Impacts of the North Atlantic Oscillation on Winter Precipitations and Storm Track Variability in Southeast Canada and Northeast US

Response to Reviewers

We would like to thank both reviewers for their time and effort to review our manuscript. We have addressed to the best of our knowledge all major and minor comments raised by the reviewers. In doing so, we feel we have crafted a revised manuscript that is more rigorous in content, and better presents the results of the study. Here we list the main changes that we have made:

- We now include an analysis of extreme precipitation and snowfall, rather than only mean precipitation and snowfall amounts. We have added a new subsection (Sect. 3.2) and a new figure, which present these results.
- We have written a new discussion section (Sect. 4), where we have moved all interpretation, discussion and comparisons to previous studies. We have therefore carefully re-written the results section (Sect. 3) to present only the most important and novel results.
- Throughout the manuscript, we have made the purpose of the manuscript clearer.
- The introduction and conclusion were made shorter.
- We have made the explanation of the storm tracking algorithm more detailed.

Below, we copy the reviewers' comments in bold and describe how each of these issues has been addressed in the revised manuscript. The revised version of the manuscript is attached after the answers to reviewers’ comments, and the changes compared to the original version are highlighted in bold.

Response to reviewer #1

In the manuscript "Impacts of the North Atlantic Oscillation on Winter Precipitations and Storm Track Variability in Southeast Canada and Northeast US" the authors present a composite analysis of snowfall, total precipitation and cyclone track densities. They focus their discussion on the northeasternmost part of the American continent. The manuscript is easy to follow and the Figures are generally clear. I do however have considerable doubts about the novelty of the findings in this article. The authors cite quite a few studies in the introduction and throughout the manuscript that considered similar diagnostics with a similar scientific question for a similar region. Not surprisingly, throughout the manuscript, the authors then describe their findings as consistent with what has been pointed out before. That is in my eyes not enough to warrant a new publication. I am nevertheless recommending major revisions in the faith that the authors will be able to derive genuinely novel results from a similar set of results to the one presented in the current manuscript. It might however require a shift or broadening of the scope of the manuscript. For example the authors could explicitly consider extreme precipitation and snowfall rather than cold season means, or relate precipitation and snowfall to weather regimes (such as Greenland blocking) rather than the NAO. Whatever the authors' choice, the motivation and purpose of the study must become much more clear, in particular in the introduction and conclusion.

We thank the reviewer for the thorough evaluation of the manuscript and appreciate the positive remarks on the structure of the manuscript and the general clarity of the figures.

We thoroughly went through the literature in order to better compare our results to earlier studies that had similar scientific questions, highlighting throughout the manuscript similarities in our results relative to other studies. We believe that this may have given the impression of a lack of novelty in our manuscript.

However, our manuscript brought many new results, which we believe will be of scientific interest. Particularly, we used reanalysis data to study the relationship between snowfall and the NAO and did a full investigation of the impact of the NAO on the winter climate of eastern Canada, which were not done before. While the precipitation and snowfall variability with the NAO in the eastern US has been studied before, we wanted to add physical explanations to these relationships. For example, the study of the storm track variability with the NAO over North America is one of the novel aspects of our manuscript and following the reviewer's suggestion, we have also included an analysis of extreme snowfall and precipitation events. Finally, we have also rewritten the introduction and the conclusion to better highlight the motivation and the purpose of the study.

The change in extreme precipitation and snowfall has been analyzed by using various extreme climate indices; the number of days with precipitation above 10 mm (R10mm), the number of days with precipitation above 20 mm (R20mm), the maximum daily precipitation (Rx1day), and the maximum 5-days precipitation (Rx5days). However, as the results are fairly similar among these indices (see Fig. R1), we only show in the revised manuscript the results for the relationship between the NAO and R10mm.

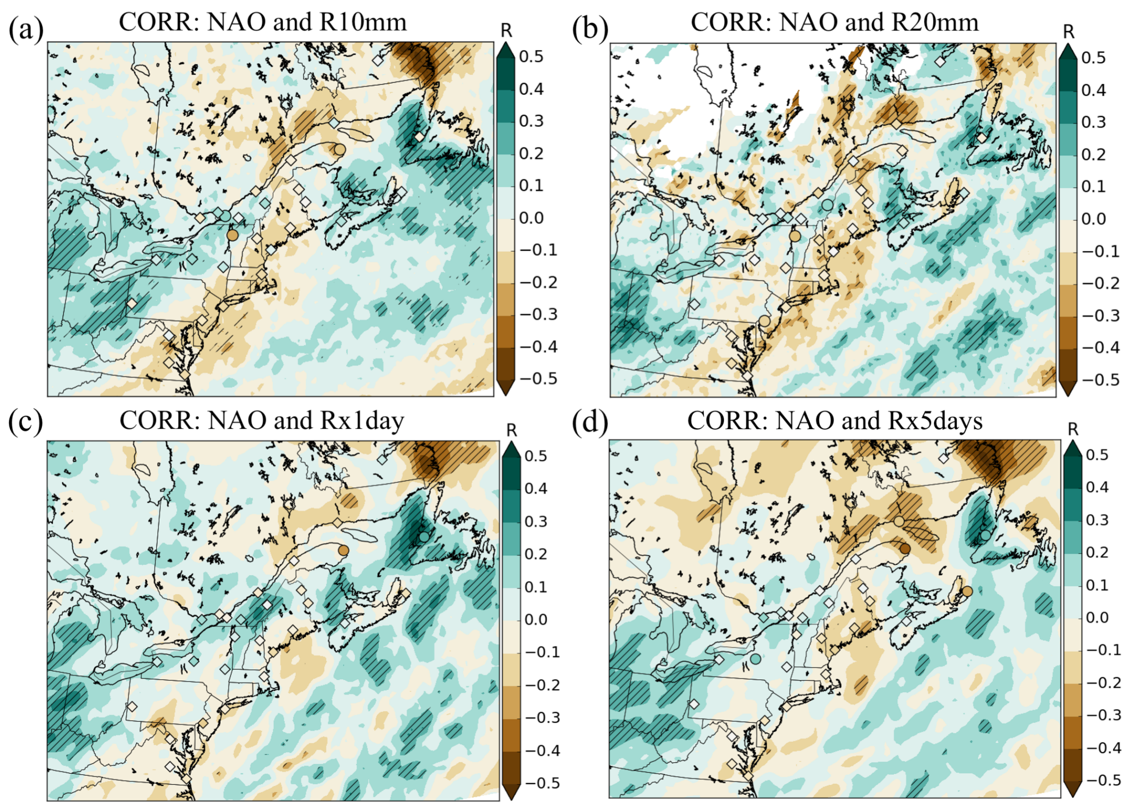

Figure R1. Correlation coefficients between the monthly NAOI and (a) R10mm, (b) R20mm, (c) Rx1day, and (Rx5days). Hatched areas represent statistically significant values at the 0.05 level. Shaded circles represent station-based correlation coefficient that are statistically significant at the 0.05 level, and diamonds represent values that are not statistically significant.

Specific major issues

L75. The preceding paragraphs list quite a number of previous studies and their explanations for the observed impact on northeastern US snowfall. In the light of these, I don't think the authors can claim that there have only been few studies on the topic, and neither that they in general are all unclear or implicit in their reasoning. In other words, it's not become clear to me which gap in the understanding the authors intend to fill.

We agree with the reviewer that the purpose of the study was not properly laid out. Indeed, several studies have also found negative correlations between annual snowfall and the NAO using station data in the northeastern US. However, to our knowledge none have explicitly investigated the link between these relationships and the changes in storm tracking during positive and negative phases of the NAO. What we wanted to say in the statement at L75 is that the relationship between precipitation/snowfall and the NAO is not strong over eastern North America, and that the mechanism responsible for the precipitation/snowfall variability in that region with the NAO was not fully investigated. We have made several changes to the introduction to better lay out the purpose of the study in the revised manuscript.

Sec 2.2: What is the motivation for developing yet another cyclone detection algorithm? There are already many variants published, some of them also applied to ERA5 and other comparatively high-resolution datasets. Specifically, if the results from this algorithm compare are well with those from other methods (L139-141), then what is the point of adding this complexity? I would urge the authors to use one of the more established methods unless there is a very good reason not to. In that case this reason will need to be convincingly laid out in the manuscript. If the authors decide to keep their own cyclone detection and tracking algorithm, this algorithm should be properly evaluated; to be able to evaluate the climatologies, I would require a larger region than the one shown in Figure 3, and also a comparison of individual cyclone tracks with those obtained from other algorithms. To make intercomparisons easier, it would further be good if the authors used the same units for their cyclone/cyclogenesis densities as in Neu et al. (2013), percentages of cyclone occurrence per time step and (1000 km)^2.

It may have not clear but we did not develop a storm tracking algorithm from scratch: It is an simple adaptation of earlier methods (Murray and Simmonds, 1991) in an effort to apply the algorithm on a high-resolution dataset (ERA5), while keeping only the cyclones that we believe are most significant for our study (minimum lifetime of 48h and displacement of 10 degrees), as the storms that bring high precipitation and snowfall to our domain of interest normally fill these conditions. This algorithm was also used in another study (Chartrand and Thériault, to be submitted) to track winter storms that caused powered outage in the province of New Brunswick, Canada, during the 2000-2013 period (see Fig. R2). The algorithm was able to successfully track these winter storms. The storm tracks of each individual storms were manually verified using satellite imagery and by looking the ERA5 Sea Level Pressure fields.

As suggested, we increased the size of the region shown the cyclone track density and cyclogenesis climatology figure (Fig. 3) to have a wider look at the track density and cyclogenesis spatial distribution. As we keep only cyclones that have a minimum lifetime of 48h and displacement of 10 degrees, a large number of cyclones are excluded, which explain the difference in climatology between this algorithm and others (e.g. those presented in Neu et al., 2003). However, the spatial distribution is well reproduced.

