Northern Hemisphere Storminess in the Norwegian Earth System Model (NorESM1-M)

Erlend M. Knudsen and John E. Walsh

Response to reviewers

We thank two anonymous reviewers for their suggestions on the manuscript. With the changes explained below, we feel that the paper is further strengthened compared to its second submission.

In the following, we go through each comment by the reviewers and explain our choices of changes in accordance to these. Where changes to the text in the manuscript are made, the relevant paragraph is reproduced from the .pdf manuscript to this .docx response, with changes written in **bold**.

Reviewer #1

1: Restructuring of 1 Introduction

We have revised the section 1 Introduction so that sea ice is no longer prominent at the start of it. Rather, we now jump right into the topic of storms (the focus of the paper) after two brief motivating sentences. The second sentence provides some historical context that motivates the present work. Only in the fourth paragraph do we now get into sea ice and its relevance for the focal topic of the paper (storms). The restructured 1 Introduction now reads as reproduced below.

Change of 1st-5th paragraph in 1 Introduction (changes in **bold**):

The Arctic climate has undergone substantial change in recent decades, and these changes are projected to continue into the future. Much of the effort to diagnose and project Arctic change has focused on temperature, sea ice and precipitation. However, climate-driven changes in storms are arguably more important considerations for Arctic residents, as well as for the heat and moisture budgets of the atmosphere. The impacts of storms are magnified by the loss of sea ice, which increases wave activity, coastal flooding and erosion and also increases the risks of vessel icing in waters newly accessible for marine transport and for other offshore activities (AMAP, 2005).

Analyses of observational data have produced mixed results on trends of high-latitude storminess. In earlier studies, Zhang et al. (2004) found an increase of Arctic cyclone activity, while McCabe et al. (2001) reported northward shifts of storm tracks over the Northern Hemisphere (NH) over the last several decades of the 20th century. Wang et al. (2006) detected a northward shift of cyclone activity, primarily during winter, over Canada during 1953–2002, and this meridional shift was confirmed more generally in a more recent study by the same group (Wang et al., 2013). The recent U.S. National Climate Assessment (Melillo et al., 2014) points to a poleward shift of storm tracks over the United States during recent decades. However, Mesquita et al. (2010) found that temporal trends of cyclones in the North Pacific Ocean have generally been weak over the 60-year period ending 2008. The U.S. Global Change Research Program (Karl et al., 2009) points to an increase of storminess on the northern Alaskan coast and to associated risks of flooding and coastal erosion along with expected sea level rise. Since any increases of coastal flooding and erosion are also related to retreating sea ice, storms in coastal areas of the Arctic can pose increasing risks regardless of whether storm activity is changing.

Previous work addressing cyclone-sea-ice linkages has shown increasing cyclone strength occurring with retreating September sea ice edge, though no relationship with cyclone counts was found (Simmonds and Keay, 2009). Increasing amounts of open water in the Arctic enhance exchanges of heat, moisture and momentum between the surface and atmosphere as a cyclone passes. Depending on the track of a cyclone, these additional fluxes can impact cyclone development. Two studies, one an evaluation of midlatitude marine cyclones (Kuo et al., 1991) and the other a case study of summer Arctic cyclones (Lynch et al., 2003), found surface energy flux input to be most important in the initial formation stages of the cyclone. Inputs in the later stages of the cyclone life cycle showed little impact. Furthermore, two case studies of Arctic cyclones found that increased surface energy fluxes in the later stages of the cyclone were not enough to overcome the large-scale dynamics (Long and Perrie, 2012; Simmonds and Rudeva, 2012). However, the former study indicated increased maximum wind speeds as the cyclone studied moved over open water, primarily through enhanced momentum exchange between the surface and atmosphere compared to what would occur over sea ice. These results indicate that the cyclone track is rather important as to whether or not changing surface conditions will significantly impact cyclone development.

In assessing linkages between recent Arctic warming and changes in storminess, polar amplification is a key consideration because it is associated with changes in baroclinicity. The polar amplification, due in part to the reduction of sea ice and snow cover**, manifests itself in the approximately two-fold difference between recent changes in the Arctic and global mean temperatures** (e.g., Bekryaev et al., 2010; AMAP, 2011). The warming of the Arctic has contributed to, and been increased by, the loss of sea ice (Stocker et al., 2013). Other important factors contributing to polar amplification appear to be the lapse rate feedback, the increase in atmospheric humidity and the fact that longwave radiation to space increases less under global warming in the cold polar regions than in the tropics (the so-called Planck Effect; Pithan and Mauritsen, 2014). Impacts of sea ice loss and Arctic warming on the atmospheric circulation in the high- and midlatitudes have been suggested by the studies of Overland and Wang (2010), Francis and Vavrus (2012) and Cohen et al. (2012), although the robustness of the midlatitude impacts has been questioned (Barnes, 2013; Barnes et al., 2014; Screen and Simmonds, 2013). Whether or not a large-scale signal of Arctic warming and sea ice loss has yet emerged from the noise of internal variability, climate models project continued Arctic warming and sea ice loss through the 21st century, increasing the likelihood of associated changes in the large-scale circulation. **Sea ice is therefore one of our foci in the assessment of changes in model-simulated storminess through the 21st century.**

Global climate models are arguably the best tools for identifying externally forced signals (greenhouse gases and aerosols) in storm activity. **They simulate polar amplification that is quite consistent with recent observed trends (Fig. 3.1 in AMAP, 2011).** In this study, we seek to validate the storm track components of two state-of-the-art global climate models over midlatitudes and high-latitudes of the NH. This is done through a comparison to a reanalysis data set. The models are the Norwegian Earth System Model version 1 with intermediate resolution (NorESM1-M) and the Community Climate System Model version 4 (CCSM4). The simulations examined here were performed as part of the Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor et al., 2012). After assessing the models' ability to capture the primary cyclone characteristics over a recent historical period, we compare the future changes of high- and midlatitude storms through the late 21st century. This evaluation is both a comparison between the time periods for each model and a model intercomparison on diverging changes towards the late 21st century. The primary metrics of storm activity here are frequency (track density) and intensity (mean intensity).

<u>2: Restructuring of 3 Results and discussion</u>

While we implemented the other 21 of the 22 comments from Reviewer #1, our attempted responses to this comment seemed to degrade the manuscript. The fusion of results and discussion allows us to discuss results as we present them and to place these results into the context of other studies, while the suggested separation of results and discussion into separate sections makes our presentation disjointed. The separation of the two sections forces readers to jump back and forth between the results and discussion.

For example, the citation to Catto et al. (2013) on line 374 (7th paragraph in 3.1.4 Precipitation), which deals with errors in model simulations of precipitation frequency and intensity, is directly relevant to the relationship between precipitation and cyclone frequency – the topic of the preceding three paragraphs of out text. It seems to us that a discussion of model deficiencies of precipitation fits best immediately after our results on the simulated precipitation.

