Response to Reviewers

Manuscript titled: *The Risk of Synoptic-Scale Arctic Cyclones to Shipping*

Authors: Alexander F. Vessey, Kevin I. Hodges, Len C. Shaffrey and Jonathan J. Day

Format of Response

The comments from the Reviewer are copied (in **GREY TEXT**) and are addressed in turn. Reponses are written in **RED TEXT**. Where text has been edited in our manuscript, tracked changes have been included within this response.

Response to Reviewer #2 – Minor Comments

Note to Reviewer #2

The authors of this manuscript thank Reviewer #2 for taking the time to read and review our revised manuscript, and reviewing it and providing feedback twice. In our opinion, these extra minor comments have helped to elevate this manuscript further, in addition to the comments that Reviewer #2 already suggested in the first round of revisions. We thank Reviewer #2 for expressing their positive review of our manuscript and saying that it "describes high quality research and is a significant contribution to the knowledge in this field". It is very pleasing to hear such a comment. Thank you for recommending our manuscript for publication.

Please see the point-by-point responses to the additional minor comments below.

Response

1. Figure 1: the sum of the values in Figures 1b and 1c should match those in Figure 1a, but they are not consistent. This means that the numbers of ships in 2010 a d 2016 quoted in Lines 220 to 226 are not consistent.

Yes, the reviewer is correct hear. We have updated Figure 1, making sure that the number of ship tracks is consistent between Figure 1a, 1b and 1c.

The updated figure is shown below:

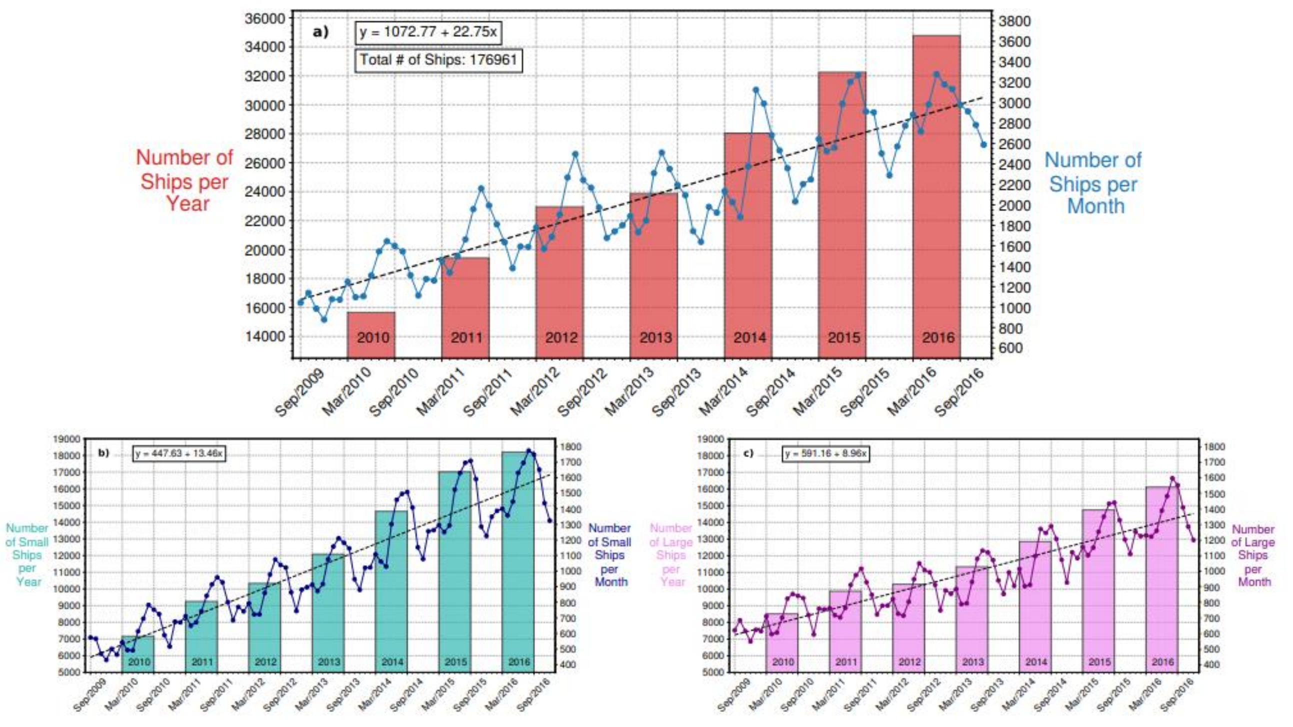

Figure 1. Trends in the frequency of **a)** all ships, **b)** all small ships with a draught less than the mean draught across all ships (4.55 m), and , **c)** all large ships with a draught more than the mean draught across all ships (4.55 m), with a unique identification number (MMSI) to travel north of the Arctic Circle (66.5°N) per year and month, from September 2009 to December 2016 from the Berkman et al. (2020a) Arctic shipping dataset.

2. Final paragraph of the Introduction: the description of the manuscript is incomplete.

Yes, the reviewer is correct here. Sections 3 – 8 describe the results from this study, and this was not noted in the prior version of the manuscript (only Section 3 was). We have updated this, to give a complete description of the manuscript.

The amended paragraph in the latest manuscript is copied below (we have included the tracked changes, so it is clear where we have removed text):

The methods used in this study are described in Section 2, including a description of the data and storm tracking method used. In Sections 3 to 8, the results from this study are described, detailing the trends and seasonal spatial distribution of past Arctic ship tracks, past intense Arctic cyclones tracks and past Arctic shipping incidents. The number of ship tracks intersected by passed intense Arctic cyclone tracks, and the proportion of these intersections that resulted in a reported shipping incident is also quantified and described. Finally, a summary of the main conclusions is given in Section 9.

3. Section 3: last sentence of the first paragraph: it would be more accurate to write "This shows that the number of ships in the Arctic and transmitting their location has increased between 2010 and 2016."

Yes, we agree with the reviewer here. The amended sentence is copied as below (we have included the tracked changes, so it is clear where we have amended text):

Between September 2009 and December 2016, 176,961 ships with a unique identification number (MMSI) travelled north of the Arctic Circle (Figure 1a). The number of ships that travelled in the Arctic increased year-on-year from 2010 to 2016 (Figure 1a). This is similarly shown by Berkman et al. (2020b, 2022). In 2010, 15,666 ships with a unique MMSI transmitted an AIS location in the Arctic, whereas in 2016, the number ships operating in the Arctic was +122% higher (more than two times greater) and approximately 34,780 ships (Figure 1). This shows that the number of ships operating in the Arctic and transmitting their location has increased between 2010 and 2016.

4. Section 3: last sentence of the second paragraph: the authors should consider removing the last part: "…, rather than an increase in the number of ships transmitting their location over this period", because there has been an increase in the number of ships transmitting their location.

Yes, we agree with the reviewer here. We have removed the last par of the sentence as suggested. The amended text is copied as below (we have included the tracked changes, so it is clear where we have amended text):

There has been a greater increase in the number of small ships with a draught of less than 4.55 metres from 7,261 in 2010 to 12,193 in 2016 (+68% increase), than the increase in the number of large ships with a draught of more than 4.55 metres from approximately 8,611 in 2010 to 10,117 in 2016 (+17% increase) (Figure 1b and Figure 1c). The draught threshold of 4.55 metres represents the mean draught of all ships that travelled in the Arctic between September 2009 and December 2016. Since 2004, when large ships were mandated to fit AIS transponders, such devices have been increasingly fitted to smaller vessels, and it became mandatory in May 2012 for all fishing vessels with a size greater than 24 metres to have AIS transponders (U.K. Gov., 2014). Such a change in regulation may have artificially increased the number of ships reporting their position when in the Arctic. But, given the increase in the number of ships shown in Figure 1 are so great, and there is a strong increase in the number of large ships that were required to have a AIS transponder from 2004, it is highly likely that the number of ships operating in the Arctic has increased.~~But, given the increase in the number of ships shown in Figure 1 are so great, and there is a strong increase in the number of large ships that were required to have a AIS transponder from 2004, it is highly likely that the number of ships operating in the Arctic has increased, rather than an increase in the number of ships transmitting their location over this period.~~

5. Conclusions, line 414: the authors have not proven that the number of ships has more than doubled from 2010 to 2016. Instead, they have presented evidence that the number of ships transmitting a signal has more than doubled.