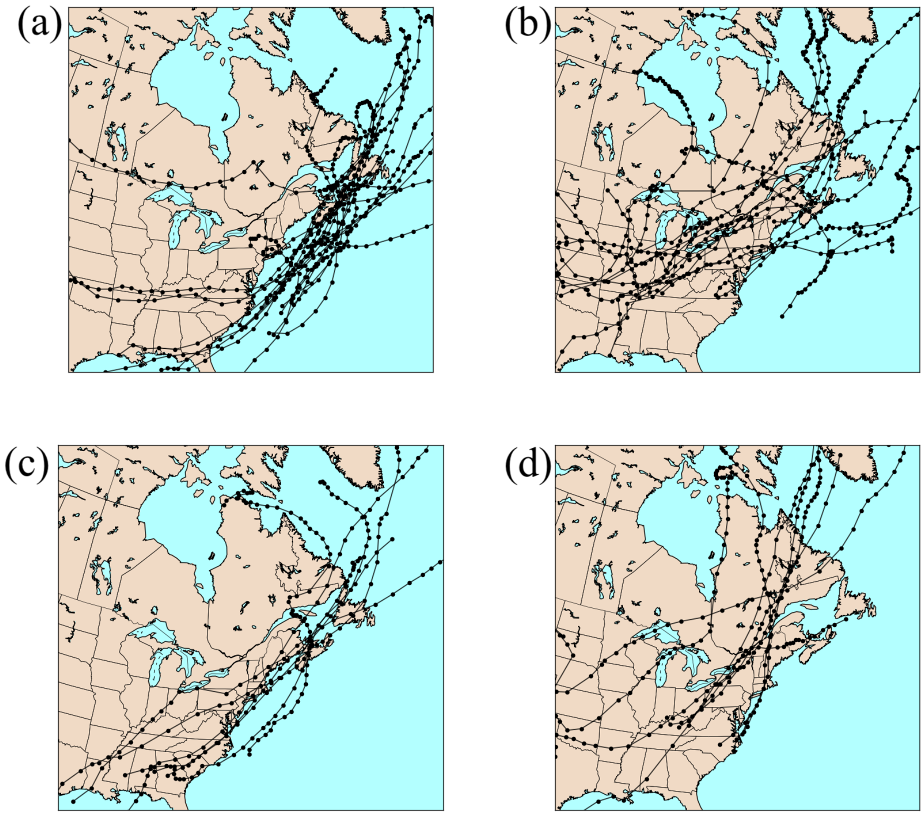

Figure R2. Adapted from Chartrand and Thériault (to be submitted). Composite tracks of 2003-2013 winter storms affecting New Brunswick Power infrastructure clustered into 4 categories based on the observed precipitation type in New Brunswick: (a) only snow events, (b) mixed events, (c) freezing rain events and (d) only rain events. Dots represent the positions of the low-pressure systems at 3-hour periods in the ERA5 reanalysis dataset.

Finally we have clarified the presentation of the algorithm used in method section and it now reads:

"

- *Because of the high resolution of ERA5, we first use a Cressman smoother (400 km influence radius) to filter out small-scale stationary local minima in the SLP field in the inter-mountain regions and retain only synoptic scale low-pressure systems. Local minima in the SLP field (SLP value is smaller than the eight neighboring grid points) are then taken as low-pressure centers for the tracking process.*
- *Cyclones trajectories construction are based on linear projection: to forecast the second position in a cyclone trajectory, the 500-hPa wind field is used; afterward, the location of*

future low-pressure centers are extrapolated (linearly projected) by using the difference between the previous and current center's locations. Matches between low-pressure centers at each time step are attempted by looking at the nearest centers found from the predicted trajectories. If several matches are possible for a single trajectory, absolute departure from predicted position and pressure with predicted value is used for matching low-pressure centers. Low-pressure center that are not matched to a previous storm track are used as first center for a new storm trajectory.

- *After each complete storm trajectory, two elimination criteria are applied in order to remove the stationary orographic features and short-lived features from the list of tracks found; a minimum total displacement of more than 10° and a minimum lifetime of 48 hours.*

"

L333-335: What exactly are these new results? Throughout the manuscript, findings have been pointed out as consistent with previous studies. This manuscript might still be redundant, if it does not add anything new, even if only few studies explicitly consider the region of southeastern Canada.

We made sure in the revised manuscript to highlight the new results of our study. For example, this part now reads:

"using a combination of station-based and high-resolution ERA5 reanalysis data over a longer and more recent period (1979-2018) compared to previous studies, our study provides additional results on the mechanisms responsible for winter precipitations and storm track variability in the northeastern US and southeastern Canada. In particular, very few studies have hitherto investigated in detail the NAO impacts in Canada, and in particular on extreme precipitation and snowfall in this region."

<u>Specific minor issues</u>

L90. Singular reads awkward, may be better: Positive values ... are .

Thank you for pointing that out, it has been changed in the revised manuscript.

L126/7: How can a spatial filter filter out stationary (in time, I would assume) minima?

The high resolution of ERA5 leads to a high number of closed stationary low-pressure centers being found in inter-mountain regions due to the calculation of sea level pressure in high terrain (e.g. within the Rocky Mountains). The spatial filter "fills" most of these small-scale features in the sea-level pressure field. We have clarified it in the manuscript. It now reads:
"Because of the high resolution of ERA5, we first use a Cressman smoother (400 km influence radius) to filter out small-scale stationary local minima in the SLP field in the inter-mountain regions and retain only synoptic scale low-pressure systems. "

L129: What is the "previous/current/next position assumption"?
This has been rephrased in the revised manuscript to make it clearer. It referred to forecasting the next position of a low-pressure center by extrapolation from the current and previous positions (linear projection). It now reads:
"Cyclones trajectories construction are based on linear projection: to forecast the second position in a cyclone trajectory, the 500-hPa wind field is used; afterward, the location of future low-pressure centers are extrapolated (linearly projected) by using the difference between the previous and current center's locations."

L134: Please provide a complete list of criteria for the cyclone detection and tracking. Otherwise your results will not be reproducible.
They have been all listed in the revised manuscript. It now reads:
"After each complete storm trajectory, two elimination criteria are applied in order to remove the stationary orographic features and short-lived features from the list of tracks found; a minimum total displacement of more than 10° and a minimum lifetime of 48 hours."

Fig 4: The purple contour is hardly visible in some of the composites/correlation maps. This makes some of the Figure panels a bit misleading, as most of the displayed signal is not significant. One way to solve the issue could be to use filled contours only for significant parts of the map, and otherwise only contour lines. Then the significant parts would stand out much more clearly.

We agree that the way we displayed statistically significant parts of the signal was not optimal. We changed these by using hatched areas in all figures that display the statistically significant parts of the change signal and correlation.

L171: The precipitation over the Great Lakes seems only marginally positively correlated with the NAO, just exceeding the zero contour.

Thank you for pointing it out, we changed this statement in the revised manuscript. It now reads: *"When moving northward or westward from the northeastern US coast, the results show a gradual reversal of correlation coefficient, which becomes slightly positive in southern Newfoundland and around the Great Lakes."*

L199: Typo: Winter snowfall. Also, may be you can relate that finding to Fig 1c, showing that the majority of precipitation comes as snow in southern Canada, and sec 3.1 already showed little impact of the NAO on total precipitation. With that in mind, the result here seems quite obvious.

Thank you for pointing that out, it has been changed in the revised manuscript. It now reads: *"In Newfoundland and Labrador, the snowfall relationship pattern with the NAO is similar to that between precipitation and NAO, which is not surprising as almost all precipitation falls as snow during the cold season in this region (Fig. 1c)."*

Figs. 5-6: Why are these a separate Figures? Logically, both would seem to fit quite well as additional panels into Fig 4.

Following this comment, we reduced the number of figures in the manuscript by combining the figures of cyclogenesis and storm track anomalies into Fig. 7 and added panels to Fig. 5 to regroup all analysis of extreme precipitation into one figure.

Figs. 7-8: Which parts of these Figures are significant, if any? I appreciate that cyclone densities and in particular cyclogenesis densities tend to be very noisy, so I would not be surprised if no part of the signal reaches statistical significance. That is fine, but should be explicitly noted.

Statistical significance was not shown in these figures. We agree that it is very relevant as we discuss thoroughly these figures in the discussion. In the revised manuscript, we displayed the statistically significant parts of these figures by using hatched areas.

Sec 3.5: At the same time, the description of these Figures in sec. 3.5 should reflect the significance of the results. Some formulations such as "considerable increase" (L238) or "strongly favored" (L244) will likely need to be toned down. This also applies to the conclusion.

As suggested, some of the formulations that we used have been toned down in the revised manuscript to reflect the significance of the results.

L245: What is "the" upper-level trough? The analysis is based on daily data, so there will be hundreds of troughs moving through the region in 40 winter seasons. Further, what is this conclusion based on? Even taking into account Fig 9 (which at this point has not been introduced yet), the conclusion seems to be too strong based on what is presented. The ridge-trough structure over the CONUS seems only slightly more pronounced during NAO- than during NAO+. Finally, more generally, composite analyses can at best hint at where there might be causal relations. Here I don't think there's an a-priori reason to believe that the 500 hPa is causing surface cyclogenesis and not vice-versa.

Thank you for this comment. Indeed, we have made a too strong conclusion given the results we obtained. We have adjusted this statement in the revised manuscript. Instead, we say that there are deeper, or more frequent troughs during negative NAO-, which in turn could favor cyclogenesis near the east coast. It now reads:

"The increase in coastal cyclogenesis near the US east coast during negative phases (Sect. 3.3) is likely caused by more frequent, or deeper troughs over the over eastern North America, as seen in the difference in the average position of the 5400 m isohypse between positive and negative phases (Fig. 9). A region of divergence aloft and positive vorticity advection then more often overlaps the high temperature contrast region near the northern edge of the Gulf Stream offshore of the US east coast, leading to stronger surface cyclogenesis."

L245, point 2: Somewhere around here the manuscript transitions from a discussion of the cyclone composites to a more open discussion of all results. It might be useful to indicate that by a (sub)section.

Following this comment, and a similar comment from reviewer #2, we decided to present all important results in section 3, and move all interpretations, discussions, and comparisons to previous studies in a specific discussion section (section 4).

L248: How do you deduce where there is a jet exit and a jet streak?

We have removed this statement, as we do not show it explicitly.

Fig 10: The values seem to exceed the color scale by far, in particular for the NAO+ composite.

We have adjusted the color scale in the revised manuscript.

L276: Why refer to Fig 11 instead of Fig 7? Figure 11 has not been introduced and described yet.

Thank you for pointing that out. This was a mistake and was corrected in the revised manuscript.