Similar reasoning applies to other subsections in 3 Results and discussion.

3: Decreasing vs. retreating sea ice edge

Change of 4th paragraph in 1 Introduction (changes in **bold**):

Previous work addressing cyclone-sea-ice linkages has shown increasing cyclone strength occurring with **retreating** September sea ice edge, though no relationship with cyclone counts was found (Simmonds and Keay, 2009). Increasing amounts of open water in the Arctic enhance exchanges of heat, moisture and momentum between the surface and atmosphere as a cyclone passes. Depending on the track of a cyclone, these additional fluxes can impact cyclone development. Two studies, one an evaluation of midlatitude marine cyclones (Kuo et al., 1991) and the other a case study of summer Arctic cyclones (Lynch et al., 2003), found surface energy flux input to be most important in the initial formation stages of the cyclone. Inputs in the later stages of the cyclone life cycle showed little impact. Furthermore, two case studies of Arctic cyclones found that increased surface energy fluxes in the later stages of the cyclone were not enough to overcome the large-scale dynamics (Long and Perrie, 2012; Simmonds and Rudeva, 2012). However, the former study indicated increased maximum wind speeds as the cyclone studied moved over open water, primarily through enhanced momentum exchange between the surface and atmosphere compared to what would occur over sea ice. These results indicate that the cyclone track is rather important as to whether or not changing surface conditions will significantly impact cyclone development.

4: Energetic arguments for changes in Arctic warming and high-latitude storms

Change of 6th paragraph in 1 Introduction (changes in **bold**):

The impacts of a warming climate on high-latitude storms are difficult to anticipate. Both models undergo Arctic-amplified warming at low levels associated with significant loss of sea ice cover in the 21st century simulations examined here. **Using an idealized, moist general circulation model, O'Gorman and Schneider (2008) showed that changes in the atmospheric thermal structure affecting the mean available potential energy can lead to changes in eddy kinetic energy. The way in which this notion will play out in actuality with a warmer Arctic and less sea ice is uncertain.** On the one hand, the increased surface fluxes of heat and moisture might be expected to fuel more and stronger storms. On the other hand, the polar amplification decreases the low-level meridional temperature gradients, reducing the potential for storm activity. Nevertheless, because upper-level temperatures show greater increases in the tropics than in the Polar Regions, upper-level meridional temperature gradients actually increase (Harvey et al., 2015). Hence, the net effect on baroclinicity cannot be simply related to baroclinic disturbances such as extratropical cyclones (Ulbrich et al., 2009). Moreover, the Arctic amplification affects the variability of the jet stream, which is directly linked to the vertically integrated meridional temperature gradient via the thermal wind equation. Barnes and Screen (2015) provide a diagnostic assessment of these connections. Here, the model set-up implies that impacts of Arctic warming, sea ice loss and changes in surface fluxes and temperature gradients are implicit in our results.

New references:

- O'Gorman, P. and Schneider, T.: Energy of midlatitude transient eddies in idealized simulations of changed climates, J. Climate, 21, 5797–5806, doi:10.1175/2008JCLI2099.1, 2008.

<u>5: Restructuring of 2 Data sets and methods</u>
Please see section 2 Data sets and methods for changes made to the manuscript. The changes are as follows:

- New subsection 2.1 Models in the new manuscript containing 1st-6th paragraph of section 2 Data sets and methods in the previous manuscript.
- New subsection 2.2 Reanalysis in the new manuscript containing 7th-8th and 14th paragraph of section 2 Data sets and methods in the previous manuscript.
- New subsection 2.3 Temporal and spatial scales in the new manuscript containing 8th paragraph of section 2 Data sets and methods in the previous manuscript.
- New subsection 2.4 Methods in the new manuscript containing 9th-13th paragraph of section 2 Data sets and methods in the previous manuscript.

<u>6: Clarification use of sea ice concentration (SIC) and sea ice extent (SIE)</u>
Please see <u>5: Restructuring of 2 Data sets and methods</u> above for new structure of section 2 Data sets and methods. Please also note the renumbering of figures in the new manuscript, where Fig. A in the previous manuscript is Fig. 1 in the new manuscript.

Change of 1st-3rd paragraph in 2.3 Temporal and spatial scales (changes in **bold**):

While the storm track analysis is based on 6-hourly zonal (u) and meridional (v) wind data, sea ice concentration (SIC), **sea ice extent (SIE),** sea level pressure (SLP) and total precipitation (hereafter referred to simply as precipitation) examined here are monthly averages. **All parameters are derived from ERA-I (historical time period only), NorESM and CCSM, with the exception of historical SIE. The latter is from the National Snow and Ice Data Center (NSIDC; Fetterer et al., 2002, updated daily). SIE is the area of all grid cells with SIC > 15 %.**

Table 1 shows the monthly mean SIE averaged over a historical and two future scenario time periods in NSIDC (historical time period only), NorESM and CCSM. The seasonal cycle of climatological monthly SIE for the previous decade is captured by the two models, although both models show weaker seasonal cycles of ice retreat compared to the observational data from **NSIDC**. Nevertheless, Langehaug et al. (2013) found the relative trends in NorESM to be close to those observed. The projected **SIE** reduction is greatest in the autumn and early winter, especially in terms of the percentage reduction from the historical values. Even the areal reductions are largest during this portion of the year **(Table 1)**. Moreover, the observed ice loss during recent decades (1979–present) is also greatest during the autumn (Stroeve et al., 2012; Rogers et al., 2013). In view of this seasonality, we focus our analysis on the **extended autumn season September through December (**SOND**)**.

Figure 1 presents the representation of SIC over the historical time period in the two models, as well as projected changes in SIC over future scenarios and

time periods relative to the historical time period. Both models **simulate a** seasonally ice-free (SIE < 1 million km^2) **Arctic Ocean** during the second half of the 21st century**, with a slightly more rapid sea ice retreat in CCSM than NorESM. This trend motivates the region of focus, where retreating sea ice is expected to modify distribution and intensity of storminess parameters.**

7: Clarification storm frequency using relative vorticity (ζ) vs. sea level pressure (SLP)
Please see 5: Restructuring of 2 Data sets and methods above for new structure of section 2 Data sets and methods.

