Author's response to Professor Don Forbes review

1.) Title: I'm not sure that the landslide which triggered this tsunami event was clearly associated with rapid regional warming. It appears to have been a case of an earthquake generated fault rupture leading to gravitational collapse, possibly related to debuttressing with glacial retreat. I understand the argument that warming may contribute to more rapid glacial retreat (debuttressing additional fjord walls) and may trigger slides or slumps in ice-rich permafrost soils, but I'm slightly uncomfortable with the current title.

Author's Response: Thank you for your comment and opinion. We agree that the title was confusing and we did not present any evidence for climatic trigger of the tsunami.

We decided to change the title into:

Arctic tsunamis threaten coastal communities and landscapes - survey of Karrat fjord 2017 tsunami effects in Nuugaatsiaq, western Greenland.

2.) Abstract:

This is too short and insubstantial. Should report major findings, including impacts on buildings and other infrastructure, and some of the social and economic impacts in Table 1, provided the supporting data are provided. It should also report the comparison drawn between effects at Nuugaatsiaq and other similar events in Greenland.

Author's Response: Thank you for your comment. In the revised manuscript we will rewrite the abstract and include more information about the socio-economic impacts and report major findings concentrated on landscape modification and tsunami deposits.

On the 17th of June 2017, a massive landslide which mobilized ca. 35–58 million m^3 of material entered the Karrat Isfjord in western Greenland. It triggered a tsunami wave with a runup height exceeding 90 m close to the landslide, ca. 50 m on the opposite shore of the fjord. The tsunami travelled ca. 32 km across the fjord and reached the settlement of Nuugaatsiaq with ca. 1-1.5 m high waves, which were powerful enough to destroy the community infrastructure, impact fragile coastal tundra landscape, and unfortunately, injure several inhabitants and cause 4 deaths. Our field survey carried out 25 months after the event results in documentation of previously unreported scale of damages in the settlement (ca. 48% of infrastructure objects including houses and administration buildings were destroyed by tsunami). We have observed a recognizable difference in the concentration of tsunami deposit accumulations between areas of the settlement overwashed by wave and areas where tsunami flooded terrain and return to the fjord. The key tsunami effects preserved in the coastal landscape were eroded coastal bluffs, gullied and dissected edges of cliffed coast in local harbour and compressed tundra by boulders or icebergs rafted on land during the event.

3.) Organization:

The paper would benefit from addition of a short section in the Introduction on the geological, topographic, and bathymetric setting, the environmental conditions to which the coast, landscape, and infrastructure pre-tsunami were adjusted (tides, waves, winds, storms, permafrost), and the pre-disaster characteristics of the community (history, population, age structure, social and economic conditions).

Further, in section 3.1 it would be helpful to provide more detail on the wave behaviour on arrival in Nuugaatsiaq – approach direction, runup, backwash, overwash in the saddle, possible refraction/diffraction around the point, and inundation limits.

The authors might also consider reorganization of the landscape impacts results section (3.2) into two or three sections such as 3.2.1 Wave runup and drainage; 3.2.2 Erosional effects, 3.2.3 Deposits.

Author's Response: Thank you for your suggestion. We have updated our manuscript with new sections (3.1.1-3.1.4 on geomorphology and glacial history, geology, permafrost and vegetation. In addition, we added the pre-disaster characteristics of the community (history and economy in section 3.2.

In addition we have added new Fig. 2 to present types of coastal zones and landscape around the settlement.

