Interactive comment on **"The effect of changing sea ice on the vulnerability of Arctic coasts"** by **K. R. Barnhart et al.**

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The authors thank Dr. Forbes for his thoughtful and constructive review. We have made changes to the text in response to his comments. Please find our comments in this document in italic. In addition, we have included a copy of the manuscript with the changes made during revision marked as one of the Author Comments.

General Comments:
This paper is a welcome addition to the literature on the changing environmental drivers of Arctic coastal erosion. It reports on a pan-Arctic analysis of coastal sea-ice concentration as derived from the 1979-2012 satellite record. This unique and valuable circumpolar synthesis is the major contribution of the paper. On this basis, the authors observe a 1.5- to 3-fold increase in the median length of the open-water season over 34 years, with large regional variance. The paper reviews pertinent literature on multi-temporal analyses of trends in shoreline retreat rates from a wide range of sites across the Arctic, finding that most studies reveal no clear correlation between erosion rates and the length of the open-water season, despite the theoretical expectation that a shorter duration of ice against the coast, particularly in more stormy seasons, should increase the probability of elevated water levels and storm wave impacts on the coast.

This provides a strong quantitative foundation for assessing the lack of correlation between climate change and coastal erosion rates on many high-latitude coasts (e.g. Forbes and Hansom 2012) and studies cited in this paper (Vasiliev, 2005; Solomon, 2005; Lantuit and Pollard, 2008; St-Hilaire-Gravel et al., 2012; among others). Nevertheless, an increase in shore retreat rates has been clearly documented on some ice-rich permafrost coasts developed in unlithified sediments, both in Siberia (Günther et al., 2013) and Alaska (e.g. Mars & Houseknecht, 2009; Jones et al., 2009). The authors of the paper under review present a detailed analysis of changes in open-water season, ice-free fetch, and coastal forcing of water level and waves in the nearshore zone for a study site at Drew Point, Alaska, where Mars and Houseknecht (op. cit.) documented more than a doubling of coastal land-loss rates between 1955-1985 and 1985-2005. They demonstrate a clear increase in extreme values of water level ('setup') and increasing fetch at Drew Point from 1979 to 2012, consistent with the observed acceleration of erosion rates. In a supplementary analysis of first and last days of open water from 6 of 7 coastal sectors in the Arctic Ocean, they document the geographic variability and differential effects of earlier breakup and later freeze-up on coastal forcing and erosion potential. This paper does not directly assess links between open water, forcing, and coastal erosion (for which see Barnhart et al., 2014), rather it clarifies the implications of changing ice concentration on a variety of processes affecting shoreline stability.

Specific Comments:

I have some misgivings about the use of 'vulnerability' in the title, as the paper deals primarily with aspects of exposure and forcing. In the authors' definition of vulnerability (page 2279, line 10), there is a component of 'capacity to resist change' which is not captured in this paper. 'Vulnerability' has a wide range of interpretations in the coastal literature, from purely physical responses to transdisciplinary analyses involving human activities and adaptive capacity. I would suggest at least to add the adjective 'physical' and alternatively to consider use of a different term.

The title has now been changed to "The effect of changing sea ice on the physical vulnerability of Arctic coasts". We have also examined all instances of the word "vulnerability" and modified it with "physical" where appropriate. While writing we struggled to find a better word than "vulnerability" for reasons including the ones that you list. Ultimately we decided that "vulnerability" was the best word. We do agree that modifying it with "physical" is an important improvement as it brings the title more in line with the text.

With respect to the whole-Arctic analysis of the ice-free season ('sea-ice-free season' seems unnecessarily cumbersome – an initial explanation would suffice), I am curious about the apparent absence of data along some coasts in Figures 1 and 2 (notably Canadian Beaufort Sea, Amundsen Gulf, Banks Island, parts of northern Greenland, and southwestern Novaya Zemlya). Does this relate to ice mobility that prevents the algorithm from recognizing fast ice along these coasts? In some cases, there may be a narrow band of landfast ice that is not recognized at the scale of the 25 km cells. Some clarification would be helpful. It would also be helpful to give the cell size when first introduced (p. 2285, line 14).