Change of 1st paragraph in 2.4 Methods (changes in **bold**):

The storm track analysis is based on the TRACK algorithm described by Hodges (1994, 1995, 1999). It uses 6-hourly 850-hPa relative vorticity (ζ) to identify and track cyclones, here calculated from the u and v fields. Rather than SLP, ζ is used for tracking due to the focus on storminess. ζ contains more information on the wind field and the high-frequency range of the synoptic scale, whereas SLP is linked to the mass field and represents the low-frequency scale better (Hodges et al., 2003). This results in generally more cyclones identified using vorticity tracking **compared to using SLP** (Hodges et al., 2011). **Not including the TRACK algorithm**, Neu et al. (2013) found the number of storms identified by methods based on vorticity to be in the middle range of those obtained using different tracking algorithms. **Rather, number of cyclones detected appears to decrease with decreasing resolution of the input data (Pinto et al., 2005).**

New references:

- Pinto, J., Spangehl, T., Ulbrich, U. and Speth, P.: Sensitivities of a cyclone detection and tracking algorithm: individual tracks and climatology, Meteorol. Z., 14, 823-838, doi:10.1127/0941-2948/2005/0068, 2005.

8: Inclusion of more polar low climatologies
Please see 5: Restructuring of 2 Data sets and methods above for new structure of section 2 Data sets and methods.

Change of 2nd paragraph in 2.2 Reanalysis (changes in **bold**):

Reanalyses **have strong difficulties** of capturing mesoscale low pressure systems (including "polar lows"), which have typical scales of 200–300 km and lifetimes generally shorter than two days (Condron and Renfrew, 2013). In a comparison of cyclones tracked from the ERA-40 reanalysis and from high-resolution satellite data, Condron et al. (2006) have shown that the failure to capture mesoscale cyclones is especially problematic in the subarctic North Atlantic. The polar low climatologies of Bracegirdle and Gray (2008)**,** Zahn and von Storch (2008) **and Zappa et al. (2014b)** also show maxima in the subpolar North Atlantic**, while Yanase et al. (2016) portray the corresponding climatologies over the Sea of Japan**. In the present study, our coarse-resolution models are compared with the coarse-resolution ERA-I reanalysis using the same tracking algorithm, so there is general consistency in the resolution and by implication in the under-capture of cyclones. Nevertheless, the estimates of cyclones reported here from all three sources (ERA-I, NorESM, CCSM) are almost certainly low relative to the actual numbers, and our findings pertain only to systems of synoptic scale and larger.

New references:

- Yanase, W., Niino, H., Watanabe, S., Hodges, K., Zahn, M., Spengler, T., and Gurvich, I.: Climatology of polar lows over the Sea of Japan using the JRA-55 reanalysis, J. Climate, 29, 419–437, doi:10.1175/JCLI-D-15- 0291.1, 2015.

9: Clarification reference to Catto et al. (2011)

Please see 11: Reference to figures in Appendix B below for new structure of section 3 Results and discussion.

Change of 3rd paragraph in 3.1 Scenario and time period comparison (changes in **bold**):

While the scaling appear more distinct for sea ice, SLP and precipitation, Figs. **3** and **4** show signs of similar behaviour for storm frequency and intensity. This is partly in contrast to Catto et al. (2011). Using the HiGEM high-resolution model, they found northeastward shift of the North Atlantic storm track for the **idealized doubled CO_2 experiment** only **and not for quadrupled CO_2. The CMIP5 model RCP4.5 and RCP8.5 scenarios here are not directly comparable as they represent weaker increases in CO_2 (up to 1.5 x CO_2 and 2.5 x CO_2 in 2070-2100 compared to 1979-2005). Nevertheless, in** our results, the northeastward shift gets stronger with scenario and time in NorESM (Figs. **3**a to **3**e and Figs. **4**a to **4**e). In CCSM, the North Atlantic storm track generally weakens with scenario and time (Figs. **3**f to **3**j and Figs. **4**f to **4**j). Overall, signals strengthen with scenario and time in both models. These results extend those of Zappa et al. (2013b), who found mean response generally larger, but **with larger inter-model spread**, for RCP8.5 than RCP4.5 in 19 CMIP5 models (not including CCSM).

10: Clarification reference to Zappa et al. (2013b)

Please see 11: Reference to figures in Appendix B below for new structure of section 3 Results and discussion.

Change of 3rd paragraph in 3.1 Scenario and time period comparison (changes in **bold**):

While the scaling appear more distinct for sea ice, SLP and precipitation, Figs. **3** and **4** show signs of similar behaviour for storm frequency and intensity. This is partly in contrast to Catto et al. (2011). Using the HiGEM high-resolution model, they found northeastward shift of the North Atlantic storm track for the **idealized doubled CO_2 experiment** only **and not for quadrupled CO_2. The CMIP5 model RCP4.5 and RCP8.5 scenarios here are not directly comparable as they represent weaker increases in CO_2 (up to 1.5 x CO_2 and 2.5 x CO_2 in 2070-2100 compared to 1979-2005). Nevertheless, in** our results, the northeastward shift gets stronger with scenario and time in NorESM (Figs. **3**a to **3**e and Figs. **4**a to **4**e). In CCSM, the North Atlantic storm track generally weakens with scenario and time (Figs. **3**f to **3**j and Figs. **4**f to **4**j). Overall, signals strengthen with scenario and time in both models. These results extend those of Zappa et al. (2013b), who found mean response generally larger, but **with larger inter-model spread**, for RCP8.5 than RCP4.5 in 19 CMIP5 models (not including CCSM).

11: Reference to figures in Appendix B

Please see sections 2 Data sets and methods and 3 Results and discussion for changes made to the manuscript. The changes are as follows:

- New subsection 3.1 Scenario and time period comparison in the new manuscript containing 1st-3rd paragraph of section 3 Results and discussion in the previous manuscript.
- Previous subsections 3.1-3.2 renamed subsections 3.2-3.3.
- Previous Fig. A renamed Fig. 1 and located in new subsection 2.3 Temporal and spatial scales.
- Previous Figs. B-E renamed Figs. 2-5 and located in new subsection 3.1 Scenario and time period comparison.
- Previous Figs. 1-8 renamed Figs. 6-13 with no changes to manuscript location.

Change of 3rd paragraph in 2.3 Temporal and spatial scales (changes in **bold**):

Figure 1 presents the representation of SIC over the historical time period in the two models, as well as projected changes in SIC over future scenarios and time periods relative to the historical time period. Both models **simulate a** seasonally ice-free (SIE < 1 million km^2) **Arctic Ocean** during the second half of the 21st century**, with a slightly more rapid sea ice retreat in CCSM than NorESM. This trend motivates the region of focus, where retreating sea ice is expected to modify distribution and intensity of storminess parameters.**

Change of 1st paragraph in 3 Results and discussion (changes in **bold**):

In the following, parameters representing storminess are presented. **Section 3.1 compares the representation of each scenario and time period in each of the models, explaining the choice of one scenario and time period for the future projections.** NorESM and CCSM **are compared to ERA-I over the historical time period in Sect. 3.2. Section 3.3 outlines** the expected changes of **the storminess** parameters towards the end of the century, as projected by NorESM and CCSM.