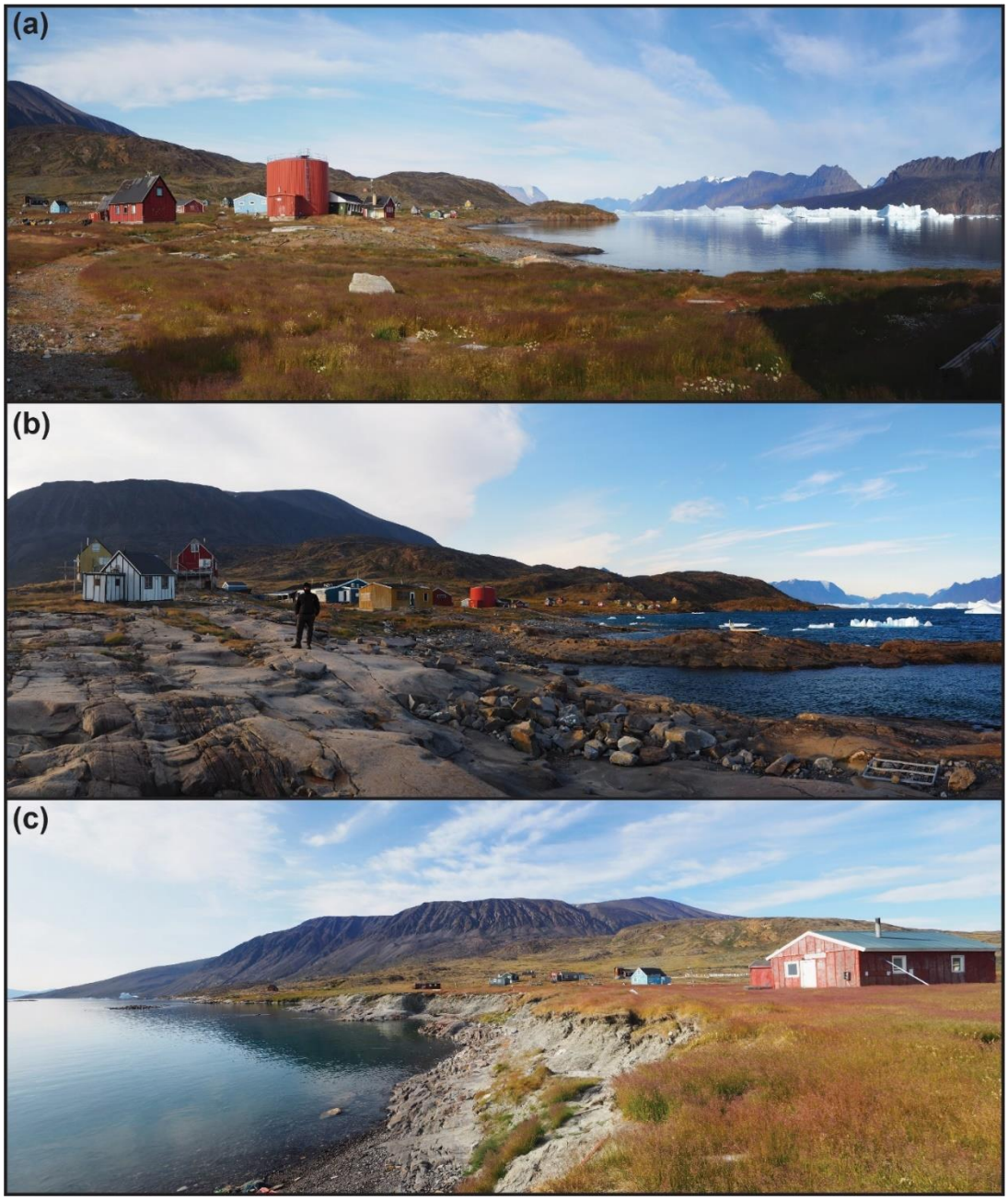

Figure 2. Coastal landscapes in Nuggatsiaq. (a) Densely vegetated (grasses and shrubs) coastal lowland with ragged shoreline dissected by rocky capes and coves with narrow beaches; (b) Main headland with exposed glacially scoured bare rock surfaces, note accumulations of boulders in rocky hollows; (c) Cliffed coast in Nuugaatsiaq harbour. Tops of the cliff were eroded and gullied by tsunami.

4.) Missing details: The most serious deficiency in my view is the lack of elevation data in relation to tsunami effects and deposits. I appreciate that this may not be readily available, particularly as they were not permitted to fly vertical photography over the settlement. However, I would be surprised if some community topographic mapping had not been undertaken in the past. Elevation data should be available through ArcticDEM (see, e.g., https://bluewaters.ncsa.illinois.edu/liferay-content/documentlibrary/18symposium-slides/porter.pdf, slide 37/40, which also shows runup estimates). This is key contextual data which present hypotheses for testing against the observations reported in this paper.

Author's Response: Thank you for suggestion. We have added new figure with a DEM (new Figure 3) presenting local topography and inundation limit (Fig. 3a). This will better visualize the scale and course of the event. In addition, in Fig. 3b we marked the location of images presenting the results of mapping of tsunami effects showed in Figs. 4 and 5.