L279-281: How do you see storm track variability and the variability in cyclone paths in Fig 7a?

We did not claim that Fig. 7 show the variability in storm tracking. We rather said that the storm track variability is visibly higher (lower) over the North Atlantic during NAO-(+) because of the tripole pattern of anomaly seen at the top right corner of Fig. 7b and 7d. Storms tend to follow more similar paths over the North Atlantic during NAO+ while theirs paths vary more during NAO-. We removed this statement in the revised manuscript as it is not clear from the figure and unnecessary.

L284. I was not aware of this name before. If there is a reason for this name that you can explain in half a sentence, you might consider adding that here.

As we realize that not all readers are familiar with the weather terms used in North America, we added a short sentence to explain the origin of this name:

“In western Canada, a positive anomaly on lee cyclogenesis during positive phases (Fig. 8a) gives way to an increase of Alberta Clippers forming over the plains and traveling eastward. Alberta Clippers (or Canadian Clippers) are cyclones that form frequently east (leeward) of the Canadian Rockies, over Alberta or the Canadian Territories during the cold season. They are called clippers as they typically travel very rapidly over the continent (clippers were some of the fastest moving ships of the 19th century).”

L290-291: What is the "Northern Rockies storm track"? This term seems a bit selfcontradictory as a storm track would cover a large area such as an ocean basin.
Similarly, Northern Rockies Lows typically refers to extratropical cyclones that form east (leeward) of the Northern Rockies (southern Alberta, Montana, Wyoming) in the western US, and afterwards travel eastward across the continent. We removed this section in the revised manuscript.

L293-297: Opposing effects for which quantity are being balanced? What result is the discussion of extreme and light precipitation based on?
We have removed this statement, as we do not show it explicitly in the figures.

L299: Why capital "Neutral"?
This has been changed in the revised manuscript.

L298-301: This seems to be the introduction to Fig 11 that I have been missing before. It however remains a bit unclear what I am to take away from Fig 11 in addition to what is already apparent from Fig 7. Further, how does this area of negative correlation conform the results of the study? This seems a very general statement which might not be equally valid for the variety of results and hypothesis presented before.
We have removed this statement and have properly introduced the figure in the result section of the revised manuscript. It is now figure 8.

L306: Here as well as in the discussion part of sec 3.5: Do the authors equate the cyclone track density and the storm track? In my opinion, that would be an justifiable assumption for the purposes of this study, but it should be explicitly mentioned.

Indeed, for the purpose of our study we equate the cyclone track density to the storm track. As suggested, we explicitly mentioned it in the revised manuscript.

L338-339: The paper has not considered extreme precipitation at all, so this final conclusion appears to be quite a stretch.

Given the addition of the analysis on extreme precipitation and snowfall, which confirm this statement, we kept it in the revised manuscript.

L341-344: If the authors keep their own cyclone tracking algorithm, this algorithm, or its results for the ERA5 reanalysis, should be made available.

The cyclone tracking algorithm will be made available upon request.

Response to reviewer #2

Chartrand and Pausata present a study into teleconnections between the North Atlantic Oscillation and wintertime precipitation and storm track variability across southeastern Canada and northeastern U.S. The authors utilize ERA5 and station observations to perform multiple tests including correlation and storm track analysis. They conclude 1) that positive (negative) NAO anomalies are associated with 1) reduced (increased) snowfall from the Mid-Atlantic U.S. to Nova Scotia CA, and 2) decreased (increased) coastal storm cyclogenesis in the vicinity of the U.S. East Coast, which is evidenced from a negative correlation between snow/precipitation ratio and the NAO index over the aforementioned region.

While I think this study has potential, the manuscript needs to be better focused and streamlined before publishing. In particular, in its current form the manuscript reads more like a review than a research paper, and I am still left wondering what is new and what has been previously reported. Along these lines, I recommend shortening the introduction, keeping only what is absolutely necessary background (e.g., the first sentence cites five previous studies in supportive of the definition of the NAO – are all of these critical?), and making a more explicit statement of motivation. In the results section, report only the results, and move interpretations and comparisons against previous work to a discussion section.

We thank the reviewer for his/her very useful comments and agree with the general suggestions. As mentioned at the beginning of this document, we have made major changes to the manuscript to make it more focused and streamlined. Notably, we have shortened the introduction and made the purpose/motivation of the study clearer, and we have moved the discussion, interpretation and comparison of results in a specific section to keep only important results in Sect. 3.

Otherwise, this additional insight to into the NAO association with winter storm tracks and snowfall distribution across the study region is valuable and should be of interest to readers.

We appreciate and thank the reviewer for the positive comment.

References

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Impacts of the North Atlantic Oscillation on Winter Precipitations and Storm Track Variability in Southeast Canada and Northeast US

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Abstract. The North Atlantic Oscillation (NAO) affects atmospheric variability from eastern North America to Europe. Although the link between the NAO and winter precipitations in the eastern North America have been the focus of previous work, only few studies **have considered extreme precipitation and** hitherto provided clear physical explanations on these relationships. In this study we revisit and extend the analysis of the effect of the NAO **on mean and extreme winter precipitations** over a large domain covering southeast Canada and the northeastern United States. Furthermore, we use the recent ERA5 reanalysis dataset (1979-2018), which currently has the highest available horizontal resolution for a global reanalysis (0.25°), to track extratropical cyclones to delve into the physical processes behind the relationship between NAO and precipitation, snowfall, snowfall-to-precipitation ratio (S/P), and snow cover depth anomalies in the region. In particular, our results show that positive NAO phases are associated with less snowfall over a wide region covering Nova Scotia, New England and the Mid-Atlantic of the United States relative to negative NAO phases**. Over the same area, the analysis of extreme snowfall revealed that there is as much as twice as many extreme snowfall events during negative phases compared to positive phases.** Henceforth, a significant negative correlation is also seen between S/P and the NAO over this region. This is due to a decrease (increase) in cyclogenesis of coastal storms near the United States east coast during positive (negative) NAO phases, as well as a northward (southward) displacement of the mean storm track over North America.

1 Introduction

The North Atlantic Oscillation (NAO) is the dominant mode of atmospheric variability in the North Atlantic (Hurrel et al., 1995). The NAO refers to swings in the atmospheric pressure difference between the Icelandic low and Azores high and is a key factor in the cool-season climate variability from the eastern coast of the United States to Siberia and from the Arctic to the subtropical Atlantic. A common measure of the NAO phase is the so-called NAO index (NAOI) that is commonly defined as the difference in the normalized sea level pressure (SLP) anomalies between Stykkisholmur/Reykjavik, Iceland and either Lisbon, Portugal, or Ponta Delgada, Azores (Hurrell, 1995). Positive NAO phases are associated with a deepening of the Icelandic low and a strengthening of the Azores high. The increased SLP gradient consequently lead to an enhanced westerly flow and a northward shift of the mid-latitude storm track (Rogers, 1990; Hurrell and Van Loon, 1997). The negative phase of the NAO is associated with weaker westerlies, an increase of meandering of the jet stream **and higher than average pressure over Greenland and Iceland, which often form blocking patterns over the North Atlantic (Shabbar et al., 2001).**

While the link between the NAO and winter precipitations in northern Europe and in the Mediterranean region **is moderately strong (Hurrell, 1995), the effects of the NAO phase on precipitation and snowfall amounts in eastern North America are known to be weaker (e.g.** Bradbury et al., 2002a**).** Various studies have shown that a slight negative correlation exists between the winter NAO phase and total winter precipitation in New England (Bradbury et al., 2002a; Ning and Bradley, 2015). A significant negative correlation between NAO and seasonal snowfall in New England (Hartley and Keables, 1998) and in other parts of northeastern US has also been reported (Kocin and Uccellini, 2004; Notaro et al., 2006; Morin et al., 2008). Moreover, Huntington et al. (2004) found a significant negative correlation between the NAO and the snowfall-to-precipitation ratio (S/P) in the northeastern US. Kocin and Uccellini (2004) have studied the snowfall climatology of the Northeast urban corridor in depth and have noticed that winters with a low NAO almost always coincide with the high snowfall years. While the low-frequency variations in the NAO proved to be quite well-correlated with seasonal snowfall in that region, their study also demonstrated that the occurrence of high-impact winter storms is strongly linked to the daily NAO value. However, Archambault et al. (2008) and Notaro et al. (2006) have found that precipitation events frequency in the northeastern US is slightly higher in positive NAO conditions. **Several studies (Stone et al., 2000; Bonsal and Shabbar, 2008; Whan and Zwiers, 2017) have investigated the relationship between precipitation and teleconnection patterns in Canada but have found that winter precipitation is generally poorly correlated with the NAO in eastern Canada.**

As extra-tropical cyclones account for almost all of the winter precipitation in eastern North America (Pfahl and Wernli, 2012), the variability in winter precipitation and snowfall can be explained by the shift in the storm track over North America and the North Atlantic. Several studies have focused specifically on the storm track variability in the North Atlantic and showed that the positive (negative) phase of the NAO **favors a more northern (southern) storm track over the North Atlantic (Rogers, 1990; Serreze et al., 1997; Riviere and Orlanski, 2007; Pinto et al., 2009**), as well as an eastward displacement of the mean trough axis over North America (Bradbury et al., 2002b). In a broader region, Wang et al. (2006) have found that a strong positive NAO is always associated simultaneously with more frequent cyclone activity in the high Canadian Arctic and less frequent activity on the east coast.

In this study we investigate the effect of the NAO on precipitation and snowfall over a wide domain covering southeastern Canada as well as the northeastern US. **Although previous studies have delved into the link between the NAO and winter precipitation in eastern North America, they have not considered extreme precipitation and snowfall. Knowing that extreme winter storms are some of the most damaging meteorological phenomenon that occur in these regions, it is highly relevant to look at the changes in extremes as well.** Furthermore, we use the recent high-resolution ERA5 reanalysis dataset (1979-2018) to track extratropical cyclones and to calculate the blocking frequency over the North Atlantic Basin. In doing so, we aim at providing a physical explanation for the precipitation and snowfall variability based on the storm track variability associated with the phases of the NAO.