Change of 1st-4th paragraph in 3.1 Scenario and time period comparison (changes in **bold**):

Figures 2 to 5 picture the representation of the storminess parameters SLP, track density, mean intensity and precipitation in the two models. For each figure, the first column represents the historical time period, with increasing RCP value and time in the succeeding columns.

Projected changes in sea ice, SLP, track density, mean intensity and precipitation **suggest a near-linear scaling** with strength of scenario (RCP4.5 and RCP8.5) and time (1979–2005 to 2037–2063 and 2074–2100) in **the two models** (Table 1 and Figs. **1** to **5**). Hence, we consider the 2037–2063 time period to be an intermediate state between the **1979–2005** and 2074–2100 periods, and the RCP4.5 scenario to be mid-way to the RCP8.5 scenario. **This explains the choice in Sect. 3.3, where** the 2074–2100 time period following the RCP8.5 scenario **is the only scenario to be compared to the historical time period.**

While the scaling appear more distinct for sea ice, SLP and precipitation, Figs. **3** and **4** show signs of similar behaviour for storm frequency and intensity. This is partly in contrast to Catto et al. (2011). Using the HiGEM high-resolution model, they found northeastward shift of the North Atlantic storm track for the **idealized doubled CO_2 experiment** only **and not for quadrupled CO_2. The CMIP5 model RCP4.5 and RCP8.5 scenarios here are not directly comparable as they represent weaker increases in CO_2 (up to 1.5 x CO_2 and 2.5 x CO_2 in 2070-2100 compared to 1979-2005). Nevertheless, in** our results, the northeastward shift gets stronger with scenario and time in NorESM (Figs. **3**a to **3**e and Figs. **4**a to **4**e). In CCSM, the North Atlantic storm track generally weakens with scenario and time (Figs. **3**f to **3**j and Figs. **4**f to **4**j). Overall, signals strengthen with scenario and time in both models. These results extend those of Zappa et al. (2013b), who found mean response generally larger, but **with larger inter-model spread**, for RCP8.5 than RCP4.5 in 19 CMIP5 models (not including CCSM).

Table 2 presents the main results of this study. Representing circumglobal averages spanning large areas, the averages for mid- and high-latitudes might cancel out variations within each region. However, the maps presented in Sects. 3.2 and 3.3 will disclose these features. The values in Table 2 are discussed in more detail in **these sections**.

12: Clarification storm track bias relative to anomalous SIC and SIE patterns

Please see 11: Reference to figures in Appendix B above for new labelling of figures.

The reference to Fig. 1 in our manuscript refers to SIC. The reference to Magnusdottir et al. (2004, particularly Fig. 2b) refers to sea ice extent. However, in their case, there is also an increase in SIC. Moreover, SIC and SIE are closely linked (please see 6: Clarification use of sea ice concentration (SIC) and sea ice extent (SIE) above). Hence, to simplify the relevant paragraph, we used "sea ice" when referring to the anomalous patterns.

Change of 2nd paragraph in 3.2.2 Track density (changes in **bold**):

Compared to ERA-I, both models depict poleward-shifted storm tracks over the North Pacific Ocean, Canadian Arctic and the Nordic Seas (Figs. **7**b and **7**c). On the contrary, the eastern branch of the North Atlantic storm track is broader and extends farther south in the models. These features offer an explanation for the poleward-shifted and wider low SLP bands in Fig. **6**. For the North Atlantic Ocean overall, cyclones in NorESM and CCSM are slightly too zonal compared to ERA- I, consistent with the winter pattern found in CMIP5 models by Zappa et al. (2013a). This leaves fewer cyclones tracking through the Greenland Sea — the region where most Arctic cyclones track (Sorteberg and Walsh, 2008). It is worth mentioning that the zonal North Atlantic storm track bias is stronger in CCSM than in NorESM (Figs. **3a, 3c, 7b and 7c**). This coincides with a **sea ice** pattern of higher (lower) SIC in the Labrador Sea (Greenland and Barents seas) in CCSM compared to NorESM (Fig. **1**f compared to Fig. **1**a). This **sea ice** anomaly pattern was also found to be associated with weaker and more zonal North Atlantic storm track in CCSM3 during winter (Magnusdottir et al., 2004).

13: Rewording from "discrepancy" to "positive bias"

Change of 3rd paragraph in 3.2.2 Track density (changes in **bold**):

In CCSM, the number of cyclones within the domain of 40–90°N is 7 % higher than in ERA-I, mainly due to the **positive bias** in high-latitudes (Table 2 and Fig. **7**c). On the contrary, there are 2 % fewer cyclones in NorESM than found in ERA-I (Table 2 and Fig. **7**b). For NorESM, this anomaly stems from its resolution, which is about four times as coarse as in the reanalysis. This leaves fewer cyclones resolved (**Pinto et al., 2005;** Hodges et al., 2011).

14: Clarification reference to signal in CCSM

Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 4th paragraph in 3.2.2 Track density (changes in **bold**):

The **cyclone frequency bias** in CCSM offers an additional explanation to the large-scale background SLP biases across the main storm tracks discussed in Sect. **3.2.1**. As more cyclones are resolved in CCSM compared to ERA-I (Table 2), a particular grid point in the main storm track undergoes lower SLP for more time steps, understandably dependent on the cyclone strength. For regions of the main storm tracks, this can lower the SLP temporal mean. This is indicated by the anomalous low SLPs over the poleward-shifted North Atlantic and North Pacific storm tracks (Figs. **6**c and **7**c). **[Sentence deleted.]**

<u>15: Clarification meaning of "more coherent"</u>
Please see <u>11: Reference to figures in Appendix B</u> above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 3rd paragraph in 3.2.3 Mean intensity (changes in **bold**):

Model biases are generally more coherent **(spatially homogeneous)** for mean intensity than track density (Figs. **8**b and **8**c compared to Figs. **7**b and **7**c), where stronger (weaker) cyclones correspond to lower (higher) SLP (Table 2). However, this relationship does not hold for sea ice-covered areas (Figs. **8**b and **8**c compared to Figs. **6**b and **6**c).

<u>16: Inclusion of conclusions on heavy vs. light precipitation from Catto et al. (2015)</u>
From Catto et al. (2015), we were not able to find results related to light/heavy frontal precipitation per se. However, we found these main conclusions:

- Frontal precipitation frequency is too high in the 18 CMIP5 models studied, while frontal precipitation intensity is too low.
- Frontal precipitation is better represented in the models than non-frontal and total precipitation.
- Frontal precipitation makes up a too large fraction of total precipitation in midlatitudes.

These main conclusions are incorporated into the altered paragraph of relevance below.

Please see <u>11: Reference to figures in Appendix B</u> above for new structure of section 3 Results and discussion.

