., & Mitchell-Wallace, K. (2009). Serial cluster- ing of intense European storms. Meteorologische Zeitschrift, 18(4), 411-424.

Anonymous Referee #2

Received and published: 15 January 2021

Review of “Windstorms in the Northeastern United States” by Frederick W. Letson, Rebecca J. Barthelmie, Kevin I. Hodges and Sara C. Pryor

The paper presents an analysis of the 10 largest windstorms over the northeastern United States during the past four decades. It combines metrics of extreme winds and precipitation based on both reanalyses and observations with tracks of the associated extratropical cyclones based on both pressure and vorticity. The time evolution of reanalysis and observational data qualitatively agrees during the storm events. The storms show typical tracks for the region but intensity about one magnitude higher than average. Several storms are associated with extreme damages over 1B$ and their winds show long return periods above one century locally.

The regional focus on the northeastern United States complements earlier windstorm studies that focus on northwestern Europe mostly. In that sense, the paper is an important contribution to the windstorm community. However, it suffers from several short- comings that limit its actual impact. The paper tends to cover too many topics without a clear focus and to combine too many approaches applied in an unusual way. It would benefit from a well-defined scope, standard methods taken from the literature and a better structure altogether. General and specific comments are listed below to help improve the paper quality.

GENERAL COMMENTS

I. The scope of the paper is vague: it appears to be the 10 most intense (or largest?) windstorms over the 40 year period 1979–2018 but this is not clearly stated or motivated. Ten is not enough for a catalog and not significant to represent severe storms but likely too much for detailed case studies. The authors somehow need to choose between increasing the sample and focusing on a few particular storms.

Our work is being conducted within a project that centers on development and use of storylines. As our modified draft now reads; ‘This research is a part of the HyperFACETS project which uses a storyline-based analysis framework. Storylines are “physically self-consistent unfolding of past events, or of plausible future events or pathways” (Shepherd et al., 2018). They provide a method of framing a research inquiry in terms of three elements: A geographic region, a historically important or notable event, and a set of process drivers for that event.’
We hope this rewording helps to clarify. For the purposes of clarifying our purpose to the reviewer we note use of storylines facilitates interactions with stakeholders (i.e. they likely remember these extraordinary events) and also enables future work – e.g. using pseudo-global warming simulations to examine how such events might evolve in the future.

II. The methods are comprehensive (4 pages of description) but uncommon and not sufficiently explained or motivated: 100 m rather than 10 m winds, 99.9th rather than 98th percentile, intensity defined as instantaneous spatial extent of extreme wind rather than the footprint of, e.g., cubed winds above some threshold. This may result in the obtained ranking of storms not matching their damage.

Please see response above. We totally understand the reviewers (and editor) have conducted previous research over northern Europe that used a different methodology but feel confident ours is ‘fit for purpose’ for example it does identify windstorms that are present in the memories of our stakeholders.

III. Analyzing compound events is certainly meaningful but throughout the paper it is unclear whether the damages associated with the 10 selected storms are due to wind, precipitation, or both. This is somehow linked to the comment above, which applies to precipitation metrics as well.

We completely concur. In our new section 3.4 (added at the request of reviewer 1) we discuss this in more detail.

SPECIFIC COMMENTS

l. 1 The title should be more specific, e.g., referring to the most severe windstorms in the region

We have modified the title to be; Intense windstorms in the Northeastern United States

l. 14–15 "Alberta Clippers", "Colorado Lows" and "Nor'easters" sound too specific for the abstract.

We think linking to the cyclone responsible for the windstorms is useful so, with apologies, invoke authors privilege.

l. 19 Why "those windstorms that occurred after the year 2000" only? What about the others?

The National Weather Service ASOS network of meteorological stations was subject to a series of notable upgrades that were concluded in 1999 (e.g. installation of sonic anemometers). Thus, verification of ERA5 winds and precipitation are most robust after the year 2000.

l. 28 In the midlatitudes?

Quite possibly, but as we exclusively cite studies from north America and Europe, we feel it is better to be specific.

l. 36–37 The second part of the sentence appears unnecessary.

We believe that the reviewer is referring to 'It lies under a convergence zone of two prominent Northern Hemisphere cyclone tracks associated with cyclones that form or redevelop as a result of lee-cyclogenesis east of the Rocky Mountains' We express it in this way because some weak cyclones do traverse the Rocky Mountains and re-intensify.

l. 43 What is to be seen on Fig. 1a?

We are notifying readers who may not know where Lake Superior is that they can see it in Figure 1a.

l. 48–49 I do not fully understand the sentence and the cited paper describes Europe only

We regret you did not understand this sentence. We have re-worded to read; 'Research on windstorm risk in Europe found that although less than 1% of cyclones that impact Northern Europe are post tropical cyclones, they tend to be associated with higher 10-m wind speeds (Sainsbury et al., 2020). Tropical cyclones are a major driver of extreme wind speeds along the U.S. eastern seaboard (Barthelmie et al. 2021) and events such as Hurricane Sandy have been associated with large geophysical hazards in the Northeast (Halverson and Rabenhorst, 2013;Lackmann, 2015).'

l. 75–99 (Section 1.2) Many studies and numbers are cited but they lack focus on the topic of the paper: windstorms over the northeastern US

We regret you disagree with our choice of literature. Reviewer 1 suggested we add more literature about windstorms in Europe so it is indeed a difficult balance to strike. Compared to northern Europe there is little prior research on windstorms in the Northeast and we believe we have cited the majority of it.

l. 86 Repetition of l. 33–34

Quite correct, we apologize and have modified the text to avoid this duplication.

l. 101–102 This requires more details here and should somehow appear in the title and abstract

We believe the reviewer is asking us to add further details regarding 'This research is inspired by and is conceptually analogous to development of the XWS (eXtreme WindStorms) catalogue of storm tracks and wind-gust footprints for 50 of the most extreme European winter windstorms (Roberts et al., 2014).' We think that would not be appropriate to the abstract of our work.

l. 105 Most intense or severe?

Yes, this is an interesting point. We decided on intense because we cannot say they are the most severe given we use a relative threshold to absolute magnitude to define them.

l. 117–120 This paragraph is unclear and seems misplaced

We regret you felt so. We wanted to explain why we select extraordinary events.

l. 120 A description of each Section is expected here

It is not required by the journal style and checked five recently published articles in this journal (Nat. Hazards Earth Syst. Sci., 21, 587–605, Nat. Hazards Earth Syst. Sci., 21, 577–585, Nat. Hazards Earth Syst. Sci., 21, 607–627, Nat. Hazards Earth Syst. Sci., 21, 481–495, Nat. Hazards Earth Syst. Sci., 20, 3521–3549). Only one (Nat. Hazards Earth Syst. Sci., 21, 607–627) had such a statement so it appears to be at the discretion of the authors. We prefer not to include it as a matter of style since it uses space without conveying essential materials so for the time being, we do not include it.

l. 121ff (Section 2) The study period is unclear and inconsistent between subsections

We regret we are a little unclear on what the reviewer is referring to 1979-2018 is the time period we used exclusively to define the windstorms. Due to the presence of enhanced measurement system prior to 2000 the detailed evaluation is performed for a subset of the windstorms that occurred after 1999.

l. 123 Over long periods? It is not an issue for case studies

We have reworded to 'Attempts to identify and characterize windstorms from a geophysical perspective and contextualize them in a climatological context have historically been hampered by limited data availability and/or quality from geospatially inhomogeneous observing networks.'

l. 128–129 Hourly or every 20 minutes?

We have reworded to; 'Thus, herein we employ once-hourly wind speeds from the ERA5 reanalysis. The wind speeds are for a height of 100-m a.g.l. at the model time step of 20 minutes and a spatial resolution of 0.25°×0.25°.'

l. 137–144 The motivation for using winds at 100 m agl is not fully convincing and slightly repetitive; this height is used for wind power mainly and may not reflect the surface impact of windstorms

We have rewritten to; 'Here we use wind speeds at 100-m because flow at this height is less likely to be impacted by sub-grid scale heterogeneity in surface roughness length and uncertainties induced by unresolved sub-grid scale variability. Near-surface wind speeds are strongly coupled to wind speeds at 100-m (i.e. within the PBL) but wind speeds at 100-m are less strongly impacted by inaccuracies and/or uncertainty in surface roughness length (z_0) (Minola et al., 2020;Nelli et al., 2020). Applying an uncertainty of a factor of two to z_0 can lead to mean differences of up to 0.75 ms^{-1} for near-surface (40 to 150 m a.g.l.) wind speeds (Dörenkämper et al., 2020). Further, the scale of events we seek to characterize are regional rather than local scale, and are necessarily driven by winds aloft.'.

l. 145 Why 3-hourly rather than hourly as above?

Because its highly redundant. Most prior research has used 6-hourly (e.g XWS).

l. 155 Which ten storms?

Reworded to; 'Precipitation intensity and hydrometeor class from ERA5 are used to identify to what degree each of the ten windstorms identified here are compound events.'

l. 168–171 I agree but this does not support the use of 100-m winds from ERA5

That is right. We believe from a theoretical perspective using 100-m a.g.l. wind speeds IS preferable (see discussion above). However, we have to be pragmatic about data availability for evaluation.

l. 175 Twice "product(s)"

Apologies. Corrected

l. 179–183 The two sentences sound repetitive

Quite. Corrected to; 'In the current work, precipitation rates over the land areas of Northeastern states from RADAR and ASOS and ERA5 that are within 200 km of the 7 RADAR are averaged in time to match the hourly resolution of ERA5 precipitation and interpolated in space to the 0.25°×0.25° ERA5 grid. (Fig. 1c).'

l. 193–195 Verb missing?

No but the 'to' was extraneous. Apologies.

l. 194 What is the caveat here? The impact is indeed expected to depend on population density

Yes, our meaning was lost here. Reworded to; Damage and mortality estimates from this dataset provide an estimate of the impact of each windstorm, with the caveat that population density and hence the potential for loss of life and damage vary markedly between U.S. counties that also vary greatly in area (Fig. 1d).

l. 210–212 This approach reflects the severity rather than intensity (storm severity index)

See response above.

l. 212–215 The motivation for using the 99.9th percentile is unclear; although the approach is disputed by other authors, the choice of the 98th percentile arises from comparison with impact data in Klawa et Ulbrich (2003)

We hope we have clarified this matter in our other responses.

l. 215–217 Why?

We believe the reviewer is referring to; 'While lower percentile thresholds have been used in previous work (Walz et al., 2017;Klawa and Ulbrich, 2003), use of the 99.9th percentile wind speed value is appropriate for identifying the truly extraordinary conditions we seek to characterize and is robust when applied to very long datasets with very large sample sizes.'

We really do seek to identify truly exceptional conditions and as we now show use of 98th percentile is not very discriminating.

l. 225 14 days appear as a very long period to separate events

Possibly but we wanted to ensure that Nor'easters' were not double counted.

l. 227 if values are instantaneous then +/-48h makes 96h

Right but as we can see none last the full time window. The data used represent 97 hours.

l. 235–236 The focus on the 10 most intense (severe?) storms should be stated clearly and early in the paper

It is mentioned in the objectives explicitly.

l. 244 Reference without brackets

Corrected.

l. 259–266 Do the centroids of extreme ERA5 winds actually coincide with extratropical cyclones, in general and for the 10 most intense cases in particular?

No – this is shown in Figure 2.

l. 267–268 If I understand correctly the intensity is solely defined as the maximum instantaneous areal extent of extreme winds?

Yes.

l. 299–305 (Table 2) The windstorm category would be useful here (AC, CL, TC, NE)

We think it is more appropriate in Table 3.

l. 306–311 What are the actual most damaging extratropical cyclones for the considered period, and are they captured by the selection?

We think the reviewer is referring to Table 2. Certainly, we identify events that stand out in the damage record but in this region flooding linked to storm surge, and heavy precipitation also yield some high NOAA storm damage reports. Perhaps this is not what the reviewer is asking. We can say these ETC are exceptional relative to others with similar tracks see Figure 6 and associated text.

l. 313–320 An additional but crucial explanation may be that the used metric is simply not appropriate… In addition to different wind height and percentile, standard metrics are based on a footprint and of some function of winds (typically cubed) rather than on an instantaneous spatial extent.

Possibly – we have further elaborated on these matters in the new section 3.4 added at the request of the other reviewer.

l. 334–336 The strongest winds often occur to the south of the pressure center but not necessarily related with the cold front (see, e.g., the Hewson and Neu 2015 paper cited above)

Quite. We were too brief here we added an additional reference that talks more about some of the other mechanisms.

l. 340–345 (Figure 2) What is the reason for the large discrepancy between RV and MSLP tracks in some cases?

This response is combined with the response to the nest comment.

l. 350–351 It would be interesting to know why it is the case (1981 and 2003 storms)

We have added text to section 3.2 that addresses this matter; For most cyclones independent tracking of the center using MSLP and RV yields results that are highly consistent (Fig. 2). Nevertheless, some discrepancies exist in part due to the spectral field smoothing. Another possibility is if there is a strong background flow due to a strong pressure gradient, the vorticity can be offset relative to the pressure minimum (Sinclair, 1994).

l. 362 Hurricane Sandy was already introduced

Deleted.

l. 363–364 How many is “several” or “multiple” grid cells? 20 mm in 24 h is far from extreme. . .

Thank you. This text has been updated to read:

“Hurricane Sandy (windstorm during 2012) is associated with total 24-hour precipitation accumulation exceeding 100 mm in 0.5% of ERA5 grid cells, and exceeding 20 mm in 46% of ERA5 grid cells.”

l. 370 (Figure 4) The histograms do not emphasize extreme (i.e., potentially damaging) precipitation. And what is precipitation type 2?

Thunderstorm. We did not refer to it because it was not present for any of our windstorms, but have added it to the caption at your request.

l. 387–390 The underestimation of station observations may be explained by the spatial variability of precipitation but there is a factor ∼2 between ERA5 and radar estimates

Quite. It is very interesting. We do not have an explanation but note this recent publication; Cucchi, M., Weedon, G. P., Amici, A., Bellouin, N., Lange, S., Müller Schmied, H., ... & Buontempo, C. (2020). WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. *Earth System Science Data*, *12*(3), 2097-2120.

l. 396–406 There is a confusion between clustering on yearly and daily time scales; I would expect the analysis focuses on the latter to distinguish between consecutive storms

We regret the confusion and have reworded.

l. 407ff (Section 3.2) This Section generally lacks structure

We have reorganized this section.

l. 408–412 How are these cyclones selected? Based on thresholds in MSLP or vorticity? The total number of extratropical cyclones likely exceeds 10 tracks per year by far

Right. we tested different limits and found this to illustrate the tracks well. Note this figure has been redrafted at the request of Reviewer 1.

l. 410 What are transitory cyclones?