The paper is organized as follows. Data and methodology are described and discussed in section 2. Section 3 presents the results obtained from statistical analysis of the winter climate and storm track variability with the NAO. **Section 4 presents a discussion of the results. Finally, the main findings are presented in section 5, along with the conclusion.**

2 Data and methods

2.1 Datasets

The NAOI used in this analysis is the monthly station-based index (Hurrell, 1995) based on the difference of normalized SLP between Lisbon, Portugal and Stykkisholmur/Reykjavik in Iceland (taken from the National Center for Atmospheric (NCAR) website: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based; Hurrell and National Center for Atmospheric Research Staff, 2020). Positive values of the NAOI are given by higher than average SLP over Portugal and lower than average SLP over Iceland. As in previous studies (Ning and Bradley, 2015; Bradbury et al., 2002a; Huntington et al., 2004), we consider the December to March period (DJFM), because consistent snowfall and winter conditions usually occur during these 4 months over most of the study area. The monthly NAOI has been used to calculate the link between winter precipitations and the NAO.

The daily snowfall, total precipitation and snowpack depth in snow water equivalent (SWE) data comes from the European Center for Medium-range Weather Forecasts (ECMWF) ERA5 high resolution (0.25°) reanalysis dataset for the period 1979-2018 (Hersbach et al., 2020). The precipitation and snowfall totals used for calculating correlations are the summed total precipitation and snowfall for each month at every grid points of the domain of interest. **The change in extreme precipitation and snowfall has been analyzed by using various extreme climate indices (R10mm, Rx1day, Rx5days, R20mm). However, the results are very similar among these indices within our domain. Therefore, for clarity in this paper we only show the results for the relationship between the NAO and the number of days with precipitation (and snowfall) >10 mm (R10mm).**

The S/P was calculated by dividing snowfall by total precipitation, as in Huntington et al. (2004). To analyze how the annual maximum of snowpack depth varies depending on the winter (DJFM) NAO phase, the seasonal maximum of SWE were taken over the course of the snow year (August 1st to July 31th), as the maximum of snow depth is sometimes achieved later than March in some parts of the domain. The winter climatology of total precipitation, snowfall, S/P and maximum seasonal SWE using the ERA5 dataset is shown in Fig. 1.

Linear correlation coefficients with the monthly NAOI were first calculated for **mean and extreme** precipitation, snowfall and S/P. For the snowpack SWE, correlation coefficients were calculated between maximum SWE and seasonal (DJFM) NAO. Correlations were calculated using the Pearson R-value method at every grid point. The statistical significance of these correlations using the p-value were determined at the 0.05 level. For statistical comparison between high NAO and low NAO months, the variables were averaged for the 40 months with the highest NAO (1st quartile) and for the 40 months with the lowest NAO (4th quartile). For the snowpack maximum SWE analysis, the 10 winters with the highest NAOI were compared to the 10 years with the lowest NAOI. To measure the statistical significance of these comparisons, the Student t test was used with a significance level of 0.05.

Daily precipitation and snowfall data from the Global Historical Climatology Network (GHCN-daily) served as validation data for the same period as the ERA5 dataset (1979-2018). The data from 29 stations well distributed in the domain has been analyzed. Of these stations, 14 are located in eastern Canada, 6 are located in New England, and 9 are located in the Mid-Atlantic region of the United States (Fig. 2). These stations were chosen based on the availability of data in the 1979-2018 period. Each station has near-complete precipitation data in this time period, which is essential for the comparison between results. Many stations that had data covering the whole time period of interest were rejected because of the high percentage of missing data during some years. Station inclusion criteria were intended to prevent stations with short, non-representative data records to bias the analysis. The same calculations on monthly precipitation, snowfall and S/P that have been done on ERA5 gridded data have been performed using the station-based data. Comparison between station-based and reanalysis data also helped validating the ERA5 data on a regional scale.

2.2 Storm tracking algorithm

In order to track individual cyclone trajectories on the ERA5 dataset, we developed a storm-tracking algorithm based on well-established methods, particularly those presented in Murray and Simmonds (1991) and Hanley and Caballero (2012). **We modified these methods rather than directly use one of them to improve the algorithm performance in tracking the extra-tropical cyclones over our domain of interest (including over mountains), when using the high resolution and 3-hourly output of the ERA5 reanalysis.** The main features of the algorithm are described here below.

- **Because of the high resolution of ERA5, we first use a Cressman smoother (400 km influence radius) to filter out small-scale stationary local minima in the SLP field** in the inter-mountain regions and retain only synoptic scale low-pressure systems. Local minima in the SLP **field (SLP value is smaller than the eight neighboring grid points)** are then taken as low-pressure centers for the tracking process.
- **Cyclones trajectories construction are based on linear projection: to forecast the second position in a cyclone trajectory, the 500-hPa wind field is used; afterward, the location of future low-pressure centers are extrapolated (linearly projected) by using the difference between the previous and current center's locations.** Matches between low-pressure centers at each time step are attempted by looking at the nearest centers found from the predicted trajectories. If several matches are possible for a single trajectory, absolute departure from predicted position and pressure with predicted value is used for matching low-pressure centers. **Low-pressure center that are not matched to a previous storm track are used as first center for a new storm trajectory.**
- **After each complete storm trajectory, two elimination criteria are applied in order to remove the stationary orographic features and short-lived features from the list of tracks found; a minimum total displacement of more than 10° and a minimum lifetime of 48 hours.**

The track density, also known as cyclone occurrence or frequency, is defined in this study as the number of cyclone centers **per 2.5° x 2.5° area. For the purpose of the study, we equate changes in the cyclone track density to changes in storm tracks.** Cyclogenesis density is defined as the number of cyclone geneses (first points in trajectories) per 2.5° x 2.5° area. The spatial distribution of both track density and cyclogenesis density climatology (Fig. 3) are well in agreement with previous work that used different tracking methods (e.g. Neu et al., 2013). In particular, the main region of lee cyclogenesis east of the Canadian and Colorado Rockies are very well represented, as well as the areas of maximum coastal cyclogenesis due to the land-sea temperature contrast just offshore of Cape Hatteras in North Carolina (Fig. 3a). **Furthermore, this storm tracking method performed very well in the tracking of specific winter storms that affected eastern Canada between 2000 and 2013 (see Chartrand and Thériault, under review).**

2.3 Blocking frequency

Blockings near Greenland (i.e. Greenland block) are known to be responsible for deeper troughs over eastern North America (e.g. Resio and Hayden, 1975), which consequently have an influence on cyclogenesis and storm track. For that reason, we investigated the changes in blocking frequency during positive and negative NAO months over the North Atlantic Basin (30°N-70°N, 85°W-0°E). The analysis of the blocking frequency using the ERA5 dataset was performed using a bi-dimensional index that identifies reversals in the meridional gradient of the 500-hPa geopotential height (Pausata et al., 2015; Anstey et al., 2013; Tibaldi and Molteni, 1990). At each grid point of latitude ϕ and longitude λ, the northward and southward meridional gradients of geopotential heights are respectively estimated following Eq. 1 and Eq. 2:

$$\Delta_N(\phi,\lambda) = \frac{Z_{500}(\phi,\lambda) - Z_{500}(\phi - 15°,\lambda)}{15°}, \quad (1)$$

$$\Delta_S(\phi,\lambda) = \frac{Z_{500}(\phi + 15°,\lambda) - Z_{500}(\phi,\lambda)}{15°}, \quad (2)$$

A blocking event at a grid point is diagnosed when two conditions are verified: (1) $\Delta_N(\phi,\lambda) > 0$, indicating a reversal of the climatological conditions with easterlies equatorward of the grid point, and (2) $\Delta_S(\phi,\lambda) < -10\, m/°$, indicating westerlies poleward of the grid point. The blocking frequency (%) is then obtained by the number of timesteps that a grid point is defined as "blocked" divided by the total number of timesteps.

3 Results

In this section we first present the relationship between the NAO and total precipitation, snowfall and S/P (Sect. 3.1): for each variable, the spatial pattern of correlations with the NAO index is discussed as well as the difference in monthly averages between high NAO and low NAO months. **In Section 3.2, extreme precipitation and snowfall are considered, as well as the link between seasonal NAO and maximum snowpack depth. Finally, in Section 3.3 we present the effect of the NAO on storm tracks and cyclogenesis in North America.**

3.1 Changes in total precipitation, snowfall, and snowfall to total precipitation ratio

For total precipitation, the results show that only a weak relationship with the NAO exists over most of the domain of interest. Nonetheless, the coastal regions of New England and the Mid-Atlantic show slightly negative correlations between -0.10 and -0.20, with limited areas showing significant values (Fig. 4b). In relative terms, these coastal areas received up to 15-20% less precipitation during positive NAO compared to negative NAO months (Fig. 4a). **When moving northward or westward from the northeastern US coast, the results show a gradual reversal of correlation coefficient, which becomes slightly positive in southern Newfoundland and around the Great Lakes.** In Atlantic Canada, the correlation coefficient is as high as 0.3 on the southern coast of Newfoundland. The correlation is instead moderately negative over Labrador, being the only area that show a clear relationship between the NAO and mean precipitation (Fig. 4b).

When looking at snowfall (Fig. 4c,d), the relationship between snowfall and the NAO is much stronger than for total precipitation, especially for the northeastern US (Fig. 4c,d). In a wide corridor from southern Nova Scotia to the southeast US, a significant negative correlation is shown together with notable decrease in snowfall during NAO positive. In the Mid-Atlantic region, the snowfall that is received during months with positive NAO is on average half the snowfall during NAO negative months. The negative correlation between snowfall and the NAO is statistically significant all over the northeastern US except at the northernmost parts of the region, which implies that high snowfall is associated with the negative phase of the NAO. Moving northward into southeastern Canada, the ERA5 results show correlations fading toward zero and becoming weakly positive in most of the region between 45°N and 50°N**. In Newfoundland and Labrador, the snowfall relationship pattern with the NAO is similar to that between precipitation and NAO, which is not surprising as almost all precipitation falls as snow during the cold season in this region (Fig. 1c).**

The relationship between winter snowfall-to-precipitation ratio and the NAO (Fig. 4e,f) shows a very similar pattern in the northeastern US as the link between snowfall and NAO (Fig. 4c,d). As for snowfall, southern New England and the Mid-Atlantic region are area with the strongest correlation between NAO and S/P. Everywhere within the northeastern US, positive NAO tends to bring a lower S/P ratio, the only exception being northern Maine. Southern parts of eastern Canada also show a decrease in S/P during positive NAO months. In southern Nova Scotia, this decrease is as high as 0.05 (i.e. from 45% to 40% of S/P), and the negative correlation is significant. In Newfoundland and northeastern Quebec, the S/P ratio is instead higher during positive NAO.