Change of 7th paragraph in 3.2.4 Precipitation (changes in **bold**):

The discussed connection between total precipitation and cyclone frequency and strength is based on an assumption that frontal precipitation is well captured in models. However, Stephens et al. (2010) found that climate models generally overestimate the frequency and underestimate the intensity of precipitation**, a conclusion Catto et al. (2015) found valid also for frontal precipitation**. These compensating errors were discussed in more detail by Catto et al. (2013**, 2015**), who found them largely to be driven by the non-frontal precipitation regimes. These findings are consistent with the biases in NorESM and CCSM.

New references:

- Catto, J., Jakob, C., and Nicholls, N.: Can the CMIP5 models represent winter frontal precipitation?, Geophys. Res. Lett., 42, 8596–8604, doi:10.1002/2015GL066015, 2015.

17: Reference to month for percentage future scenario changes
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

We have clarified to what region, month and model percentages in subsection 3.2 Future scenario changes refer to. These changes are reproduced below.

Some of sentences are left unchanged as the text before the percentages clarify region, month and model of interest. This is the case for 4th and 7th paragraph in 3.3.2 Track density, 1st paragraph in 3.3.3 Mean intensity and first occurrence in 6th paragraph in 3.3.4 Precipitation.

Change of 2nd-6th paragraph in 3.3.2 Track density (changes in **bold**):

According to NorESM and CCSM, fewer cyclones will track along the current main storm tracks in the North Atlantic and North Pacific oceans towards the end of the century (Fig. **11**). This explains the 3.9 **% (NorESM)** to 6.5 % **(CCSM)** reductions in midlatitudes found in Table 2 **(for SOND)**, with up to 20.1 % **(NorESM)** and 21.7 % **(CCSM)** drops in WNA and NWE activity, respectively (Table 3**; both for September**). On the other hand, there are signals partly indicating more cyclones poleward of this in the two models in Fig. **11**.

The general reduction in North Pacific cyclones is associated with more cyclones in parts of the Bering Sea (Fig. **11**). However, no consistent tendency is found for the two models and two months, explaining the highly varying changes for BWA in Table 3 (from −13.4 % **in NorESM** to +15.5 % **in CCSM, both for December**). A comparison to Harvey et al. (2015) reveals that this signal of a poleward shift of the North Pacific storm track was more apparent in CMIP3 models.

NorESM projects a stronger northward shift than CCSM in the North Pacific sector (Figs. **11**a and **11**c compared to Figs. **11**b and **11**d), although December averages within the chosen regions suggests the opposite (+18.2 % in WNA, −13.4 % in **BWA**; Table 3). While **NorESM indicates** more cyclones to track through the Bering Strait and into the Arctic Ocean in September, a more zonal pattern **is projected** in the North Pacific Ocean **for December,** with a significant **track density** increase in a band around 50°N (Figs. **11**a and **11**c). This pattern is not found in CCSM (Figs. **11**b and **11**d), which rather projects strong increases along the North American and Siberian Arctic coasts in December (Fig. **11**d). The latter feature is mostly a consequence of coinciding enhanced cyclone generation (not shown).

Fewer cyclones track across the North Atlantic Ocean overall in both months and models (Fig. **11**). NorESM, like the majority of CMIP5 models (Feser et al., 2015, and references therein), project an eastward extension of the North Atlantic storm track (Figs. **11**a and **11**c). This evolution occurs downstream of an already too zonal storm track compared to the reanalysis (Fig. **7**b), with a 10.2 **% (December)** to 12.8 % **(September)** increase in NWE (Table 3). CCSM **also** represents the North Atlantic storm track too zonal originally (Fig. **7**c), but projects no clear indications of a more zonal storm track towards the end of the 21st century (−21.7 **% for September** to +1.2 % **for December over** NWE in Table 3).

No significant changes are found in NEE (Table 3 and Figs. **11**a and **11**c). Rather, both NorESM and CCSM show weak reductions in NEE track density (−11.6 **% in CCSM** to −0.8 % **in NorESM**; Table 3) associated with enhancements in the Greenland Sea in September (Figs. **11**a and **11**b). Fig. **1** reveals that the latter increase coincides with a sea ice retreat in the Greenland Sea over the century. These results follow those of Deser et al. (2000), Magnusdottir et al. (2004) and Knudsen et al. (2015), who found storm activity to be very sensitive to the sea ice variations east of Greenland. Moreover, Chen et al. (2015) showed a corresponding sensitivity in synoptic activity here associated with variations in the surface mass balance of the Greenland Ice Sheet.

Change of 5th + 7th paragraph in 3.3.3 Mean intensity (changes in **bold**):

According to the two models, cyclones generally weaken in WNA (−6.2 **% for September** to 0 % **for December, both in NorESM**) and strengthen in BWA (−1.4 **% in NorESM for September** to +8.3 % **in CCSM for December;** Table 3 and Fig. **12**). This mainly follows from the poleward-shifted storm track and track density pattern discussed in Sect. **3.3.2**, although the negligible change in cyclone intensity starkly contrasts the 18.2 % increase in cyclone frequency in WNA for December in NorESM (Table 3) — especially if one would have expanded the region southward. In the coastal regions from Oregon to British Columbia, the number of cyclones significantly increases while their strength significantly decreases (Fig. **11**c compared to Fig. **12**c). The opposite holds true in BWA (Table 3), demonstrating the closer resemblance between the two models for mean intensity than track density.

In NWE, cyclones weaken by 5.9 **% (NorESM)** to 8.9 % **(CCSM)** in September and intensify by 1.3 **% (CCSM)** to 4.2 % **(NorESM)** in December (Table 3). **[Sentence deleted.]** The signal for NEE is less clear, although the changes for the continental areas of the region seem to be anticorrelated with the corresponding continental changes in NWE (Fig. **12**).

Change of 1st + 6th-7th paragraph in 3.3.4 Precipitation (changes in **bold**):

Both models project significantly wetter conditions in high-latitudes by the end of the century compared to the historical time period, with the SOND mean rising 31.8 **% (CCSM)** to 38.2 % (**NorESM;** Table 2). As seen in Fig**. 13**, this applies to both September and December. However, differences between September and December are apparent in midlatitudes. While there is an overall increase also here (8.0 **% in CCSM** to 10.7 % **in NorESM**; Table 2), large areas of reduced precipitation occur in September (Figs. **13**a and **13**b). These are mainly the eastern North Pacific and North Atlantic oceans, the latter giving most of Europe drier conditions by the end of the century.