We are using it in the context of transient weather systems, i.e. moving. Not, for example, the thermal low that dominates the desert Southwest.

l. 416–419 This was already stated above.

We believe the reviewer may be referring to ; ‘Consistent with past research employing other reanalysis data sets (Ulbrich et al., 2009), results from application of the cyclone detection and tracking algorithm to ERA5 output also indicate the U.S. Northeast exhibits a high frequency of transitory cyclones (Fig. 6). Also in accord with expectations, the tracks followed by the windstorms are generally characteristic of those dominant cyclone tracks, and derive from a mixture of intense nor’easters (NE), Alberta Clippers (AC), deep Colorado lows (CL), and decaying tropical cyclones (TC) (Table 3, Fig. 6).‘ We think it is worth linking our work to past research and expectations since we have not yet describe the cyclone climatology.

l. 425–429 This belongs to the Introduction

We believe the reviewer MAY be referring to; ‘The Great Lakes are known to have a profound effect on passing cyclones during ice-free and generally unstable conditions that prevail during September to

November (Angel and Isard, 1997). Particularly during the early part of the cold-season, cyclones that cross the Great Lakes are frequently subject to acceleration and intensification via enhanced vertical heat flux and low-level moisture convergence due to the lake-land roughness contrast (Xiao et al. 2018). Cyclones such as Alberta Clippers that transit the Great Lakes during periods with substantial ice cover are subject to less alteration (Angel and Isard, 1997).' We concur and have moved this text.

l. 436 The impact of the 2018 (not 2017) windstorm may be due to precipitation rather than wind mostly

Thank you for catching that typo. Yes, it is possible. Please see the new section 3.4.

l. 436–447 The impact is already discussed above (e.g., l. 418–424) and in other sections. Please reorganize

Done.

l. 450–460 (Figures 6–7) Same question as l. 340–345 (Figure 2)

See response above.

l. 463ff (Section 3.3) I am lost in the numerous details and wonder what to learn from this additional section

We believe the reviewer is referring to the return periods analysis. They earlier asked do our analysis approach identify real extremes. We believe this section is crucial to answering yes!

l. 496–502 This belongs to the Introduction

We regret we are unsure what text the reviewer is referring to.

l. 503 It is the first mention of the "largest" windstorms

Quite- we regret this typo and have corrected it.

l. 518–520 I do not agree on the accord with damage estimates

We have reworded to; The statistically significant correlation between the ERA5 windstorm intensity estimates and independent damage estimates provides further confidence in the fidelity of the windstorm catalogue presented herein.

l. 530–533 This is not convincing

We wonder if the reviewer is referring to; 'These cyclones, however, exhibit considerably higher intensities (from both RV and MSLP perturbations) that are an order of magnitude higher than mean values sampled on those same tracks (Fig. 7). With the possible exception of Hurricane Sandy, these windstorms are largely differentiable from the cyclone climatology in terms of their intensification rather than the associated cyclone storm track.' We have reworded to; 'These cyclones, however, exhibit intensities (from both RV and MSLP perturbations) that are an order of magnitude higher than mean values sampled on those same tracks (Fig. 6). With the possible exception of Hurricane Sandy, these windstorms follow tracks that are not infrequent in the cyclone climatology.'

l. 560ff (References) Please . . . increase . . . spacing . . . between . . . lines

Done. Thank you.

~~Windstorms~~ Intense windstorms in the Northeastern United States

F. Letson[1], R. J. Barthelmie[2], K.I. Hodges[3] and S. C. Pryor[1]

[1]Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York, USA
[2]Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York, USA
[3]Environmental System Science Centre, University of Reading, Reading, United Kingdom

Correspondence to: F. Letson (fl368@cornell.edu), S.C. Pryor (sp2279@cornell.edu)

Abstract. Windstorms are a major natural hazard in many countries. ~~Windstorms~~ Intense windstorms during the last four decades in the U.S. Northeast are identified and characterized using the spatial extent of locally extreme wind speeds at 100 m height from the ERA5 reanalysis database. During all of the top 10 windstorms, wind speeds in excess of their local 99.9th percentile extend over at least one-third of land-based ERA5 grid cells in this high population density region of the U.S. Maximum sustained wind speeds at 100 m during these windstorms range from 26 to over 43 ms^{-1}, with wind speed return periods exceeding 6.5 to 106 years (considering the top 5% of grid cells during each storm). ~~The property~~Property damage associated with these storms, ~~(~~inflation adjusted to January 2020,~~)~~ ~~is~~ ranges from $24 million to over $29 billion. Two of these windstorms are linked to decaying tropical cyclones, three are Alberta Clippers and the remaining storms are Colorado Lows. Two of the ten re-intensified off the east coast leading to development of Nor'easters. These windstorms followed frequently observed cyclone tracks, but exhibit maximum intensities as measured using 700 hPa relative vorticity and mean sea level pressure that are five to ten times mean values for cyclones that followed similar tracks over this 40-year period. The time-evolution of wind speeds and concurrent precipitation for those windstorms that occurred after the year 2000 exhibit good agreement with in situ ground-based and remote sensing observations, plus storm damage reports, indicating that the ERA5 reanalysis data have a high degree of fidelity for large, damaging windstorms such as these. A larger pool of the top 50 largest windstorms exhibits evidence of serial clustering, but to a degree that is lower than comparable statistics from Europe.

1 Introduction

1.1 Hazardous wind phenomena

Hazardous wind phenomena span a range of scales from extra-tropical cyclones down to downburst and gust fronts associated with deep convection (Golden and Snow, 1991). Herein we focus on large-scale, long duration 'windstorms' associated with extratropical cyclones since they are likely to have the most profound societal impacts. These large-scale windstorms are a feature of the climate of North America and Europe and a major contributor to weather-related social vulnerability and insurance losses (Della-Marta et al., 2009;Feser et al., 2015;Hirsch et al., 2001;Changnon, 2009;Ulbrich et al., 2001;Haylock, 2011;Lukens et al., 2018;Marchigiani et al., 2013).

This analysis focusses on windstorms in the Northeastern region of the United States (U.S.) as defined in the National Climate Assessment (USGCRP, 2018) (Table 1, Fig. 1a). ~~Here we focus on the Northeastern U.S. states (Fig. 1a,~~

~~Table 1) because this region~~It experiences a relatively high frequency of damaging storms, in particular during the cold season (Hirsch et al., 2001), and exhibits relatively high exposure due to both the large number of (i) highly populated, high-density urban areas (Fig. 1d (SEDAC, 2020;U.S. Census Bureau, 2019)) and (ii) high-value (insured) assets. For example, New York state ranks tenth of fifty U.S. states in total direct economic losses related to natural hazards, with estimated losses of $12.54 billion in 2009$ between 1960 to 2009 (Gall et al., 2011).

~~This region~~The Northeastern states exhibit~~s~~ a very high prevalence of mid-latitude cyclone passages (Hodges et al., 2011;Ulbrich et al., 2009) and the associated extreme weather events (Bentley et al., 2019). ~~It~~ They lie~~s~~ under a convergence zone of two prominent Northern Hemisphere cyclone tracks associated with cyclones that form or redevelop as a result of lee-cyclogenesis east of the Rocky Mountains (Lareau and Horel, 2012). The first is associated with extra-tropical cyclones that have their genesis in the lee of Rocky Mountains within/close to the U.S. state of Colorado and typically track towards the northeast (Colorado Lows, CL) (Bierly and Harrington, 1995;Hobbs et al., 1996). The second is characterized by cyclones that have their genesis in the lee of Rocky Mountains in/close to the Canadian province of Alberta and track eastwards across the Great Lakes (Alberta Clippers, AC). Previous research has found that these cyclones generally move southeastward from the lee of the Canadian Rockies toward or just north of Lake Superior (Fig. 1a) before progressing eastward into southeastern Canada or the northeastern United States, with less than 10% of the cases in the climatology tracking south of the Great Lakes (Thomas and Martin, 2007). The Great Lakes are known to have a profound effect on passing cyclones during ice-free and generally unstable conditions that prevail during September to November (Angel and Isard, 1997). Particularly during the early part of the cold-season, cyclones that cross the Great Lakes are frequently subject to acceleration and intensification via enhanced vertical heat flux and low-level moisture convergence due to the lake-land roughness contrast (Xiao et al. 2018). Cyclones such as Alberta Clippers -that transit the Great Lakes during periods with substantial ice cover are subject to less alteration (Angel and Isard, 1997). The northeastern states are also impacted by decaying tropical cyclones (TC) that track north from the Gulf of Mexico or along the Atlantic coastline (Baldini et al., 2016;Varlas et al., 2019;Halverson and Rabenhorst, 2013). ~~Consistent with recent r~~Research on ~~the~~ windstorm risk in Europe ~~that~~ found that although less than 1% of cyclones that impact Northern Europe are post tropical cyclones, ~~these systems~~they tend to be associated with higher 10-m wind speeds (Sainsbury et al., 2020). Tropical cyclones are also a major driver of extreme wind speeds along the U.S. eastern seaboard (Barthelmie et al., 2021) and events~~,~~ such as Hurricane Sandy have been associated with large geophysical hazards in the U.S. Northeast (Halverson and Rabenhorst, 2013;Lackmann, 2015). This region also experiences episodic Nor'easters, extra-tropical cyclones that form or intensify off/along the U.S. east coast and exhibit either retrograde or northerly track resulting in a strong northeasterly flow over the Northeastern states (Hirsch et al., 2001;Zielinski, 2002).

Table 1. Summary of the states that comprise the Northeastern region as defined by the National Climate Assessment (USGCRP, 2018). State abbreviations and population from the 2010 U.S. Census are also given (U.S. Census Bureau, 2019).

Name	Abbreviation	2010 Population
United States	US	308,745,538
Northeastern Region	NE	64,443,443
Connecticut	CT	3,574,097
Delaware	DE	897,934
District of Columbia	DC	601,723
Maine	ME	1,328,361
Maryland	MD	5,773,552
Massachusetts	MA	6,547,629
New Hampshire	NH	1,316,470
New Jersey	NJ	8,791,894
New York	NY	19,378,102
Pennsylvania	PA	12,702,379
Rhode Island	RI	1,052,567
Vermont	VT	625,741
West Virginia	WV	1,852,994

There is evidence that intense winter wind speeds in the mid-latitudes have increased since 1950, due in part to increased frequency of intense extra-tropical cyclones (Ma and Chang, 2017;Vose et al., 2014). While long-term trends such as this from reanalysis products are subject to the effects of changing data assimilation (Bloomfield et al., 2018;Befort et al., 2016;Bengtsson et al., 2004), the 56 member twentieth century reanalysis exhibits a positive trend in the 98th percentile wind speed over parts of the U.S. including the Northeastern states that are the focus of the current research (Brönnimann et al., 2012) ~~(Fig. 1, Table 1)~~.

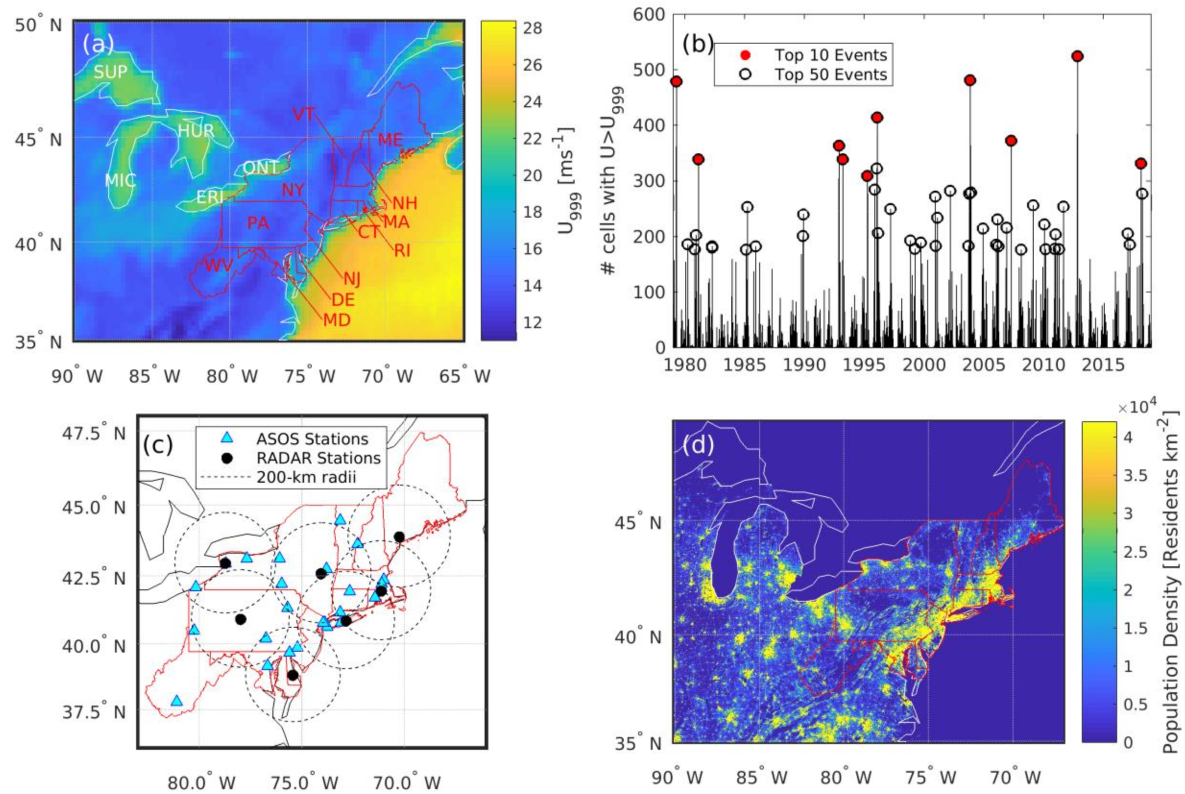


Figure 1. (a) 99.9th percentile wind speed (U_{999}) from ERA5 for each grid cell in the Northeastern U.S. derived using hourly wind speeds at 100 m a.g.l. during 1979-2018. Borders of the 12 Northeastern states are shown in red. The Great Lakes are each labelled in white, with the first three letters of their names: Superior (SUP), Michigan (MIC), Huron (HUR), Erie (ERI) and Ontario (ONT). (b) Time series of the number of ERA5 grid cells over the Northeastern states that exceed their local U_{999} value (out of 924 cells). The 50 largest-magnitude events are circled in black, and the top ten events are marked in red. (c) Locations of the 24 ASOS stations and 7 RADAR stations used for validation of ERA5 wind speed and precipitation values. The dotted circles show the area with 200-km radius from each RADAR station (d) Population density of the Northeast at a spatial resolution of 30 arc-seconds (~1 km; data from the 2010 U.S. Census available from the Socioeconomic Data and Applications Center (SEDAC, 2020)).