All over the domain of interest, the ERA5 and station-based results are consistent with each other. Only small differences exist between the results. Notably, for the correlation between snowfall and the NAO over southern Quebec, a slight negative correlation also exists with station results, although not with ERA5 results. Overall, these results indicate that the NAO has a much larger impact on the variability of winter precipitation and snowfall in the northeastern US compared to southeastern Canada.

3.2 Changes in extreme precipitation, snowfall, and maximum snow depth

The relationship between the monthly NAO and extreme precipitation is fairly similar to the relationship between the NAO and total precipitation. However, the results for extreme precipitation are noisier, and there are more inconsistencies between reanalysis-based and station-based results, which is explained by the much larger variability in the amount of days per months with precipitation >10 mm compared to the variability of the mean precipitation. In the coastal regions of the northeastern US, there is a slight negative correlation that reaches statistical significance in some areas. There is on average 20 to 30% less >10 mm days during positive NAO months compared to negative NAO months in that region. The inverse results are seen over the Canadian Maritimes and south of the Great Lakes, where positive NAO months see on average slightly more heavy-precipitation days than negative NAO months.

The relationship is again much stronger when we look at extreme snowfall (days with snowfall >10 cm) rather than extreme precipitation (Fig. 5c,d). A significant negative correlation exists in a large area covering the entire Mid-Atlantic region, southern New England, and parts of southern Nova Scotia. The densely populated region between Boston, MA, and Washington, DC are found to be affected up to twice as much by extreme snowfall days during NAO negative months compared to positive months (Fig. 5c). The extreme snowfall over eastern Canada is less affected by the NAO phase, with very limited areas that show significant correlations, except over eastern Labrador, where a negative correlation is seen between the two variables.

While the spatial distribution of the correlation coefficient between the NAO and SWE (Fig. 5e,f) is less homogeneous, it is coherent with the results for the mean and extreme snowfall. This is not surprising as high snowfall is well correlated with maximum SWE in winter. Significant negative correlation is again shown in the Mid-Atlantic coastal region. As south of 40°N, snow that falls during storms usually stays on the ground only for few days, this also suggest that there is an increase of heavy snowstorms affecting the Mid-Atlantic during negative NAO winters. Although not statistically significant, negative NAO winters tend to be linked to a 15-30% increase in snow cover depth in New England compared to positive NAO. In eastern Quebec, there is a significant positive correlation between SWE and NAO, which is also consistent with the positive correlation with snowfall and S/P.

As the snowpack is strongly affected by temperature, negative correlations and increase of maximum SWE in the northeastern US during negative NAO could also be partly explained by the colder conditions prevailing in that region during the negative phase (Fig. 6), which was also pointed out in previous studies (Notaro et al. 2006; Ning and Bradley, 2015). In a similar manner, colder temperature witnessed during a positive NAO phase in eastern Quebec (Fig. 6; also in Wettstein and Mearns, 2002) can explain the positive correlation between SWE and the NAO found in that region.

3.3 Changes in storm tracking

In order to better understand the causes of the precipitation and snowfall anomalies discussed in the previous **sections**, we analyze the changes in track density and cyclogenesis across North America associated with the two phases of the NAO **(Fig. 7).**

During positive NAO conditions, the results show a considerable positive anomaly on lee cyclogenesis in Western Canada compared to neutral conditions (Fig. 7a), giving way to an increase in cyclonic activity in Canada and the Arctic during a positive NAO phase (Fig. 7b). However, over the US, there is no significant changes in storm tracking, except for a slight decrease in lee cyclogenesis over Colorado (Colorado Lows) and Montana (Northern Rockies Lows).

The most notable result is the increase in cyclone occurrence in the western North Atlantic just offshore of the northeastern US coast during a negative phase of the NAO (Fig. 7d). While a decrease in cyclone occurrence is seen in that region during a positive phase (Fig. 7b), the anomaly is not as strong as during a negative phase. This implies that negative NAO conditions particularly favor an increase in frequency of Nor'easters (coastal storms). Near both Cape Hatteras and Cape Cod, which are two typical regions of coastal storms cyclogenesis on the US east coast (Davis et al., 1993), the cyclogenesis is strongly favored during negative NAO (Fig. 7c). Another important aspect of the changes in the storm track is the southwest-northeast oriented dipole in the cyclone occurrence anomaly over the eastern half of the continent during negative NAO months (Fig. 7d). This dipole suggests a southward shift in the storm track as the storm track density decreases over southeast Canada and northeast US but increases over southeast US.

The spatial pattern of correlation between the NAO and track density (Fig. 8) are consistent with the anomalies of cyclone occurrence for both positive and negative NAO. Large areas of significant negative correlation are obtained over the southeast US and in the western North Atlantic between 35°N and 45°N, as well as over Labrador. Over Canada's Western and Arctic regions, the correlation is instead positive, with statistical significance that covers a large area. The results also show that more cyclones tend to follow the typical North Atlantic storm track during positive phases, with more cyclones passing directly over Newfoundland and over the North Atlantic, south and east of Greenland during NAO positive phases.

Cyclogenesis, and the storms displacement are directly related to the upper-air circulation. For that reason, we have also investigated the relationship between NAO and the mean 500-hPa geopotential height. The link between these two variables is more evident over the North Atlantic (Fig. 9), as it is closely related to the definition of the NAO. A dipole pattern of strong positive correlation in the subtropical and mid-latitudes North Atlantic, and negative correlation in the subpolar North Atlantic is clearly shown. This pattern extends over eastern North America. Over southeastern Canada and northeastern US, a positive correlation is seen, indicating higher 500-hPa geopotential heights during positive NAO conditions. The difference in the average position of the 5400 m isohypse

between positive and negative phases could indicate that troughs are more likely to be present over the eastern part of the continent during negative NAO.

4 Discussion

The results presented in the previous section provide insight on the mechanism of winter climate variability in relationship with the NAO. Changes in mean circulation patterns associated to the NAO over North America and the North Atlantic produce significant shifts in cyclogenesis and associated storm tracks, directly impacting regional precipitation and snowfall in the region.

The increase in coastal cyclogenesis near the US east coast during negative phases (Sect. 3.3) is likely caused by more frequent, or deeper troughs over the over eastern North America, as seen in the difference in the average position of the 5400 m isohypse between positive and negative phases (Fig. 9). A region of divergence aloft and positive vorticity advection then more often overlaps the high temperature contrast region near the northern edge of the Gulf Stream offshore of the US east coast, leading to stronger surface cyclogenesis. While their cyclogenesis is favored during a negative NAO phase, the spatial pattern of anomalies shows that cyclones tend to take a more zonal and southern path in the Atlantic (Fig. 7d). Rogers (1990), Serreze et al. (2002), and Pinto et al. (2009) also observed that during negative NAO phases, coastal storms often diverge from the continent near the 45th parallel and follow a track almost directly east, as opposed to continuing on a more typical northeastward trajectory following the coastline. This result suggests that they tend to affect the region in the vicinity of their formation area, with strong onshore flow and heaviest snowfall north of their path. But as they rapidly move offshore, their effects are not felt as much in areas further up the east coast. This could explain why the Mid-Atlantic region and New England have slight negative correlations between NAO and precipitation (mean and extreme), but not Atlantic Canada (Fig. 4b, 5b). The more zonal storm track of coastal storms during negative phases is likely caused by the much higher frequency of blockings near Iceland and Greenland, as presented in Fig. 10 (also in Shabbar et al., 2001; Woollings et al., 2008). The presence of a blocking high over Greenland forces the storms to move south of it, which is visible in the significant decrease in number of storms over Newfoundland and south of Greenland (Fig. 7d).

As the position of the rain/snow boundary during winter storms is strongly linked to the location relative to the storm center (e.g. Donaldson and Stewart, 1989), the southward shift in the storm track over the eastern half of the US explain the more frequent extreme snowfall event, higher snowfall and S/P witnessed all over the northeastern US and Nova Scotia during negative NAO months. This relationship found between snowfall, S/P and the NAO is consistent with previous studies that found out that major snowstorms that affected the Northeast US are often associated with a negative NAO (Kocin and Uccellini, 2004; Hartley and Keables, 1998).

Over Labrador, a lower (higher) cyclone occurrence during NAO positive (negative) relative to neutral (Fig. 7d) is consistent with the negative correlations found between precipitation and the NAO and between snowfall and the NAO. The higher occurrence of cyclones over Labrador and the western Labrador Sea during negative NAO may be also caused by the more frequent development of a Greenland blocking high during these NAO phases (Fig. 10). While most of the coastal storms will take a zonal path well south of the blocking high, some coastal storms, along with systems coming from the west, will be steered north, west of Greenland because of the anticyclonic circulation associated with the blocking high. Therefore, the results show a higher occurrence of cyclones in the western part of the Labrador Sea, bringing higher-than-normal precipitation to Labrador and southwestern Greenland (Fig. 4a), which was also pointed out in Auger et al. (2017). As they take a more northern track, these low-pressure systems advect warm air in the region, lowering the S/P.

In western Canada, a positive anomaly on lee cyclogenesis during positive phases (Fig. 8a) gives way to an increase of Alberta Clippers forming over the plains and traveling eastward. Alberta Clippers (or Canadian Clippers) are cyclones that form frequently east (leeward) of the Canadian Rockies, over Alberta or the Canadian Territories during the cold season. They are called clippers as they typically travel very rapidly over the continent (clippers were some of the fastest moving ships of the 19th century). Although they are not usually associated with very heavy precipitation, there is an increase of their occurrence during positive NAO over Canada and the northern US (Fig. 7a). This response could have a significant impact on the occurrence of storms in the Prairies region of Canada, such as an increase of prairie blizzards frequency. **Furthermore, it explains the slight positive correlation between extreme precipitation and the NAO around the Great Lakes (Fig. 5b), as these storms tend to move eastward and pass over the Great Lakes. However, these extreme events are mostly in the form of rain as no correlation between extreme snowfall and the NAO is present in that region.**

5 Summary and conclusion

In this study we examined the variability of the winter climate in relation with the NAO during the winter season over North America, **with a particular focus on extreme precipitation and snowfall** in the northeastern US and southeastern Canada. In order to better understand these changes in precipitation and snowfall, we also investigated the storm track and cyclogenesis variability associated with the NAO phases, as well as the changes in blocking frequency across the North Atlantic Basin.