Of the four regions, two months and two models in Table 3, only Septembers over the WNA region in NorESM and over the NWE region in CCSM are projected to become drier (4.1 and 12.0 %, respectively). However, compared to the significant increase in precipitation over the domain (Table 2 and Figs. **13**a and **13**b), the **September** 5.8 and 5.7 % increases in WNA in CCSM and NWE in NorESM, respectively, are **also** relatively small (Table 3). Again, the poleward-shifted North Pacific and North Atlantic storm tracks are likely causes, leaving Septembers in the more northern BWA **18.0 % (CCSM) to 23.8 % (NorESM) wetter and NEE wetter by 11.7 % (NorESM) to 13.0 % (CCSM)** (Table 3 and Figs. **11**a, **11**b, **13**a and **13**b). More cyclones in the Bering, North and Greenland seas partly explain the significant increase in precipitation over the continental area to their east: Alaska, southern and northern Norway (Figs. **11**a, **11**b, **13**a and **13**b).

In December, the poleward storm track shift is less significant (Figs. **11**c and **11**d), giving **10.1 % (CCSM) to 15.5 % (NorESM)** more precipitation in WNA and **8.7 % (CCSM) to 19.7 % (NorESM) in** NWE (Table 3 and Figs. **13**c and **13**d). The models still project significantly wetter conditions in BWA and NEE (although with an exception of NEE in CCSM; Fig. **13**d), highlighting the increased availability of warmer air to hold moisture in the most rapidly warming region and season (Stocker et al., 2013).

18: Reason for more cyclones expected to track through the Bering Strait in September
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 4th paragraph in 3.3.2 Track density (changes in **bold**):
NorESM projects a stronger northward shift than CCSM in the North Pacific sector (Figs. **11**a and **11**c compared to Figs. **11**b and **11**d), although December averages within the chosen regions suggests the opposite (+18.2 % in WNA, −13.4 % in **BWA**; Table 3). While **NorESM indicates** more cyclones to track through the Bering Strait and into the Arctic Ocean in September, a more zonal pattern **is projected** in the North Pacific Ocean **for December,** with a significant **track density** increase in a band around 50°N (Figs. **11**a and **11**c). This pattern is not found in CCSM (Figs. **11**b and **11**d), which rather projects strong increases along the North American and Siberian Arctic coasts in December (Fig. **11**d). The latter feature is mostly a consequence of coinciding enhanced cyclone **genesis** (not shown).

19: Clarification fostering cyclones vs. cyclogenesis
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 3rd paragraph in 3.3.3 Mean intensity (changes in **bold**):
For September, both NorESM and CCSM project a significant increase in cyclone strength over the Arctic Ocean (Figs. **12**a and **12**b). By the end of the century, the Arctic is essentially ice-free by September in NorESM and CCSM (Table 1 and green lines in Figs. **12**a and **12**b). Hence, as the atmosphere cools off more rapidly than the ocean in autumn, strong vertical gradients of temperature and moisture arise. Heat fluxes enter the atmosphere, destabilize the air column and thus **promote cyclogenesis**. Additionally, the enhanced latent heat release and reduced friction (and low-level convergence) due to the sea ice melt might also intensify the cyclones. This intensification might account in part for the SLP deepening over the Arctic seen in Table 2 and Fig. **10**. Stronger cyclones have lower SLP, and this tendency is consistent with the observational results of Sepp and Jaagus (2011).

20: Reference to cyclone frequency and intensity tendency south of 40°N
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 7th paragraph in 3.3.3 Mean intensity (changes in **bold**):
Bengtsson et al. (2006, 2009) found that storms are likely to become less frequent and less intense at midlatitudes, but more numerous and stronger at high-latitudes by the late 21st century compared to the late 20th century. Although mainly focusing on the winter (DJF) and summer (JJA) seasons, the NH averaged signal was also apparent in the

autumn (SON) season. Our results in Figs. **11** and **12** strengthen this conclusion. **[Dependent clause deleted.]**

21: Reference to sea ice retreat in bullet points in 4 Conclusion
We have revised the section 4 Conclusion so that sea ice is no longer prominent at the start of it.

1st-2nd bullet point in 4 Conclusion in the previous manuscript is merged into one point (2nd + 1st) and placed last (7th) of the bullet points in the new manuscript.

Change of 7th bullet point in 4 Conclusion (changes in **bold**):

The models reproduce the observed seasonality of the sea ice loss and the general patterns of **SLP** and cyclone metrics, although the storm tracks (densities) and intensities are somewhat less sharp relative to ERA-I because of the coarser resolution **in the models**. The ongoing **(observed)** and projected **(modelled)** retreat of sea ice is greatest in autumn, creating the potential for increased fluxes of sensible and latent heat from the surface to the atmosphere during these months.

22: Rewording cyclone fostering to promoting cyclogenesis
Please see 21: Reference to sea ice retreat in bullet points in 4 Conclusion above for new structure of bullet points in section 4 Conclusion.

Change of 3rd bullet point in 4 Conclusion (changes in **bold**):

Cyclones are generally expected to weaken over midlatitudes and strengthen over high-latitudes, although this is more apparent for September than December. The intensification is especially marked in areas of sea ice retreat, where heat fluxes into the atmosphere, latent heat release and reduced friction **promote cyclogenesis.**

Reviewer #2

1: Rephrasing listing of implications for precipitation increase

Change of Abstract (changes in **bold**):

Metrics of storm activity in Northern Hemisphere high- and midlatitudes are evaluated from historical output and future projections by the Norwegian Earth System Model (NorESM1-M) coupled global climate model. The European Re-Analysis Interim (ERA-Interim) and the Community Climate System Model (CCSM4), a global climate model of the same vintage as NorESM1-M, provide benchmarks for comparison. The focus is on the autumn and early winter (September through December) — the period when the ongoing and projected Arctic sea ice retreat is greatest. Storm tracks derived from a vorticity-based algorithm for storm identification are reproduced well by NorESM1-M, although the tracks are somewhat better resolved in the higher-resolution ERA-Interim and CCSM4. The tracks show indications of shifting polewards in the future as climate changes under the Representative Concentration Pathway (RCP) forcing scenarios. Cyclones are projected to become generally more intense in the high-latitudes, especially over the Alaskan region, although in some other areas the intensity is projected to decrease. While projected changes in track density are less coherent, there is a general tendency towards less frequent storms in midlatitudes and more frequent storms in high-latitudes, especially the Baffin Bay/Davis Strait region in September. Autumn precipitation is projected to increase significantly across the entire high-latitudes. Together with the projected **loss of sea ice and** increases in storm intensity and sea level, this increase in precipitation implies a greater vulnerability to coastal flooding and erosion, especially in the Alaskan region. The projected changes in storm intensity and precipitation (as well as sea ice and sea level pressure) scale generally linearly with the RCP value of the forcing and with time through the 21st century.

2: Rewording from very strong to more adequate statement on reanalyses capturing mesoscale low pressure systems

Please see 5: Restructuring of 2 Data sets and methods above for new structure of section 2 Data sets and methods.