1.2 Socioeconomic consequences of windstorms

Economic losses associated with atmospheric hazards are substantial. Data from Munich Re indicate that annual 'weather related' losses at the global scale in 1997-2006 were US \$45.1 billion (inflation adjusted to 2006 \$) (Bouwer et al., 2007). In 2013, globally aggregated losses due to natural hazards were estimated at US\$125 billion (Kreibich et al., 2014). Data from the contiguous U.S. indicate 168 "billion-dollar disaster events" linked to atmospheric phenomena during 1980-2013 (Smith and Matthews, 2015). In the U.S., three-quarters of total damages from natural hazards derive from hurricanes, flooding, and severe winter storms (including windstorms) (Gall et al., 2011). There is also evidence of a trend towards increasing economic impact from natural hazards within the U.S. even after adjusting for inflation. According to one report; 'Nationwide, annual losses rose from \$4.7 billion in the 1960s to \$6.7 billion in the 1970s, \$7.6 billion in the 1980s, \$14.8 billion in the 1990s, and \$23.6 billion in the 2000s' due to a combination of more frequent disasters, disasters of larger scale and changes in societal resilience (Gall et al., 2011). ~~Here we focus on the Northeastern U.S. states (Fig. 1a, Table 1) because this region experiences a relatively high frequency of damaging storms, in particular during the cold season (Hirsch et al., 2001), and exhibits relatively high~~

exposure due to both the large number of (i) highly populated, high-density urban areas (Fig. 1d (SEDAC, 2020;Census, 2019))) and (ii) high-value (insured) assets. For example, New York state ranks tenth of fifty U.S. states in total direct economic losses related to natural hazards, with estimated losses of $12.54 billion in 2009$ between 1960 to 2009 (Gall et al., 2011).

Windstorms present a hazard to the built environment, transportation, especially to aviation (Young and Kristensen, 1992), and multi-energy systems including the electric grid (Bao et al., 2020;Wanik et al., 2015). In 2016 the annual cost of grid disruptions within the U.S. were estimated to range from approximately $28 billion to $209 billion (Mills and Jones, 2016). Composite events characterized by the co-occurrence of ice accumulation and wind are particularly hazardous to the built environment, aviation and energy infrastructure (Sinh et al., 2016;Jeong et al., 2019). For example, in the 1998 Northeastern ice storm ice deposition combined with high winds led to the toppling of 1,000 transmission towers, loss of power to 5 million people, and 840,000 insurance claims valued at $1.2 billion (Mills and Jones, 2016). This work seeks to advance understanding of the character and causes of extreme windstorms in the Northeast.

1.3 Objectives of this research

This research is inspired by and is conceptually analogous to development of the XWS (eXtreme WindStorms) catalogue of storm tracks and wind-gust footprints for 50 of the most extreme European winter windstorms (Roberts et al., 2014). Specific goals of the research reported herein are to:

1) Present a new method for identifying and physically characterizing severe windstorms. This method is applied to forty-years of hourly output from the ERA5 reanalysis to extract the 10 most intense windstorms over the U.S. Northeastern states and describe them in terms of their location, spatial extent, duration, and severity. We further evaluate the degree to which these windstorms are composite extreme events, wherein high wind speeds co-occur with extreme or hazardous precipitation.
2) Verify aspects of the windstorms as characterized based on ERA5 reanalysis output using wind speed observations from sonic anemometers and precipitation characteristics from RADAR and in situ rain gauges, plus storm damage reports.
3) Contextualize these windstorms in the long-term cyclone climatology. Specifically, we track each windstorm over time and space using two indices of intensity derived from mean-surface pressure and relative vorticity and contextualize these events in the cyclone climatology for 1979-2018.
4) Evaluate these windstorms in terms of the return periods of extreme wind speeds derived using the Gumbel distribution applied using annual maximum wind speeds for 1979-2018.

This research is a part of the HyperFACETS project which uses a storyline-based analysis framework. Storylines are "physically self-consistent unfolding of past events, or of plausible future events or pathways" (Shepherd et al., 2018). They and provide a method of framing a research inquiry in terms of three elements: A geographic region, a historically important or notablen event, and a set of process drivers for that event.

2 Data and Methods

2.1 ERA5 reanalysis

Attempts to identify and characterize windstorms from a geophysical perspective and contextualize them in a climatological setting have historically been hampered by limited data availability and/or quality from geospatially inhomogeneous observing networks. Further, time series from in situ wind measurement networks exhibit substantial inhomogeneities due to factors such as station relocations, instrumentation changes, changes in conditions around individual measurement stations, changes in measurement frequencies and/or integration periods (Pryor et al., 2009;Wan et al., 2010). Thus, herein we employ once-hourly wind speeds from the ERA5 reanalysis. The wind speeds are for a height of 100 m a.g.l. at the model time step of 20 minutes and a spatial resolution of 0.25°×0.25°. This study focuses on windstorms within a study domain that extends from 35 to 50°N and 65 to 90°W (Fig. 1a). The events are defined using data from the 924 ERA5 land-dominated grid cells over the twelve Northeastern states (two-letter abbreviations given in Table 1).

The ERA5 reanalysis is derived using an unprecedented suite of assimilated in situ and remote sensing observations (Hersbach et al., 2020). It ~~and~~ exhibits relatively high fidelity for wind speeds (Kalverla et al., 2020;Olauson, 2018;Kalverla et al., 2019;Pryor et al., 2020;Jourdier, 2020;Ramon et al., 2019). However, it is important to acknowledge that wind parameters from any model do not fully reflect all scales of flow variability (Skamarock, 2004) and underestimate extreme wind speeds (Larsén et al., 2012), particularly in areas with high orographic complexity and or varying surface roughness length. Here we use wind speeds at 100 m height because ~~Further,~~ the scale of events we seek to characterize are regional rather than local scale, and are necessarily driven by winds aloft. F~~f~~low at this height is less likely to be impacted by sub-grid scale heterogeneity in surface roughness length and uncertainties induced by unresolved sub-grid scale variability. Near-surface wind speeds are strongly coupled to wind speeds at 100 m (i.e. within the PBL) but wind speeds at 100 m are less strongly impacted by inaccuracies and/or uncertainty in surface roughness length (z_0) (Minola et al., 2020;Nelli et al., 2020). Applying an uncertainty of a factor of two to z_0 can lead to mean differences of up to 0.75 ms^{-1} for near-surface (40 to 150 m a.g.l.) wind speeds (Dörenkämper et al., 2020). ~~Further, the scale of events we seek to characterize are regional rather than local scale, and are necessarily driven by winds aloft.~~ Estimates of wind gusts at a nominal height of 10 m are generated as a post-processing product from the ~~from~~ ERA5 reanalysis product using the sustained wind speed at 10 m along with a term representing shear stress and a convective term (Minola et al., 2020). The association between these wind gust estimates and sustained wind speeds at 100 m are also presented and provide a link to previous research on European windstorms that focuses on wind gusts.

Cyclone tracking and intensity estimates presented herein employ three-hourly mean sea level pressure (MSLP) and relative vorticity at 700 hPa (RV) fields from ERA5. Previous research has indicated relatively good consistency between cyclone climatologies derived using ERA5 and other recent reanalyses (Gramcianinov et al., 2020;Sainsbury et al., 2020). RV values at 700 hPa are used rather than 850 hPa as in the XWS European analysis due to the presence of high elevation areas in U.S. cyclone source regions. Further, the three-hourly fields from ERA5 used herein are direct products of the reanalysis, whereas the 3-hourly values used in XWS were based on 6-hourly ERA Interim reanalyses combined with ERA Interim forecast values for the intervening time steps (Roberts et al., 2014).

Compound events, windstorms which exhibit a co-occurrence of extreme precipitation and/or freezing rain with high winds, are associated with amplified risk (Zscheischler et al., 2018;Sadegh et al., 2018). Precipitation intensity and hydrometeor class from ERA5 are used to identify to what degree each of the ten windstorms identified here are compound events. The hydrometeor classes reported by ERA5 are; rain, mixed rain and snow, thunderstorms, wet snow, dry snow, freezing rain, and ice pellets and are differentiated based largely on the temperature structure in the reanalysis model (https://confluence.ecmwf.int/display/FUG/9.7+Precipitation+Types). Prior analyses of ERA5 precipitation values have indicated skill relative to in situ observations and gridded data sets over the U.S. (Tarek et al., 2020;Sun and Liang, 2020).

2.2 Observational data

Wind speeds and precipitation characteristics during the windstorms are identified using ERA5 and are validated using in situ measurements from 24 National Weather Service (NWS) Automated Surface Observation System (ASOS) stations and seven NWS RADARs (Fig. 1c). Since major upgrades to the NWS systems were conducted in 2000, this evaluation is focused on windstorms that occurred after that year. Five minute measurements of in situ wind speeds at 10 ~~-~~m a.g.l. used in this evaluation derive from ice-free two-dimensional sonic anemometers (Schmitt IV, 2009), while the in situ observations of precipitation intensity reported from the ASOS network derive from heated tipping-bucket rain gauges (Tokay et al., 2010). In the absence of widespread in-situ wind speed observations from tall towers (which would be more comparable to the 100-m wind speeds from ERA5), these 10-m wind speed observations represent the best available validation data set for the occurrence of high winds throughout the Northeast states. NWS protocols document accumulated precipitation since the last hour, sampled every minute and reported every five minutes (Nadolski, 1998). For the current comparison to ERA5, these are averaged to generate hourly rainfall rates.

Precipitation rates from seven NWS dual polarization RADAR (Kitzmiller et al., 2013) are used to provide an areally-averaged comparison of ERA5 (Fig. 1c). NWS RADAR precipitation products are the ~~product~~ result of extensive development efforts (Cunha et al., 2015;Villarini and Krajewski, 2010;Straka et al., 2000) and have been employed in a wide array of applications (Letson et al., 2020;Seo et al., 2015;Krajewski and Smith, 2002). Precipitation intensity rates derived from RADAR reflectivity are reported in 41,400 cells using 1° azimuth angle and a range resolution of 2 km. In the current work, precipitation rates over the land areas of Northeastern states from RADAR and ASOS and ERA5 that are within 200 km of ~~each~~ the 7 RADAR are averaged in time to match the hourly resolution of ERA5 precipitation and interpolated in space to the 0.25°×0.25° ERA5 grid ~~. For comparison with ERA5, mean precipitation rates in each hour of the windstorm are computed from ERA5, ASOS and RADAR over the land areas of Northeastern states that are within 200 km of the 7 RADAR stations used herein~~ (Fig. 1c).

2.3 NOAA Storm Events Database

The U.S. National Oceanic and Atmospheric Administration (NOAA) provides detailed information on "the occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce" at the county level in the NOAA Storm Events Database (https://www.ncdc.noaa.gov/stormevents/). These records are subject to some inhomogeneities associated with digitization of transcripts prior to 1993, and standardized into 48 event types in 2013 (https://www.ncdc.noaa.gov/stormevents/details.jsp?type=collection). They but are compiled from a range of county, state and federal agencies in addition to the NWS. Like all hazard loss datasets they are subject to reporting inaccuracies and inconsistencies (Gall et al., 2009), but they represent a long and relatively consistent record, and are widely used (Young et al., 2017;Konisky et al., 2016). Damage and mortality estimates from this dataset to provide an estimate of the impact of each windstorm, with the caveat that population density and hence the potential for loss of life and damage vary markedly between U.S. counties that also vary greatly in area (Fig. 1d).

2.4 Method used to characterize windstorms

A range of different techniques have been developed and applied to identify and characterize atmospheric hazards including extreme windstorms. Some rely on an assessment of the severity of the events such as insured losses or human mortality/morbidity. O, others prescribe a level of rarity (i.e. are probabilistic), while others prescribe a level of intensity (i.e. the occurrence of extreme values of some physical phenomena) (Stephenson, 2008). Here we employ a methodology based on the intensity and spatial extent of extreme wind speeds. This approach is conceptually similar to storm severity indices derived from European work based on the maximum 925 hPa wind speed within a 3° radius of the vorticity maximum and the area over which wind speeds at that height exceed 25 ms^{-1} (Roberts et al., 2014;Della-Marta et al., 2009). It also draws from earlier work that used an index defined as the product of the cube of the maximum observed wind speed over land, the areas impacted by damaging winds (> 25.7 ms^{-1}) and the duration of damaging winds (Lamb, 1991).

This analysis employs hourly wind speeds at 100 -m a.g.l. for 1979-2018 in all 924 land-dominated grid cells over the Northeastern states. The methodology applied to identify and characterize the ten largest windstorms does not employ an absolute threshold of wind speed, but rather exceedance of locally determined thresholds defined by the 99.9th percentile wind speed value (U_{999}). A local U_{999} threshold is used, rather than an absolute wind speed threshold in ms^{-1}, in part because storms affecting urban areas, which may not be prone to high wind speeds, are especially damaging to infrastructure. While lower percentile thresholds have been used in previous work (Walz et al., 2017;Klawa and Ulbrich, 2003), use of the 99.9th percentile wind speed value is appropriate for identifying the truly extraordinary conditions we seek to characterize and is robust when applied to very long datasets with very large sample sizes. Use of locally determined thresholds also enables direct comparison of the spatial scale and intensity of windstorms derived using the ERA5 data at 100 m a.g.l. and near-surface wind speed observations from 100 m a.g.l.. Exceedance of the local 99.9th percentile wind speed value (U_{999}) value is considered in both cases based on the ~20 year record from each ASOS station and the 40 years of ERA5 data, and comparisons are made at an hourly resolution by averaging all ASOS wind speeds within a given hour.