First, we show that while there is only a slight negative correlation between precipitation and the NAO in the northeastern US, the average and extreme snowfall is instead significantly affected by the NAO phase in that region. Both reanalysis and station-based results show that positive NAO phases tend to bring considerably less snowfall compared to negative NAO phases months over a wide region covering Nova Scotia, New England and the Mid-Atlantic of the United States. Henceforth, a significant negative correlation is also seen between the snowfall-to-precipitation ratio and the NAO in the same region. **These results are explained by the increase in cyclogenesis of coastal storms near the US east coast during negative NAO phases, as well as a southward shift in the mean storm track over the United States. This increase in cyclogenesis is likely caused by more frequent, or deeper troughs over the eastern US.** During negative

NAO phases, the more frequent blocking over Greenland also forces cyclones to follow a more southerly and zonal storm track in the North Atlantic, leading to fewer cyclones tracking directly over New England and Atlantic Canada. As a result, negative correlations between the NAO and precipitation, snowfall and S/P in coastal northeastern US slowly fades when moving northward 45° N. Moreover, positive NAO phases are linked to a considerable increase in lee cyclogenesis east of the Canadian Rockies compared to neutral NAO conditions. **As cyclones that form due to lee cyclogenesis usually travel eastward across the continent to affect southeastern Canada, a slight positive correlation is found between cyclone occurrence and the NAO over most of eastern Canada. This causes more frequent extreme precipitation events to occur around the Great Lakes during positive NAO months.** Even with the increase (decrease) of cyclone occurrence during NAO positive (negative) over southeastern Canada, the only regions where total precipitation is significantly positively correlated to the NAO phase are southern Ontario, and limited parts of eastern Quebec and southern Newfoundland.

To conclude, using a combination of station-based and high-resolution ERA5 reanalysis data over a longer and more recent period (1979-2018) compared to previous studies, our study provides additional results on the mechanisms responsible for winter precipitations and storm track variability in the northeastern US and southeastern Canada. In particular, very few studies have hitherto investigated in detail the NAO impacts in Canada, and in particular on extreme precipitation and snowfall in this region. Given that global forecast models can predict reasonably well large-scale regimes such as the NAO at a lead time of several weeks (e.g. Johansson, 2007; Scaife et al., 2014; Black et al., 2017), the results presented in this study could prove valuable for improving the sub-seasonal forecasting of the probability of the occurrence of precipitation events, in particular heavy snowfall events.

Data availability. ERA5 reanalysis data are provided by the European Centre for Medium-Range Forecasts (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5; Hersbach et al., 2020). The NAO index data are provided by the National Center for Atmospheric Research (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based; Hurrell and National Center for Atmospheric Research Staff, 2020). **The cyclone tracking algorithm is made available upon request.**

Author contributions. JC performed most of the analysis and the writing of the manuscript. FSRP contributed to the analysis design, interpretation of the results, and writing of the manuscript.

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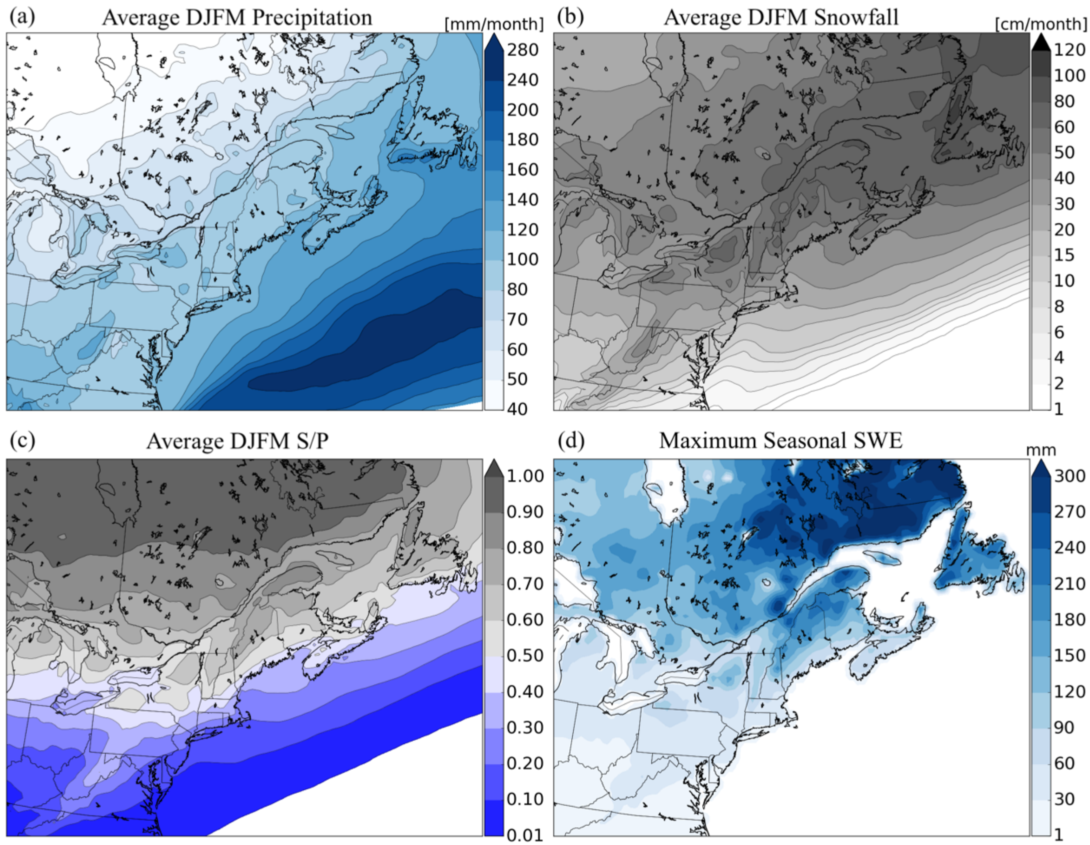


Figure 1. ERA5 1979-2018 climatological values of winter (December to March, DJFM) (a) total precipitation, (b) snowfall and (c) snowfall-to-precipitation ratio. (d) Average maximum SWE of the snowpack over the course of a snow year (August 1st-July 31th).

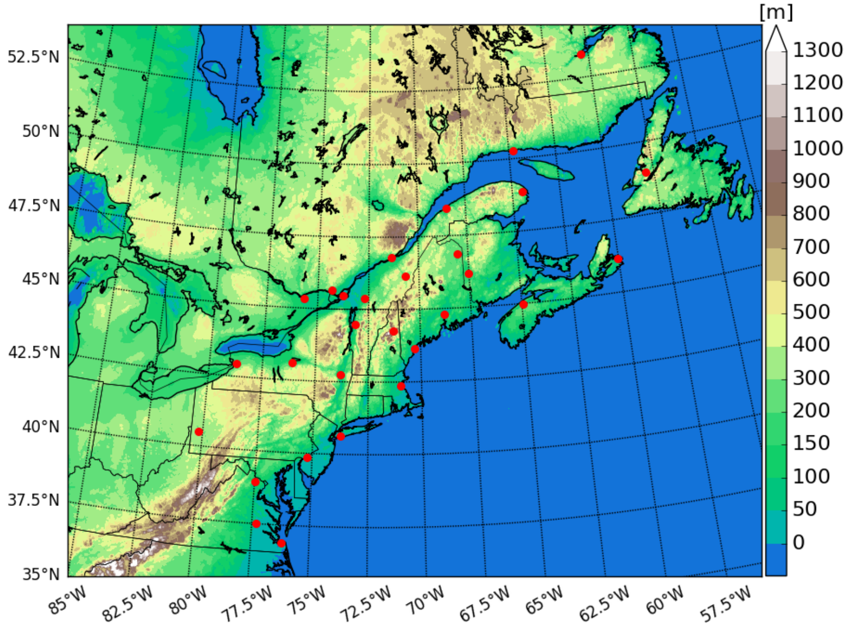


Figure 2. Map of the domain of interest with elevation included. Red dots represent the locations of the weather stations used in the study as data validation. The elevation data shown is ETOPO1 1 Arc-Minute Global Relief (retrieved from https://www.ngdc.noaa.gov/mgg/global/; Amante and Eakins, 2009).

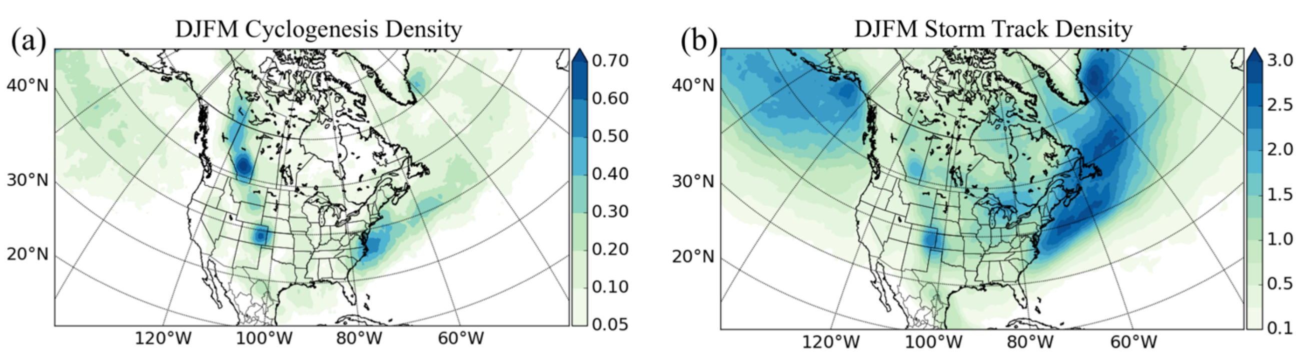


Figure 3. ERA5 average cool-season (December to March) (a) cyclogenesis density and (b) storm track density (or cyclone occurrence) over the 1979-2018 period. The units are cyclones per month per 2.5° x 2.5° area.