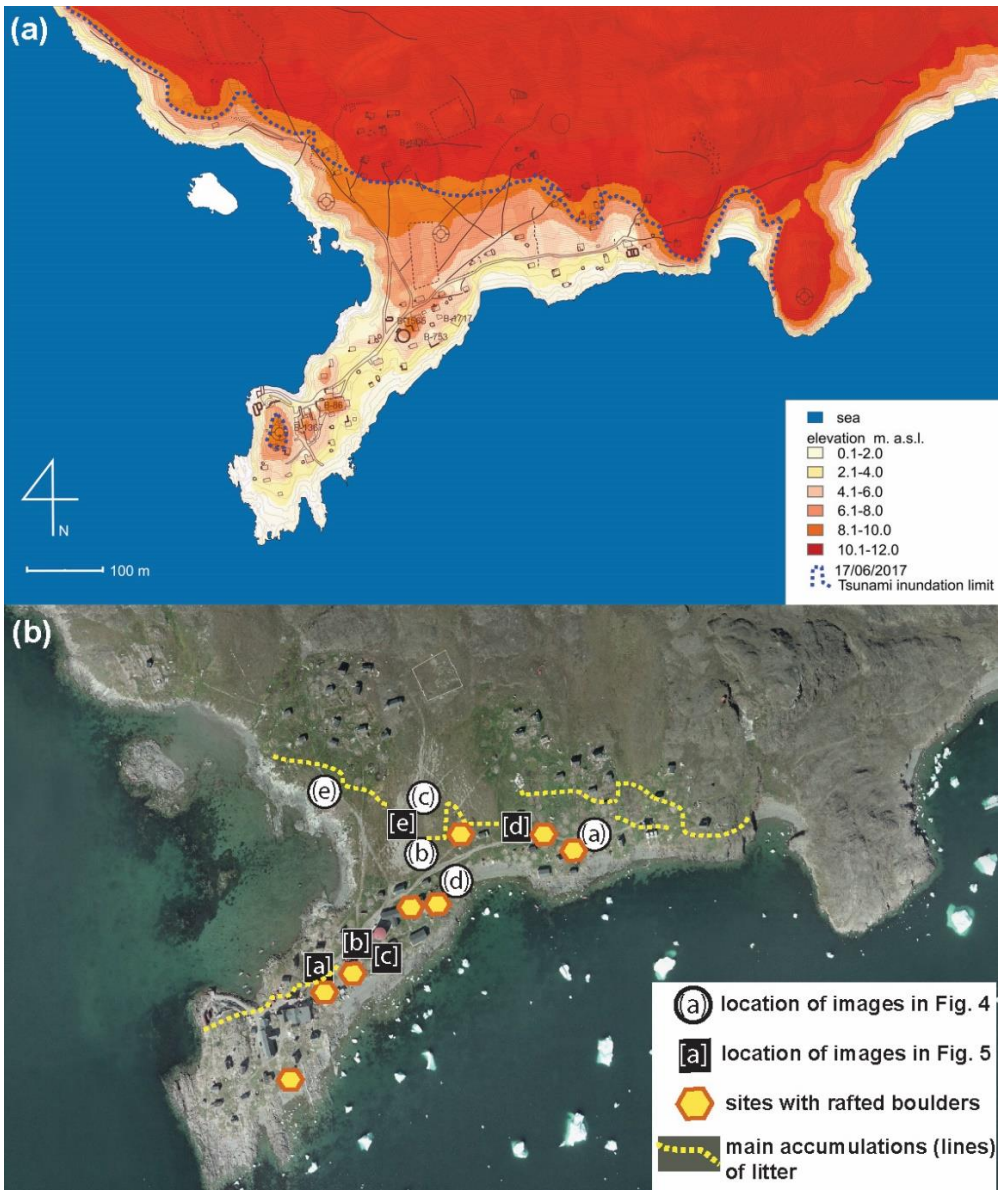

Figure 3. (a) Digital elevation model (2-m DEM, https://www.pgc.umn.edu/data/arcticdem/) of Nuugaatsiaq with marked tsunami inundation limit (wave flooded the terrain up to 8 m a.s.l). (b) Overview map of the settlement with marked location of images from Fig. 4 and 5. Lines of litter visible in the landscape 2 years after the event and sites were large boulders rafted by tsunami were marked too. Background: technical map of settlement from nunagis.gl

5.) In addition, the analysis of shore-zone and backshore slope effects would benefit from an understanding of the pre-existing morphology, slope angles, surficial geology, and nearshore bathymetry (if available). For example, were the backshore slopes fully vegetated or already subject to some slope failure? Is there any sand in the beaches and/or nearshore? If not, this would support the apparent absence of extensive sand deposits resulting from the tsunami. What was the source of the boulders scattered across the wash zone? Were they all iceberg-rafted, or were some derived from the shore zone?