As shown in Fig. 1a, there is marked spatial variability in the 99.9th percentile wind speed (i.e. the wind speed exceeded on slightly over 3500 hours during the forty-year period). U_{999} ranges from over 28 ms^{-1} over the Atlantic Ocean down to 12 ms^{-1} over some land grid cells due to the higher surface roughness and topographic drag. Windstorms are identified as periods when the largest number of ERA5 grid cells exceed their local (ERA5 grid cell specific) 99.9th

percentile wind speed value ($U>U_{999}$). A further restriction is applied in that no event may be within 14 days of any other, to avoid double-counting of any individual storm (Fig. 1b, Table 2).

The peak hour of $U>U_{999}$ coverage within the Northeast states for each of the ten most intense storms is referred to herein as the peak windstorm time (t_p), and the 97 hours including and surrounding (±48 hours) surrounding that timet$_p$ are referred to as the storm period. For each hour of each storm period a high-wind centroid is identified using the mean latitude and longitude of all grid cells where $U>U_{999}$.

Precipitation associated with each of the ten most intense windstorms is also evaluated using ERA5 precipitation totals and types. The analysis of precipitation centers focusses on a 24-hour period centered on the peak windstorm time (t_p). Precipitation statistics including 24-hour total precipitation, hourly precipitation rates, and the frequency of each precipitation type is characterized for all land grid cells in Northeastern states that exceed their local U_{999} value at any point in this 24-hour period.

Research from Europe indicates evidence of serial clustering of windstorms (Walz et al., 2018). Although our focus is primarily on the ten most intense and extensive windstorms, a larger sample of 50 events is extracted using the methodology described above but relaxing the temporal separation from 14 to 2 days, to examine the degree to which spatially extensive windstorms over the Northeast as manifest in ERA5 are serially clustered (Fig. 1b). This analysis employs a Poisson distribution fit to the annual occurrence rate for these 50 events and the dispersion index (D) of (Mailier et al., 2006):

$$D = \frac{\sigma^2}{\mu} - 1 \tag{1}$$

Where σ^2 and μ are the variance and mean of the distribution of the annual rates of occurrence. For , which for a Poisson distributed random variable σ^2 and μ are equal (Wilks, 2011a). $D > 0$ indicates the presence of temporal clustering. The significance of D is evaluated using a bootstrapping analysis in which 10,000 samples are drawn with replacement and the dispersion index is calculated for each, similar to a method used in (Pinto et al., 2016).

2.5 Development of a cyclone climatology

A cyclone detection and tracking algorithm (Hodges et al., 2011) is applied to 3-hourly ERA5 MSLP and 700hPa RV global fields that have been subjected to T42 spectral filtering for RV (corresponding to a 310-km resolution at the equator) and T63 filtering for MSLP (210 km at the equator) with the large scale background removed for total wavenumbers ≤ 5. These spectral filters are designed to restrict detection to tropical and mid-latitude cyclones (Hoskins and Hodges, 2002). The location and intensity of the cyclones are identified using the local maxima in RV and the minima (i.e. negative deviations) in MSLP . These are anomalies identified in therelative to the filtered fields, obtained from the spectral filtering which has the large-scale background removed for the tracking. RV cyclone intensities are shown in units of 10^{-5} s^{-1}, and MSLP intensity estimates are given in hPa scaled by -1. These anomalies are relative to removal of the large--scale background for $n \leq 5$, where n is the total wavenumber in the spherical harmonic representation of the field. The cyclones are tracked by first initializing a set of tracks based on a nearest-neighbor method which are then refined by minimizing a cost function for track smoothness as in the XWS European analysis (Roberts et al., 2014). Cyclones only contribute to the climatology if they persist for ≥ eight time steps (24 hours). The cyclone detection algorithm is applied separately to MSLP and RV with the results being used to provide a qualitative assessment of the uncertainty in the cyclone tracks.

Tracks associated with each windstorm are identified by identifyingfrom the geographic centroid of ERA5 grid cells where U > U_{999} and secondly if thefrom the local maximum of MSLP (scaled by -1) and RV anomalies that tracked into the Northeast study domain during the storm period. The date and location on which the cyclone associated with each windstorm are first identified by the tracking algorithm are used to identify the source area of each windstorm and the location and time at which the detection algorithm ceases to identify a cyclone are used to describe the end of the cyclone track. Subjective evaluation of the cyclone tracks associated with each windstorm are is used to identify the type of cyclone associated with each windstorms. A cyclone is identified as an; Alberta Clippers (AC) if the cyclone track originates over the North American continent north of 40°N, deep as a Colorado lows (CL) if the track originates over the North American continent south of 40°N, and as a decaying tropical cyclones (TC) if the track originates south of 30°N over a water grid cell. The term n) and nor'easters (NE) is applied if the cyclone retrogrades towards the coastline after moving offshore and/or is associated with strong northeasterly flow over the Northeastern states.- Alberta Clippers

Consistent with past research (Hirsch et al., 2001) all of the top-10 windstorms identified using the largest spatial extent of locally extreme wind speeds in the ERA5 data occur during cold season months (October to April). Thus, the cyclone track density used to contextualize the windstorms is restricted to only those months. This analysis further focusses solely on cyclones that track into the Northeastern domain. These restrictions allow direct evaluation of the degree to which the windstorms are typical of the prevailing cyclone climatology.

2.6 Calculation of long-term period wind speeds

Peak wind speeds (U_{peak}) during each of the windstorms are expressed in terms of their return period (*RP* in years) to provide a metric of the degree to which these events are exceptional. These statistics are computed for each ERA5 grid cell by fitting a double exponential (Gumbel) distribution to annual maximum wind speeds (U_{max}) (Mann et al., 1998):

$$P(U_{max};\alpha,\beta) = e^{-e^{-(U_{max}-\alpha)/\beta}} \quad (2)$$

Where the distribution parameters α and β are derived using maximum likelihood estimation. The U_{peak} estimates for each ERA5 grid cell are then evaluated in terms of their return period (*RP* in years) using (Wilks, 2011a;Pryor et al., 2012):

$$RP = \frac{1}{1-P(U_{peak})} \quad (3)$$

This method is similar to that used for grid-point-based wind speed return period calculations in previous work (Della-Marta et al., 2009), which resulted in return periods of 0.1 to 500 years when considering 200 prominent windstorms in Europe.

Uncertainty intervals on the return period wind speeds are assigned using the 95% confidence intervals on the α and β parameters as derived using maximum likelihood estimation.

2.7 Loss Index

Previous research has advocated use of a Loss Index (LI) to identify societally relevant wind storms (Klawa and Ulbrich, 2003):~~.~~

$$LI = \sum_{NE\ grid\ cells} pop(cell) \left(\frac{U_{max}(cell)}{U_{98}(cell)} - 1 \right)^3 \qquad (4)$$

Where pop(cell) is the population of a reanalysis grid cell, U_{max} is the 24-hour maximum wind speed in that grid cell and U_{98} is the local, long-term 98th percentile wind speed. Here we evaluate the degree of correspondence between this LI applied here to wind speeds at 100 -m and NOAA storm damage reports using linear fitting with zero intercept. Variance explanation (R^2) values for fits with forced zero intercept is computed using:

$$R^2 = \frac{\sum \widehat{Y_i^2}}{Y_i^2} \qquad (5)$$

Where $\widehat{Y_i^2}$ is the estimated value of damage (Y) for each storm (i) and Y is the observed value for that event (Eisenhauer, 2003) from NOAA storm damage reports.

3 Results

3.1 Windstorm identification and characterization

The top-10 windstorms during 1979-2018 over the Northeastern states identified using the method described above are summarized in Table 2. During the peak hour (t_p) of each of these windstorms, 309 to 524 (33 to 56%) of the 924 ERA5 land-dominated grid cells exhibit $U>U_{999}$ (Table 2). For context, 10% of ERA5 grid cells co-exhibit $U>U_{999}$ in <1% of hours. The windstorms are not concentrated in any sub-period of the 40 years under consideration (1979-2018) and no individual year contained two of the top ten windstorms (Fig. 1b). Hence, in the following the windstorms are referred to below by their (unique) year of occurrence, and in all figures and tables results are displayed in decreasing order of windstorm magnitude as defined using the spatial extent of $U>U_{999}$ at t_p (Table 2).

The maximum wind speed at 100 m a.g.l. in any ERA5 grid cell at the peak hour range from 25 to 41 ms^{-1}, while the maximum during the storm period ranges from 26 to 44 ms^{-1} (Table 2)~~.~~. These maximum wind speeds do not scale with the storm intensity as measured by the number of grid cells that exceed their local 99.9th percentile wind speeds (Table 2). For example, the windstorm during March 1993 ~~was~~ is associated with the highest absolute wind speeds but ~~was~~ is manifest in a relatively small number of ERA5 grid cells. Maximum wind gusts at 10 -m a.g.l. exceed the sustained wind speeds at 100 -m a.g.l. at both the peak hour and over the entire windstorm. Maximum wind gusts from ERA5 for all windstorms are well above the U.S. National Weather Service 'damaging winds' threshold of 25.7 ms^{-1} (Trapp et al., 2006) (Table 2). The spatial correlation coefficient between 100-m sustained wind speeds and wind gusts at 10 m at t_p is > 0.68 for all storms and > 0.8 for 8 out of the 10 storms, indicating that the 100-m sustained wind speeds~~s~~ analyzed herein are strongly related to near-ground wind gusts in the ERA5 reanalysis.

Table 2. Summary of the top 10 windstorms listed in rank order of spatial extent ~~events~~. The time of max coverage (t_p) shows the time and date with the greatest geographic extent of high wind speeds. # cells indicates the count of ERA5 grid cells with U > U_{999} at t_p. The maximum precipitation accumulated in any Northeastern state land grid cell is given for in the 24 hours surrounding the storm peak. Maximum sustained wind speeds at 100 m and wind gusts (G) at 10 m are given for Northeastern state land grid cells during each storm, for both t_p and the entire wind storm period (97 hours). Property damage for the Northeastern states is based on NOAA Storm damage reports and is accumulated over the duration of the period for which the associated cyclone (defined using RV) is evident. Inflation adjusted property damage are derived using inflation estimates from the U.S. Bureau of Statistics (bls.gov/data/inflation_calculator.htm). For comparative purposes results from an analysis using a 98th percentile wind speed threshold are shown in the final two columns. U>U_{98} storm rank denotes the rank of windstorms defined using that local threshold and # cells U>U_{98} indicates the number of NE grid cells that exceed their local 98th percentile value.

Time of max coverage (t_p)	# cells U>U_{999}	Max U at t_p [ms^{-1}]	Max U during storm period [ms^{-1}]	Max G at t_p [ms^{-1}]	Max G during storm period [ms^{-1}]	Max 24-hour precip [mm]	Property Damage [M$]	Property Damage [M$] Inflation adjusted to January 2020	U>U_{98} Storm Rank	# cells U>U_{98}
10/30/12 00:00	524	34.27	41.8	34.44	42.43	146.03	25,304	29,100	3	864
11/13/03 20:00	481	26.04	29.95	36.58	37.18	39.02	1,119	1,600	29	717
4/6/79 20:00	479	28.53	31.88	31.98	33.99	34.19	586	2,233	34	697
1/27/96 15:00	414	25.76	30.81	29.69	37.02	60.64	1,298	2,181	2	876
4/16/07 16:00	372	29.56	32.44	31.04	34.07	79.06	392	502	24	729
11/13/92 03:00	363	25.53	28.34	30.4	31.94	54.01	42	79	5	838
2/11/81 04:00	339	24.81	29.08	27.66	36.61	93.02	8	24	20	746
3/13/93 21:00	339	40.95	43.15	34.38	38.49	84.33	34	62	12	806
3/2/2018 19:00	331	31.66	33.1	33.77	35.39	84.71	164	172	48	641
4/5/95 20:00	309	24.21	26.29	32.96	32.96	19.19	225	389	114	511

All ten windstorms are associated with substantial damage reports within the Northeast states (Table 2, Fig. 2) and nine of the ten storms were responsible for deaths in the Northeast states (Fig. 2). There is not direct correspondence between the ranking of the windstorms in terms of the number of ERA5 grid cells with $U > U_{999}$, and the amount of damage and human mortality as reported in the NOAA Storm Data, but the four highest-magnitude windstorms (2012, 2003, 1979, and 1996, i.e. those ranked 1-4) all have property damage totals above any of the other six windstorms (Table 2). Further, although NOAA Storm Data indicate only modest total economic costs associated with property damage during the 1992 windstorm, there are reports of widespread damage in counties across much of the Northeast (Fig. 2). The lack of complete correspondence between the centroid of windstorms, as identified using the methodology presented here, and property damage in the NOAA dataset is likely due to the following: (i) Occurrence of localized extreme (damaging) winds that are manifest at scales below those represented in the ERA5 reanalysis (e.g. downbursts from embedded thunderstorms, sting jets and other mechanisms (Li et al., 2020;Clark and Gray, 2018)). ~~(Hewson and Neu, 2015) suggest a~~A grid resolution of 20 km or higher ~~is~~ maybe required to fully capture damaging winds (Hewson and Neu, 2015). (ii) S~~S~~patial variability in insured assets ~~(e.g.~~ (Nyce et al., 2015) ~~and~~ (Brown et al., 2015)~~)~~. (iii) Possible inconsistences in storm-reporting practices across counties (~~See~~ see NOAA storm data publications for details: https://www.ncdc.noaa.gov/IPS/sd/sd.html). Nevertheless, although many factors dictate economic losses from windstorms, the Pearson correlation coefficient (r) between the number of grid cells with $U > U_{999}$ at t_p and inflation adjusted property damage exceeds 0.66, and r between the maximum wind speed and inflation adjusted property damage is 0.56. For a sample size of 10, using a t-test to evaluate significance (Wilks, 2011a), these correlation coefficients differ from 0 at confidence levels of 95% and 90%, respectively. Thus, this geophysical intensity metric captures aspects of relevance to storm damage.