Yes, we agree with the reviewer here. We have updated the manuscript as suggested, and the amended sentence is as follows (we have included the tracked changes, so it is clear where we have amended text):

~~The number of ships in the Arctic has more than doubled from 2010 to 2016, and highest density of ship and intense cyclones in the Arctic occurs over the Barents Sea, around Iceland and over Baffin Bay~~ The number of ships operating in the Arctic and transmitting their location using AIS transponders has more than doubled from 2010 to 2016, and the highest density of ship and intense cyclones in the Arctic occurs over the Barents Sea, around Iceland and in Norwegian Seas

6. Conclusions: this is lengthy and contains some repetition. It would be of much benefit to the reader if its length was reduced by 30 to 50%.

Yes, we agree with the reviewer that the conclusions section is long and contains some repetition. After reviewing the previous manuscript, we have made changes to make it more concise, and we have reduced the word count by approximately 35%.

The amended Conclusion section is as follows (we have included the tracked changes, so it is clear where we have amended text):

9 Conclusions

The risk posed by Arctic cyclones to ships has seldom been quantified due to the lack of publicly available ~~data of~~ past Arctic ship track~~s~~ data. Such data is often privately owned and difficult and costly to obtain. However, the lack of publicly available historic ship track data has been somewhat reduced by Berkman et al. (2020a), who ~~made~~ published Arctic ship~~ping data publicly available for~~ track data derived from Automated Identification System (AIS) transponders over a limited time period between September 2009 and December 2016. ~~Such a dataset can be used~~ This publicly available dataset is used in this study with past shipping incident reports and past cyclone tracks to quantify how many ships ~~are presently~~were impacted by hazardous weather conditions caused by Arctic cyclones, and how many Arctic shipping incidents have occurred following the passage of a cyclone.

~~This study explores annual trends and seasonality in the number of ships travelling north of the Arctic Circle (66.5°N), and Arctic shipping incidents. Historic ship tracks are combined with the tracks of past intense Arctic cyclones, to determine the number of ships intersected by intense Arctic cyclones, and the number of these that coincided with a reported shipping incident.~~ Overall, the number of ships operating in the Arctic (north of 66.5°N) exposed to intense Arctic cyclones ~~is increasing. This is primarily driven by a~~ has greatly increased ~~of the number of ships operating in the Arctic between 2010 and 2016, which may be related to decreasing Arctic sea ice extent that is a consequence of global warming~~ between 2010 and 2016. Intense Arctic cyclones are found to very frequently intersect ~~with~~ Arctic ship tracks, with tens of thousands of intersections occurring each year. But the percentage of intersections that lead to a reported shipping incident is extremely small. This suggest that past Arctic cyclones are not hazardous to ships. Instead, ships appear to be able to travel into and withstand the most hazardous conditions caused by the most hazardous Arctic cyclones. But only a very small percentage of these intersections caused a reported shipping incident, suggesting that past Arctic cyclones are not hazardous to ships, and ships are instead able withstand weather conditions caused by the most hazardous Arctic cyclones.

- The number of ships operating in the Arctic and transmitting their location using AIS transponders has more than doubled from 2010 to 2016, and the highest track density of ships and intense cyclones in the Arctic occurs over the Barents and Norwegian Seas, around Iceland~~ and over Baffin Bay~~

~~It is expected that the significant decrease in~~ Arctic sea ice extent has declined greatly over the last few decades ~~in response~~due to global warming. ~~has led to more shipping in the Arctic (e.g., Browse et al., 2013; Lasserre, 2014; Melia et al., 2016; Lasserre, 2019).~~ It is shown in this study that the annual number of ships operating and transmitted their location in the Arctic has ~~in fact~~ increased year-on-year from 2010 to 2016, from 15,666 ships in 2010 to 34,780 ships in 2016.~~, similarly to Berkman et al. (2020b, 2022). In 2010, a total of 15,666 ships travelled north of the Arctic Circle, but this number was more than double in 2016, where 34,780 ships travelled in the Arctic.~~