Author's Response: thank you for your detailed set of questions. The information about local geomorphology, sedimentology and vegetation was very scarce, but we have tried to increase the level of detail in description of sediments and pre-event characteristics of coastal landscape.

In general, local beach are very small, with thin layer of mixed sand and gravel and accumulations of glacier-derived boulders.

6.) Socio-economic impacts: The analysis of building losses and displacement is an important part of the socio-economic impact, including the relative performance of various foundation types. However, Table 1 provides an extensive list of social and economic impacts of the event that receive no attention whatsoever in the text. These represent a variety of impacts, some of which may be based on data and some of which may be more hypothetical or based on hearsay. It is difficult to assess the validity of this list without further details. At the same time, if the analysis of socioeconomic impacts is limited to infrastructure impacts, this should be more explicit on line 41.

Author's Response: Thank you for your comment. We agree that we slightly exaggerated the role of our paper in presenting the socio-economic impacts of this event. We concentrate on the infrastructure damages which is an important economic impact. This is the first case in the Arctic, where tsunami damaged the settlement which was not abandoned. We have developed our discussion using the data presented in Table 1.

7.) Specific scientific comments:

Line23: Delete "Even as Arctic tsunamis are often presented in media coverage as a part of polar myths" and begin sentence "Their increasing frequency . . ."

Ad. Thank you for suggestion. We have deleted this confusing part of a sentence. Now the sentence stands as:

Their increasing frequency in this rapidly warming region already poses a serious threat to a fragile polar coastal environment and infrastructural needs of human communities.

Line 41: As noted above, this promises "insights into . . . socioeconomic impacts" but it is not until we study Table 1 that we discover the community is abandoned and the survivors are dispersed to two other communities.

Ad. Thank you for your comment.

We have rephrased our study aim to better present the paper content and not be accused of overstatements:

'Here we report on the largest documented tsunami wave in Greenland to date (runup height ca. 90 m), which resulted from a massive landslide to Karrat Fjord and destroyed the settlement of Nuugaatsiaq on the 17th of June

2017 (Figure 1). Based on field survey carried out two years after the event, our study provides insights into the lasting tsunami-induced geo-ecological changes in coastal landscape and in addition presents inventory of tsunami damages to settlement infrastructure.'

We have added new paragraph in section 3 *Research area - 3.2 Settlement history and economy* where we present the key facts on Nuugaatsiaq settlement. We have mentioned about community abandonment too.

Lines 49-50: "The largest boulders and litter lines were marked with a handheld GPS" – To me this raises the expectation that these data will be shown and used to demarcate a runup limit (or at least a zone of known runup), preferably in relation to topography, for which you need elevation data (see above).

Author's Response. Thank you for suggestion, we have added collected data in new Fig. 3b.

Line 50: Re "careful survey of vegetation cover change" – The paper reports a lush growth of grasses obscuring some tundra blocks, boulders, and debris. It is unclear whether this vegetation is different in composition or productivity from what formed the vegetation cover prior to the event or if it differs from the cover beyond the runup limit. Can the authors report species (line 82) and further details?

Author's Response. Thank you for suggestion, we have added more details regarding thickness and type of sediments found in the tundra.

Lines 89-90: ". . . vegetation cover (grasses) was covered by a relatively thin layer of tsunami deposits" – Delete 'relatively' – it is not meaningful. What type of deposits? - composition, thickness, location(s). Line 90: Salt patches "covering the exposed or inundated grounds" – I'm unsure what this means – occurs on noninundated surfaces as well?

Author's Response. Thank you for suggestion, we have added more details regarding thickness and type of sediments found in the tundra.

Lines 93-94: Re ". . . some pars of the grass cover were [compressed] by fragments of icebergs washed [onshore, or also by the waves" - as is common in wave overwash of vegetated dunes on exposed coasts.