In previous work, the local 98th percentile value has been used to identify windstorms in Germany as it roughly corresponds to wind gusts at 10 m that may cause property damage (Klawa and Ulbrich, 2003). Events with widespread exceedance of the 98th percentile threshold are common over the U.S. Northeast during the 40 years of ERA5 output. For example, 139 events have sustained wind speeds in excess of their local -98th percentile in over half of all ERA5 grid cells. Thus, herein, a higher threshold (99.9th percentile) is used to distinguish ten extraordinary windstorms. All ten also appear on the list of storms chosen using a 98th percentile threshold, with nine of the ten appearing in the top 50 (Table 2).

Several of the windstorms identified using our approach have been previously identified in independent analyses further confirming the reliability of the detection method. For example, Hurricane Sandy, the most intense windstorm in this analysis (Table 2), is a historic storm that moved parallel to the coast before making landfall in southern New Jersey on 29 October and caused $50 billion of damage (Lackmann, 2015). According to ~~the~~ ERA5 output at its peak, over 300,000 km^2 of the Northeastern states exhibited wind speeds at 100 m a.g.l. that exceeded the locally determined U_{999} (Fig. 3). The 8th most intense windstorm (Table 2) is the "Storm of the Century" of 12-14 March 1993 that formed in the Gulf of Mexico and caused widespread damage in Florida and along the Atlantic coast before entering the Northeast (Huo et al., 1995).

The synoptic-scale structure of extra-tropical cyclones is complicated (Hoskins, 1990;Earl et al., 2017). ~~Generally, but not uniformly,~~ M~~m~~aximum wind speeds are often, but not always, associated with low-level jets that occur along the cold fronts of extra-tropical cyclones (Hoskins, 1990;Browning, 2004). Consistent with that expectation, the centroid of ERA5 grid cells with $U>U_{999}$ tends to move in parallel with the cyclone track locations but are generally displaced to the south/southeast (Fig. 2).

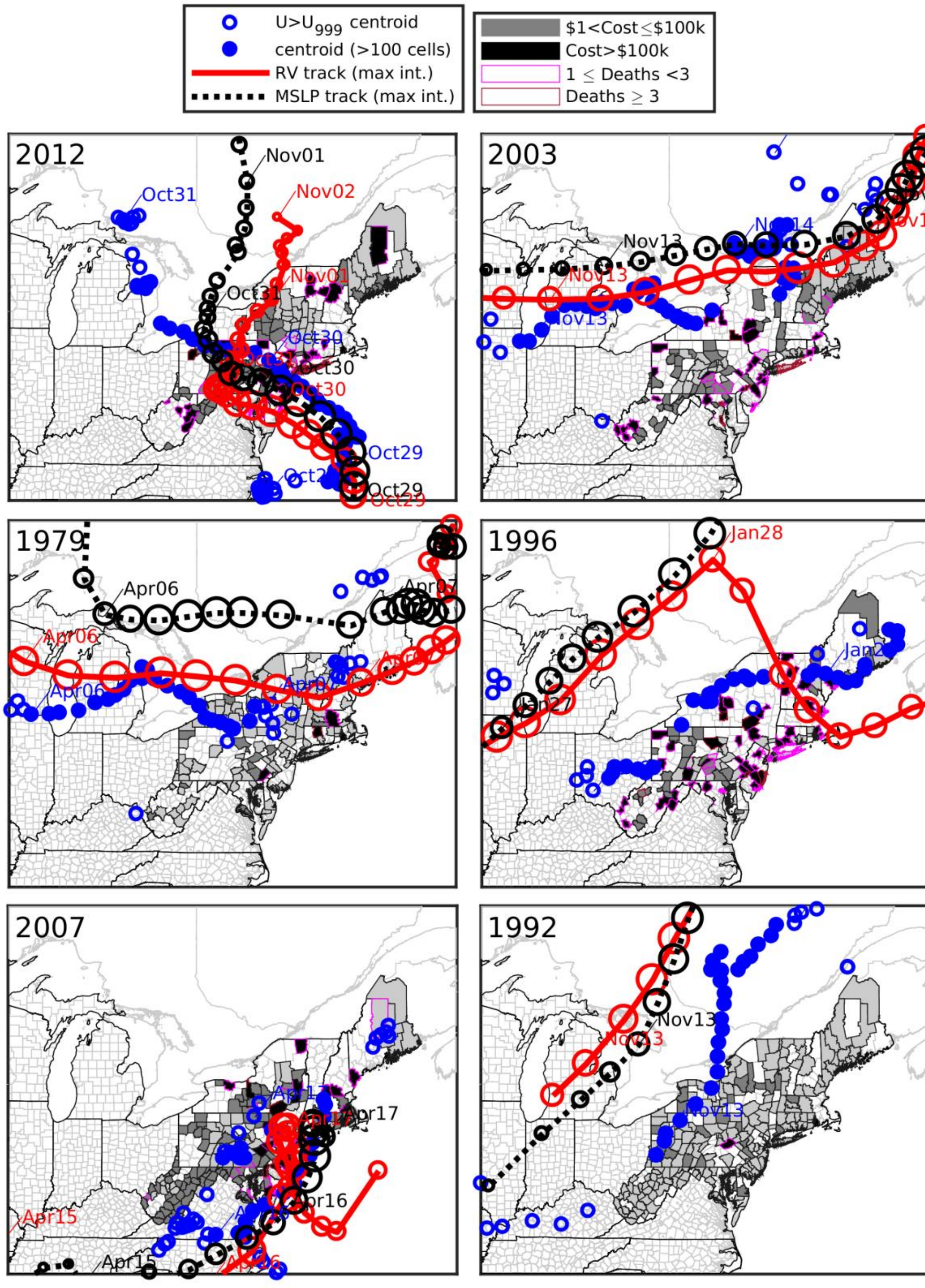


Figure 2. Windstorm centers as the geographic center of all ERA5 grid cells for U > U_{999} (blue). Markers are filled when there are >100 cells over this threshold. Timing and location of the cyclone centers as diagnosed from MSLP and relative vorticity at 700 hPa are shown in black and red, respectively. Markers every 3 hours along each track have a diameter corresponding to track intensity. The underlying shading shows the county-level damage and deaths in the Northeastern states associated with each event as diagnosed from the NOAA storm reports.

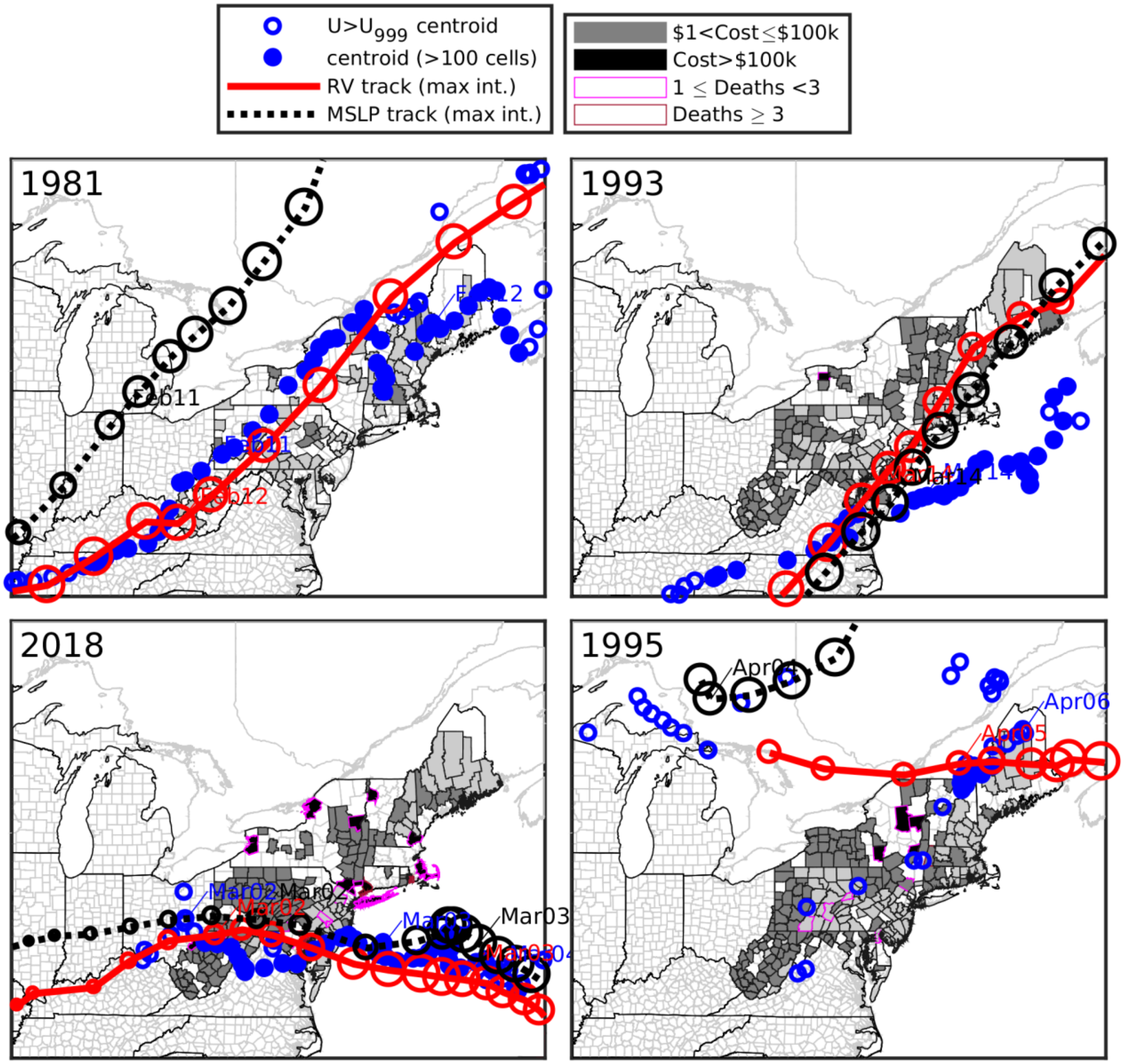


Figure 2 (cont).

Previous research has reported that reinsurance contracts commonly employ a 72 hour window to describe a 'single event' (Haylock, 2011). All of the windstorms identified in this work transited the Northeastern study domain in < 72 hours. Intense wind coverage ($U>U_{999}$) is generally concentrated in the ±10 hours around the storm peak time, t_p (Fig. 3), although some windstorms had longer duration and a slower decay in widespread intense wind speeds with significant coverage remaining >10 hours after t_p (Fig. 3).

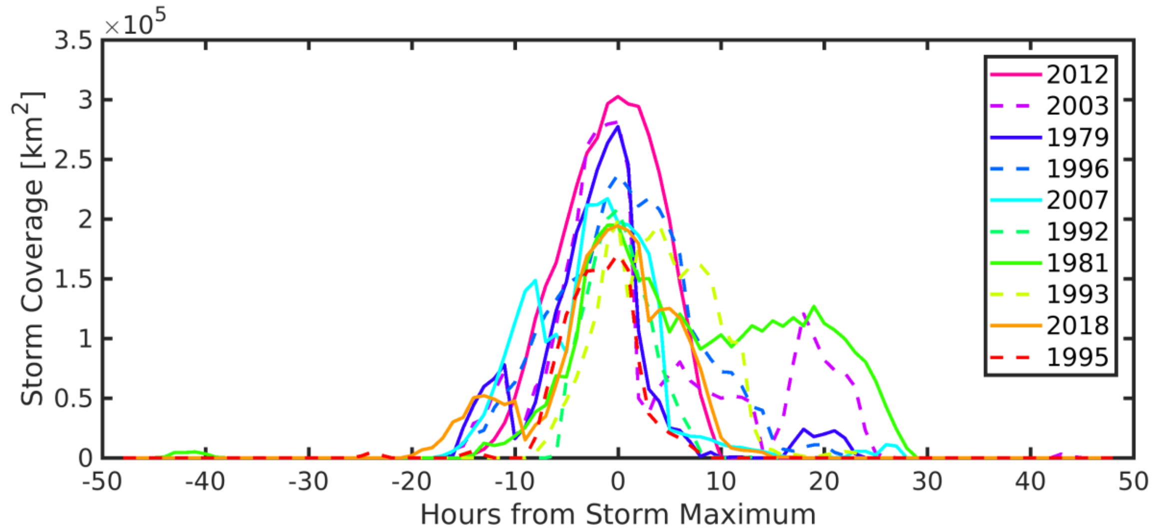


Figure 3. Spatial extent of the windstorms measured in km^2 over the Northeastern states relative to t_p. The spatial extent is described as the area of ERA5 grid cells wherein the U > U_{999}. Values are shown for 48 hours preceding and following each windstorm peak.

Twenty-four-hour precipitation totals, used as an indicator of flooding potential, and maximum precipitation rates, used as an indicator of transportation hazards, vary substantially among the ten windstorms, but virtually all of the windstorms were associated with some form of ~~extreme~~ intense or hazardous precipitation (Fig. 4). Consistent with observational evidence (Munsell and Zhang, 2014), Hurricane Sandy (windstorm during 2012) is associated with total 24-hour precipitation accumulation exceeding 100 mm in 5 grid cells within the Northeast, and nearly half (46%) of grid cells exhibit precipitation accumulations of over 20 mm. Heavy precipitation, both in terms of maximum precipitation intensity and total accumulated precipitation, is also associated with the 1993 windstorm resulting from a decaying TC that formed a NE (Fig. 4). Windstorms with lowest precipitation totals occurred in 2003, 1979 and 1995 and are associated with AC. Freezing rain, which in conjunction with high winds is a particular hazard to electrical infrastructure and transportation, is present during the windstorms in 1992, 1981 and 1993 (Fig. 4). There is also snow indicated in at least one location in the domain in every storm, except for Hurricane Sandy. Thus, six of the ten windstorms might be classified as compound events due to the occurrence of freezing rain and/or widespread heavy rain identified using the American Meteorological Society threshold of > 0.76 $mmhr^{-1}$ (AMS, 2012) in > 40% of grid cells which also exceed U_{999}.