Arctic ship and intense cyclone track density is greatest year-round in the Barents and Norwegian Seas~~,~~ and ~~in Baffin Bay~~around Iceland. This is especially the case in winter and spring, where ~~there~~ ships are rarely found in trans-Arctic shipping ~~tracks~~routes, and there is a higher track density of intense Arctic cyclones in those regions. In summer and autumn, Arctic ship tracks are found ~~across most of the~~more widely across the southern Arctic and in the trans-Arctic shipping routes of the Northern Sea Route (NSR) - along the coastline of Eurasia, and the North-West Passage (NWP) - through the Canadian Archipelago~~. But, in every season, the highest density of ship tracks is over the Barents and Norwegian Seas, and in Baffin Bay. The number of ships operating in the Arctic appears correlated with Arctic sea ice extent, with a higher number of ships operating in the Arctic coinciding with lower Arctic sea ice extent. The maximum number of ships operating in the Arctic occurs typically in late summer and early autumn months, when Arctic sea ice is typically as its minimum extent.~~

The number of ships operating in the Arctic correlates with Arctic sea ice extent, with a higher monthly and seasonal number of ships operating in the Arctic coinciding with lower Arctic sea ice extent in late summer and early autumn months. The number of ships travelling through the NSR and NWP has increased from 2010 to 2016, with. ~~Of these shipping routes, t~~the NSR typically ha~~s a higher number of~~ving more ship transits than the NWP per year. This is likely due to the ~~Northern Sea Route~~NSR being ~~more~~ typically more ice-free in summer and autumn months than the ~~North-West~~

~~Passage~~NWP, where sea ice tends to be thicker and less susceptible to melting.~~ The maximum number of ships operating in the Arctic appears to coincide with the minimum Arctic sea ice extent in September.~~

– The number of reported shipping incidents has increased from 2010 to 2016, ~~however~~but, the total number of reported shipping incidents is only approximately 0.1% of the total number of ships operating in the Arctic

Between ~~2005~~ 2010 and ~~2017~~2016, ~~there were a total of 250 reported shipping incidents north of the Arctic Circle, with 158 occurring between 2010 and 2016. But between 2010 and 2016, a total of 176,961 ships travelled north of the Arctic Circle between 2010 and 2016 (Figure 1). So, approximately only 0.1% of ships in the Arctic reported a shipping incident from 2010 and 2016.~~ a total of 176,961 ships travelled in the Arctic between 2010 and 2016, but there were only a total of 158 reported shipping incidents, which is approximately only 0.1% of the total number of ships. Most of the ships that ~~did~~ reported an incident had a gross tonnage of less than 1,000 tn, suggesting that smaller vessels, such as fishing vessels, are more prone to incidents than larger ships, such as cargo vessels. Most reported shipping incidents ~~mostly~~ occurred near the coastlines of the Arctic, and fewer incidents ~~are~~ were located in the ~~more~~ open Arctic Ocean. The ~~number of ships travelling in the Arctic increased year-on-year from 2010 to 2016, and this increase has likely resulted in the increase in~~ increasing number of reported shipping incidents from 2010 to 2016 is likely a consequence of the number of ships travelling in the Arctic increasing year-on-year, but the number of reported incidents remains a very small percentage of all ships operating and travelling in the Arctic.~~reported shipping incidents in the Arctic, but only approximately 0.1% of all ships reported an incident between 2010 and 2016~~.

– Despite Arctic ships being very frequently intersected by the track of an intense Arctic cyclone, only a handful of these intersections resulted in a report shipping incident

~~Past Arctic ship tracks have been combined with Arctic cyclone tracks derived from ERA-5 to determine the number of ships intersected by intense Arctic cyclones. Past reported shipping incidents published by Protection of the Arctic Maritime Environment Agency (2023) are also used to confirm whether these intersections between ship tracks and cyclones resulted in a shipping incident. Results show that the highest density of intense Arctic cyclones is over Barents, Greenland and Iceland Seas in all seasons, which is also where the highest density of Arctic ships occurs.~~ Between 2010 and 2016, a total of 32,103, 15,246 and 4,633 ship tracks were intersected and located within 3° (approximately 333 km) of an Arctic cyclone, with the significant wave height at the ship's location being greater than 2.5 m, 4.0 m and 6.5 m respectively. But only 9 reported shipping incidents (0.2% of the all intersections with significant wave height greater than 6.0 m) were found to have occurred within two days of the intersection between Arctic ship and intense cyclone. So, the vast majority of past reported shipping incidents appear unrelated to the passage of intense Arctic cyclones.