Change of 2nd paragraph in 2.2 Reanalysis (changes in **bold**):

Reanalyses **have strong difficulties** of capturing mesoscale low pressure systems (including “polar lows”), which have typical scales of 200–300 km and lifetimes generally shorter than two days (Condron and Renfrew, 2013). In a comparison of cyclones tracked from the ERA-40 reanalysis and from high-resolution satellite data, Condron et al. (2006) have shown that the failure to capture mesoscale cyclones is especially problematic in the subarctic North Atlantic. The polar low climatologies of Bracegirdle and Gray (2008)**,** Zahn and von Storch (2008) **and Zappa et al. (2014b)** also show maxima in the subpolar North Atlantic**, while Yanase et al. (2016) portray the corresponding climatologies over the Sea of Japan**. In the present study, our coarse-resolution models are compared with the coarse-resolution ERA-I reanalysis using the same tracking algorithm, so there is general consistency in the resolution and by implication in the under-capture of cyclones. Nevertheless, the estimates of cyclones reported here from all three sources (ERA-I, NorESM, CCSM) are almost certainly low relative to the actual numbers, and our findings pertain only to systems of synoptic scale and larger.

New references:

- Yanase, W., Niino, H., Watanabe, S., Hodges, K., Zahn, M., Spengler, T., and Gurvich, I.: Climatology of polar lows over the Sea of Japan using the JRA-55 reanalysis, J. Climate, 29, 419–437, doi:10.1175/JCLI-D-15- 0291.1, 2015.

3: Clarification reference to Catto et al. (2011)
Please see 9: Clarification reference to Catto et al. (2011) above.

4: Rewording from signal to track density bias in CCSM
Please see 14: Clarification reference to signal in CCSM above.

5: Removal of sentence on why CCSM resolves more cyclones than ERA-I
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 4th paragraph in 3.2.2 Track density (changes in **bold**):

The **cyclone frequency bias** in CCSM offers an additional explanation to the large-scale background SLP biases across the main storm tracks discussed in Sect. **3.2.1**. As more cyclones are resolved in CCSM compared to ERA-I (Table 2), a particular grid point in the main storm track undergoes lower SLP for more time steps, understandably dependent on the cyclone strength. For regions of the main storm tracks, this can lower the SLP temporal mean. This is indicated by the anomalous low SLPs over the poleward-shifted North Atlantic and North Pacific storm tracks (Figs. **6**c and **7**c). **[Sentence deleted.]**

6: Inclusion of uncertainty to statement on orographic precipitation
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 3rd paragraph in 3.2.4 Precipitation (changes in **bold**):

Firstly, frontal precipitation accounts for a large fraction of the precipitation, as seen from the close similarity between the precipitation (Figs. **5a, 5f and 9a**) and cyclone track density fields (Figs. **3a, 3f and 7a**). Secondly, orographic precipitation is **assumed to be** the second most important component to the precipitation. This can be seen from the maxima where the main storm tracks reach land (the west coasts of North America, Scotland and Norway, and the south coasts of Greenland and Iceland in Figs. **5a, 5f and 9a**). Moreover, local maxima in connection with the Rocky and Cantabrian mountains, the French and Dinaric alps, as well as Caucasus and the mountains of Japan point to the role of the water bodies to the west of these mountains (Figs. **5a, 5f and 9a**). As the westerly wind crosses these waters, the air gains moisture that later result in orographic precipitation on the windward side of the mountains as the air is forced upwards.

7: Rephrasing of statement on impact of cyclone frequency vs. intensity on precipitation
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion.

Change of 6th paragraph in 3.2.4 Precipitation (changes in **bold**):

For this reason, and due to the fewer cyclones resolved (Sect. **3.2.2**), we would expect to see less precipitation in NorESM than ERA-I. However, the difference over the domain is only a 1 % reduction (Table 2). This indicate that cyclone frequency **may have** a greater impact on precipitation than cyclone strength, as the corresponding negative biases over the domain for track density and mean intensity are 2 and 5 %, respectively. CCSM, with both more and stronger cyclones, has 10 % more precipitation over the domain than does ERA-I (Table 2).

<u>8: Clarification sentences explaining choice of Septembers and Decembers in Figs. 5-8</u>
Please see <u>11: Reference to figures in Appendix B</u> above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 1st paragraph in 3.3 Future scenario changes (changes in **bold**):

The following sections outline the projected changes in the four storminess parameters described in **Sects. 3.1 and 3.2** over 2074–2100 relative to 1979–2005 following the RCP8.5 scenario in NorESM and CCSM. **Because storm tracks, frequencies and intensities change substantially from September to December, four-month means can obscure the key features of individual calendar months. Accordingly, we present time period averages for the boundary months September and December in Table 3 and Figs. 10 to 13 rather than the four-month means SOND as in Table 2 and Figs. 1 to 9.**

<u>9: Rewording from "cyclone generation" to "cyclogenesis"</u>
Please see <u>11: Reference to figures in Appendix B</u> above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 4th paragraph in 3.3.2 Track density (changes in **bold**):

NorESM projects a stronger northward shift than CCSM in the North Pacific sector (Figs. **11**a and **11**c compared to Figs. **11**b and **11**d), although December averages within the chosen regions suggests the opposite (+18.2 % in WNA, −13.4 % in **BWA**; Table 3). While **NorESM indicates** more cyclones to track through the Bering Strait and into the Arctic Ocean in September, a more zonal pattern **is projected** in the North Pacific Ocean **for December,** with a significant **track density** increase in a band around 50°N (Figs. **11**a and **11**c). This pattern is not found in CCSM (Figs. **11**b and **11**d), which rather projects strong increases along the North American and Siberian Arctic coasts in December (Fig. **11**d). The latter feature is mostly a consequence of coinciding enhanced cyclone **genesis** (not shown).

<u>10: Rewording from "too" to "also"</u>
Please see <u>11: Reference to figures in Appendix B</u> above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 5th paragraph in 3.3.2 Track density (changes in **bold**):

Fewer cyclones track across the North Atlantic Ocean overall in both months and models (Fig. **11**). NorESM, like the majority of CMIP5 models (Feser et al., 2015, and references therein), project an eastward extension of the North Atlantic storm track (Figs. **11**a and **11**c). This evolution occurs downstream of an already too zonal storm track compared to the reanalysis (Fig. **7**b), with a 10.2 **% (December)** to 12.8 % **(September)** increase in NWE (Table 3). CCSM **also** represents the North Atlantic storm track too zonal originally (Fig. **7**c), but projects no clear indications of a more zonal storm track towards the end of the 21st century (−21.7 **% for September** to +1.2 % **for December over** NWE in Table 3).