We have changed the phrase "sea-ice-free" to "open-water" – we agree it is less cumbersome.

With respect to the absence of data, the lack of data simply reflects that we only show cells with p-values of less than 0.05. We added additional text to this section to make this point clear. This statement is also made in the relevant Figure captions.

In addition, we have added the cell size both when cells are introduced in this section and earlier in the paper in the "Data" section.

With respect to Mackenzie River discharge (p. 2289, lines 25-27), studies of ice affected peak discharge at the head of the delta (e.g. Beltaos, 2012), since the work of Overeem and Syvitski (2010), have resulted in revised discharge values that show no significant trend in total annual discharge (Lesack et al., 2013). Lesack et al. (2013, 2014) have shown, however, that despite no change in the date of freshet initiation, breakup in the Mackenzie Delta is occurring earlier.

Thank you for the updated reference list. We have changed this section to read "Along the Canadian Beaufort sea in the Mackenzie Delta region the open-water season has expanded around 1 day yr^{-1}. Mackenzie river total annual discharge has not increased over 1964--2011 (Lesack et al., 2013); however, while there is no observed change in the date of freshet initiation, the duration between freshet initiation peak flow has shortened, and breakup in the Mackenzie Delta is occurring earlier (Lesack et al. 2013, 2014)."

The authors have reasonably excluded the Canadian Arctic Archipelago (CAA) from their analysis in Figure 16 (p. 2301, lines 27-28 & p. 2302, line 1). However their statement about sea ice persisting in the CAA throughout the summer season is misleading and applies only to the northwestern sector. Open water is extensively and increasingly prevalent throughout the rest of the region, including the Northwest Passage.

Sentence changed to "We do not show the Canadian Arctic (Sector 7) as sea ice persists along the northwestern portion of this segment of coast throughout the summer season."

Figure 5 presents the pan-Arctic distribution of coastal erosion rates (Lantuit et al., 2012) in a different and useful way. However the caption for Figure 5 states that "deposition occurs primarily in deltaic regions, for example the McKenzie [sic] delta in the Beaufort Sea." Apart from the misspelling ('Mackenzie' is correct), this overlooks the fact that the delta is transgressive and retreating across almost its entire front (Solomon, 2005; Forbes and Hansom, 2012). Zones of local progradation along the Beaufort Sea coast occur on coastal barriers, spits, and forelands west of the delta. However, in the original published map (Lantuit et al., 2012, figure 6), the areas of progradation are plotted west of Herschel Island along the Alaska coast and may relate to delta aggradation at the mouths of North Slope rivers from the Colville east.

The caption now reads "Deposition along the Beaufort sea occurs in deltaic regions from the Colville River east and along coastal barriers, spits, and forelands west of the Mackenzie River delta."

The results of this paper have great value, but it is important to recognize that the erosion processes operating at Drew Point are particular to low, ice-rich permafrost bluffs in ice-bonded but otherwise unlithified sediments, as found on the Arctic coastal plain in Siberia, Alaska, and northwestern Canada, but are not universally applicable across the Arctic. As they state in their conclusions (p. 2303, line 13), coastal erosion is affected "by lithology, geomorphology, and ice content" to which we might add orientation and exposure, storm climate, ice dynamics, relative sea-level trend, and sediment supply, among other factors.

We agree that the erosion process operative is not universally applicable. However, Drew Point is a location where we can link coastal erosion to nearshore conditions and sea ice change. We think that this general approach is broadly applicable. We have added text at the beginning of the section (5.2) that focuses on Drew Point to make this distinction clear.