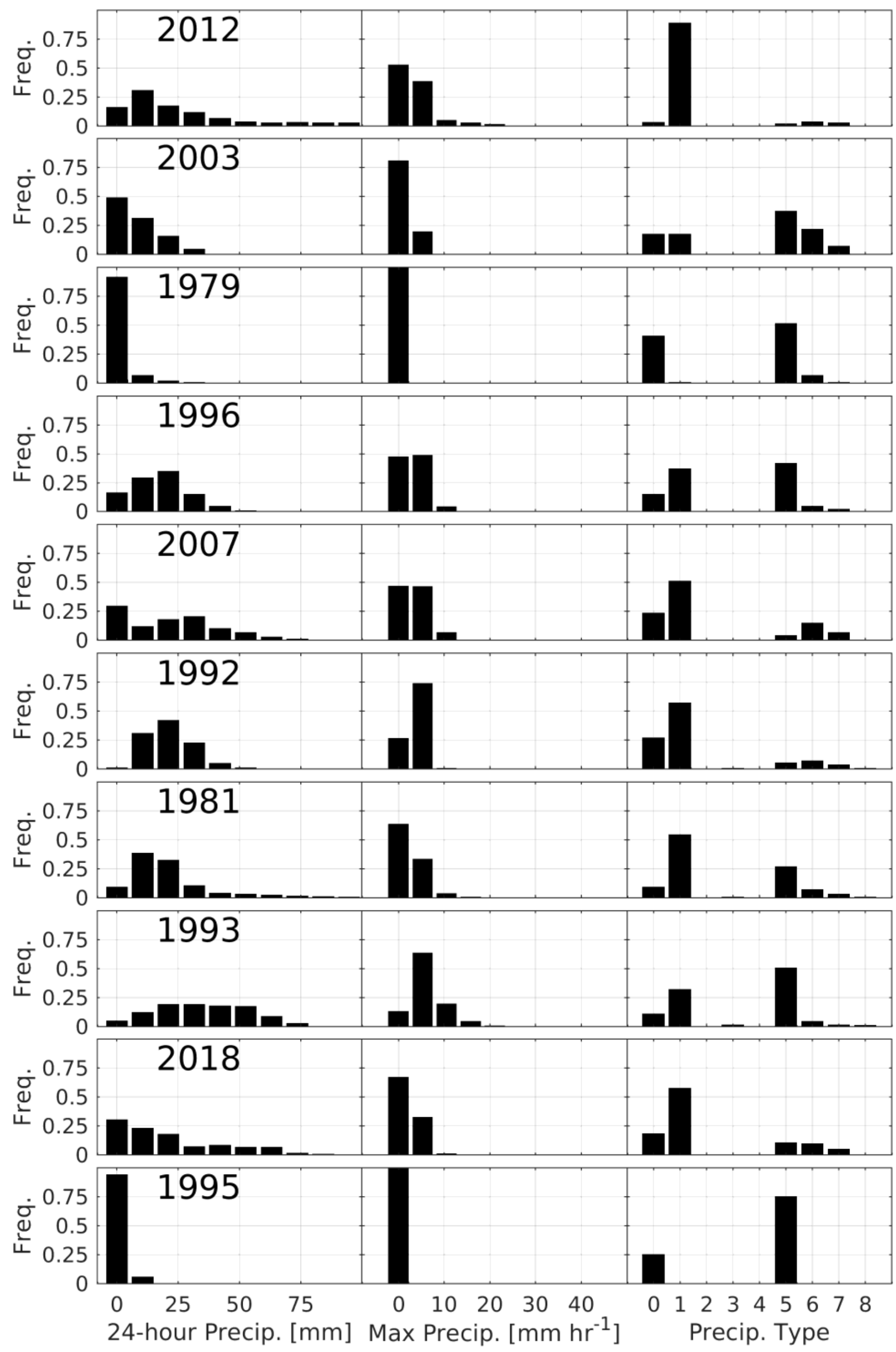


Figure 4. Histograms of precipitation totals and maximum precipitation rates and precipitation types for the 24 hours centered on each storm peak across ERA5 land-based grid cells in the Northeastern states. The frequencies are the fraction of grid cells in each class (out of 924). Precipitation types are as follows: No precipitation (0), rain (1), thunderstorm (2), freezing rain (3), snow (5), wet snow (6), mixture of rain and snow (7) and ice pellets (8).

Four of the top-10 windstorms occurred after 2000 (2012, 2003, 2007 and 2018, Table 2), and thus high quality ASOS and RADAR data are available for comparison with estimates from ERA5 for these events. For the 2012, 2003 and 2018 windstorms there is good agreement between the spatial extent of locally extreme wind speeds from ERA5 and

ASOS, and the duration of intense wind speeds (Fig. 5). The agreement is less good for the 2007 windstorm possibly due to the low density of ASOS stations in the U.S. state of Maine where the ERA5 output indicate the wind maximum was manifest for a substantial fraction of the storm period (Fig. 2). For the other three windstorms the fraction of ERA5 grid cells in the Northeastern states with $U>U_{999}$ closely matches the fraction of ASOS stations in the same area that exceed their local U_{999} threshold during each hour of the storm period (Fig. 5). The timing of storm precipitation in the ERA5 data is also in good agreement with observational estimates from RADAR and ASOS stations, consistent with assimilation of RADAR precipitation and ~~weather~~ in situ station data (Lopez, 2011;Hersbach et al., 2019). The period with most intense precipitation occurred concurrently with the high wind speeds during Hurricane Sandy, but largely well before t_p in the 2007 and 2018 windstorms (Fig. 5), consistent with previous work characterizing extra-tropical cyclones (Bengtsson et al., 2009). Mean ERA5 precipitation rates in Northeast states during these ten storms are consistently somewhat higher than estimates from RADAR, but below ASOS point measurements, reflecting spatial variability in rainfall intensity at scales below those manifest in a network of point measurements (Villarini et al., 2008).

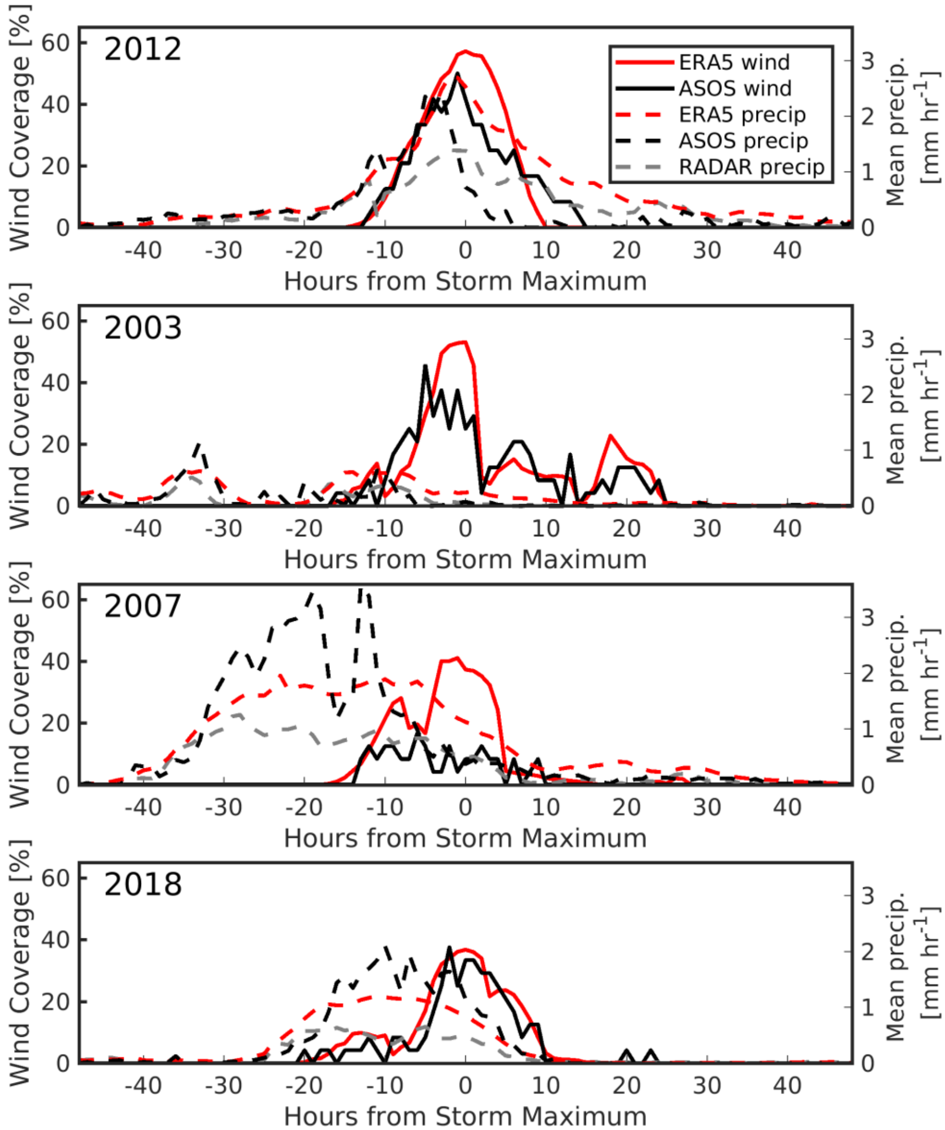


Figure 5. Time series of high wind coverage and mean precipitation rate during the four windstorms that occurred after the year 2000. Each subplot includes the fraction of ERA5 grid cells with over-threshold wind speeds ($U > U_{999}$), the number of ASOS stations with over-threshold wind speeds, the mean precipitation rate (in land areas of Northeast states within 200 km of a RADAR station) from ERA5, NWS RADAR and ASOS point observations.

A larger sample of 50 windstorms ~~was~~ is also drawn from the 40-year time series to examine the serial dependence. In this analysis ~~This analysis relaxed~~ the 14-day exclusion window used in the identification of the top 10 windstorms is reduced to a 2-day window. While the top ten windstorms considered in detail herein all have spatial extent of between 309 and 524 grid cells, the 11th- through 50th-ranked storms in the set used to characterize seriality have a mean extent of 216 grid cells, and range in extent from 176 to 309 cells, further indicating that the top ten storms are distinct in the 40-year time series (Fig. 1). One windstorm (on January 19th, 1996) is excluded by use of a 14-day separation window from the list of the top ten storms but is included if a 2-day exclusion period is used. It would have been ranked number ten.

These top 50The probability distribution of the annual counts of windstorms are is relatively well described by a Poisson distribution. in terms of counts per calendar year. The resulting dispersion value (D) is 0.18 indicating evidence for serial dependence or alternatively stated that these windstorms are clustered in fewer years than would be expected for independent events. Of 10,000 bootstrapped samples, 99.97% had dispersion indices above zero. While this D value is symptomatic of serial clustering for windstorms that impact the Northern USA, it is lower than those computed for regions of European in earlier research using the 20th century ERA reanalysis and a 98th percentile wind speed threshold (Walz et al., 2018). The lower amount of serial clustering of windstorms in the Northeastern states at the annual timescale is indicative of a lower probability of multiple damaging windstorm events occurring within a single year. While the top ten windstorms considered in detail herein all have spatial extent of between 309 and 524 grid cells, the 11th- through 50th-ranked storms in the set used to characterize seriality have a mean extent of 216 grid cells, and range in extent from 176 to 309 cells, further indicating that the top ten storms are distinct in the 40-year time series (Fig. 1).

3.2 Cyclone detection and tracking

Consistent with past research employing other reanalysis data sets (Ulbrich et al., 2009), results from application of the cyclone detection and tracking algorithm to ERA5 output also indicate the U.S. Northeast exhibits a high frequency of transitory cyclones (Fig. 6). Also in accord with expectations, the tracks followed by the windstorms are generally characteristic of those dominant cyclone tracks, and derive from a mixture of intense nor'easters (NE), Alberta Clippers (AC), deep Colorado lows (CL), and decaying tropical cyclones (TC) (Table 3, Fig. 6).
For most cyclones independent tracking of the center using MSLP and RV yields results that are highly consistent (Fig. 2). Nevertheless, some discrepancies exist. These likely arise, at least in part due, to the spectral field smoothing. Another possibility is if there is a strong background flow due to a strong pressure gradient, the vorticity can be offset relative to the pressure minimum (Sinclair, 1994).

Cyclone intensities for the top 10 windstorms are an order of magnitude above the mean intensities for cold-weather cyclones at the same locations over the U.S. for both RV and MSLP (Fig. 7, Table 3). Windstorms with the highest intensities tend to pass over the ocean (2012, 1993 and the 2018 storm). Both the 2012 and the 1993 windstorms (ranked #1 and #8, see Table 2) are the result of decaying tropical cyclones, with the 1993 system transitioning to become a NE (Fig. 2 and 6, Table 3). The 2012 windstorm (Hurricane Sandy) exhibited extremely high intensity and is also associated with the largest area (number of grid cells) with $U>U_{999}$. It was also associated with by far the largest amount of property damage and deaths (Fig. 2, Table 2). Five of the 10 storms are associated with Colorado Lows, consistent with the high prevalence of such cyclones (Booth et al., 2015) (Fig. 6). These storms generally impacted the smallest areas and tend to be associated with substantial but lower amounts of property damage than TC or AC (Table 2).
The 2018 windstorm is associated with a CL that stalled over the Atlantic coast and re-intensified to form a NE. Although this event was not the most geographically expansive, its track over very high-density population areas and high value assets led to high associated storm damage (Fig. 2). Five of the 10 storms are associated with Colorado

Lows, consistent with the high prevalence of such cyclones (Booth et al., 2015) (Fig. 6). These storms generally impacted the smallest areas and tend to be associated with substantial but lower amounts of property damage than TC or AC (Table 2).

The Great Lakes are known to have a profound effect on passing cyclones during ice-free and generally unstable conditions that prevail during September to November (Angel and Isard, 1997). Particularly during the early part of the cold-season, cyclones that cross the Great Lakes are frequently subject to acceleration and intensification via enhanced vertical heat flux and low-level moisture convergence due to the lake-land roughness contrast (Xiao et al. 2018). Cyclones that transit the Great Lakes during periods with substantial ice cover are subject to less alteration (Angel and Isard, 1997). The 2003, 1979 and 1995 windstorms are associated with Alberta Clippers (Table 3) that exhibit initially low intensities, but rapidly intensify as they pass across the Great Lakes region (~80°W and 45°N). Cyclone intensities for these three storms increased by an average of 16% for RV and 33% for MSLP during their crossing of the Great-Lakes longitudes (92°W to 76°W). Consistent with a priori expectations, tThese windstorms occurred when Great Lakes ice cover was minimal (https://www.glerl.noaa.gov/data/ice/atlas/ice_duration/duration.html). Both 2003 and 1979 windstorms events (ranked #2 and #3) exhibit large spatial scales (Fig. 3) and resulted in substantial property damage (Table 2).