11: Reason for stronger decrease in cyclone frequency than intensity
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 1st paragraph in 3.3.3 Mean intensity (changes in **bold**):

Towards the end of the century, cyclones are generally projected to weaken over midlatitudes (including the main storm tracks) and strengthen over high-latitudes (Table 2 and Fig. **12**). This corresponds to the overall picture in Fig. **11**, although the high-latitude amplification is clearer for intensities (Table 2). On the other hand, the weakening in midlatitudes is smaller, with an average 2 % reduction in mean intensity over the domain of the two models compared to 4 % decrease in track density. In other words, while there is a projected decrease in number of storms crossing the North Atlantic and the North Pacific oceans, their strength will not drop proportionally. **This result illustrates the lack of linear relationships between storm intensities and frequencies. It is consistent with the projections of tropical cyclone activity in Stocker et al. (2013), characterized by an increase in global mean maximum wind speed, but by either a decrease or no change in the global frequency.**

12: Rephrasing statement on association between cyclone frequency and intensity
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 4th paragraph in 3.3.3 Mean intensity (changes in **bold**):

The heat flux potential is even stronger in December when the temperature gradient between the ocean and the atmosphere is greater. As a result, the future time period ice-free areas of the Sea of Okhotsk, Bering and Chukchi seas are projected to be characterized by more intense cyclones (Figs. **12**c and **12**d). However, only minor changes are found along the Atlantic sea ice edge, and NorESM also indicates a significant decrease in cyclone strength over most of the Arctic Ocean (Fig. **12**c). The latter feature is most likely a result of the significant reduction of the number of cyclones (Fig. **11**c). **[Dependent clause deleted.]** Conversely, in the rapidly winter-warming Russian sector (Stocker et al., 2013), cyclones are projected to become more intense (Figs. **12**c and **12**d) and, in NorESM, also more numerous (Fig. **11**c).

13: Rephrasing statement on delayed seasonality of storm intensity
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 7th paragraph in 3.3.3 Mean intensity (changes in **bold**):

In NWE, cyclones weaken by 5.9 **% (NorESM)** to 8.9 % **(CCSM)** in September and intensify by 1.3 **% (CCSM)** to 4.2 % **(NorESM)** in December (Table 3). **[Sentence deleted.]** The signal for NEE is less clear, although the changes for the continental areas of the region seem to be anticorrelated with the corresponding continental changes in NWE (Fig. **12**).

14: Rewording from “too” to “also”
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 6th paragraph in 3.3.4 Precipitation (changes in **bold**):

Of the four regions, two months and two models in Table 3, only Septembers over the WNA region in NorESM and over the NWE region in CCSM are projected to become drier (4.1 and 12.0 %, respectively). However, compared to the significant increase in precipitation over the domain (Table 2 and Figs. **13**a and **13**b), the **September** 5.8 and 5.7 % increases in WNA in CCSM and NWE in NorESM, respectively, are **also** relatively small (Table 3). Again, the poleward-shifted North Pacific and North Atlantic storm tracks are likely causes, leaving Septembers in the more northern BWA **18.0 % (CCSM) to 23.8 % (NorESM) wetter and NEE wetter by 11.7 % (NorESM) to 13.0 % (CCSM)** (Table 3 and Figs. **11**a, **11**b, **13**a and **13**b). More cyclones in the Bering, North and Greenland seas partly explain the significant increase in precipitation over the continental area to their east: Alaska, southern and northern Norway (Figs. **11**a, **11**b, **13**a and **13**b).

15: Relativity of precipitation changes over the Norwegian west coast and the Gulf of Alaska
Please see 11: Reference to figures in Appendix B above for new structure of section 3 Results and discussion and for new labelling of figures.

Change of 8th paragraph in 3.3.4 Precipitation (changes in **bold**):

Totalled over the full season SOND, the projected changes in precipitation in Fig. **13** might have severe consequences for multiple regions. Two of these are the Norwegian west coast (here defined 58–63°N, 5.0–7.5°E) and the Gulf of Alaska (here defined 58–63°N, 135–155°W). They are currently among the wettest regions in the extratropical NH. If we would believe the **RCP8.5** projections from the models, an additional **40 mm** (**+5.0 %;** CCSM) to **133** mm (**+24.1 %;** NorESM) and 71 **mm** (**+15.9 %;** NorESM) to 115 mm (**+21.0 %;** CCSM) precipitation will fall over the Norwegian west coast and the Gulf of Alaska, respectively, over each SOND season during the years 2074–2100 compared to 1979–2005.

16: Rewording from “due to the required tracking method criteria” to “due to data availability” for the use of only one ensemble member per model
Change of 1st paragraph in 4 Conclusion (changes in **bold**):

In this study, we have used a vorticity-based storm-tracking algorithm to analyse changes in metrics of storminess in high- and midlatitudes through 2100 in the NorESM1-M global climate model. The main findings obtained from NorESM1-M are generally supported by the results obtained from a second model, CCSM4, which was examined for comparison purposes. The two models were also compared to the reanalysis data set ERA-Interim for the historical time period. Results are based on only one ensemble member for each model due to **data availability**.

17: Rephrasing statement on linear scaling of RCP value and time for storminess parameters
Please see 21: Reference to sea ice retreat in bullet points in 4 Conclusion above for new structure of bullet points in section 4 Conclusion.

Change of 1st bullet point in 4 Conclusion (changes in **bold**):

For the two models (with one ensemble member each), the projected changes in storm intensity**, sea ice, sea level pressure (SLP) and precipitation all** appear to scale generally linearly with the RCP value of the forcing scenario**. The changes in these variables also appear to be generally linear functions of** time through the 21st century.

18: Rewording from "sea level pressures" to "sea level pressure values"

Please see 21: Reference to sea ice retreat in bullet points in 4 Conclusion above for new structure of bullet points in section 4 Conclusion.

Change of 2nd bullet point in 4 Conclusion (changes in **bold**):

A significant projected decrease of the SLP over the Arctic Ocean during the 21st century appears to be partly a consequence of the diminishing sea ice cover on the same time scales. These changes are consistent with increased heating of the lower troposphere over areas of sea ice loss, resulting in increased thicknesses in the lower troposphere, and increased geopotential heights and mass divergence aloft. Accordingly, **SLP values** are projected to decrease over the Arctic Ocean and increase farther south, significantly over the North Atlantic Ocean, coinciding with reduced midlatitude storm track activity.

19: Clarification association between changes in cyclone frequency and intensity

Please see 21: Reference to sea ice retreat in bullet points in 4 Conclusion above for new structure of bullet points in section 4 Conclusion.

Change of 5th bullet point in 4 Conclusion (changes in **bold**):

Over the whole domain circumpolar north of 40°N, there is a tendency of slightly fewer and weaker cyclones towards the end of the century. However, the reduction in frequency (4 %) is larger than intensity (2 %), indicating that changes in cyclone strength do not **correspond directly to changes in** cyclone frequency.

20: Numbering of figures

Please see 11: Reference to figures in Appendix B above.