Previously we stated: "Yet a full understanding of how changing sea ice will impact coasts depends on both the form and substrate of the coast and the way in which sea ice influences the nearshore conditions in a particular *area."*

We have added the following text: "While the erosion processes operative at Drew Point are not universally applicable to all Arctic coasts, the link between coastal dynamics and sea ice through the nearshore conditions exists along all ice-affected coasts."

In addition, we have added some of the additional factors you mention to the sentence in the conclusion so it now reads: "…the relationship between changing open-water conditions and coastal erosion are complicated by lithology, geomorphology, ice content, orientation, storm climate, ice dynamics, relative sea-level trend, and sediment supply, among other factors."

The paper is well written and very clean, with few errors and mostly good figures. I am not convinced that panels B-E of Figure 9 are necessary and Figure 16 was extremely difficult to work out. Panels F-H of Figure 12 are missing and some captions refer to left and right panels when they appear one above the other.

We have elected to retain panels B-E of Figure 9 because we think it assists in showing the process of modeling set up and wave height from sea ice concentration maps, wind speed, and wind direction. You are correct to point out that panels F-H of Figure 12 are missing. They were in a prior figure version. We have removed the remaining references to them. With respect to Figure 16, after discussion with colleagues about how best to improve the clarity of this figure, I have changed the legend entry for the PDF of the beginning and end of the open water season. I recognize that there is a lot of information in this figure.

Technical Corrections: [page,line(s)]: correction
We thank you for your attention to detail. We have made changes in response to each correction.

[2277]: See comment above re title.
Title changed to "The effect of changing sea ice on the physical vulnerability of Arctic coasts".

[2278,2]: 'Shorefast' is not essential to this statement and it is generally not shorefast ice that governs the open-water fetch. Simplest solution here is to omit the first word 'shorefast'.
Word "Shorefast" removed.

[2278,4]: Delete comma after 'duration' and 'the' before 'summertime'.
Comma and "the" removed.

[2278,13]: Hyphenation ('sea ice free' not hyphenated here, hyphenated above on line 4). Note my comment above suggesting the simpler phrase 'ice-free' (or use 'open-water').
All phrases "sea-ice-free" changed to "open-water".

[2278,14]: Change 'has' to 'have'.
"Has" changed to "have".

[2278,16]: In my experience, notch (or 'niche') incision is not submarine (although it may occur when the base of the beach is submerged in a storm surge) – e.g. Forbes et al. (2014, Figure 16c,d) show good examples of notching from Tuktoyaktuk Island in the Canadian Beaufort, photographed after the storm event and exposed at the back of the low-tide beach.

By "submarine" we mean that notch incision occurs under the water level. In the case of notch incision, we agree with your observations along Tuktoyaktuk Island -notch incision occurs when the base of the bluff is below the water level during storm surge. We suspect that the larger issue is that notch incision occurs along the base of the bluff, which is not permanently submarine. We have modified the two instances of the word "submarine" in the text to reflect that notch incision occurs when water levels are set up to above the base of the bluffs.

For example: "The bluffs erode through the process of failure on an ice wedge after water levels are set up to the base of the bluffs resulting in a notch carved at the base of the coastal bluff by submarine erosion."

[2279,8]: Fix punctuation for IPCC reference.
"IPCC (2013)" changed to "(IPCC, 2013)".

[2281,14]: Delete 'the' before 'vulnerability' and add 'of' to read "... and increasing vulnerability of Arctic..."
Sentence changed to "... and increasing vulnerability of Arctic..."

[2282,1]: Should 'blocks' be 'bluffs'? – I know we are talking about block failure, but it seems inappropriate here.
Yes, you are correct, it should be bluffs.