It is surprising how frequently Arctic ship tracks are intersected by an intense Arctic cyclone, as the track of an intense Arctic cyclone would likely be communicated through weather forecasts~~. Given that ships likely have radio or weather forecast equipment onboard, the ship would likely be aware of the incoming intense cyclone. A publicised example of this is the SS El Faro shipping disaster in 2015, where the ship knowingly (from weather forecasts) travelled into the track of Hurricane Joaquin, which led to the sinking of that ship (Fedele et al., 2017; Vanity Fair, 2018). It would be expected that ships may~~ allowing ships to avoid the forecasted paths of the intense Arctic cyclones. ~~From~~ In this study, ~~it is evident that Arctic ship tracks frequently intersect and are impacted by the tracks of intense Arctic cyclones~~numerous ships found to be positioned and impacted by the tracks of the most intense Arctic cyclones, but ~~very few of these intersections result in a reported shipping incident. So, perhaps ships are able to withstand and continue to operate in such hazardous conditions caused by intense Arctic cyclones~~were able to withstand the severe weather conditions and no shipping incidents were reported.

This study suggests that cyclones are not a dominant cause of reported Arctic shipping incidents in the present climate, even though ships are frequently impacted by intense Arctic cyclones. ~~The risk of synoptic-scale Arctic cyclones to ships and its crew and cargo is found to be low and perhaps mitigated by the ships ability to withstand the most intense sea conditions caused by the most intense Arctic cyclones between 2010 and 2016.~~ However, ships could also experience other consequences than damage to the ship and crew, such as business interruption and delays in transit~~.~~ and ~~Damage~~ damage could also occur to port facilities. ~~, which is not considered in this study. This study is also limited to using ship track data from September 2009 to December 2016. Although we conclude that synoptic scale cyclones pose a low risk to Arctic shipping, that is not to say that all severe weather is not a threat for shipping in the Arctic. For example, Polar lows, which are smaller scale phenomena in the sub-polar seas have been implicated in the loss of a numerous small vessels (Rasmussen, 2003) and often have an impact on the normal shipping operations (Moreno-Ibáñez et al., 2021).~~ Although we conclude that synoptic scale cyclones pose a low risk to Arctic shipping, other severe weather phenomena not considered in this study, such as Polar lows, which have been found to impact normal shipping operations (Rasmussen, 2003) and to have caused the loss of numerous small vessels (Rasmussen, 2003), could threaten shipping in the Arctic.

This study exemplifies the capabilities of open access risk analysis and quantifies the risk of past Arctic cyclones impacting Arctic shipping, and ~~also~~ the number of past shipping incidents caused by ~~the passage of an intense~~ Arctic cyclones, which could be useful for decision-making institutions, the insurance industry, and the public. This study relies on open ~~-~~access atmospheric, ship~~ping~~ track~~s~~ and shipping incidents data repositories. Whilst there are considerable amounts of freely available atmospheric data available from various institutions, open ~~-~~access social data such as ship tracks and shipping incidents is much less attainable ~~scarcer. Such social data is even~~and is often privatised. Consequently, this study was limited to investigating the risk of Arctic cyclones to shipping in such a short time-period ~~of history~~ and between 2010 to 2016. ~~The establishment of the Polar Code in 2014 by the International Maritime Organization shows that regulatory authorities expect the number of ships in the~~

~~Arctic to increase in the following years.~~ As global warming continues to rapidly change the Arctic, extensive and up-to-date ship track and incident data needs to be more publicly available, so that the risks to shipping can be monitored and ultimately mitigated.