Tracking of windstorms is a key determinant of societal impacts. The 2018 windstorm is associated with a CL that stalled over the Atlantic coast and re-intensified to form a NE. Although this event is not the most geographically expansive, its track over very high-density population areas and high value assets led to high associated storm damage (Fig. 2). The 2012 and 2018 windstorms had high wind speed centroids that are closely aligned from the cyclone centers. They passed over highly populated areas including New York, and are associated with recorded damage in the hundreds of millions of dollars (Fig. 2, Table 2). The Conversely, the 1993 windstorm high wind speed centroid is out over the Atlantic Ocean which may partly explain the lower loss of life and property damage associated with this event (Fig. 2). The AC associated windstorms (2003, 1979, 1995) tracked west-east and have maximum intensity centers across the north of the region. They are and thus were also associated with lower damages over the U.S. than other the other windstorms. Cyclones associated with the windstorms in 1992, 1996, 1981 tracked from the southeast to the northwest but their centers diagnosed from MSLP remain east of the region as do those from RV in 1992 and 1996. The geographic centroids of high wind speeds track through Virginia, Pennsylvania, and New York in all three yearsevents. Inflation-adjusted damage amounts are very different for these storms and range from $24 million for the 1981 windstorm to $2181 million for the 1996 windstorm (Fig. 2 and 7).

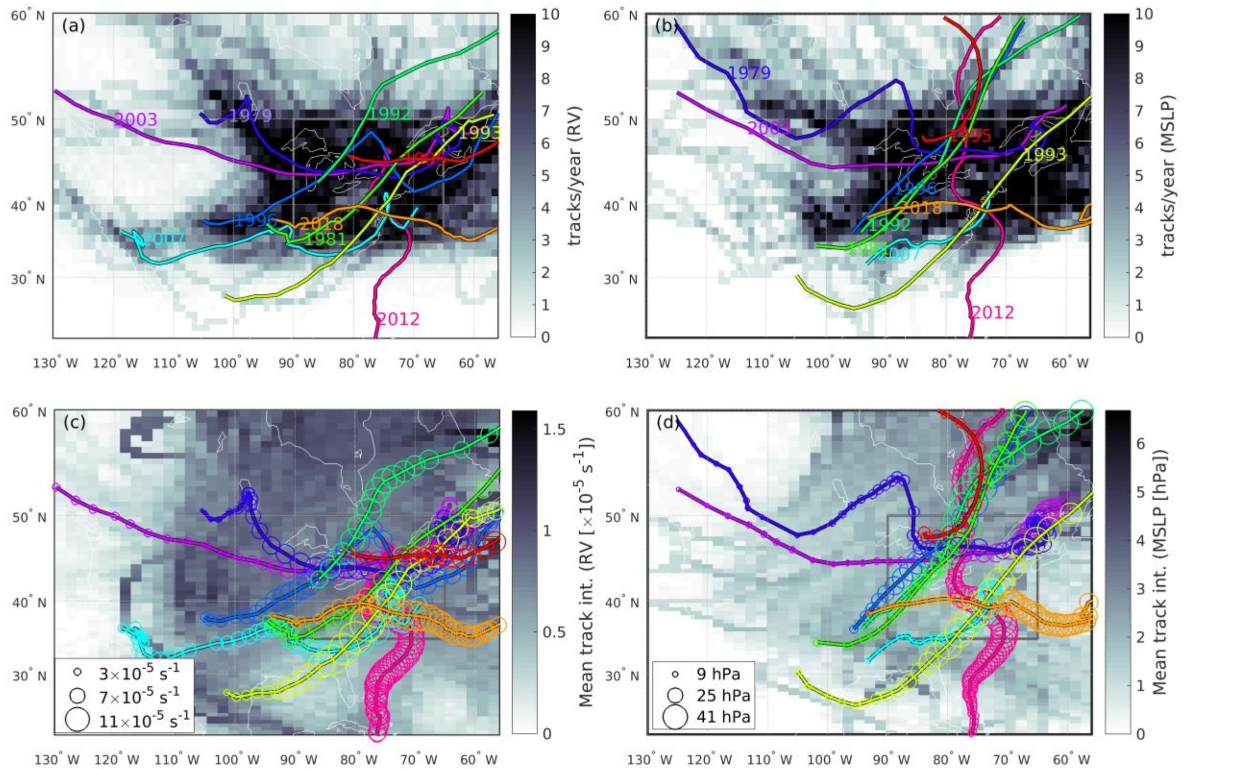
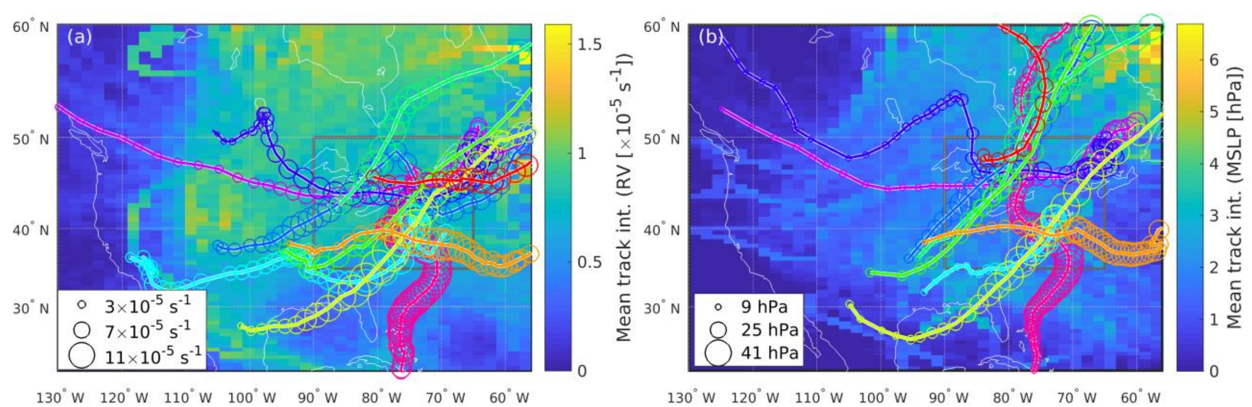


Figure 6. Cyclone tracks associated with each of the top 10 windstorms (individual colors) plotted over a heat map of cyclone densities for (a) relative vorticity (RV) and (b) mean sea level pressure (MSLP). Cyclone intensities for analyses of (c) 700 hPa RV and (d) MSLP (shown as an absolute value) for each of the top 10 windstorms (where the symbol diameter scales with intensity) plotted over a heat map of mean cyclone intensities. Symbol sizes shown in the figure legends represent the 10th, 50th and 90th percentile cyclone intensities from among the top 10 windstorms. Track densities and intensities in all four panels are computed at the ERA5 grid resolution and then averaged to a 1°×1° grid to aid legibility. These background field values include only cyclones that track into the Northeast rectangle (shown in grey) during cold months (October-April 1979-2018) and are anomalies identified in the filtered fields, obtained from the spectral filtering which has the large-scale background removed for the tracking. Color coding of the cyclone tracks associated with each windstorm is as in Fig. 3.

~~**Figure 6. Cyclone tracks associated with each of the top 10 windstorms (individual colors) plotted over a heat map of cyclone densities. Cyclone frequencies are computed at the ERA5 grid resolution and then averaged to a 1°×1° grid to aid legibility. These densities include only cyclones that track within the Northeast rectangle (shown in grey) during cold months (October-April 1979-2018) for (a) relative vorticity and (b) MSLP. Color coding of the cyclone tracks associated with each windstorm is as in Fig. 3.**~~



~~**Figure 7. Cyclone intensities for analyses of (a) 700 hPa relative vorticity and (b) mean sea level pressure (shown as an absolute value) for each of the top 10 windstorms (where the symbol diameter scales with intensity) plotted over a heat map of mean cyclone intensities. Cyclone intensities are computed at the ERA5 grid resolution and then averaged to a 1°×1° grid to aid legibility. These intensities include only cyclones that track within the Northeast rectangle (shown in grey) during cold months (October-April 1979-2018) and are anomalies identified in the filtered fields, obtained from the spectral filtering which has the large scale background removed for the tracking. Symbol sizes shown in the figure legends represent the 10th, 50th and 90th percentile cyclone intensities from among the top 10 windstorms, and color coding of the cyclone tracks associated with each windstorm is as in Fig. 3 and Fig. 6.**~~

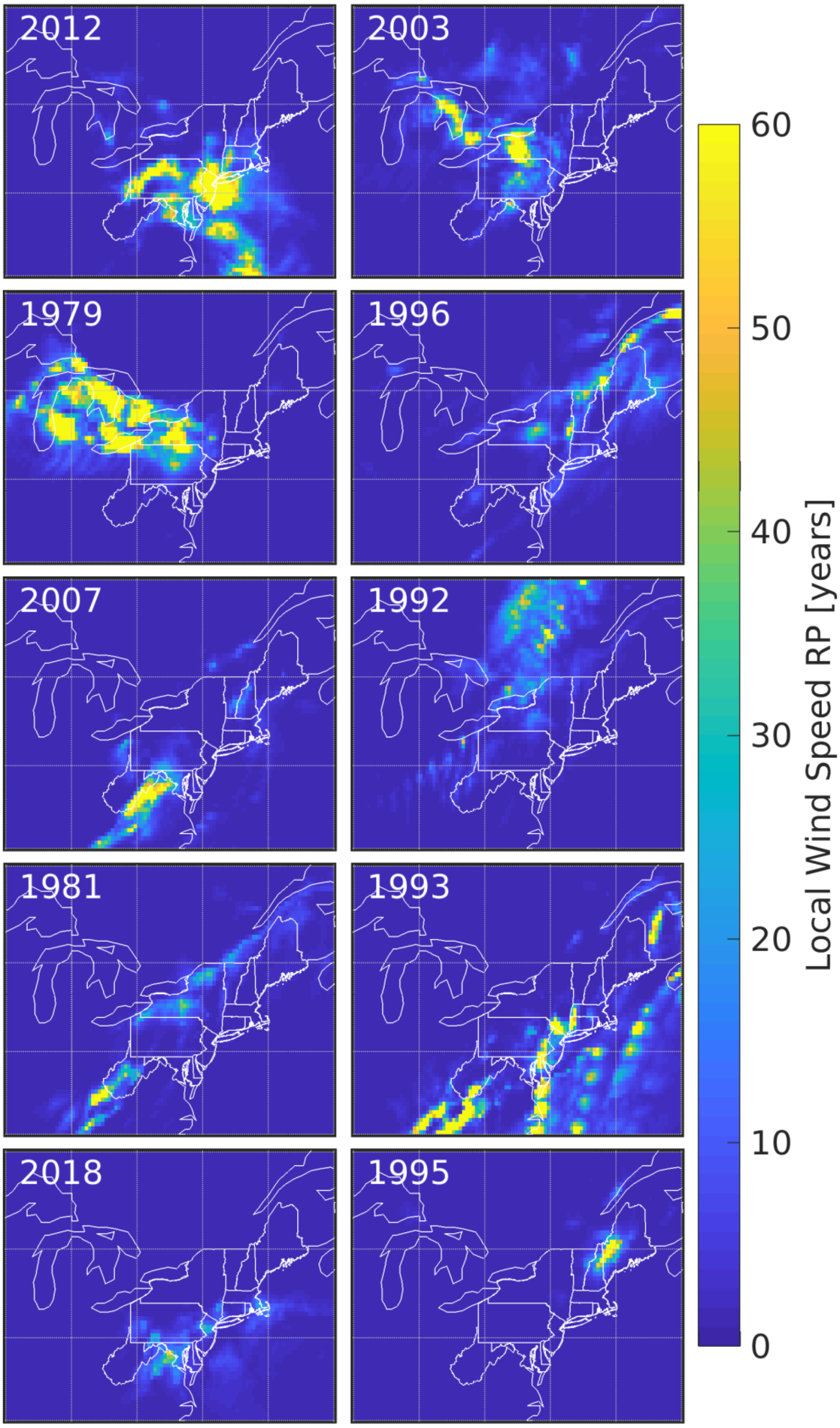
3.3 Windstorm Return Periods

All ten windstorms are associated with long return-period (RP > 50 years) wind speeds in at least some ERA5 grid cells. ~~,~~Data from some grid cells within the Northeast indicate ~~with~~ return periods of ~~exceeding~~ over 100 years for the 2012 windstorm. Defining a single return period for each windstorm is difficult due to the multiple degrees of freedoms, but the median (50th percentile) and highest 5 percent (95th percentile) of ERA5 grid cell estimates provide some qualitative assessment of probability. The median RP computed for all 924 grid cells ranges from 1 to 5 years across the ten windstorms (Table 3), while at least 5% of grid cells are characterized by wind speeds during each of the ten windstorms with RP of 6.5 to 106 years (Table 3, ~~Fig. 8~~Fig. 7). The number of ERA5 grid cells that exhibit their annual maximum value during the storm period ~~are~~ is positively correlated with the three metrics of return periods; (i) median RP, (ii) 95th percentile RP and (iii) median RP for grid cells that exhibited $U>U_{999}$ (r: 0.45 to 0.64), consistent with the longest-RP wind speeds being associated with the largest windstorms (~~Fig. 8~~Fig. 7, Table 3). For the two windstorms caused by TC that entered the Northeastern states ~~from the Atlantic~~ (2012 and 1993), high-RP wind speeds are concentrated along the coast. The 2003 and 1979 windstorms, the highest-magnitude Alberta Clippers, are associated with extreme high return-period wind speeds in the Great Lakes region. Wind speeds over a large number of grid cells over and around the Great Lakes ~~exhibited their 50-year RP estimates~~l had RP of > 50 years during the 1979 windstorm. Indeed, this windstorm, while not the most spatially expansive (Table 2), is the event with the largest number of ERA5 grid cells in excess of 50-year RP wind speeds in the Northeast domain. The Colorado Low associated windstorms (1996, 2007 and 1981) have their highest-RP winds in the mountainous regions of West Virginia, New York, Vermont, and Maine (WV, NY, VT, and ME).

Extrapolation to low probability, long return period wind speeds from limited duration time series is naturally associated with substantial uncertainties (Wilks, 2011b). For example, the 95% confidence intervals ~~for~~on the 95th percentile of grid cell RP values during the ten windstorms range from 30 to over 500 years for Hurricane Sandy with a best estimate of 106 years (Table 3). Irrespective of the precise RP for these windstorms, this analysis emphasizes the truly exceptional nature of these events.