[2284,7]: Add semicolon after 'trations' and delete 'and' to read "sea ice concentrations; meteorology from ... "
Semicolon added and "and" deleted

[2286,25]: Change first 'an' to 'a'.
Changed

[2286,26]: Change 'varies' to 'vary'.
Changed

[2288, 6]: Change 'storms' to 'storm'.
Changed

[2288,15]: Change 'between' to 'for' – usage "between 1984-2002" equates to 'between ... to ...', whereas it should be 'from ... to ...' or 'between ... and ...'
Changed

[2288,16]: Delete 'between'.
Changed

[2288,19]: Delete 'between'.
Changed

[2288,25]: Change dash to ' and '.
Changed

[2289,5]: Ditto.
Changed

[2289,24]: Change 'Canada' to 'Canadian'.
Changed

[2290,1]: Delete second 'are'.
Removed

[2290,11]: Delete 'is'.
Removed

[2290,24]: I assume 'following' should be 'preceding'.
Yes, it should be "preceding", the word has been changed.

[2291,7]: Delete 'what' and change 'once' to 'one'.
Removed and changed.

[2291,9]: Change 'made' to 'determined' or 'averaged'.
Changed to "determined"

[2291,15]: Add 'that' to read "... it is the passage of storms that does ..."
Sentence changed.

[2294,10]: The Atmospheric Environment Service is now the Meteorological Service of Canada. It would be appropriate here to refer to "Canadian Ice Service charts ..."
Sentence now refers to "Canadian Ice Service charts ..."

[2298,11]: Note panel ‘f’ missing.
Reference to subplot 12f removed.

[2298,12]: Change ‘also’ to ‘did’.
Changed.

[2299,10]: Add comma after ‘storm’ and change “wind-based definition of a storm” to ‘latter’.
Changed.

[2299,21]: Add word ‘at’ before ‘Barrow’.
“at” added.

[2299,23]: Delete ‘to’ before ‘Barrow’.
“to” deleted.

[2303,2]: Fix punctuation for Barnhart et al. reference.
Punctuation fixed.

[2306,6-12]: Delete duplicate reference to Lantuit et al. 2012.
Duplicate reference removed.

[2317,caption]: Fix Fig. 5 caption as noted above.
The caption now reads “Deposition along the Beaufort sea occurs in deltaic regions from the Colville River east and along coastal barriers, spits, and forelands west of the Mackenzie River delta.”

[2318,caption]: Delete duplicate ‘the’ in line 2 of Fig. 6 caption.
Duplicate “the” removed.

[2322,caption]: The “white” lines appear yellow to me. Note upper and lower panels are referred to a left and right.
“White” changed to “yellow” and “right” and “left” changed to “lower” and “upper”.

[2325,caption]: Add missing panels or delete last 3 lines.
I have removed the last three lines of the Figure 12 caption. In a previous draft I had an additional row of subplots.

[2326,caption]: Reference to Fig. 12c and f needs to be fixed depending on whether F-H in Fig. 12 are added or not.
References to Fig 12 f removed here and in the text.

[2327,Fig.14]: Typo in legend of panel A – ‘Positive cet up’
Legend text fixed.

References not cited in original paper [this is not a request to cite them]:
Thank you for these references!

Beltoas, S.: Mackenzie Delta flow during spring breakup: uncertainties and potential improvements, Can. J. Civ. Eng., 29, 579-588, doi:10.1139/L2012-033, 2012.
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Forbes, D.L., Manson, G.K., Whalen, D.J.R., Couture, N.J., and Hill, P.R.: Coastal products of marine transgression in cold-temperate and high-latitude coastal-plain settings: Gulf of St Lawrence and Beaufort Sea, in: Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences, edited by: Martini, I.P. and Wanless, H.R., Geological Society, London, Spec. Pub. SP388, first published on-line May 13, 2014, doi:10.1144/SP388.18, 2014.
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Lesack, L.F.W., Marsh, P., Hicks, F.E., and Forbes, D.L.: Local spring warming drives earlier river-ice breakup in a large Arctic delta, Geophys. Res. Lett., 41, 1560-1566, doi:10.1002/2013GL058761, 2014.