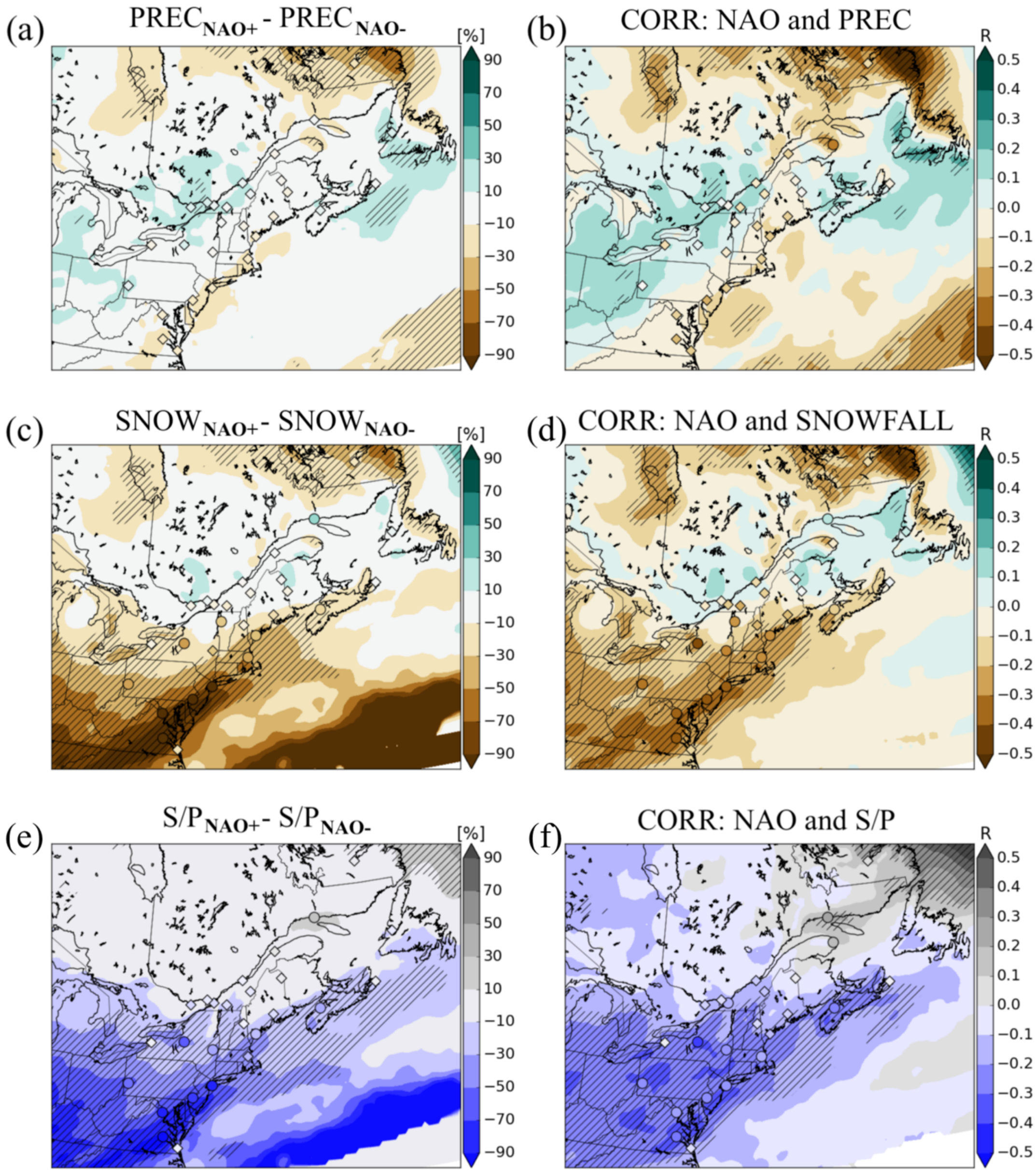


Figure 4. (a) Relative difference between average precipitation during positive NAO and negative NAO months (40-months composites, 1st and 4th quartiles) in winter (DJFM), positive values mean more precipitation during high NAO. (b) Correlation coefficients between monthly precipitation and monthly NAOI. **Hatched areas represent statistically significant values at the 0.05 level.** Shaded circles represent station-based correlation coefficient that are statistically significant at the 0.05 level, and diamonds represent values that are not statistically significant. (c), (d) as in (a) and (b), but for the relationship between monthly NAO and snowfall. (e), (f) as in (a) and (b), but for the relationship between monthly NAO and S/P.

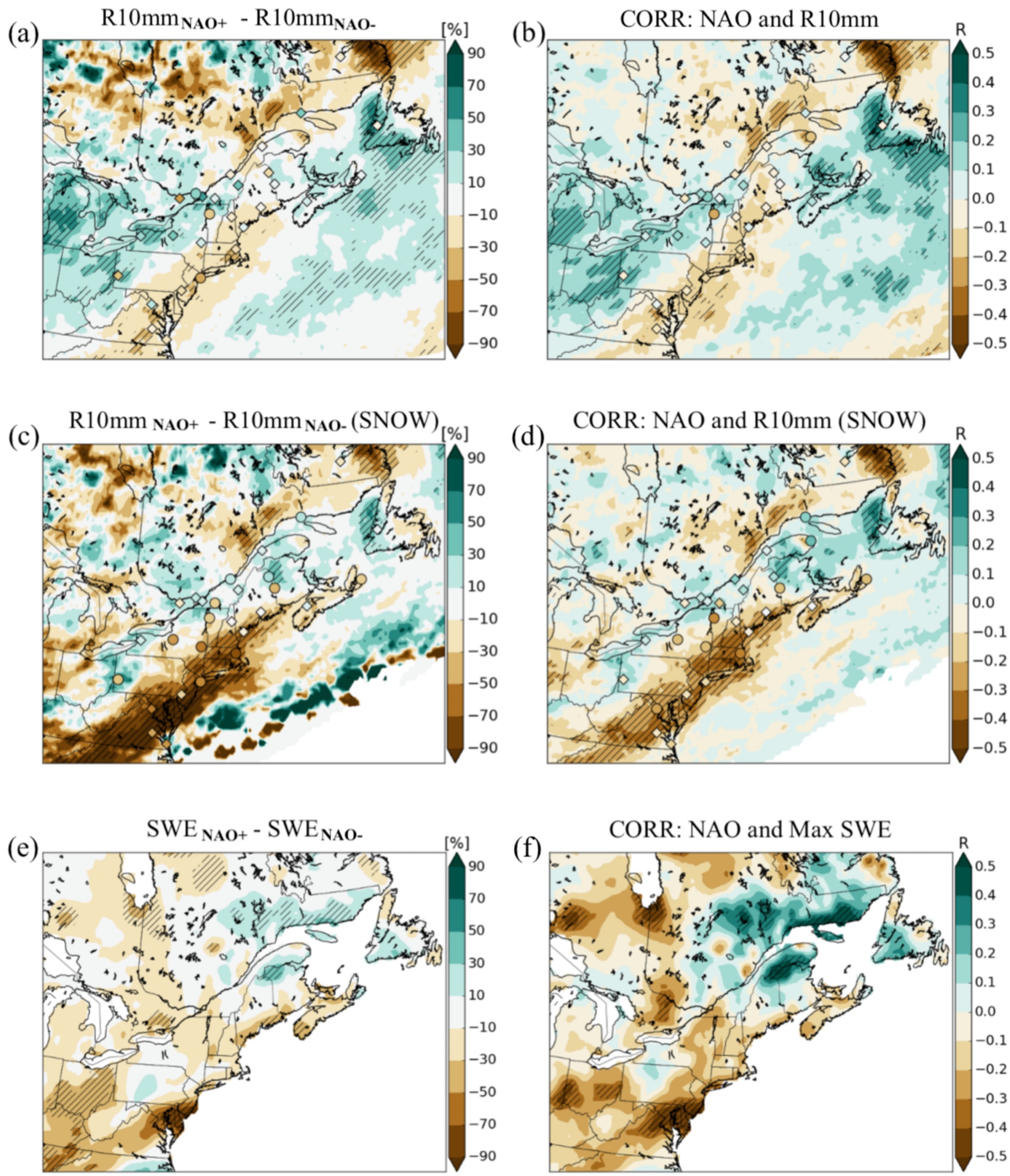


Figure 5. (a) Relative difference between the number of heavy precipitation days (>10 mm, R10mm) during positive NAO and negative NAO months (40-months composites, 1st and 4th quartiles) in winter (DJFM). (b) Correlation coefficients between number of heavy precipitation days and monthly NAOI. Hatched areas represent statistically significant values at the 0.05 level. Shaded circles represent station-based correlation coefficient that are statistically significant at the 0.05 level, and diamonds represent values that are not statistically significant. (c), (d) as in (a) and (b), but for the relationship between monthly NAO and the number of heavy snowfall days (>10 cm). (e), (f) as in (a) and (b), but for the relationship between cold season averaged NAO and annual maximum snowpack depth.