Table 3. Windstorm details (windstorms are ordered as in Table 2). Cyclone type is based on subjective evaluation of results from the cyclone detection and tracking algorithm: AC = Alberta Clipper. TC = Tropical Cyclone. CL = Colorado Low. NE = Nor'easter. Max intensity is the maximum cyclone intensity along the storm-associated cyclone tracks for RV (x10^{-5} s^{-1}) and MSLP (scaled by -1, hPa). # cells with U_{max} indicates the number of grid cells for which the maximum wind speed for the storm year occurred within the storm period. Median RP is the 50th percentile return period for maximum wind speed in each Northeastern grid cells during each storm period, while p95 is the 95th percentile RP. Also shown is the median RP for grid cells that exhibited $U>U_{999}$ at the storm peak. All RP values include a 95% confidence interval in parentheses.

Cyclone type	Cyclone track start			Cyclone track end			Max intensity: RV [10^{-5} s^{-1}] / MSLP [-1 hPa]	# cells with U_{max}	Median RP [years] (95% CI)	p_{95} RP [years] (95% CI)	Median RP of cells exceeding U_{999} [years] (95% CI)
	Time	Lat [°N]	Lon [°W]	Time	Lat [°N]	Lon [°W]					
TC	10/18/2012 9:00	11.61	61.1	11/2/2012 0:00	46.92	74.95	14.3/49.1	530	4.6 (2.9-9.3)	105.8 (29.7-583)	12.2 (5.8-34.8)
AC	11/11/2003 0:00	52.97	129.82	11/23/2003 6:00	50.39	68.5	10.5/36.9	494	2.3 (1.8-3.6)	34.9 (12.9-138.3)	5.5 (3.3-12.1)
AC	4/4/1979 0:00	50.61	105.62	4/8/1979 21:00	46.98	63.88	10.0/32.1	412	1.6 (1.4-2)	43.6 (15.6-178.9)	6.4 (3.7-14.6)
CL	1/26/1996 0:00	37.91	105.01	2/1/1996 6:00	57.08	41.55	10.5/45.4	488	3.5 (2.4-6.7)	19.4 (8.3-62.7)	5.1 (3.1-10.9)
CL/NE	4/11/2007 21:00	36.44	118.73	4/17/2007 18:00	39.56	69.32	12.4/39.6	462	1.6 (1.4-2.1)	18.1 (7.9-59.3)	3.7 (2.5-7.3)
CL	11/12/1992 21:00	42.71	86	11/15/1992 12:00	57.06	45.63	11.2/50.1	343	1.5 (1.3-1.8)	6.5 (3.7-14.8)	3 (2.1-5.4)
CL	2/11/1981 0:00	37.44	94.5	2/16/1981 6:00	63.41	37.65	8.9/56.3	523	2.2 (1.7-3.4)	22.2 (9.4-72.1)	6.6 (3.7-15.1)
TC/NE	3/12/1993 6:00	27.37	101.4	3/15/1993 18:00	51.88	52.39	15.3/49.2	536	2.1 (1.7-3.2)	36.8 (13.6-144.1)	5.4 (3.2-12)
CL	3/1/2018 3:00	38.14	93.72	3/6/2018 6:00	42.13	53.31	13.3/40.9	310	1 (1-1)	14.1 (6.5-43.5)	4.9 (3-10.5)
AC	4/4/1995 15:00	45.88	80.74	4/10/1995 6:00	62.63	58.16	9.5/24.2	94	1 (1-1)	14.4 (6.7-42.4)	2.3 (1.8-3.6)



~~Figure 8~~Figure 7. Return period (in years) of storm-maximum wind speed (U_{peak}) in each ERA5 grid cell associated with each windstorm. The color scale is truncated at ~~50~~ 60 years for legibility. B~~b~~ut, for example, the RP of the maximum wind speeds at 100 -m ~~maximum return period value~~ during Hurricane Sandy (2012) exceeds 100 years for multiple grid cells. Northeastern state borders ~~are shown in red~~ and coastlines (Atlantic Ocean and Great Lakes) are shown in white.

3.4 Loss Indices and comparison to NOAA storm damage estimates

Population weighting means loss index contributions (Equation 4) for the ten windstorms identified herein are generally maximized in the coastal grid cells that comprise the northeastern urban megapolis that extends from New Jersey to Massachusetts and includes the city of New York (Fig 8).

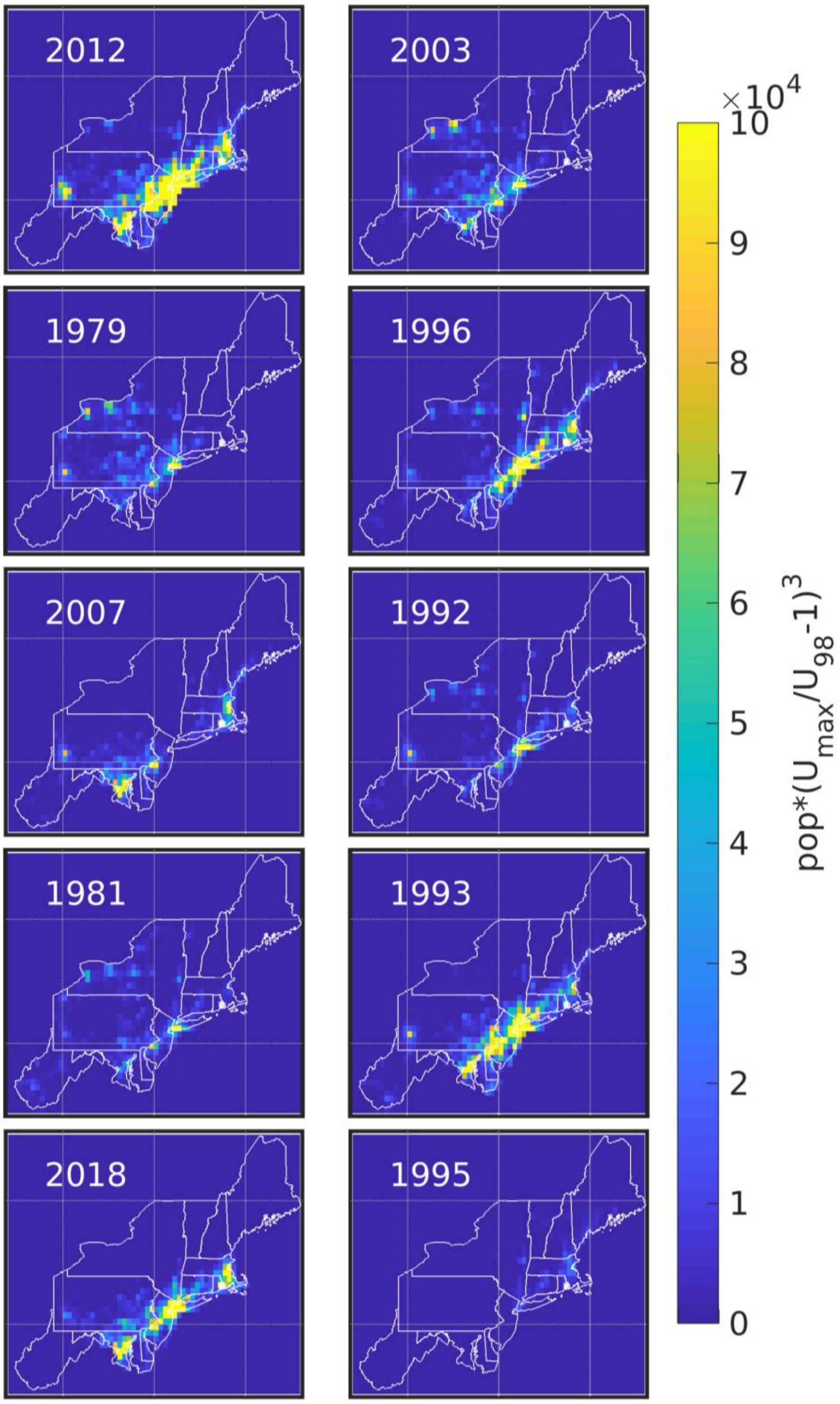


Figure 8. Contribution to the loss index (LI; Equation 4) from each ERA5 grid cell associated with each windstorm. Northeastern state borders and coastlines (Atlantic Ocean and Great Lakes) are shown in white.

The number of ERA5 grid cells in NE states that exceed their 99.9th percentile wind speed and LI both exhibit positive correlations with the NOAA storm damage report totals for the windstorms. A linear fit with zero intercept of NOAA storm damage in millions of US$ inflation adjusted to January 2020 and the number of cells exceeding U_{999} ~~are correlated with storm damage among the 10 storms~~exhibits variance explanation (R^2) -of 0.24 and a slope of 1.1×10^7. A linear fit of NOAA storm damage and the LI has an R^2 of 0.75 and a slope of 554. However, a substantial fraction of variability in economic losses associated with these ten very high magnitude and large spatial extent windstorms is not well described by either predictor. This is partly due to co-occurrence of other geophysical hazards (including flooding due the composite nature of some of these events, see Figure 4). For example, t~~T~~he 2012 storm (Hurricane Sandy, ranked #1 in this analysis) is associated with greater property damage than would be predicted by either the LI or number of cells exceeding U_{999}, due to damage from storm surge and related flooding (Xian et al., 2015). Further, population density is a crude index of socioeconomic exposure or the presence of high value assets. Future work could explore the degree to which inclusion of a wealth index improves these associations (Pielke and Landsea, 1998).

4 Concluding Remarks

The U.S. Northeast exhibits high socio-economic exposure to atmospheric hazards due to the presence of major urban centers with high population density and high density of insured, high-value assets (Table 1, Fig. 1), and windstorms present a substantial fraction of historically important climate hazards in this region. The Northeastern states are also experiencing population increases that are projected to continue into the future (Zoraghein and O'Neill, 2020). This increase in population may result in increased exposure to this hazard even in the absence of any change in windstorm frequency or intensity. Thus, there is great value in improved characterization of these events.

The ten ~~largest~~ most intense windstorms in the Northeast U.S. during 1979-2018 covered 33 to 57% of ERA5 land cells in the Northeastern states with wind speeds exceeding the locally determined 99.9th percentile threshold (Table 2). Although all ten events occurred during the cool season months of October through April, they are distributed throughout the forty-years, and no individual year exhibits more than one of these events (Fig. 1b). However, when a larger pool of the top 50 largest windstorms is considered, ~~clear~~ evidence of serial clustering emerges. Return periods for wind speeds in the upper 5% of ERA5 grid cells during these 10 windstorms range from 6.5 to 106 years (Table 3, Fig. 7). Many of these windstorms exhibit co-occurrence of extreme and/or hazardous precipitation and thus may be considered composite events.

Any windstorm catalogue is, to some degree, a product of the dataset on which it is predicated, and the windstorms identified herein are derived using a methodology that preferences intense but large-scale events. Their characteristics will naturally differ from severe local storms. The windstorms identified independently and objectively in this work are consistent with historically notable events. Further, precipitation and wind speeds from ERA5 for windstorms that occurred after 2000 exhibit good agreement with in-situ observations from the NWS ASOS network and NWS dual-polarization RADAR, consistent with assimilation RADAR precipitation and weather station data streams by the ECMWF data assimilation protocols and past evaluations of the ERA5 reanalysis (Fig. 5). The ~~accord between~~statistically significant correlation between the ~~geophysical data streams and the~~ ERA5 windstorm intensity estimates and independent damage estimates provides further confidence in the fidelity of the windstorm catalogue presented herein.

The cyclone tracks associated with the ten windstorms are consistent with the climatology of cold-season cyclones and thus the associated extra-tropical cyclones are a mixture of; Alberta Clippers, Colorado Lows, decaying Tropical Cyclones and Nor' easters (Fig. 6). These cyclones, however, exhibit ~~considerably higher~~ intensities (from both RV and MSLP perturbations) that are an order of magnitude higher than mean values sampled on those same tracks (Fig. ~~7~~6). ~~With the possible exception of Hurricane Sandy,~~ With the possible exception of Hurricane Sandy, these windstorms follow tracks that are not infrequent in the cyclone climatology~~these windstorms are largely differentiable from the cyclone climatology in terms of their intensification rather than the associated cyclone storm track~~. It is also notable that the most intense AC events occurred during periods of low ice cover in the Great Lakes, which may imply windstorms associated with AC events are likely to intensify under climate change as results of reduced icing of these water bodies (Smith, 1991).

Inflation-adjusted (to January 2020) property damage totals for each of the windstorms range from $24 million to $29 billion (Table 2). While there is not perfect agreement in the ranking of these storms between high wind coverage and property damage, the top four storms in terms of extent do all have higher damage totals than the next six.

This windstorm catalogue is intended to characterize extreme windstorms in the Northeastern U.S. and may have value in efforts to evaluate the validate climate and natural hazard catastrophe models. Planned extension of the ERA5 reanalysis to 1950 may provide an opportunity to further extend this analysis to include elements related to non-stationarity in windstorm probability, with the caveat that such detection will be challenging due to changes in the assimilated data. Research is underway to dynamically downscale these windstorms using the Weather Research and Forecasting model to examine sub-grid scale variability in extreme wind speeds and the sensitivity of these events to global climate non-stationarity.

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Data Availability

ERA5 reanalysis output are available from https://climate.copernicus.eu/climate-reanalysis. NWS RADAR data are available from the National Climatic Data Center; https://www.ncdc.noaa.gov/data-access/radar-data. NWS ASOS data are available from ftp://ftp.ncdc.noaa.gov/pub/data/asos-fivemin/. The NOAA Storms database is available at; https://www.ncdc.noaa.gov/stormevents/. Historical estimates of Great Lakes ice cover are available from: https://www.glerl.noaa.gov/data/ice/atlas/ice_duration/duration.html.

Author Contribution

All four authors participated discussion about the goals and methods for this paper. SCP devised the analysis framework. FL had primary responsibility for performing the analyses. FL, SCP and RJB wrote the majority of the manuscript text. KH provided analysis tools, expertise, advice and context for cyclone tracking. RJB and SCP performed analyses on the societal impact of these windstorms. RJB and SCP acquired the funding and computing resources to make this research possible.

Competing Interests

The authors declare that they have no conflict of interest.

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