Author's Response. Thank you for suggestion. We have explained that some parts of the grass cover were compressed by the fragments of icebergs or ice-floes washed on shore by tsunami. In sites where ice-berg or ice-floe were deposited and melted away grasses were weighted down and melt-out sediments (gravel, sand, mud) was observed between grass blades. Such spots were surrounded by lush grassy tundra. In many

sites tundra was compressed also by tsunami-derived boulders both eroded from beaches and melted out of icebergs (Fig. 3b).

Lines 107-122: Are there any recognizable differences between areas of wave overflow (into harbour) and area of wave uprush, followed by drainage?

Author's Response: Thank you for question and suggestion. Indeed, we reanalysed our field observations and introduced a differentiation between wave overflow (saddle area) and area of wave uprush and drainage located in the eastern part of settlement.

Line 111: I assume this is referring to modification by snowmelt runoff, but the text "modified by snow-melt flow tsunami deposits accumulations" is confusing and meaningless.

Author's Response: Thank you for spotting this error. We have rewritten the sentence. We have found several sites were the thin layer (3-5 cm) of tsunami deposits were already slightly reworked by flowing water (snowmelt).

Line 112: Here and elsewhere, you reference "the lowland" – I assume this is the low part of the peninsula ridge and might be best described as the "saddle" through which the waves washover over into the west harbour. This is a recognized landscape term.

Author's Response: Thank you for this suggestion, we were looking for a proper term and your advice helped us a lot. Now the description of study site and our figures are much clearer.

Line 118: ". . . at the border" – meaning?

Author's Response: Thank you for this suggestion, we have deleted this term and rewritten this sentence

Line 128: You state that damage to 26 buildings was documented. What percentage of all buildings in the community does this represent? Were some undamaged? Does it include all damaged buildings?

Author's Response: Thank you for your question. We have added more detailed information here. 48% of Nuugaatsiaq buildings (both housing, administrative or technical objects like tanks) were destroyed by tsunami.

Line 130: Not clear what is meant by "point foundations" – Is this what we call block foundations in Canada? Simple piles of wooden blocks and wedges supporting the sills. Or something else?

Author's Response: Thank you for your question. We have consulted the proper technical term with building engineers and changed the name into 'pier foundations'

Lines 160-162: What about Qullisssat? Abandoned for other reasons?

Author's Response: Thank you for your question. Qullisssat was abandoned almost 30 years before the tsunami impact. The main reason for abandonment was the collapse of economic base of settlement – coal mine.

Line 165: We need, at least briefly, results and discussion pertaining to other social and economic impacts listed in Table 1, or otherwise they stand as unsubstantiated statements.

Author's Response: We have changed the structure of the described results, extended their description using the content of the table one information. Now the paragraph (4.3.2) stands as:

The Karrat fjord tsunami, which hit Nuugaatsiaq settlement in 2017, was the first event which had such a devastating effect on inhabited Arctic settlement, both in terms of landscape modification and infrastructure damage. Previous waves known from the Arctic region such as Lituya (1958), Taan (2015) flooded unpopulated and remote areas. In Greenland the Paatuut tsunami (2000) damaged the infrastructure of Qullissat, however in this case, due to the closure of unprofitable coal mine (1972) the settlement was already abandoned years before the event. Therefore, this is the first time an assessment of social and economic effects of a tsunami in this region was possible to undertake (Table 1).

The financial data from the Government of Greenland (Naalakkersuisut) documents (Forslag til TILLÆGSBEVILLINGSLOV for 2017, from 2018/8), shows the costs associated with the relocation of tsunami victims of 14 877 000.00 DKK (ca. 2 248 085.00 USD [15.05.2020]) which can be treated as a rough estimate of an economic cost of the event. The document also declares a one-off payment to tsunami victims amounting to DKK 50,000 (7548.00 USD [15.05.2020]). In our opinion the total economic cost was significantly higher as the total market value of 45 destroyed settlement infrastructure objects (incl. buildings) was not included in the reports. Nevertheless, the settlement remains abandoned to this day and the threat of another tsunami wave remains active (Fritz et al. 2018; Paris et al. 2019). Apart from the tragedy of 4 fatalities, 9 wounded inhabitants and countless dog deaths, the catastrophe still has its social repercussions. Thirty-nine people were evacuated and separated into the settlements of Uummannaq and Qaarsut. The Displaced have lost their life's work, their hunting area, sentimental value, and social bounds. In their new places more expensive rent, isolation and adaptation difficulties often awaits them (*personal communication* of local respondent).