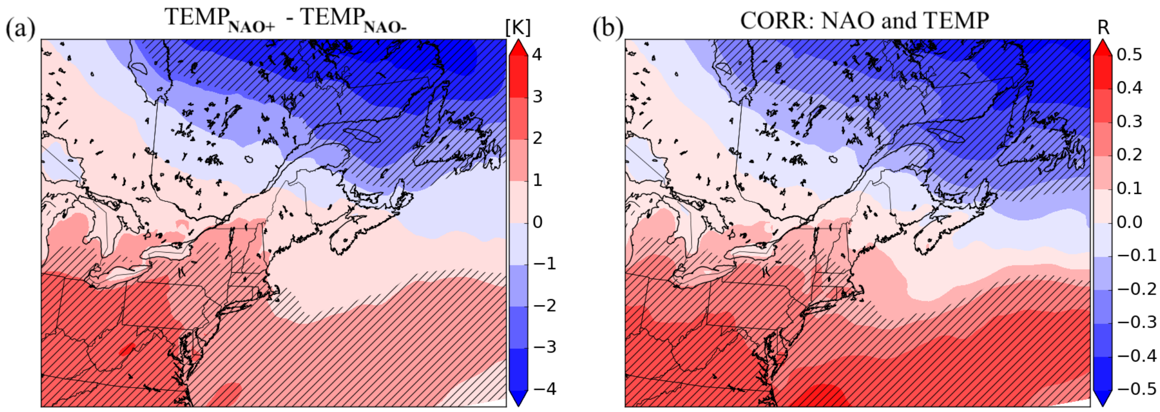


Figure 6. (a) Relative difference between average temperature during positive NAO and negative NAO months (40-months composites, 1^{st} and 4^{th} quartiles) in winter (DJFM), positive values mean warmer temperatures during high NAO. (b) Correlation coefficients between monthly temperature and monthly NAOI. **Hatched areas represent statistically significant values at the 0.05 level.**

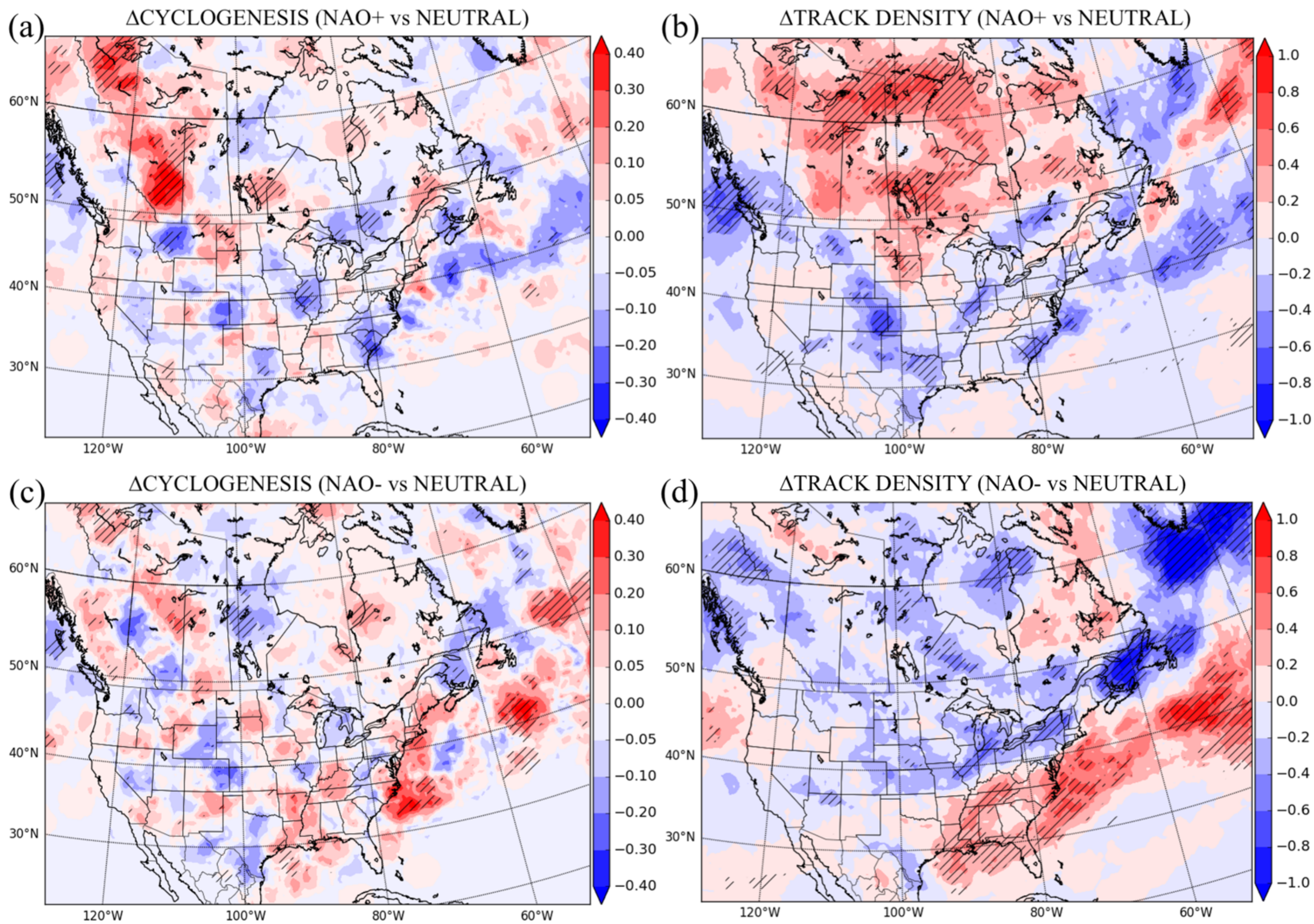


Figure 7. Anomalies of (a,c) cyclogenesis and (b,d) track density (cyclone/month per 2.5° x 2.5° area) over the course of (a,b) positive NAO and (c,d) negative NAO months (40-months composites, 1st and 4th quartiles) in winter (DJFM), positive values mean higher cyclone occurrence. Anomalies are calculated in relation to an average neutral NAO month. **Hatched areas represent statistically significant values at the 0.05 level.**

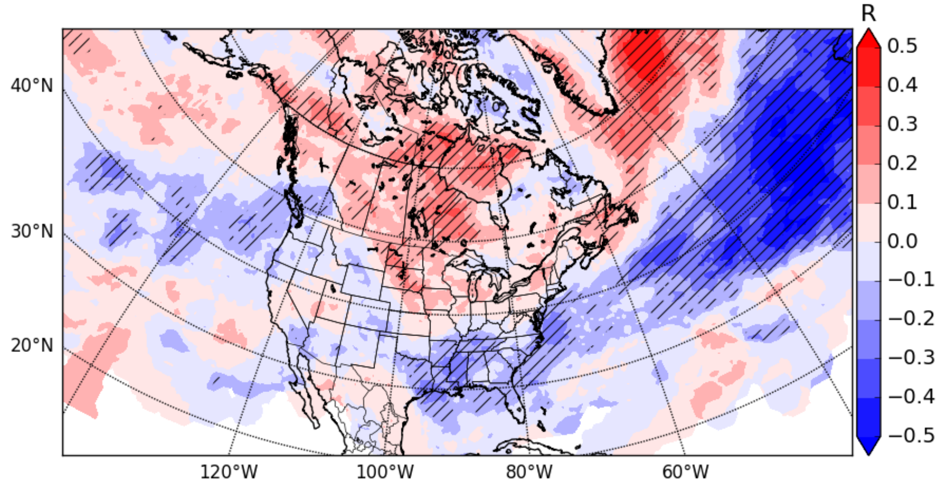


Figure 8. Track density correlation with the monthly NAOI in winter (DJFM). **Hatched areas represent statistically significant values at the 0.05 level.**

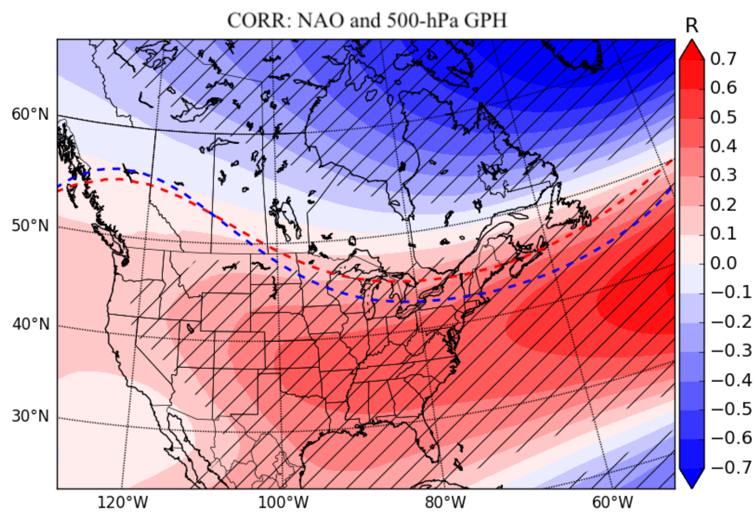
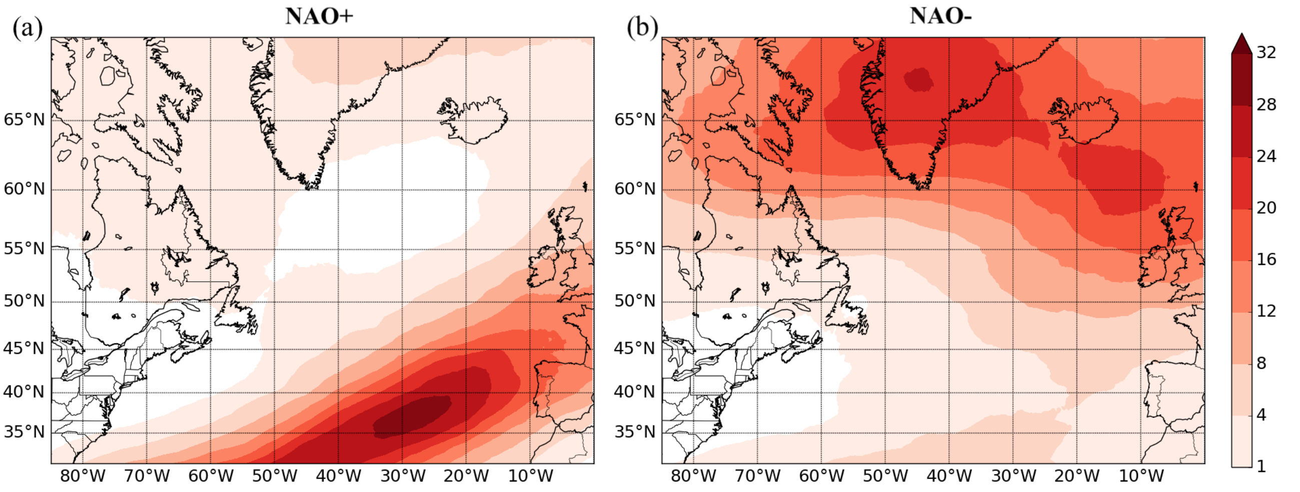


Figure 9. Correlation coefficients between monthly 500-hPa geopotential heights and monthly NAOI in winter (DJFM). **Hatched areas represent statistically significant values at the 0.05 level.** Dashed lines represent the average position of the 5400 m geopotential height isohypse during average low NAO months (blue) and average high NAO months (red).



510 **Figure 10.** Blocking frequency averaged over (a) positive NAO months and (b) negative NAO months (40-months composites, 1st and 4th quartiles in winter (DJFM).