From the perspective of environmental protection and coastal management, the remaining material and waste in the settlement area still constitute a serious hazard. Despite the considerable effort from the local government to secure the site through reinforcement of damaged constructions, pumping fuel out of the tanks, the removal of batteries and engines from machines and vehicles, we mapped significant amounts of waste (Fig. 7 e-g). We found broken pieces of electronic equipment, ammunition, rotting food supplies, bags with faecal matter, sledge dog carcasses, and other municipal waste which had not been disposed from the settlement before and after the event (Fig. 7). In Nuugaatsiaq plastic litter is widespread not only along narrow beaches (already mixed with beach sediments), but also spread long main road of the settlement and around overwashed saddle between southern coast and harbour, and subject to further transport by strong winds (Fig. 7). Plastic waste is a serious problem of Arctic coastal environments and Nuugaatsiaq case is unfortunately another contributor to this type of environmental pollution (e.g. Cózar et al. 2017; Bergmann et al. 2017; Jaskólski et al. 2018). After the evacuation of Nuugaatsiaq the disposal of waste and better securing of damaged infrastructure at the site is hindered by the existing high risk of another tsunamigenic landslide in Karrat Fjord (Paris et al. 2019).

Line 179: Change "are going to be" to "are likely to be"

Author's Response: Thank you for your suggestion. Corrected

Line 190: Change “are going to be” to “are projected to be”

DONE

Lines 196-197: First conclusion bullet – Change to “. . . directly impacted an Arctic inhabited settlement and forced it evacuation.”

DONE

Lines 205-207: Reference to explanation “by the local morphology and geology . . .” – This is why we need more details on the study site in the introduction.

DONE. With new paragraph on physical geography, climate and geology this should be much more clear now.

Line 208: Re “mapped tsunami deposits” – These need to be shown on the map. Lines 213-214: Delete final clause “and are analogous to . . . Yukon” – This is highly debatable.

DONE

General query: No reference anywhere to permafrost or frozen ground. Is this area permafrost-free?

Author’s Response: Thank you for question. The study area was historically included in the continuous permafrost zone (Christiansen and Humlum, 2000). Most recent northern hemisphere permafrost map based on the modelling of temperature at the top of the permafrost (2000-2016) at the 1 km2 scale presented by Obu et al. (2019) place it close to the boundary zone between continuous and discontinuous permafrost zone. To our knowledge no direct ground temperature measurements have been conducted in the close surroundings.

General query: Most far-travelled boulders seem to be ascribed to ice-rafting. Large waves can transport large boulders tens to hundreds of metres across relatively smooth surfaces (such as a grassed slope or saddle), so I would not be surprised if some boulders were deposited by the waves (after all they toppled the front-end loader).

Author’s Response: Thank you for comment. We agree with your suggestion that boulder could be derived from beach/coastal zone. We have observed accumulation of large boulder spread long the pocket beaches and rocky coves.

References line 241, Chao et al: 2018 here but 2017 on line 61. References lines 254-256: State of the Arctic Coast 2010 was published in 2011.

Author’s Response: Thank you for correction. We have corrected the references.

Figure 1: Please plot elevations and runup limits on this or similar map.

Figure 2: Would appreciate locations of a, b, c.

Figure 3: Please provide locations. These figures are too small to be easily comprehended.

Figure 4: It is unclear whether some yellow buildings mark the displaced position of red buildings. The legend describes red buildings as destroyed, so if some were moved, they should have another colour representing original locations of displaced buildings. Also, on this map or Figure 1c or another, please plot mapped deposits in relation to runup limits.

Figure 5: Good to have locations for all these figures. They are very small but legible.

Author's Response: Thank you for suggestions and comments regarding our figures. We have corrected all of graphical design in the paper and introduced 7 new figures.

8.) Editorial comments: These are numerous and could be provided to the authors most easily in a Word or rtf document. Note several missing references: Bessette-Kirton et al. 2017; Clinton et al. 2017. I can provide some additional references re tsunami hazards in Baffin Island if desired

Author's Response: We have corrected the reference list and add or deleted the missing works. Thank you also for your offer. We would be very grateful for your help with the revised manuscript. Additional references for Baffin Island would be useful too.